Universidade de Aveiro Departamento de Engenharia Civil
Ano 2016

António José Pereira de Figueiredo

ESTRATÉGIAS DE EFICIÊNCIA ENERGÉTICA E CONFORTO PARA CLIMAS DO SUL DA EUROPA: OTIMIZAÇÃO DA PASSIVE HOUSE E DE SOLUÇÕES COM PCM

ENERGY EFFICIENCY AND COMFORT STRATEGIES FOR SOUTHERN EUROPEAN CLIMATE: OPTIMIZATION OF PASSIVE HOUSING AND PCM SOLUTIONS

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Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Engenharia Civil, realizada sob a orientação científica do Doutor Romeu da Silva Vicente, Professor Associado do Departamento de Engenharia Civil da Universidade de Aveiro e coorientação do Doutro José Claudino Cardoso, Professor Associado do Departamento de Engenharia Civil da Universidade de Aveiro e da Doutora Maria Fernanda da Silva Rodrigues, Professora Auxiliar do Departamento de Engenharia Civil da Universidade de Aveiro

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Thesis submitted to University of Aveiro to fullfill the requirements of the Doctoral Program in Civil Engineering, held under the scientific supervision of Doctor Romeu da Silva Vicente, Associate Professor at the Civil Engineering Department of University of Aveiro and scientific co-supervision of Doctor José Claudino Cardoso Associate Professor at the Civil Engineering Department of University of Aveiro and Doctor Maria Fernanda da Silva Rodrigues, Assistant Professor at the Civil Engineering Department of University of Aveiro.

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agradecimentos

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Por fim, a ti, por todo o significado que tens…

palavras-chave

eficiência energética; Passive House; simulação dinâmica; conforto adaptativo; análise de sensibilidade; materiais de mudança de fase; algoritmos evolucionários; otimização com múltiplos objetivos.

resumo

A procura de soluções de sustentabilidade holísticas que conduzam ao cumprimento dos desafios impostos pela Convenção-Quadro das Nações Unidas sobre as Alterações Climáticas é uma meta estimulante. Explorar esta tarefa resulta num amplo número de possíveis combinações de estratégias de poupança energética, sendo estas alcançáveis através do conceito definido pela Passive House (PH) e pela utilização de materiais de mudança de fase que se revelam como materiais inovadores neste contexto.

Reconhecendo que este conceito já se encontra estabelecido e disseminado em países de climas frios do centro e norte da Europa, o presente trabalho de investigação foca-se na aplicabilidade e adaptabilidade deste conceito e correspondentes técnicas construtivas, assim como os níveis de energia, para climas do sul da Europa, nomeadamente em Portugal continental. No sudeste da Europa, adicionalmente à necessidade de cumprimento dos requisitos energéticos para aquecimento, é crucial promover e garantir condições de conforto no verão, devido ao elevado risco de sobreaquecimento. A incorporação de materiais de mudança de fase nas soluções construtivas dos edifícios, utilizando a energia solar para assegurar o processo de mudança de fase, conduz a soluções de elevado potencial para a redução global da energia consumida e do risco de sobreaquecimento.

A utilização do conceito PH e dos materiais de mudança de fase necessitam de ser adaptados e otimizados para funcionarem integrados com outros sistemas ativos e passivos, melhorando o comportamento térmico dos edifícios e minimizando o consumo energético. Assim, foi utilizado um algoritmo evolutivo para otimizar a aplicabilidade do conceito PH ao clima português através do estudo e combinação de diversos aspetos construtivos, bem como o estudo de possíveis soluções construtivas inovadoras com incorporação de materiais de mudança de fase minimizando as funções objetivo para o cumprimento das metas inicialmente definidas.

keywords

energy efficiency; Passive House; dynamic building simulation; adaptive comfort; sensibility analysis; phase change materials; evolutionary algorithms; multi-objective optimization.

abstract

Pursuing holistic sustainable solutions, towards the target defined by the United Nations Framework Convention on Climate Change (UNFCCC) is a stimulating goal. Exploring and tackling this task leads to a broad number of possible combinations of energy saving strategies than can be bridged by Passive House (PH) concept and the use of advanced materials, such as Phase Change Materials (PCM) in this context.

Acknowledging that the PH concept is well established and practiced mainly in cold climate countries of Northern and Central Europe, the present research investigates how the construction technology and energy demand levels can be adapted to Southern Europe, in particular to Portugal mainland climate. For Southern Europe in addition to meeting the heating requirements in a fairly easier manner, it is crucial to provide comfortable conditions during summer, due to a high risk of overheating. The incorporation of PCMs into building solutions making use of solar energy to ensure their phase change process, are a potential solution for overall reduction of energy consumption and overheating rate in buildings.

The PH concept and PCM use need to be adapted and optimised to work together with other active and passive systems improving the overall building thermal behaviour and reducing the energy consumption. Thus, a hybrid evolutionary algorithm was used to optimise the application of the PH concept to the Portuguese climate through the study of the combination of several building features as well as constructive solutions incorporating PCMs minimizing multi-objective benchmark functions for attaining the defined goals.

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NOTATION

The notation has not been all placed, because some of them are described throughout the document.

ACR – Air Change Rate

AHU – Air Handling Units

BWM – Box Whisker Mean

CICFANO – Complexo Interdisciplinar de Ciências Físicas Aplicadas à Nanotecnologia e à Oceanografia

CTF – Conduction Transfer Function

C.U – Compact Unit

CV RMSE – Coefficient of Variation of the Root Mean Square Error

CMA-ES – Covariance Matrix Adaptation Evolution Strategies

DGEG – General Division for Energy and Geology

DBES – Dynamic Building Energy Simulation

EP – Energy Plus

EPBD – Buildings Energy Performance Directive

EU – European Union

EMS – Energy Management System

GFP – Gas-Filled Panels

GHE – Green House Effects

GHG – Green House Gases

GOF – Goodness Of Fit

HVAC – Heating Ventilation and Air Conditioning

HDE – Hybrid Differential Evolution

IAQ – Indoor Air Quality

IEA – International Energy Agency

IEQ –Indoor Environmental Quality

ISO – International Organization for Standardization

IWEC – International Weather for Energy Calculations

IBPSA – Building Performance Simulation Association

LCA – Life Cycle Assessment

LCC – Life Cycle Cost

LSF – Light Steel Frame

LNEG – National Laboratory for Energy and Geology

LVDT – Linear Variable Differential Transformer

NIM – Nano Insulation Materials

nZEB – Near Zero Energy Buildings

PCM – Phase Change Materials

PH – Passive House

PHPP – Passive House Planning Package

RMSE – Root Mean Square Error

RCCTE – Thermal Buildings Regulation

RSECE – Regulation of Energy Systems Air Conditioning

RECS – Service Buildings Energy Efficiency Regulation

REH – Residential Buildings Energy Efficiency Regulation

SCE – Building Certification System

SHGC – Solar Heat Gain Coefficient

TPES – Total Primary Energy Supply

TZ – Thermal Zone

UNFCCC – United Nations Framework Convention on Climate Change

VIP – Vacuum Insulation Panels

CHAPTER 1

INTRODUCTION, OBJECTIVES, OVERVIEW AND OUTLINE

Chapter outline

1.1 – Background and motivation

1.2 – Objectives

1.3 – Outline and document organization

1.4 – Global methodology

1. INTRODUCTION, OBJECTIVES, OVERVIEW AND OUTLINE

Abstract Chapter 1 of this thesis begins with a short background and motivation, which introduces the research by providing the guidelines that set the stage for the presented work. Furthermore, the purpose and the objectives are clearly addressed to state the knowledge to contribute to the research carried out. Lastly, this chapter is closed with the outline and document organisation and a global methodology flowchart of the thesis is presented.

1.1 – Background and motivation

A large share of primary energy is currently consumed in urban settlements at the building level, with alarming environmental disorder and import. Thus, the environmental concerns and the need to decrease the energy consumption at the world scale, targeted by the United Nations Framework Convention on Climate Change (UNFCCC), has led to new and more restrict practice and policies. These concerns are an opportunity to develop new efficiency and sustainability solutions to meet the Nearly-Zero Energy Buildings (nZEB) goals. The nZEB concept is a challenge not only at European level but also at a global context due to the high impacts of the building sector on the energy consumption and on the environment. To support the development of eco-efficient buildings the European Union (EU) framework program Horizon 2020 [1] is presently the most important financial instrument for research (around 70,000 million € over seven years, 2014-2020), of which it is expected that around 35% of the financial budget will be related with climate expenditure [2].

To achieve these goals it is necessary to progressively abandon the use of energy derived from nuclear, coal, oil and gas derived energy in favour of renewable energy sources, such as: wind, hydro, solar, biomass, and geothermal [3]. Additionally, the use of thermal insulation materials is currently the most effective way of reducing energy losses in buildings, thus reducing energy demand. The traditional materials used for this purpose are: expanded polystyrene, mineral wool, extruded polystyrene, rigid foam of poly-isocyanurate or polyurethane and increasingly the expanded chipboard cork (non-exhaustive list) [2, 4-7]. However, these materials are associated with high impact in terms of toxicity, and the requirements in terms of energy saving in buildings over the years, lead to a growth of the thickness of traditional thermal insulation materials. Vacuum insulation panels (VIP) are one of the most promising building insulation materials which can be an alternative to traditional materials [2, 8]. These materials provide an insulation performance almost ten times higher than current materials. Moreover, other advanced insulation materials are also very promising such as aerogel, gas-filled panels (GFP), nano insulation materials (NIM) and finally phase change materials (PCM) [8, 9] that are under the scope of this thesis. Phase change materials incorporated into building constructive solutions, and using solar energy to ensure their phase change process, are a potential passive solution for an overall reduction of energy consumption used for heating and cooling in buildings. The phase change materials have been developed over the last 40 years and their potential advantages as well as drawbacks in the use of building solutions applications are identified. The greatest advantage of the use of PCM is their high energy storage capacity during the phase change process. During this process, the PCM has the capacity to store and release large amounts of energy in comparison with the common building materials.

In recent years (2000-2009 period), the energy consumption in EU buildings has not changed significantly, but on the other hand, in the South Western European countries the cooling energy demand has increased [10, 11]. Therefore, it is important to highlight the need to thoroughly understand and assess the parameters of thermal codes adopted in those countries by optimizing insulation thickness for mitigation of the cooling demand without undertaking a high overheating risk in summer. Current research in this field (reducing cooling demand) is focusing on the following construction components and strategies: reflective pavements, permeable and water retentive pavements, passive evaporative cooling walls, heat absorbing phase change materials, cool roofing materials, green facades and green roofs, night ventilation, ground cooling and floor slab cooling [2, 12-15]. Thus a broad range of passive strategies to assure good comfort levels and indoor air quality should be explored to reduce the energy consumption and to improve the indoor environmental quality. The Passive House (PH) concept is a possible basis to fulfil this goal, although it is necessary to adapt the building technology and requirements to the local climate data, in respect to more complex features.

In focus in this thesis, are school buildings that are responsible for a significant percentage of the energy consumption in the public sector. Regarding these buildings, in Europe there is a growing concern of the need for the use of sustainable strategies ranging from materials, constructive solutions and other passive measures in new and refurbished buildings. A study of the energy consumption in school buildings, developed in Northern European countries, revealed that the heating demand can be reduced up to 75% and the electricity consumption can be reduced by 40% [16]. Therefore this building typology and use (school buildings) deserves special attention because of the environmental conditions inside classrooms, (temperature, relative humidity and Indoor Environmental Quality (IEQ)) that influence user's health and their overall performance. Some authors classified the IEQ in these buildings typology as "poor" [17-23]. In order to reduce the energy consumption in school buildings and ensure the IEQ conditions, some countries have sponsored programs for the retrofit and refurbishment. However, in the bibliography database of some studies carried out, it has been proved that the performance of buildings after deep interventions sometimes is very different from the predicted in the design stage [24-27]. In this scope, the thermal performance of classrooms must be previously evaluated with results provided by *in-situ* monitoring campaigns. With validated and calibrated results, optimised solutions can be pursued and the design project can be more accurate for the desired comfort conditions.

In sum, this thesis builds on the trend, focusing on sustainable building design including the use of renewable energy sources and the development of new technologies and materials.

1.2 – Objectives

The main goal of this study is to deepen and increase the knowledge of techniques for energy saving in buildings on the following levels:

i. Passive House implementation and compatibility for South European climate;
   a. Sensitivity analysis of lightweight steel buildings to comply with the requirements defined by PH standards;
   b. PH features optimization for implementation in Portugal mainland for massive building typology with a contemporary architecture (high glazing areas) as a representative case study;

ii. Development of innovative construction systems and solutions using different types of PCMs;
   a. Mechanical and thermal characterization of concrete with incorporation of microencapsulated PCM;
   b. Classrooms monitoring and comfort assessment of paraffin PCM panels incorporated into partition walls and false suspended ceilings;
   c. Overheating optimization using constructive solutions containing different types of PCMs.

This study contributes partially on energy efficiency and indoor comfort strategies for residential and school buildings to ensure that construction, design criteria, and retrofitting strategies, achieve maximum/optimised energy efficiency levels and maintain indoor environmental quality.

To tackle the presented main goals, three buildings typology are under scope: (i) a detached building of contemporary architecture with lightweight steel structure; (ii) a detached building of contemporary architecture with a concrete frame structure and double leaf masonry infill walls; (iii) a department building at the University of Aveiro that incorporates PCM innovative constructive solutions.

For the first challenge (lightweight steel building) a numerical model was developed from the original design solution. Parametric studies were carried out in order to assess and improve thermal comfort and to meet the requirements defined by the PH concept. For the second challenge (building with concrete frame and masonry walls) a numerical model was also developed from the original solution designed to comply with the upgraded Portuguese thermal code (running in 2012 [28]). Parametric and optimization studies were once again carried out with the same purpose indicated for the first challenge. For the final challenge a school department was studied. Firstly, the influence of microencapsulated PCM over a thermally activated concrete screed slab mechanical and thermal properties were quantified. Secondly, two classrooms of this building were monitored over the period of one year (temperature and relative humidity). In this case study, the main goal was to minimize overheating risk resourcing to PCM solutions.

1.3 – Outline and document organization

The work herein presented is divided into seven chapters developing on the following topics carried out:

The first chapter presents a brief introduction of the main topic of the developed work, followed by the description of the main objectives proposed for each chapter. Then, the outline is depicted and as well as the document organization. The final section of this chapter presents the research methodology strategy followed, illustrated using a flow diagram, to thoroughly understand the link between chapters.

Chapter 2 is dedicated to thermal comfort and energy performance assessment of the PH concept to the Portuguese climate. This chapter starts with a brief introduction on the topic, followed by a recent and compact state-of-art wherein on the PH standard and principal applications around the world, focusing on Southern European climates. The case study is presented and characterized according with the original constructive solutions and simulated using on-site climate database. Thus, a sensitivity analysis, changing passive and hybrid features were performed complying with the PH requirements. Then, the constructive solutions and systems are depicted to attain a PH compliant building for the Aveiro region. Finally, this study was applied for different district capitals of Portugal mainland representative of each climate zone depicted in the study.

Chapter 3 presents a general framework on the issue of mechanical and thermal characterization of concrete incorporating phase change material. This study starts by referencing recent research on concrete and mortars incorporating PCM. Then, an experimental campaign was developed around the objective of quantifying the influence of microencapsulated PCM loading over the concrete mechanical and thermal properties. The research begun with the preparation of *in-situ* specimens produced at the construction site during concreting activities of the floor slabs followed and complemented with additional laboratorial specimens. Specimens produced were used to assess mechanical and thermal properties and then the results were compared with results from literature.

Chapter 4 outlines a study on the Passive House optimization for the Portuguese climate. This study is based on the strategy presented in Chapter 2 and represents an evolution, as a different approach to validate the PH concept when applied to Portuguese climate conditions. However, this work was developed on a representative contemporary architecture building built with concrete frame structure and masonry cavity walls infills complying with the Portuguese thermal code (running in 2012 [28]). This building was monitored during the last week of August and in the first week of December 2013 with thermo-hygrometer sensors to record temperature and relative humidity. The monitored values were used to validate the dynamic numerical model of the original construction and a sensitivity analysis is performed and compared with an optimization approach using an evolutionary algorithm. Thus, and analysing the results, the optimiser was used to assess the PH adaptability for the Portuguese climate. Finally a sum of constructive solutions and equipment combinations, as well as other recommendations are presented to support designers, owners and contractors.

Chapter 5 focuses on the overheating issue inherent to lightweight buildings constructed in southwest European climates with low thermal inertia. After the work carried out on the PCM and optimization topics, the research work presented in Chapter 2 was deepened, focusing on the overheating reduction issue. This work starts by removing the equipment for cooling and the variable parameters were defined. The overheating and energy heating demand were the objective functions. Then some features with expected direct influence on the energy balance were combined and optimised with different PCM solutions. The last part of this task was set to promote the development of a new PCM solution material which combines different melting points.

Chapter 6 starts with the detailed description of the case study (department building at University of Aveiro Campus). The main objective of this study is to characterize the indoor thermal comfort of two indoor rooms of the department building. As referred in section 1.2 this building has been monitored over one whole year (temperature and relative humidity). The rooms with the same indoor space and geometry, orientation, opaque constructive solutions, glazed area and use, were monitored to be compared. In one of these rooms PCMs panels were incorporated into the partition wall and false ceiling in the form of panels, and the other room has no application of PCM to be considered the reference room. The results were evaluated in accordance with EN 15251 [29] to characterize indoor comfort rate during all seasons of the year. Then a dynamic numerical model was created with the goal of tackling overheating reduction using different PCM solutions combined with different air flow ventilations rates. The calibration issue, typically observed in numerical models, was tackled with a new methodology proposed for dynamic model calibration using an evolutionary algorithm. Thus, and after the model calibration, a multi-objective optimization was developed to optimise the PCM efficiency over the overheating reduction, as well as, the global heating demand. Lastly a simple economic analysis on the PCM solution used is discussed and compared with the optimised solutions.

Finally, Chapter 7 resumes the main results and presents future work proposals.

1.4 – Global methodology

This section aims to systematize the thesis organization and the link between the research activities (experimental and numerical). Thus, and to clearly expose all the work developed, in the scope of the thesis, Figure 1.1 flowchart is presented.

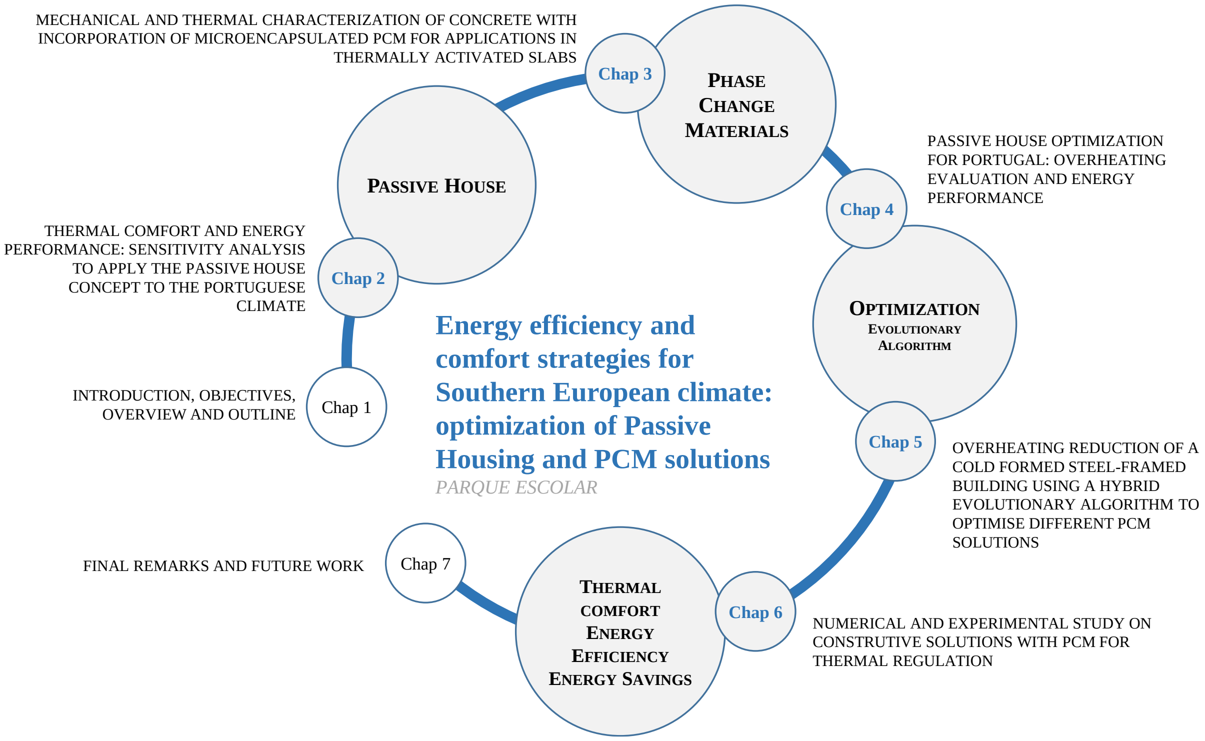


Figure 1.1 – Flowchart of the thesis

As shown in Figure 1.1, the thesis starts with an overall introduction followed by the objectives and the overview. Then, the Passive House concept is studied, associated to light steel frame building typology using a sensitivity analysis as a strategy. This case study will be used and re-assessed in the Chapter 5 after the PCMs introduction. Thus, Chapter 3 introduces PCMs and a mechanical and thermal characterization campaign of concrete mixtures with the incorporation of microencapsulated PCM. These PCM solutions with the capacity to store energy will be explored in Chapters 5 and 6 for overheating reduction and energy efficiency. In Chapter 4 the Passive House concept is again applied to another case study (building of massive construction with higher thermal inertia), however the strategy was changed by the use of an evolutionary algorithm for different features optimization. Regarding Chapter 5, as indicated, the case study was already presented in Chapter 2, and an optimization approach was developed using PCM solutions with the main goal of overheating reduction. Chapter 6 is dedicated to thermal comfort evaluation and energy efficiency using PCM solutions optimization, as a strategy for energy saving and overheating reduction. In this chapter, the University department building is used as case study in which experimental and numerical studies were developed. Finally Chapter 7 sums up the main findings of the thesis and presents future work proposals.

CHAPTER 2

THERMAL COMFORT AND ENERGY PERFORMANCE: SENSITIVITY ANALYSIS TO APPLY THE PASSIVE HOUSE CONCEPT TO THE PORTUGUESE CLIMATE

Chapter outline

2. THERMAL COMFORT AND ENERGY PERFORMANCE: SENSITIVITY ANALYSIS TO APPLY THE PASSIVE HOUSE CONCEPT TO THE PORTUGUESE CLIMATE

Work related to this chapter was published in the **Building and Environment** – The International Journal of Building Science and its Applications. Impact Factor: 3.34 ·DOI: 10.1016/j.buildenv.2016.03.031

Abstract The need to apply the Passive House concept to Mediterranean countries climate is regarded as being of great importance to support countries such as Portugal to reduce its primary energy demand associated to buildings consumption and thus, devising a cost-efficient strategy to meet the targets pointed out by the recast of the EPBD 2010/31/EU. In this sense, the present research intends to contribute to the implementation of the Passive House concept in Portugal, by means of a detailed study for the Aveiro region and a more broad analysis examination for different district capitals of Portugal mainland. A detached two-storey lightweight steel structure of contemporary architecture was modelled as case study for the Portuguese climate, based on its original design solutions and resorting to the EnergyPlus® software. From this original model, sensitivity analyses were carried out in order to meet the parameters defined by PH standards. The improved results from the climate region of Aveiro, in Portugal, have led to a reduction of the 62%, 72% and 4.4% for the heating demand, cooling demand and overheating rate, respectively (comparing the improved solution with the original as reference). It was therefore possible to meet the PH requirements, proving its applicability to the Portuguese climate and for this particular building technology.

2.1 – Introduction

In recent decades, as societies are increasingly more dependent on energy, the impact resulting from fossil fuels and the nuclear power energy exploitation threats sustainable limits. Recently, substantial efforts have been made by governments, environmental protection bodies and decision-makers to face these threats and the consequences of climate change and shortage of natural resources. Since the 1970s, the need to downsize the energy consumption and concentrate our energy market on renewable energy sources led to the development of several sustainable strategies, such as solar thermal for domestic hot water preparation, presently mandatory for new constructions and deep refurbishments. During the last decade, the energy consumption in European buildings has not increased significantly, however buildings account for 40% of total energy consumption in the EU [30]. As an example, detailing this indicator for countries as the Netherlands and United Kingdom (UK), buildings account for 35% and 47% of the total energy use, respectively [31, 32]. In Portugal, according to the General Division for

Energy and Geology (DGEG), the energy consumption in 2009 related to residential buildings represented approximately 17% of the total primary energy supply [33]. Moreover, according to the BPIE [34], in terms of floor area, the EU residential stock represents 75% of the total EU building environment, stressing out the influence of residential buildings over the EU total energy consumption. Therefore, energy reduction in the built environment is a crucial measure to be followed.

Based on these evidences and following the Kyoto protocol, in December 2002, the Energy Performance of Buildings Directive (EPBD) was approved by the EU Parliament aiming to promote the improvement of the energy performance of buildings, considering outdoor climate and local conditions, as well as indoor climate requirements and cost-effectiveness [35]. Eight years later, the recast of the previous Directive was approved, introducing new requirements, definitions and deadlines. According to this recast, buildings constructed after 2020, or after 2018 in the case of public service buildings, are required to be nZEB [36]. By implementing these measures, the European Parliament expects to comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change, and to comply with its long term commitment to maintain the global temperature rise below 2º C, and its commitment to reduce, by 2020, overall greenhouse gas emissions by at least 20% below 1990 levels, or by 30% in the event of an international agreement being reached [30].

Within this framework, the Passive House concept has emerged as a very promising solution to reduce the energy demand of buildings by promoting low energy building technology, and to achieve these challenging goals towards the environment. The aim of the PH concept is to provide an acceptable and even improved indoor environment in terms of IAQ and thermal comfort at minimum energy demand and cost [37]. The PH standard can be met independently from materials, design concept or technology applied, and is based on five main principles: excellent thermal insulation; efficient windows; perfect air tightness; minimisation of thermal bridges and a ventilation system with heat recovery. An extended description of the Passive House principles and thermal requirements can be found in [38].

According to the Passive House concept, in order to achieve this standard it is essential that the building complies with the following requirements: i) the space heating energy demand is not to exceed 15 kWh/m^2a of net living space (treated floor area) per year or 10 W/m^2 peak demand; ii) the primary energy demand, the total energy to be used for all domestic applications (heating, hot water and domestic electricity) must not exceed 120 kWh/m^2a of treated floor area; iii) in terms of air tightness, a maximum of 0.6 air changes rate (ACR) per hour at a 50 Pa pressure difference, as verified with an on-site pressure test (in both pressurised and depressurised states is established); iv) thermal comfort must be met for all living areas during winter as well as in summer, with not more than 10% of the hours in a given year over 25º C [39-41].

Defining thresholds for thermal comfort has been an extremely challenging task since it depends on both quantifying factors, such as temperature or air velocity, and non-quantifying factors of both psychological and sociological nature. Nonetheless, currently there are four different codes based on physiological models, accounting for people's needs when facing different thermal environments, which define indoor thermal comfort: ASHRAE 55 [42]; EN 7730 [43]; EN 15251 [29] and ISO/TS 14415 [44]. Comfort and energy demands of buildings are commonly evaluated through steady state and transient analysis. Since static approach do not provide enough information for supporting decisions concerning optimal design solutions, dynamic analysis was undertaken in the present work as they currently embody useful computational features for several fields of application. Figure 2.1 presents some of the concepts herein mentioned, as well as the relevant features from building solutions and technology for energy efficiency in buildings, from passive design to hybrid solutions commonly used and also the definitions from nZEB to Plus Energy buildings.

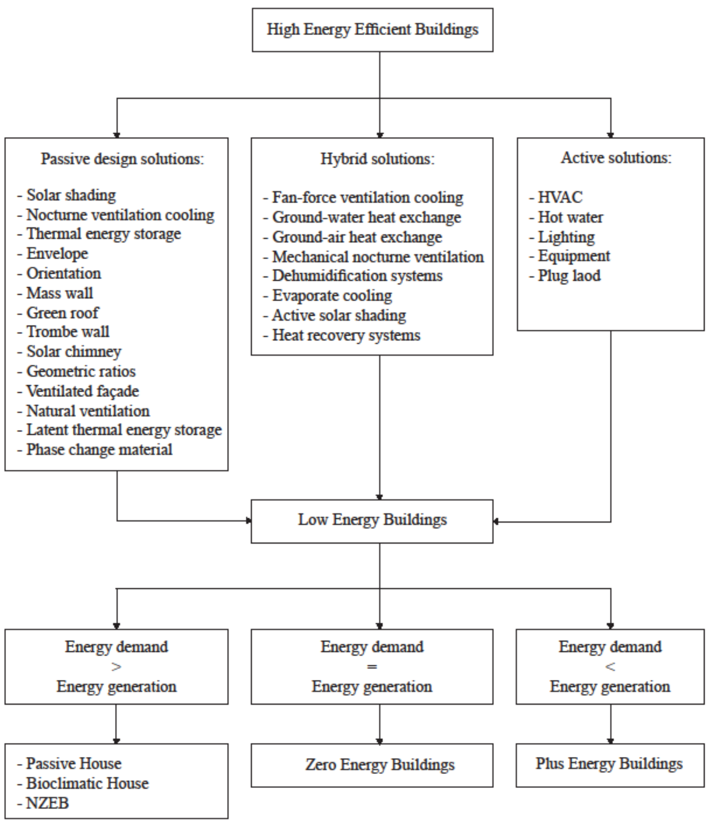


Figure 2.1 – High energy efficient buildings diagram

Although the Passive House standard has been initially developed for Central European countries, where space cooling during the warmest annual seasons is not a worrying issue, however for buildings located in other geographical areas such as Mediterranean countries, cooling energy demand is increasingly more necessary to avoid overheating in summer [45, 46]. A number of studies have reported better thermal comfort in winter than in summer and it is expected, with the climate change, a negative impact on summer comfort in buildings [47]. Thus, several studies were developed over the PH concept implementation in Southern Europe. Viorel Badescu and Nicolae Rotar [48] have developed a study on the PH concept implementation for Romania. This study was performed with a general climate conditions comparison between Germany and Romania. The authors concluded that the thermal envelope design solutions for Romania may be more permissible when compared with the German based solutions.

In Portugal, to tackle the EPBD recommendations, the government defined as targets to increase in 40% the energy efficiency of buildings through publishing the following regulations: the National Action Plan for Energy Efficiency (Resolution of the Ministers Council of no. 80/2006) [49]; the review of the old Thermal Regulations for both residential (RCCTE, Decree-Law no. 80/2006, 4th April) [28] and office buildings (RSECE, Decree-Law no. 79/2006, 4th April) [50], and the introduction of the National System for Energy and Indoor Air Quality Certification of Buildings (SCE, Decree-Law no. 78/2006, 4th April) [51]. Presently, the codes have been upgraded both residential and small office buildings undergoing major refurbishments or changes to its external envelope are required with to comply the requirements defined in REH and RECS [52, 53]. The implementation of these measures is intended to reduce energy consumption levels through more accurate calculations and to set greater requirements for the thermal quality of buildings, which has resulted in the improvement of the thermal comfort of residential buildings [54].

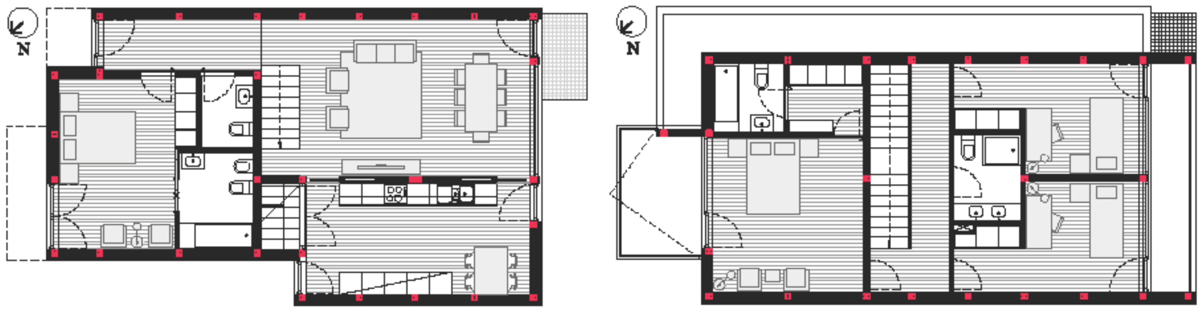
Facing the reality of the Portuguese residential building stock [54], it is important to thoroughly understand and assess the parameters of thermal codes adopted in Mediterranean countries by optimising insulation thickness for the mitigation of cooling demand without originating a high overheating risk in summer, still complying with the Passive House standards. The Passive-On project (promoted and coordinated by the end-use Efficiency Research Group of Politecnico di Milano) ran from January 2005 to the end of September 2007 and focused on the PH concept application for Southern Europe and Mediterranean climates. In these regions, the main problem of household energy use is not only to provide warmer houses in winter but also to provide cooler houses in summer, limiting the overheating rate. In this project it was concluded that the Passive House concept is viable, however deeper studies are essential to adapt and detail the technical and constructive solutions for specific regions in Southern and Mediterranean climates.

Other research projects developed by regional institutions have also focused on the PH concept application in other countries. CEPHEUS project within the THERMIE programme of the European Commission, that began in January 2008 and finished December 2012 promoted the construction of 250 housing units to Passive House standards in five European countries, with evaluation of building operation through systematic measurement programmes. PASS-NET was a project established a co-operation network of Passive House promoters spreading the knowledge on PH standard within Europe. The PassREg project ended in April 2015, targeted the implementation of nZEBs throughout the Europe using PH supplies as much as possible by renewable energies as the foundation. A final report was created and edited with the name "Passive House Regions with Renewable Energies". The EuroPHit research consortium [55], is a project develop and driven towards the existing building stock is still ongoing. This project goals engages int te EnerPhit standard on a step-by-step approach. This project led to the creation of an accessible informational brochure that highlights the successes of the EuroPHit project and case studies.

2.2 – Case study of a light steel frame building

2.2.1 – Building general characterisation

The present case study building, in Figure 2.2, consists of a prefabricated lightweight two-storey LSF structure (Light Steel Frame) with a volume of 420 m^3, a treated floor area of 148 m^2 and an untreated area of 75 m^2 corresponding to the underground garage zone, which is isolated from the main structure and therefore was not considered as a treated area in the current study. A building with this area and geometry, is considered as a representative of a contemporary single family building. This case study was chosen, due to a growing tendency of pre-fabricated construction systems as a faster and more economic building solutions. The constructive technology is composed of prefabricated elements, offering significant cost reduction potential and at the same time allows for improved quality control. However, this building technology presents a low thermal inertia and a consequential risk of overheating as major weaknesses, therefore highlighting the necessity to adapt the building constructive technology and requirements to the local climate. The building form factor was evaluated in 0.84 estimated according to the national thermal code.

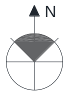
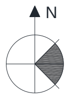
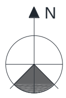
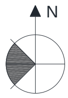


(a) (b)

Figure 2.2 – Architectural blueprints of the case study building: (a) ground floor; (b) first floor levels

Table 2.1 presents the building total window-to-wall ratio, evaluated in 16.4%. According to this table one can observe that the largest glazed surfaces are Southwest-oriented to optimise solar gains. However, more efficient shading techniques are required to prevent overheating risk in the warm season.

Table 2.1 – Total and glazing surfaces in m2 and the window-to-wall ratio of the case study building (%)

	Total				
Total surfaces	198.4	35.7	63.5	35.7	63.5
Glazing surfaces	32.5	11.5	-	21.0	-
Window-to-wall ratio	16.4	32.3	-	58.7	-

The building's facade walls are mainly composed of metallic modular system elements, which should be carefully designed, detailed and installed in order to minimise energy losses. Table 2.2, resumes some fundamental properties of materials adopted for the ground floor level, facade walls and roofing system, namely the insulation thickness (I. Thickness), the thermal transmission coefficient (*U−Value*) and the inner surface mass of each solution, which evaluates their influence over the building thermal inertia.

Table 2.2 – Thermal properties of adopted constructive solutions

Element	Insulation Thickness (mm)	U-Value ($W/m^{2\circ}C$)	Inner Surface Mass (kg/m^3)
Ground floor slab	30	0.78	919.50
Facade walls	60	0.33	31.60
Flat roof	50	0.36	8.90

In addition Figure 2.3 clears out the detached solution scheme adopted in this envelope solution (original model).

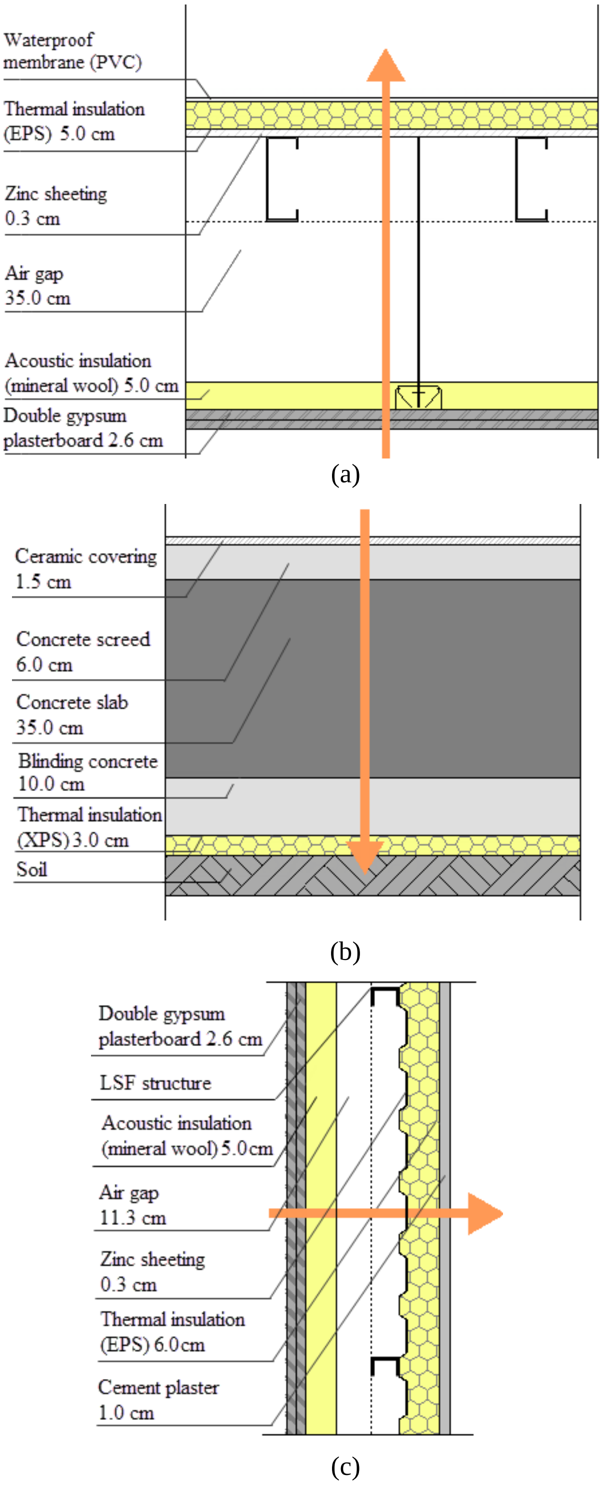


Figure 2.3 – Envelope construction solutions of the original model: (a) Flat roof (b) Ground floor slab (c) Facade walls

Windows are composed of PVC frames (U_{Frame} = 2.00 W/m^2 ºC) with double glazing (U_{Glass} = 1.30 W/m^2 °C). This solution consists of a 6 mm thick exterior glazing pane, a 14 mm thick air partition and a second glazing pane of 5 mm. The front door entry (U_{Door} = 3.30 W/m^2 °C) is composed of 3 mm PVC, 19 mm MDF (medium density fibreboard) and 1.5 mm aluminium. The geometrical heterogeneity (different frame and glazing area) observed among the glazed surfaces led to different *U−Values* values. In order to optimise the sensitivity analysis, an average value, $U_{w,inst}$, was calculated for each facade wall, according to the PHPP (Passive House Planning Package) data Sheet [40]. Thus, a Solar Heat Gain Coefficient (SHGC) of 0.53 and *U−Value* of 1.79 and 1.68 W/m^2 °C were obtained for the glazing of the Northeast and Southwest facades, respectively.

2.2.2 – The climate of Portugal regions

In accordance with the World Map of Köppen [56], which is based on the monthly and annual values of daily mean air temperature and rainfall (Geiger Climate Classification), Portugal is located in the Csa (centre and north of the country) and Csb (south of the country) regions (C – warm temperature; s – summer dry; a – hot summer; b – warm summer).

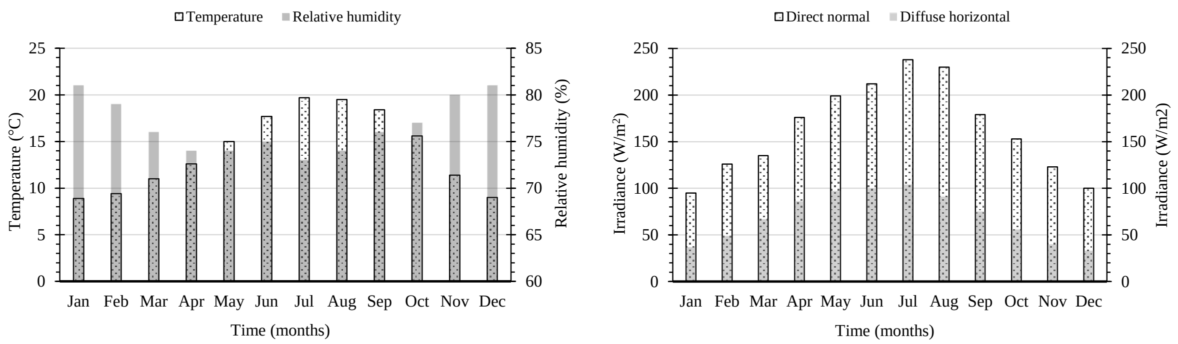
The assessed building is located in a suburb of the city of Aveiro, in the North coast of Portugal, about 10 km away from the Aveiro city centre and 15 km away from the Atlantic coast (40 60′ North latitude, 8°60′ West longitude and 50 m above sea level).

To broadly characterize the different climatic regions of the country, two regions, representative of the interior North and South (Bragança and Évora) and four other near to the coast (Oporto, Aveiro, Lisbon and Faro) were under study (see Figure 2.4). Coimbra although have the influence of the coast, could be considered as a representative region of the interior centre.

Figure 2.4 – Portugal mainland map with regions under study

The climatic database for Bragança, Oporto, Coimbra, Lisbon, Évora and Faro were taken from ASHRAE – International Weather for Energy and Calculations (IWEC) and for Aveiro it was taken from the National Laboratory for Energy and Geology (LNEG). The weather files provided by IWEC were defined from an eighteen year period (1982-1999) and from LNEG compiling average values from measurements carried out between 1961 and 1990 (thirty years). The weather input file values were taken from a hourly database, for the: air temperature; relative humidity; direct (solar) normal irradiance; and diffuse horizontal irradiance. Solar irradiation was estimated for different orientations resourcing to the Munner algorithm contained in weather file.

Figure 2.5 shows the main weather data contents used in the simulations for Aveiro region.



(a) (b)

Figure 2.5 – Weather data for Aveiro region (source LNEG): (a) average monthly air temperature and relative humidity; (b) average monthly solar irradiance

Plots (Figure 2.5 (a) and (b)) shows that the hottest months as well as higher irradiance are July and August with the lowest relative humidity. It also shows the lowest temperature occurs from December to February with the highest relative humidity.

For the other regions under study a summary of the weather data is shown in Table 2.3.

Table 2.3 – Weather data main properties

Month	Average air temperature (ºC)			Relative humidity (%)			Direct (solar) normal irradiance (W/m^2)			Diffuse horizontal irradiance (W/m^2)		
	Brag.	Oporto	Coimb	Brag.	Oporto	Coimb	Brag.	Oporto	Coimb	Brag.	Oporto	Coimb
Jan	4.3	9.4	9.6	85	80	80	86	78	125	37	43	38
Feb	6.0	10.7	11.0	83	81	80	132	117	104	47	54	61
Mar	9.3	11.6	12.7	62	78	70	170	174	151	75	68	81
Apr	10.8	13.2	13.1	70	77	72	170	206	189	91	88	96
May	12.9	14.5	15.6	70	78	76	185	227	171	110	99	118
Jun	17.6	17.8	19.0	65	75	74	266	262	211	107	98	119
Jul	21.7	19.0	20.8	56	80	76	301	254	246	88	88	98
Aug	21.0	19.4	21.1	52	76	69	254	236	239	86	87	88
Sep	17.5	18.0	20.6	56	82	74	214	183	179	78	76	83
Oct	13.2	15.5	16.9	74	77	82	127	144	147	64	58	62
Nov	8.4	12.2	12.2	81	81	84	112	67	79	42	45	51
Dec	5.6	10.3	11.2	88	82	81	69	80	83	33	34	40
	Lisb	Évora	Faro	Lisb	Évora	Faro	Lisb	Évora	Faro	Lisb	Évora	Faro
Jan	10.6	8.8	11.8	82	81	75	130	118	137	38	45	47
Feb	11.5	10.2	12.4	79	69	81	145	105	156	55	67	59
Mar	12.8	12.5	14.8	77	65	72	163	222	234	67	67	68
Apr	14.6	13.2	15.8	73	74	71	193	146	220	88	122	93
May	17.3	17.2	18.6	72	61	72	237	230	275	97	115	97
Jun	20.1	19.8	21.1	70	61	70	250	235	309	101	120	86
Jul	22.3	22.7	23.9	66	58	59	284	295	339	100	91	72
Aug	22.6	23.0	23.7	65	56	66	278	274	292	90	83	76
Sep	21.3	22.0	21.8	70	61	74	211	185	266	75	91	64
Oct	17.8	17.2	20.2	75	72	78	170	145	191	60	70	60
Nov	13.6	12.1	15.5	81	72	74	146	88	142	44	55	51
Dec	11.0	10.5	13.2	81	82	77	142	87	114	36	44	45

2.3 – Dynamic simulation

Dynamic building simulation is an important tool used to detail and effectively assess comfort and energy demand in buildings. As steady state methods do not provide enough detailed information required to support decisions towards the best and optimal design solution, dynamic simulation software such as EnergyPlus® (EP), allows to accurately determine several variables extremely useful for designers and engineers, which might contribute for reducing the running costs of energy demand.

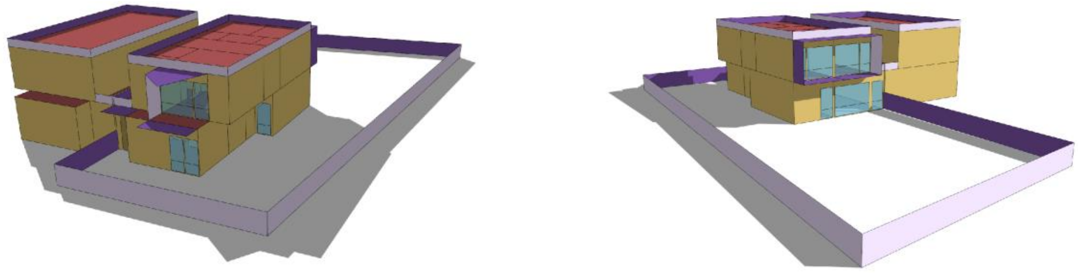
In 2008, Crawley et al. [57] carried out a comparative study confronting the features and capabilities of current simulation softwares on assessing the energy performance of buildings. EnergyPlus® software has been tested and validated since 1993 and is presently rated as a reference tool for sub-dynamic thermal simulation [57, 58]. Moreover, this software was considered the best energy simulation program for the calculation of the energy flow through windows [59]. Its source code is both readable and editable, representing this way, an important advantage for the research and academic community.

2.3.1 – Numerical model and general assumptions

In this section it is presented the dynamic thermal simulation model performed resourcing to EnergyPlus® software and an OpenStudio® cross-platform with graphical interface to support full building energy modelling of the EP calculation tool.

EnergyPlus® is a simulation engine with input and output of text files, in which loads calculated (by a heat balance engine) at a user-specified time step, are passed to the building systems simulation module at the same time step. This software enables the calculation of heating and cooling systems and plant and electrical system response. Integrated simulation allows users to evaluate realistic system controls, moisture adsorption and desorption in building elements, radiant heating and cooling systems, and inter-zone air flow [60]. In the present work the conduction transfer function (CTF) model for the algorithm of surface heat balance calculation methodology was considered. To assess the annual energy demand for heating and cooling an ideal system air loads to control the indoor air temperature was defined. This system is operated by a thermostatic control for a specified temperature range with double function with a dead band for free running between 20 and 26 °C. This system allows to simulate a traditional HVAC system, and adding features allows to simulate a compact unit with heat recovery and bypass capacity. Air flow for cooling and heating is the purposeful flow of air from the ideal system air loads directly into a thermal zone.

Figure 2.6 presents the Northeast and Southwest views of the numerical model designed through the SketchUp® plug-in, whereas the adjacent building was modelled only to account for shading issues. The numerical model was assembled by defining eight thermal zones, corresponding to the internal compartments of the building. Thermal zone TZ1, which includes the hall and the staircase, establishes the connection between the two floor levels and thus is considered in both of them. In this way, and according to the Fig. 5, thermal zones are distributed as follows: the ground floor level includes thermal zones from TZ1 to TZ4 and the first floor from TZ5 to TZ8. Moreover, the architectural use of each thermal zone is described in the caption of Figure 2.7.



(a) (b)

Figure 2.6 – SketchUp® numerical model geometry: (a) Northeast view and (b) Southwest view

(a) (b)

Figure 2.7 – Ground floor (a) and first floor (b) levels thermal zones, where: TZ1 – Hall, living room and staircase, TZ2 – Kitchen, TZ3 –Ground floor suite bedroom, TZ4 – Ground floor bathroom, TZ5 – First floor suite bedroom, TZ6 – First floor bathroom, TZ7 –First floor single room and TZ8 – First floor single room

Based on the steady state analysis performed in the building design phase all the internal gains were added and considered a constant value of 2.1 W/m^2. This value was considered in the model in order to compare dynamic simulation and steady state analysis results.

2.3.2 – Monitoring campaign and model calibration

This section presents the temperature monitoring campaign and thermal dynamic model validation results. The temperature sensors used in the monitoring campaign has an accuracy of 0.5 °C and a resolution of 0.1 °C.

The building was monitored from the 22nd October to 22nd December and the exterior weather data was collected from a local weather station, located 6 km away from the building site. Air temperature, relative humidity, direct normal irradiance, diffuse horizontal irradiance, wind speed and direction data were registered and collected from the local weather station with a time step of 10 min. All thermal zones, excluding TZ1, TZ4 and TZ6 were monitored and used during the calibration process. A real profile with a respective schedule for occupation, electric equipment and lighting were defined by the residents themselves during this period and were applied in the numerical model for calibration purpose. The calibration process was performed by comparing the recorded indoor air temperature and simulated data, evaluating Coefficient of Variation of the Root Mean Square Error (*CV RMSE*). The overlapping of results shows a *CV RMSE* of 8.5% and by the comparison to the limits defined according to ASHRAE [61], IPMVEP [62] and FEMP [63] guidelines the model was considered validated.

2.4 – Sensitivity analysis results

2.4.1 – Original building analysis

Initially, the original building thermal performance was characterised with a mechanical ventilation system with capacity to provide a constant air flow rate from the outdoor air of 0.6 h^{-1} for each thermal zone (considered as natural ventilation for simulation purpose, without heating or cooling inputs). The energy need to keep this equipment in function was not considered in the thermal balance. Moreover, to summarise the obtained results, four thermal zones were selected as representative of the overall building performance (TZ1, TZ3, TZ5 and TZ7). Figure 2.8 represents the temperature variation for each of these zones for an annual period. If on one hand, one can observe that thermal zone TZ7 reaches higher temperatures, mainly due to the 6 $m^2$of glass area, Southwest-oriented and low surface mass of inner surfaces, on the other hand, thermal zones TZ3 and TZ5, which are Northwest oriented, present lower temperature curves.

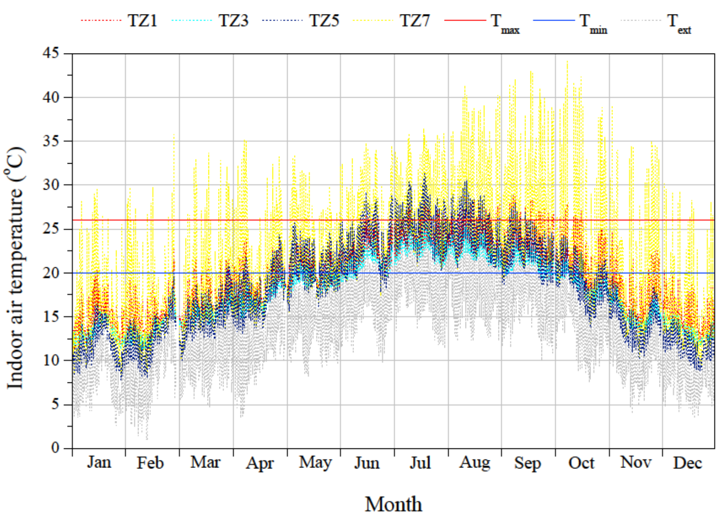


Figure 2.8 – Annual indoor air temperature results for the original building model and outdoor air temperature

From analysing Figure 2.8 it is also possible to verify that indoor temperatures exceed significantly the comfort limit (20 °C ≤ $T_{comfort}$ ≤ 26 °C) [29], leading the authors to conclude that the original building requires further improvement to meet the outlined thermal comfort.

2.4.2 – Methodology for sensitivity analysis

As the original building model condition does not comply the required comfort limit, several numerical simulations were carried out in order to assess and achieve an improved thermal response of the studied building. The initial priority was to prevent overheating during the summer and reducing the annual energy demand, attaining simultaneously higher thermal comfort levels inside the building. Firstly, the thermal performance and influence of incorporating a mechanical ventilation system (HVAC – heating, ventilation and air conditioning) was studied over the original building condition, as explained in the following Section 2.4.3. Subsequently, an exclusively passive approach was considered in Section 2.4.4, to comply with heating energy demand and primary energy issues, imposed by the PH standards. Finally, in Section 2.4.5, a hybrid approach was studied by introducing a mechanical ventilation system with heating recovery (designated hereinafter as Compact Unit), improving the thermal performance global efficiency and reducing discomfort issues. The methodology can be schematically depicted in Figure 2.9.

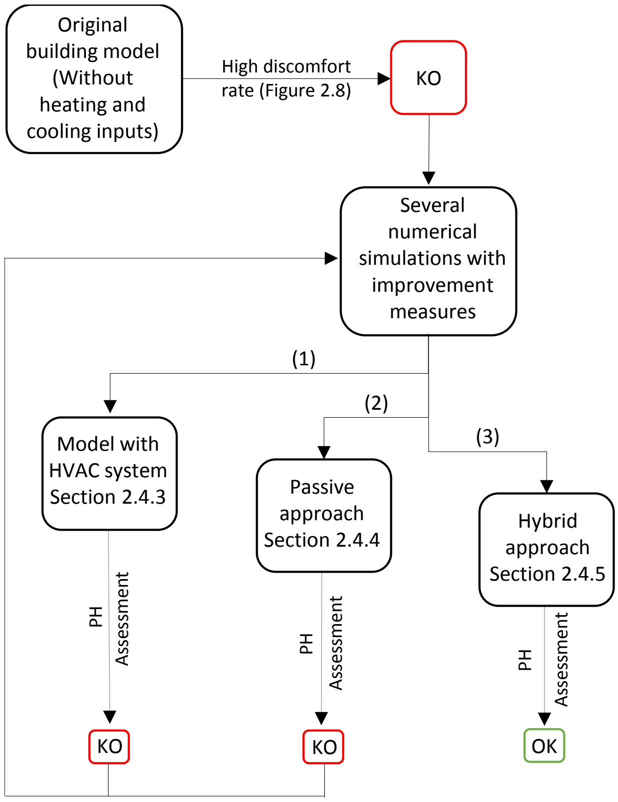


Figure 2.9 – Methodology followed

According to the sensitivity analysis diagram carried out in this work and displayed in Figure 2.10, four base models from M1 to M4 were defined combining and varying features such as mechanical and natural ventilation techniques for heating and cooling, the thickness of external envelope thermal insulation, glazing type and frame properties, global thermal inertia, compatibility with natural ventilation and use of automatic solar protection systems. The features summarised in Figure 2.10 are designated as follows: T.I.1 – thermal insulation of 3, 6 and 5 cm for the ground floor, external walls and roof, respectively; T.I.2 – thermal insulation of 6 cm for the ground floor and 8 cm for external walls and roof; T.I.3 – thermal insulation of 10 cm for the ground floor and 12 cm for the external walls and roof; N.I. – normal inertia solution; I.I. –increased thermal inertia solution; D.G. – double glazing system; T.G. – triple glazing system; A.S. –automatic solar protection system (see device schedule presented in Table 2.4 in Scenario 3); M.S. – manual solar protection system (see device schedule presented in Table 2.4 in Scenario 2); M1 – original model with HVAC for heating and cooling; M2 – original model with a mechanical heat recovery system used for heating and night ventilation for cooling (without a mechanical cooling system); M3 – original model with a mechanical heat recovery and a mechanical cooling system with bypass mode and M4 – the original model with a mechanical heat recovery, a mechanical cooling system with bypass mode and night ventilation. In sum for each base model ($M_{i,n}$) all features were combined in a total of 24 models using: 3 thermal insulations thickness solutions; 2 values of thermal inertia; 2 types of window solutions; and 2 shading operational modes. In total and considering the four base models 96 runs were simulated and analysed. The feature combination that lead to the final solution, is displayed in Figure 2.10 through the red line path.

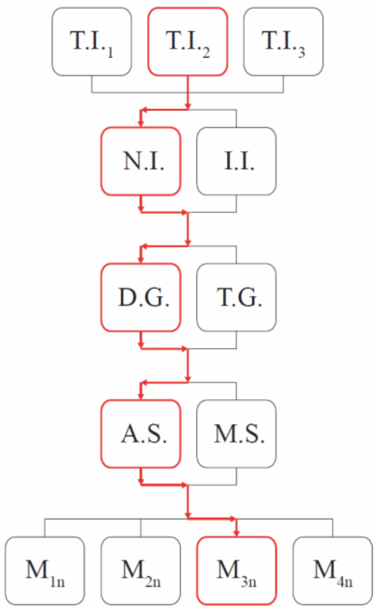


Figure 2.10 – Sensitivity analysis diagram

This final solution (red line path) complies with PH energy demand limits associated to the minimum insulation thickness and double window glazing solution.

Table 2.4 – Exterior shading protection device schedule

Scenario 1 – Manual System		
Winter	100% Closed	From 18.00 to 08.00
Summer	100% Closed	From 00.00 to 08.00
Scenario 2 – Manual System		
Winter	100% Closed	From 18.00 to 08.00
Summer	70% Closed	From 08.00 to 00.00
	100% Closed	From 00.00 to 08.00
Scenario 3 – Automatic System		
Winter	100% Closed	From 18.00 to 08.00
Summer	70% Closed	From 08.00 to 00.00[a]
	100% Closed	From 00.00 to 08.00

a) All the heating zones contain a temperature sensor, whereas 70% of the window's height is protected when the temperature reaches 23°C.

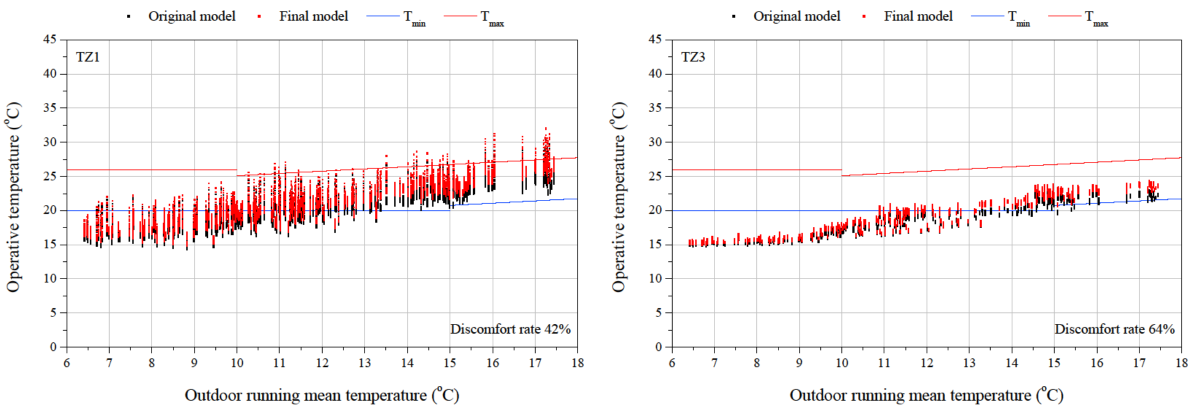
The natural ventilation was taken into account by opening bottom hung windows during the night period, high oscillations of indoor air change rates were observed by analysing the results from base models M1 and M4, which were modelled considering the night ventilation strategy, leading to extended periods of indoor discomfort. Hence, due to the unpredictability of this variable, the authors found highest accuracy in results by not considering the wind effect, allowing to eliminate eventual nocturne noise issues, increasing the indoor comfort. For this reason, the results related to models M2 and M4 base models were not presented here.

2.4.3 – Initial approach

In order to improve the thermal performance of the building, a first attempt consisted in incorporating a HVAC system (heating, ventilation and air conditioning) for heating and cooling with a temperature set-point range between the above mentioned comfort limits, assuring the indoor admissible temperature values. As expected, despite discomfort issues were solved by integrating this HVAC system, the energy demand value for heating (36.3 kWh/m^{2}a) and the value of primary energy (122.2 kWh/m^{2}a) exceeds the limits imposed by the Passive House standards [46]. The energy demand value for cooling (6.6 kWh/m^{2}a) is below the PH limits, however this value could be progressively reduced. Following the original building energy characterisation with the HVAC system the M1 base models were ran. Results reveals that the most of the models carried out for the region of Aveiro have met the Passive House requirements. These compliant solutions present a sustainable balance between current building materials and technology and the Portuguese climate. Hence, in order to understand the improvement process and to analyse the effective contribution of passive and hybrid approaches in terms of indoor thermal comfort, two different approaches were defined separately.

2.4.4 – Passive approach

Passive techniques are those achieved only by changing and optimising the thermal insulation, glazing solution, thermal inertia and solar protection system. According to the EN 15251 [29], the assessed thermal zones (just by increasing thermal insulation and using automatic solar protection system) show significant improvements for the heating season when compared to the original building condition. The indoor thermal comfort was evaluated according the adaptive comfort algorithms for Portugal with the accepted deviation of the indoor operative temperature defined by EN 15251 [29]category II with normal expectation for new building design. The overheating identified in thermal zone TZ7, related to larger dimensions of glazed surfaces and to a lower value of inner surface mass of constructive solutions (walls and floor), was solved with an automatic solar protection system. The differences between temperature points of thermal zones, in Figure 2.11, are strongly related to the respective orientation within the building.



(a) (b)

Figure 2.11 – Passive approach temperature results for winter season for zones: (a) TZ1, (b) TZ7, (c) TZ3 and (d) TZ5 (…)

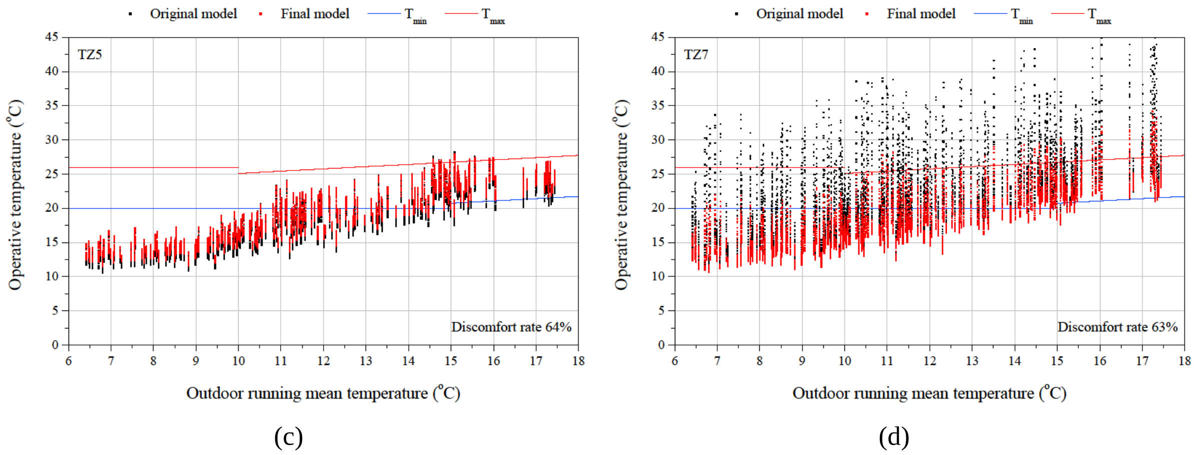


Figure 2.11 – (…) Passive approach temperature results for winter season for zones: (a) TZ1, (b) TZ7, (c) TZ3 and (d) TZ5

Figure 2.11 shows comfort assessment for the cooling season. Again, establishing a comparison between the original and the improved model, there is an overall overheating reduction over the assessed thermal zones. Highlight that the results shown in Figure 2.11 and 2.10, compare the original building solution described in Section 2.2.1 with the final model solution identified by the red line path (see Figure 2.10).

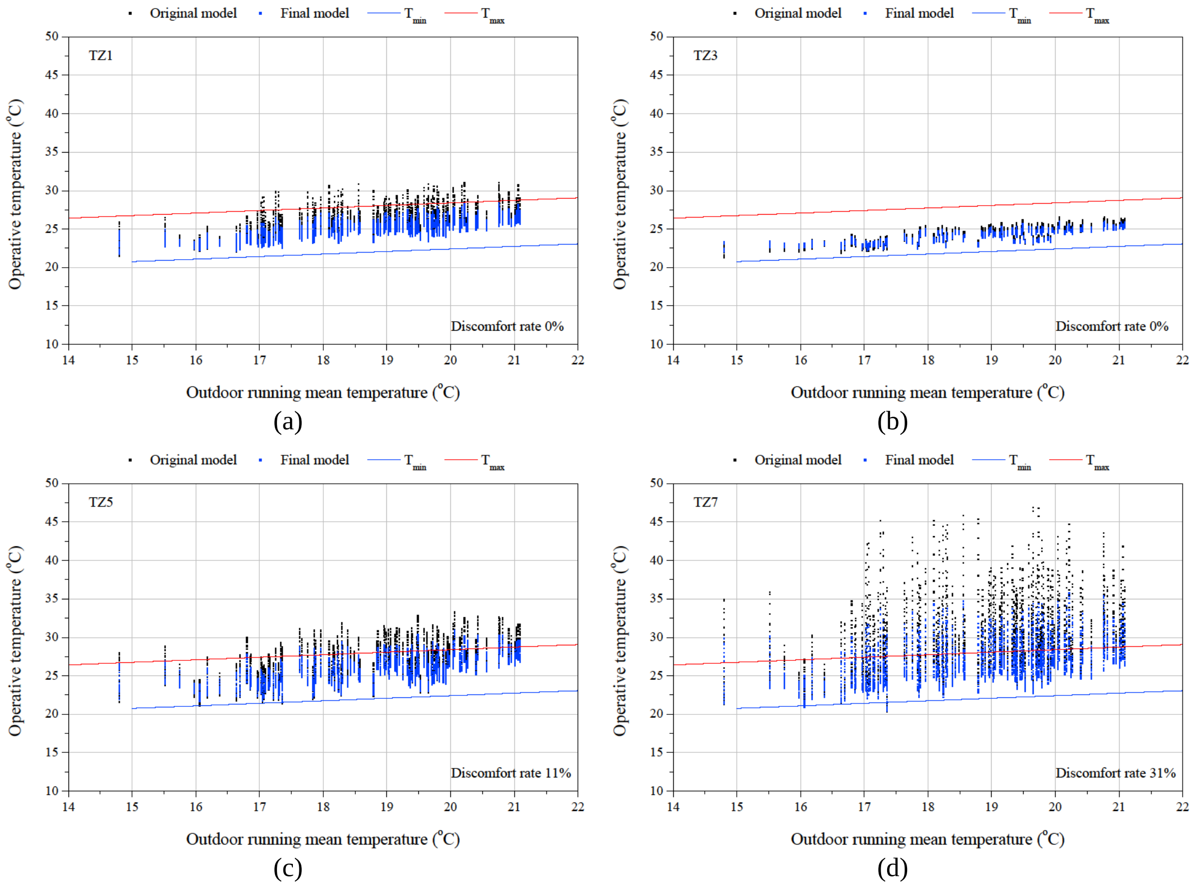


Figure 2.12 – Passive approach temperature results for summer season for zones: (a) TZ1, (b) TZ7, (c) TZ3 and (d) TZ5

Although in zone TZ3 the interior thermal performance was not significantly changed by the improved model, the temperature varies inside the comfort limit during practically the entire summer season. Despite a significant decrease have occurred on TZ1 and TZ5 interior temperatures, the greatest impact was observed, as expected, in thermal zone TZ7, with an important overheating reduction.

In sum, although this passive approach led to significant improvements regarding the overheating issue, from analysing both Figure 2.11 and 2.10, long periods of discomfort are still observed. In this context, and as the initial approach with the HVAC system (in the previous Section 2.4.3) failed the PH requirements in terms of cooling and heating energy demand, the authors stress the need of an efficient mechanical ventilation system to address this gap, according to the PH certified systems.

2.4.5 – Hybrid approach – final model

Finally, the hybrid solution consisted in introducing a mechanical ventilation system for both seasons with heat recovery during the winter and bypass mode during the summer. Bypass is a feature of the mechanical ventilation system that provides an increased rate of outdoor air flow directly to the zones, bypassing the heat exchanger. In the summer period the bypass system is activated by differential dry bulb temperature, which means, the bypass will activate and increase the outdoor air flow rate above the initial air change rate of 0.6 h^{-1} until to a maximum of 1.2 h^{-1}, in case the outdoor air temperature is lower than the indoor air temperature. It is important to refer that the cooling system with the bypass system does not have the capacity to react immediately to ensure that the indoor temperature is always bellow the upper limit defined by the setpoint, which means that very short overheating periods can occur. The results from Figure 2.13 are related to the final model (resulting from the M3 base models), in which a compact unit system was considered to control the indoor environment with intermediate levels of insulation thickness were considered (ground floor 6 cm, facade walls 8 cm, roofing system 8 cm), and incorporating double glazing and automatic solar protection system. In terms of ventilation system, the model was equipped with a heat recovery (80% efficiency) for the winter season and an automatic controlled bypass for the summer. The heat recovery efficiency is defined as the change in supply temperature divided by the difference in entering supply and relief air temperatures.

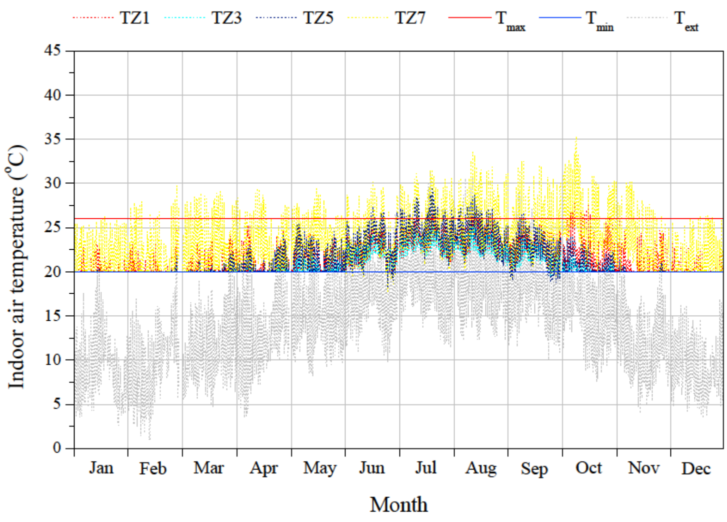


Figure 2.13 – Annual indoor air temperature for the final solution

Moreover, to comply this type of functionality, a compact unit was chosen, incorporating ventilation and passive recovery units, as well as supplementary energy efficient heating system (to offset the air temperature when the heat exchanger cross flow is not sufficient).

Through observing Figure 2.13 it is possible to note the variation of the temperature in each thermal zone for the improved thermal model. Moreover, during the heating season thermal discomfort issues were solved. With this model, higher comfort levels (indoor temperature) and significant reductions of the model energy demand were achieved, when compared to its original condition (see Fig. 6). Hence, heating demand was reduced in 62% (from 36.3 to 13.7 kWh/m^{2}a), cooling demand was reduced in 72% (from 6.6 to 1.8 kWh/m^{2}a), and the primary energy demand was reduced in 30% (from 122.3 to 85.2 kWh/m^{2}a).

The comparison between both passive and hybrid improvement strategies implemented over the original and improved models for winter and summer seasons, are presented in Figure 2.14, respectively.

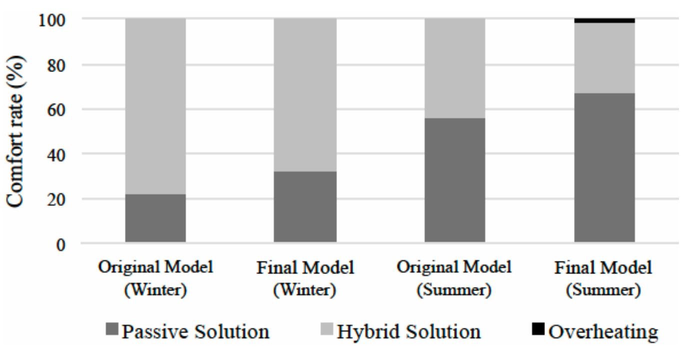


Figure 2.14 – Comparison between both passive and hybrid strategies

Each plot shows the contribution of each implemented strategy, in terms of comfort rate, to achieve the required interior comfort limit (20 °C $\leq T_{comfort} \leq$ 26 °C). Through these results, shown in Figure 2.14, it was observed that the mechanical ventilation system has a significant impact during the winter season when compared to the summer, whereas the bypass was found not enough to achieve 100% comfort. Nonetheless, the small percentage of discomfort is somehow negligible when compared to the cooling energy savings (from 6.6 to 1.8 kWh/m^{2}a).

2.4.6 – Steady state and dynamic simulation results comparison

This section presents a brief comparison between steady state approach using PHPP tool and thermal dynamic simulation results (final model) to achieve PH requirements. A solution using levels of insulation of 10 cm for ground floor, 12 cm for facade walls and roofing system with double window glazed solution were needed to meet to the PH energy requirements. This envelope solution leads to an energy demand of 12.7 kWh/m^{2}a and 4.0 kWh/m^{2}a for heating and cooling, respectively. Comparing the energy demand from the steady state approach (results attained and presented in Section 2.4.5) an increase of 7.3% for heating demand and a reduction of 55% for cooling demand using thermal dynamic simulation. Double glazed window solution was attained for both calculation methods however with PHPP analysis 4 cm of additional insulation thickness was needed for all external envelope solutions, to meet PH requirements. Observing the attained results, the steady state method used to estimate the overall energy performance of the case study leads to a more demanding envelope solution compared with the dynamic simulation.

2.4.7 – Particular analyses

In order to address the issue of overheating risk in the most alarming thermal zones (TZ7 and TZ8), two particular analyses were carried out, a first one approaching the solar protection system management and the second considering a thermal inertia increase. For both analyses the original numerical model was considered for the two hottest weeks of August, from the 8th to 22th.

The first analysis aimed to understand the influence of the occupant's behaviour in terms of solar protection systems management. For this purpose, three different scenarios were considered: (i) Scenario 1 in which the solar protection system was not activated manually during the day; (ii) Scenario 2 where the solar protection system was activated manually during the day to minimise solar gains and (iii) Scenario 3, in which the solar protection system is activated automatically. In order to prevent overheating risk during the summer season, an exterior shading solution was considered and optimised with the schedule routine presented in

Table 2.4. Due to this fact, and to guarantee indoor daylight minimum conditions, it was considered that the shading system enables solar light through 30% of the window's total height. Still with regard to Table 2.4, please note that during the remaining hours the exterior shading protection solution is fully disabled.

The main difference between Scenario 1 and Scenario 2, is that in Scenario 2 the occupants close the solar protection system till 70% of the window's height. Due to this fact, it is possible to guarantee the indoor daylight minimum conditions and at the same time reduce the overheating risk. Figure 2.15 represent the temperature values for each scenario for thermal zone, TZ7. Through the results obtained in the Figure 2.15, it is possible to conclude that the solar protection system is essential to minimise the overheating rate. The thermal performance between Scenarios 2 and 3 is similar with notable reduction of the maximum temperatures. The global building overheating rates of 15.3%, 6.4% and 7.9% were achieved for Scenarios 1, 2 and 3, respectively. A small difference is noticeable after comparing the overheating rate between Scenarios 2 and 3.

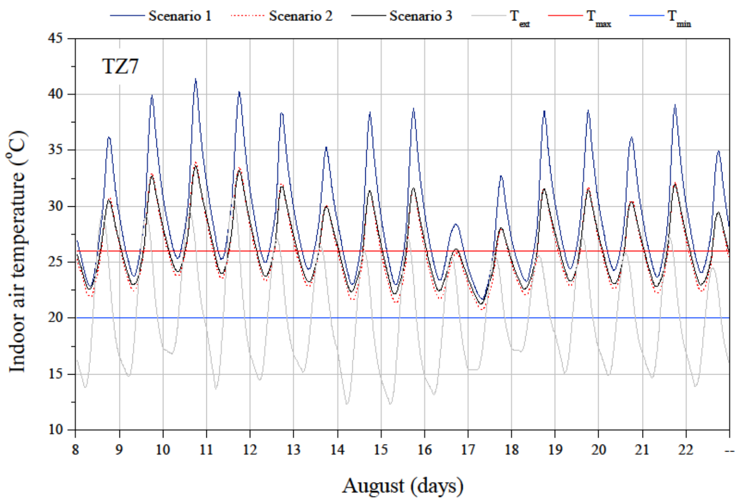


Figure 2.15 – Influence of the occupants behaviour in terms of solar protection systems management

As a conclusion, an automatic system is not obligatory if the occupants close the exterior blinds in order to minimise the solar gains during the hottest hours of the day. However, with the automatic system it is possible reduce significantly the overheating rate, thus decreasing the activation temperature for descending the shading device. The overheating rate achieved for activation temperatures of 23 °C, 22 °C, 21 °C and 20 °C, were 7.98, 7.13, 6.71 and 6.48, respectively. That value was reduced to the lower comfort limit. A maximum reduction of 1.5% in the global overheating rate is verified, through the change of the activation temperature from 23 °C to 20 °C.

The second particular study consists in understanding the influence of increasing thermal inertia of both interior compartment walls and exterior envelope walls on the building's overheating ratio. The present case study is a light steel frame building classified as medium level of thermal inertia [52]. It was concluded through a detailed study of the constructive solutions that the thermal inertia was concentrated on the ground concrete floor slab. To overcome this issue two different scenarios were studied: (i) Scenario 1, considering minimum levels of insulation (ground floor 3 cm, walls 6 cm and roof 5 cm) and (ii) Scenario 2, with minimum levels of insulation but a 2 cm layer of cement plaster was added on both sides of partition walls, as well as on the inner surface of external envelope walls.

Comparing the indoor temperature values of both scenarios, in Figure 2.16, a significant reduction of the temperature swings and the maximum temperature values was observed, for thermal zone, TZ7 (reduction from 41 °C to 35 °C on August 11). The overheating rates were calculated at 15.23% and 12.94%, for Scenarios 1 and 2, respectively, and a global reduction of the overheating rate of 2.3% was achieved just by increasing the thermal inertia of the interior compartment and exterior walls.

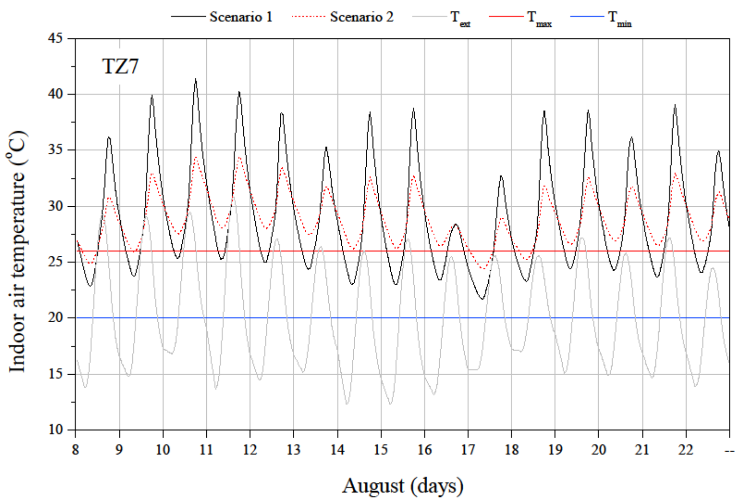


Figure 2.16 – Influence of increasing thermal inertia of walls on the building's overheating rate

2.5 – Additional analyses

Following the sensitivity and particular analyses carried out previously, additional analyses based on the same building model were performed for different climate zones in Portugal mainland, such as the cities of Bragança, Oporto, Coimbra, Lisbon, Évora and Faro, in order to understand the application of Passive House requirements for these locations.

To broadly represent the different climate regions in Portugal, from North to South, main capital districts were chosen to study. The information of each climate zone in study is summarised in the Table 2.5, in accordance with Köppen climate classification. The Aveiro region climate classification was detailed previously in Section 2.2.2.

Table 2.5 – Climate zones temperature (°C)

Climate zone		Average	Summer	Winter
Bragança	Csb[a]	12.4	2.4 – 36.2	-6.0 – 26.2
Oporto	Csb	14.3	2.8 – 32.0	0.0 – 27.0
Coimbra	Csa[b]	15.4	3.9 – 37.5	-1.7 – 29.6
Lisbon	Csa	16.3	7.9 – 36.0	4.1 – 26.6
Évora	Csa	15.8	9.6 – 38.4	1.6 – 29.4
Faro	Csa	17.8	11.0 – 37.0	2.0 – 32.0

a) Temperate climate with dry and mild summer. **b)** Temperate climate with warm summer.

2.5.1 – Scenarios selection

The heating and cooling energy demand, for the best 10 simulations (S_i – notation used to identify the simulation number) for each different climate region selected out from the models M1 and M3, are represented in Figure 2.17. From those simulations, the one according to the Passive House requirements and has the highest energy demand was defined the best efficient solution. Choosing the simulation with the highest but compliant energy demand is getting closer to the original Portuguese constructive methods, by using lower levels of thermal insulation and prioritising double glazing. Nevertheless, the Figure 2.17 shows a wide range of solutions that meet the PH criteria in terms of energy demand for heating and cooling and the final decision can therefore be based on a real understanding and can be taken by the owner or the designer.

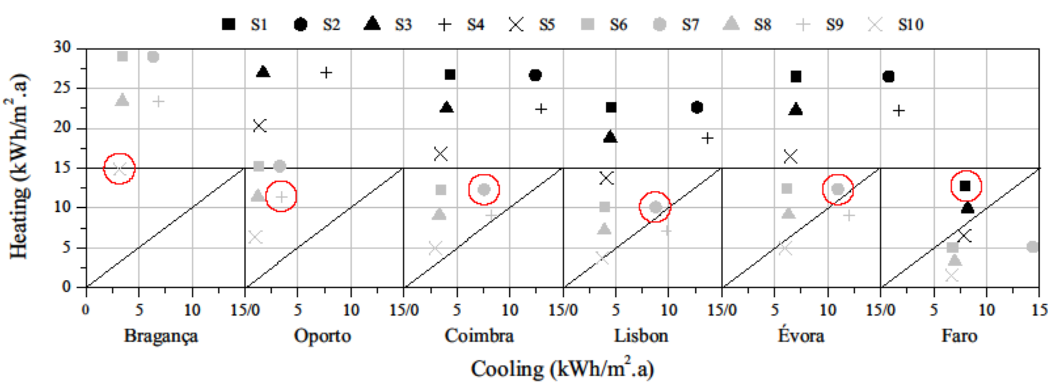


Figure 2.17 – Heating and cooling energy demands for the studied climate regions

In Table 2.6 the main features implemented on each evaluated climate zone (constructive solutions and ventilation systems) are displayed. For Aveiro region the best features to comply with the PH requirements were previously presented in Section 2.4.5 and is assigned with a red line presented in Figure 2.10. The abbreviation code and initials for each single feature present in this table is according to Figure 2.10. It is important to refer that all simulations were modelled considering 0.6 h^{-1}. Air renovation is assured by a compact unit ventilation system, assuming that the house has a highly controlled air change rate associated to a very air tight external envelope.

Table 2.6 – Features incorporated in the final models for each climate zone evaluated

		Bragança	Oporto	Coimbra	Lisbon	Évora	Faro
Simulation		S10	S9	S7	S7	S7	S7
External thermal insulation	$T.I._1$	-	-	✓	✓	✓	✓
	$T.I._2$	-	✓	-	-	-	-
	$T.I._3$	✓	-	-	-	-	-
Glazing system	D.G.	-	✓	✓	✓	✓	✓
	T.G.	✓	-	-	-	-	-
Solar protection devices	M.S.	-	✓	✓	✓	✓	-
	A.S.	✓	-	-	-	-	✓
Ventilation strategy	C.U.[a]	✓	✓	✓	✓	✓	-
	HVAC	-	-	-	-	-	✓

a) The Compact Unit modelled comprises a heat recovery system with a cross flow exchanger and bypass devices.

In this section all the simulations were performed using a mechanical ventilation system for cooling and heating (HVAC and C.U.) without a passive approach that uses only natural ventilation strategy during the summer season.

2.5.6 – Energy demand for different climate zones

Figure 2.18 presents the energy demand of the best models in Table 2.6, for each climate region evaluated. From these results, on one hand, heat recovery system is required during the heating season for almost all the climate regions, except Faro, where the traditional HVAC system is enough to assure thermal comfort with an energy demand for cooling and heating below the PH limits. For the Lisbon region, an HVAC system was found sufficient to meet the Passive House heating and cooling limits, however maximum levels of thermal insulation and triple glazing was required (Scenario S5), which is not common of the Portuguese practice. Thus, for this region a C.U. was used in the analysis (models M3) and the PH limits for energy demand were achieved combining double glazing and minimum levels of thermal insulation thickness solutions (see Table 2.6). Moreover, Faro is the region that needs less insulation thickness to comply with the energy limits due to higher exterior temperatures and area ratio between windows and facade. As expected, although Passive House requirements were successfully overcome for all the evaluated climate regions, the constructive solutions should be adapted and adjusted to such requirements.

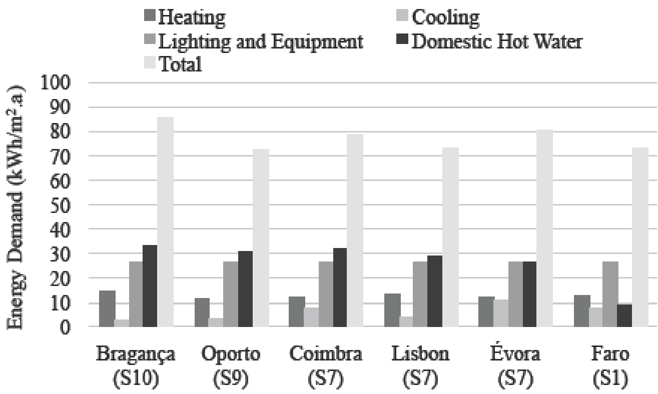


Figure 2.18 – Energy demand of the evaluated model systems for different climate regions

2.6 – Final remarks

The results provide a meaningful contribution for the study, implementation and interest of the Passive House concept for the Portuguese building context and climate. Dynamic simulation carried out took into account simultaneously: thermal loads, thermal energy balance and ventilation systems. From the results attained, it is stressed that the Passive House concept is adaptable and should be highly incentivated to be applied to Mediterranean and Southern European countries such as Portugal, where overheating issues during the cooling season is assumed as the main setback to achieve the PH standard. Moreover, it is fundamental to bear in mind that the constructive solutions should always be adapted in function of the climate demand and construction techniques and industry.

The results for the Aveiro region revealed that the original model (without a mechanical ventilation system) led to long periods of thermal discomfort during the heating season, as well as overheating during the summer season. In this sense, the improved final solution resulting from an hybrid approach have led to higher comfort levels, with significant reductions of the energy demand, over 60% for heating and 70% for cooling.

In terms of envelope solutions Bragança and Lisbon (considering a traditional HVAC system for Lisbon) regions require triple glazing windows and thermal insulation of 10 cm for the ground floor and 12 cm for the exterior walls and roof to achieve the PH requirements. Coimbra, Évora and Faro regions require double glazing windows and thermal insulation of 3, 5 and 6 cm for the ground floor, external walls and roof, respectively. Finally the Oporto region, requires double glazing windows and thermal insulation of 6, 8 and 8 cm, for the ground floor, external walls and roof, respectively to achieve the PH requirements.

With the additional analysis carried out, it was studied the influence of changing thermal insulation thickness, glazing solutions and ventilation system, over the building thermal and energy performance, allowing to successfully comply with the Passive House requirements for all the different Portuguese climate regions evaluated.

The particular analysis has confirmed the need of increased thermal inertia of light steel frame buildings, in order to attenuate the temperature swing and to reduce both maximum and minimum temperature peaks. To minimise the overheating, it is highly recommended the use of external shading protection systems, activated automatically with a temperature control trigger.

Reminding the focus on the two main denominators and referred to in the thesis title “Passive House” and “Phase Change Materials”, this chapter presented and discussed the first contact with the Passive House concept using a real case study presented. Following, the work developed in Chapter 3, brings out the subject phase change materials.

CHAPTER 3

MECHANICAL AND THERMAL CHARACTERIZATION OF CONCRETE WITH INCORPORATION OF MICROENCAPSULATED PCM FOR APPLICATIONS IN THERMALLY ACTIVATED SLABS

Chapter outline

3. MECHANICAL AND THERMAL CHARACTERIZATION OF CONCRETE WITH INCORPORATION OF MICROENCAPSULATED PCM FOR APPLICATIONS IN THERMALLY ACTIVATED SLABS

Work related to this chapter was published in the **Construction and Building Materials** – An International Journal dedicated to the investigation and innovative use of materials in construction and repair. Impact Factor: 2.30 DOI: 10.1016/j.conbuildmat.2016.02.225

Abstract Evolution towards sustainable building design is a current goal worldwide, shaping codes and policies, to achieve such goal the construction industry and sector requires new energy saving concepts and building materials. The objective of this study is to quantify the influence of microencapsulated phase change material over the concrete mechanical and thermal properties. The experimental tests on concrete with PCM yielded resistance loss up to 66% and 52% for compression and bending strength respectively, comparatively with the reference concrete specimens, without PCM.

Thermal performance of concrete incorporating PCM was also evaluated. The results showed that the incorporation of PCM can contribute to reduce the energy demand in buildings.

3.1– Introduction

Amongst the strategies to achieve the EPBD goal (previously presented in section 2.1), building solutions with the incorporation of phase change materials, either in new buildings or in retrofitting of existing buildings is a promising solution. PCMs are materials with a predetermined fusion, melting and solidifying at a given temperature, with the ability to store and release high amounts of energy due to their phase change [64]. There are two processes related to the phase change of PCM. When PCM changes from the solid to liquid state an endothermic process occurs, in other words, the PCM stores energy in the latent form. When the reverse process is observed, that is, the phase change process from the liquid to the solid state an exothermic reaction ocours wherein the accumulated energy is released.

One of the main advantages of PCM, compared to common building materials, is their energy storage capacity, since they have the capability of storing latent heat in addition to the sensible heat. This advantage, combined with the possibility of using PCMs incorporated into system components that employ renewable energy sources (solar thermal or geothermal sources) that promote the PCM phase change process and are compatible with the phase change temperature range, is a good passive and sustainable solution to reduce the energy consumption levels of buildings.

This study mainly focused on assessing the structural characterization of concrete with the incorporation of PCM in the concrete mixture, in a proportion of the total weight. As the incorporation of PCM into the concrete was performed *in-situ*, this yielded in 3.21% relative percentage of the resulting mixture of 75kg microencapsulated PCM, for 1m^3 of ready mixed concrete.

The PCM incorporation in concrete is an area scarcely explored due to its complexity in combining and optimizing several characteristics, in particular structural and thermal properties (mechanical resistance, susceptibility to cracking, hardening process, thermal conductivity, etc.). However, the concrete is presented as a material that due to its mass has a great thermal activation potential, which can be enhanced by the incorporation of PCMs in the specific cases of thermally activated slabs. In addition to the mechanical behaviour of PCM incorporation into concrete, thermal characterization tests were also carried out.

Currently the trend of the vertical construction systems are evolving towards solutions with low thermal mass, as is the case of the use of lightweight partition walls in new buildings and retrofitting actions, leaving the floor slabs as the constructive solutions with the highest superficial thermal mass, which may be explored for the energy efficiency of buildings. The use of materials or solutions incorporating PCM promotes thermal energy storage, bridging this limitation of low thermal inertia.

At present, there are numerous studies on the application of PCM in construction components and active solutions, however there are still challenges in effective and practical use of these materials when applied.

Entrop, Brouwers and Reinders [65] aimed to study the influence of the PCM incorporated in a surface layer of concrete (50 mm) slabs, in space heating during the evening and early night in a moderate climate, making use of daily solar irradiation as a source for thermal energy. In this case study the authors used models with a reduced scale with an opening south orientated, to simulate a space of a dwelling with a concrete slab incorporated with PCM in a proportion of 4.9%. As a result they found that the use of PCMs incorporated in the concrete floors shows that PCMs can store thermal energy without the need of a mechanical system. Regarding the thickness of the concrete layer incorporating PCM (50 mm) it was found that it has a high latent heat capacity, although an extensive time lapse to be fully charged is required.

Hunger and other authors [66] present a set of experimental results using different amounts of PCM incorporated in self-compacting concrete mixtures in percentages of 1%, 3% and 5%. With this work it was possible to conclude that by increasing the amount of PCM incorporated in the concrete lead to a lower thermal conductivity and increased heat capacity, improving significantly the thermal performance of concrete and therefore energy savings. On the other hand, significant losses in mechanical strength were observed. Loss of 30% was obtained for 1% of PCM incorporated in the concrete, 53% for 3% of PCM and of 71% for 5% of PCM incorporated. From microscopic analysis it was found that a large portion of the polymer microcapsules which encapsulates the paraffin was destroyed during the mixing process, thereby releasing the PCM from the interior of the capsule into the surrounding concrete aggregates. As a main conclusion, the compressive strength of the specimens still satisfies the requirements of most structural applications.

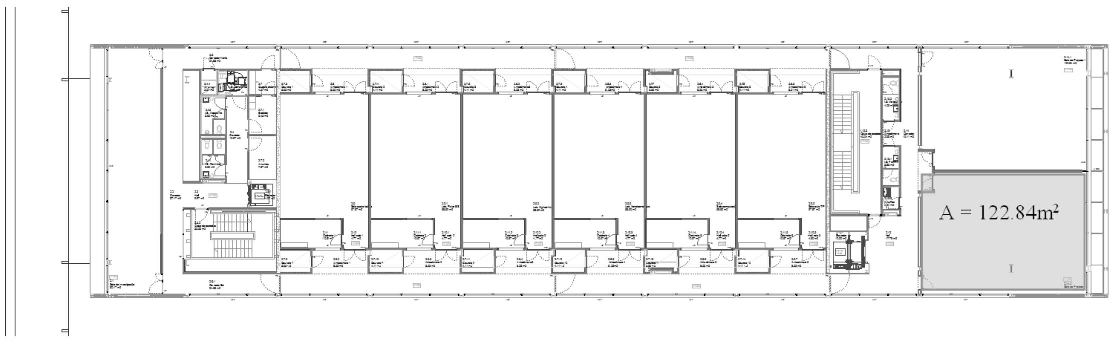
Luisa Cabeza and other authors [67] focused on studying the thermal behaviour of concrete with incorporating of PCM in 5% of its weight. Two real size concrete models were used to study the effect of the PCM (with a melting point of 26 °C) incorporation in the concrete. Various boundary conditions for the test model were evaluated and simulated. The results of this study revealed the energy storage capacity of the concrete walls with incorporated PCM, improving the thermal inertia, which results in lower internal temperatures within these test compartments when faced with similar construction references without PCM. The results also demonstrate a real opportunity in energy saving for buildings.

In 2012 Michal Pomianowski and other authors [68] evaluated the energy efficiency of a hollow core slab solution thermally activated with a surface layer of concrete with microencapsulated PCM. This study aimed to characterize the thermal properties of a new combined material that consists of standard concrete with microencapsulated PCM. Numerical and experimental investigation were carried out over properties such as thermal conductivity and specific heat capacity. As a conclusion it was found that the use of concrete with PCM in thermally activated slabs reduces cooling requirements of the thermal activation system. With this work it was found that further composition studies should be undertaken regarding concrete with microencapsulated PCM in order to optimise the solutions.

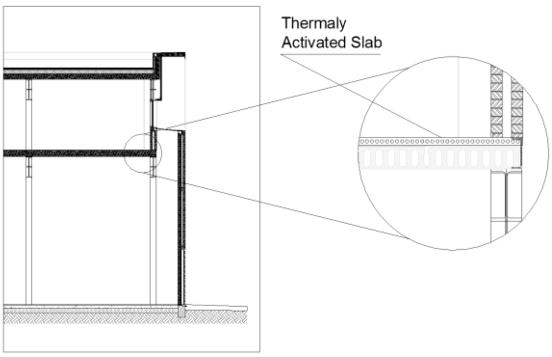
Other constructive solutions that incorporate PCM into different building elements, from masonry wall solutions [9, 68-71]; window shutters [72-74]; window glazing [75-77]; and miscellaneous constructive solutions [15, 78-86], are presently commercial based products on the market and presently are driving the evolution of building components.

3.2 – Building description

The possibility of using full-scale models in the experimental studies of new constructive solutions translates into more accurate results regarding the actual behaviour of the material (or constructive solution) when applied in the environment in which it operates. Thus, in the construction of a department building referred as CICFANO (for Nanotechnology and Oceanography studies), at the University of Aveiro Campus, PCM was incorporated into an 80 mm thick concrete screed, involving the piping of a geothermal system of a thermally activated slab. Figure 3.1 presents the cross-section, where the PCM is incorporated into the concrete screed over the structural concrete slab.



(a) 2nd floor plan with identification of the compartment in study (in green)



(b) Cross section of the compartment and detail of the floor slab

Figure 3.1 – Compartment under study with application of microencapsulated PCM (without scale)

PCM was used in the top layer of the geothermal exchangers of a thermally activated hollow core prefabricated slab. The room (see Figure 3.1a) was selected because there is another room with similar geometry, volume and solar orientation, at the same storey level which is considered as a reference room to compare thermal behaviour in future thermal monitoring studies of indoor air and relative humidity studies. The PCM energy storage capacity is an advantage to reduce the time use of the heat pumps, or to potentiate a lower daily cyclical thermal differential (between day use and night inactivity), thereby reducing the heating energy demand in the winter period. In sum, the incorporation of PCM into the concrete screed will contribute to the indoor air temperature swing attenuation, to increase the thermal comfort and to reduce the energy demand of any active system in terms of cooling and heating for daily to weekly cycle.

The brief building description is only made to link the research work around PCM incorporated in concrete, between laboratory tests characterization and final application. Thus, the building is out of the work develop in this chapter, whereas a full description of the department building will be presented and framed in Chapter 6.

3.3 – Characterization of the concrete incorporating PCM

3.3.1 – Concrete composition characterization

Concrete type C30/37 (European concrete class classification) was used for the concrete screed over the prefabricated slab panels as a compression layer. The screed layer has a concrete thickness of 80 mm which involved the 20 mm geothermal exchangers. Table 3.1 shows the concrete screed composition.

Table 3.1 – Concrete screed composition

Concrete nomenclature	Cement (kg)	Fly ash (kg)	Fine sand: 0-2mm (kg)	Fine sand (0-4mm) (kg)	Gravel type 1 (6/14) (kg)	Gravel type 2 (11/22) (kg)	Plasticizer (kg)	Water (l)
C30/37.S2.XC4(P).D22.C10.4	218	112	240	450	570	650	3.62	145

NOTE: Pozzolan cement CEM IV – Produced at Cimpor in Souselas; Fly ash – From central thermoelectric - EDP – Sines; Plasticizer – Sikament 400 Plus – by Sika; Super plasticizer – Viscocrete 3008 – by Sika

3.3.2 – PCM characterization

The microencapsulated PCM incorporated into the concrete is the commercial BASF® Micronal® DS 5001. PCM was added and mixed homogeneously into concrete, representing

3.21% relative to the concrete weight of 1m^3. Table 3.2 lists the properties of the microencapsulated PCM used.

Table 3.2 – PCM properties (from manufacturer)

Product designation	Product type	Melting point approx. (ºC)	Operational range (ºC)	Overall storage capacity approx..	Latent heat capacity approx. (J/g)	Apparent density approx. (kg/m^3)
Micronal DS 5001	Pulver	26	10 - 30	145	110	250 to 350

According with Table 3.2 the incorporated microencapsulated PCM has a melting point of 26 °C so that, by ensuring that the secondary loop of the geothermal system that allows the circulation of a thermal fluid at about 30-32 ºC in heating and 10-15 ºC in cooling, the temperature of the concrete screed over the slab will be within the temperature range of the phase change of the PCM during the heating process.

Additional, it was performed a DSC (differential scanning calorimetry) laboratory test to evaluate the latent heat capacity of the used PCM. DSC analysis of specimens was executed for both cycles (heating and cooling) in between 10 ºC and 50 ºC at the rate of 1 ºC/min.

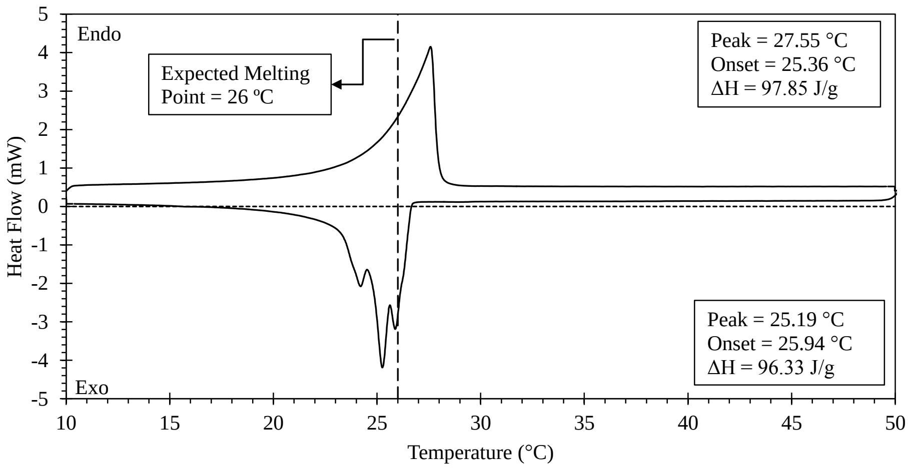


Figure 3.2 – DSC curve of paraffin with dynamic measurement method at 1 ºC/min

Comparing the manufacturer properties (see Table 3.2) with the experimental results from DSC analysis (see Figure 3.2) it can be concluded that the melting point is approximately 26 ºC, and the latent heat capacity is approximately 11% higher in respect to the values appointed by the manufacture.

The microcapsules are small polymeric containers PMMA filled with the organic based PCM (paraffin). Despite the benefits of the application and use of microencapsulated PCM, there are some concerns that must be considered and that motivate the study of the mechanical resistance of the microcapsules to stirring and mixing.

3.3.3 – Mixture process

The PCM was added to the fresh concrete on site. The mixing process was executed in two phases from two different concrete mixtures (in the second mixture, water was added before adding PCM). During this process important aspects were observed resulting from the mixing process, and subsequently from the application over the structural slab:

i. The water absorption by the PCM is very high, (a great deal more than the manufacture adverted) which created difficulties in respect to the pumping process for a S2 class concrete;

ii. It is desirable that the PCM should be added in the final stage of the mixing process to reduce the mechanical impacts between the aggregates and the polymer capsules during the mixing process to minimize the PMMA shell bursting;

iii. No atypical temperature development during the chemical reactions of the concrete in the mixing process was observed;

iv. Segregation of fines "surface slurry" of PCM in the fresh concrete was observed in the form of small pockets;

iv. The superficial finishing of the concrete was carried out without added difficulties;

v. Some outcrops and retentions were verified.

Figure 3.3 shows the procedures concerning quality control of the concrete and PCM mixing process and application on site.

(a)

(b)

(c)

(d)

Figure 3.3 – Stages of the concrete screed execution: (a) concrete temperature, (b) slump test, (c) pumping and concrete application, (d) concrete applied before the finishing

During the mixing process and application it was possible to conclude that greater control in the method of mixing PCM into the concrete can prevent the formation of pockets of PCM and avoid the occurrence of some outcrops.

3.4 – Experimental tests: description and characterization

For the concrete characterization in terms of compression and bending strength, NP EN 12390-3 and NP EN 12390-5 [87, 88] standards were followed, during the specimens preparation on site (see Figure 3.4). A total of 18 concrete specimens with cubic shape and standardized dimensions of 150x150x150 mm^3 and 12 cylindrical specimens with a diameter of 150 mm with height twice the value of the diameter and 12 rectangular beam specimens (800x200x200 mm^3) were prepared.

Figure 3.4 – Specimens preparation during the concreting on site

The mechanical and thermal characterization of the concrete was performed resourcing to the following laboratory tests:

i. Uniaxial compression tests on standard specimens;
ii. Bending tests (two load points) on specimens with standard dimensions;
iii. Temperature profile evaluation of the test specimens surfaces after the test, with thermal imaging;
iv. Evaluation of the temperature influence on the PCM phase change in the specimens mechanical strength in compression and bending;
v. Temperature controlled trials to assess the concrete with incorporated PCM energy storage capacity.

3.4.1 – Procedure and test instrumentation: mechanical tests

The mechanical characterization in terms of compression was performed using a universal testing machine (see Figure 3.5) with compression capacity of 3000 kN complying with the requirements defined by the standard compression tests NP EN 12390-3 [87]. The specimens (standard cubes) were tested after a 28th day curing period.

Figure 3.5 – Uniaxial compression tests

The mechanical characterization tests regarding bending, were performed in a closed steel frame structure in which the load was applied using a hydraulic actuator with 100 kN capacity. The load was applied at a constant speed (with displacement control), and recorded with an electronic load cell. In addition to recording the applied load, the vertical displacements were controlled with Linear Variable Differential Transformer (LVDT) sensors placed on the two opposite faces of the specimens to control eventual rotation caused during the load course application.

Figure 3.6 shows the setup test, the load cell and the displacement sensors used.

(a)

(b)

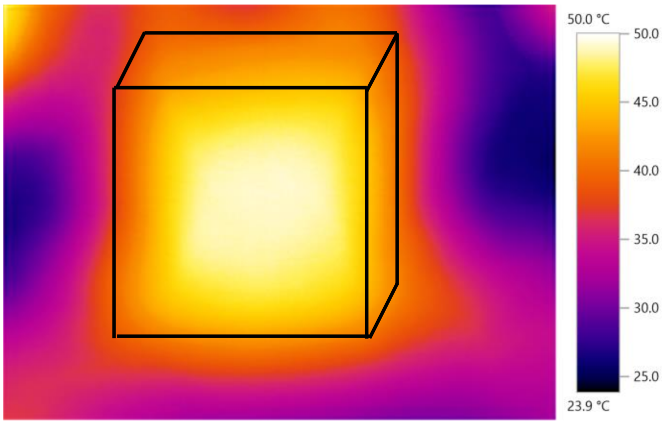
(c)

(d)

Figure 3.6 – Test frame and instrumentation: (a) closed steel test frame, (b) test setup, (c) load cell, (d) displacement sensor LVDT

All mechanical characterization tests in compression and bending, performed on specimens pre-warmed at 50 °C were controlled by thermal imaging in order to ensure that the total mass of concrete (both surfaces and interior) is heated at a constant temperature.

(a)



(b)

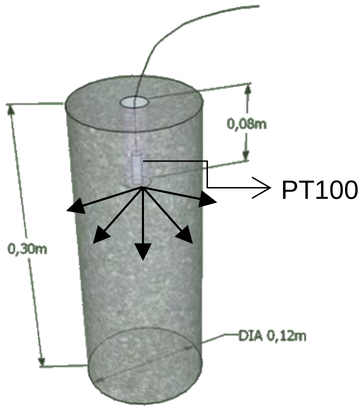
Figure 3.7 – Compression test: specimens failure and internal temperature control: (a) conical failure of uniaxial compression specimens, (b) thermal image after failure with the temperature scale in degrees

With thermal imaging it was assured that all tests were carried out, with a temperature difference below 1 °C.

3.4.2 – Procedure and test instrumentation: thermal tests

In addition to the referred tests it was also evaluated the thermal behaviour of the concrete incorporating PCM, that is, in simple terms, the inertial capacity. Thus 7 mm diameter holes were made with a depth of 80 mm into the cylindrical specimens centre for the introduction of a PT100 temperature probe. The hole was sealed and isolated to ensure that the heat exchanged would occur through the concrete core outward (see Figure 3.8). The test procedure consisted in placing two cylindrical concrete specimens (one with PCM and another the reference concrete) into a climate chamber (see Figure 3.8) at a target temperature of 40 °C. Thus, the test specimens were subjected to the same heating and cooling curve.

(a)



(b)

Figure 3.8 – Temperature setup test (a) test chamber, (b) Test specimen with PT 100 probe in the specimen core

The temperature monitoring of the chamber and in the specimens were made resourcing to a data logger ICP®. To the data logger ICP® were connected five PT100 probes. Three of them were used to monitor and record the temperature within the chamber and the other two were placed inside the test specimens as described before.

3.5 – Final results and remarks

This section presents the results for all specimens with and without PCM incorporation: i) compression tests; ii) bending tests; iii) and in thermal behaviour of concrete incorporating PCM.

3.5.1 – Compression tests

Table 3.3 shows the main results, in terms of density and compressive strength. The results shown are average values, which correspond to a mean value of three test series. In this context, for clearer analysis the following nomenclature was used:

i. PCM I – Concrete with PCM incorporation resulting from the first mixture;
ii. PCM II – Concrete with PCM incorporation resulting from the second mixture;
iii. BR I – Reference concrete resulting from the first mixture;
iv. BR II – Reference concrete resulting from the second mixture;
v. PCM I Temp – Concrete with PCM incorporation resulting from the first mixture and heated to a temperature of 50 °C;
vi. BR I Temp – Reference concrete resulting from the first mixture heated to a temperature of about 50 °C.

Table 3.3 – Mechanical compression and density results

Test specimen[(a)]	Test specimen image	Ultimate Maximum Stress[(b)] (MPa)	Density[(b)] (kN/m³)	Failure type	Observation
PCM-I		15.50	21.81		-
PCM-II		18.33	22.06		PCM mixing with the concrete by stages combined with the prior introduction of water
BR-I		57.77	24.40		-
BR-II		49.73	24.58		-
PCM-I-Temp		17.00	21.43		Temperature after testing $t_{surface}$ = 48.93°C $t_{interior}$ = 51.27°C
BR-I-Temp		54.00	24.15		Temperature after testing $t_{surface}$ = 49.03°C $t_{interior}$ = 49.00°C

(a) Testing at 28 days | (b) Average Values of 3 test specimens

From the results shown in Table 3.3 it is possible to conclude that:

i. Density loss in concrete was approximately 10.5% in average with the addition of PCM;

ii. Concrete compressive strength loss with incorporated PCM was about 68% in average;

iii. The influence of the incorporation method of the PCM and the addition of water in the mixture process led to a lower loss of compression strength in the concrete specimens with PCM incorporation;

iv. Ultimate strength has been increased approximately 8% influenced by heated specimens in the concrete incorporated with PCM.

3.5.2 – Bending tests

A total of 12 test specimens with rectangular dimensions were tested according to NP EN 12390-5 [88] standard.

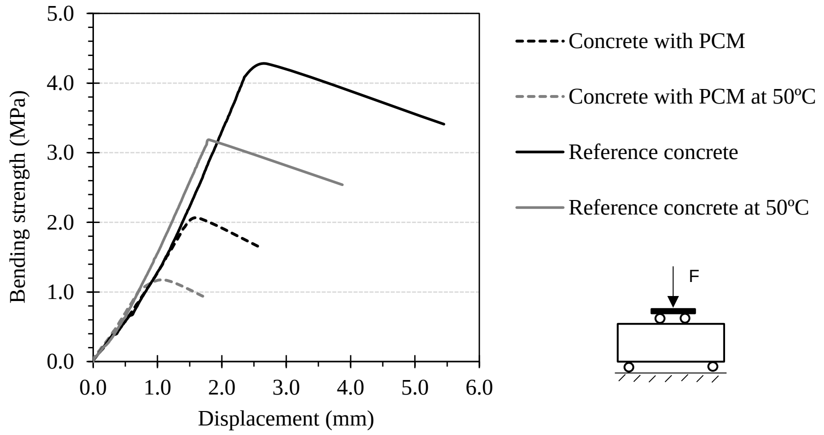


Figure 3.9 – Bending strength displacement results

The results shown in Figure 3.9 allowed to conclude that the initial stiffness of the elastic bending of the test specimens with and without PCM are similar. In terms of maximum bending strength, significant losses were observed for the concrete incorporating PCM especially for the specimens exposed to temperature effect (50 °C). In sum it is possible to state:

i. A reduction of 25% in bending strength for the specimens incorporating PCM in comparison to the reference concrete test specimens, and a reduction of 43% for the concrete incorporating PCM in the specimens with temperature influence;
ii. Loss of 51.75% of the maximum bending strength for the specimens incorporating PCM in comparison to the reference concrete test specimens, and 63% loss when the specimens were subjected to the temperature effect.

3.5.3 – Thermal behaviour tests

The thermal behaviour performance was assessed to evaluate the energy storage capacity of the concrete with PCM incorporation during the phase change process. The specimens were placed into a chamber and heated to a target temperature of 40 ºC. Reaching this temperature, the chamber was cooled down until achieving ambient air temperature. In Figure 3.10 it is shown the temperature profiles for both curves of the test specimens and the interior chamber temperature.

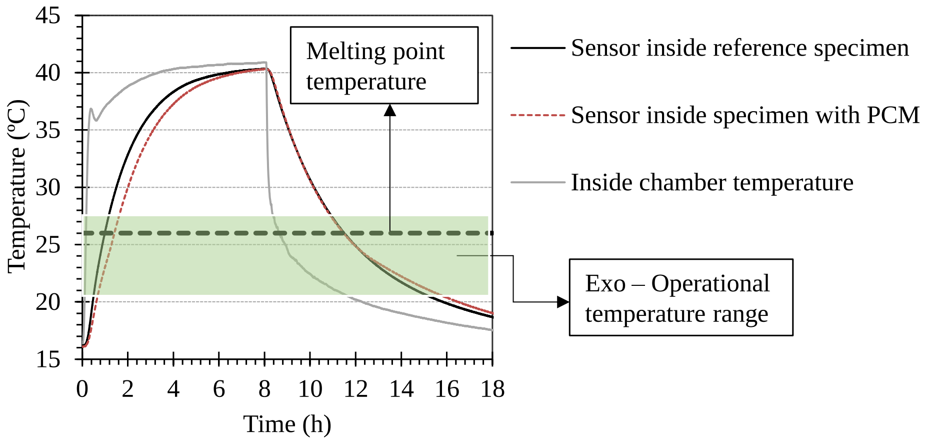


Figure 3.10 – Temperature profiles in the interior of the chamber and in the specimens core

Figure 3.10 shows that the temperature profile of concrete with PCM, during the heating phase, revealing a slower temperature increase than the reference specimen. In the cooling phase (after reaching 40 ºC) a temperature differential of approximately 1 °C was observed. This slight difference is due to the PCM exothermic process that releases energy previously stored and which causes the temperature of the specimen not to quickly decrease. It is important to highlight again that the PCM incorporation in the concrete was 3.21% by weight of the total mass, which represents a small percentage of the concrete mixture.

From the achieved results of the increase of the thermal capacity and a reduction of the temperature drop is observed for the specimen with PCM. Considering that the PCM incorporation into concrete can be managed for higher dosages if applied in a superficial layer of the slab (compression screed layer of a thermally activated slab) the presented results could be exponentially improved.

3.6 – Comparison with other research work results

Research on the mechanical characterization of concrete with incorporation of PCM is still a new trend, moreover in the case of thermally activated slabs. Although the mechanical behaviour of render mortars are somewhat comparable with the behaviour of the concrete, this study focused on the literature of structural concrete with PCM.

In Table 3.4 are presented mechanical characterization results from other studies on concrete and mortars with PCM incorporation. The loss of compression and bending strength always corresponds to a comparison between the test specimen with and without PCM in the respective proportions indicated.

Table 3.4 – Other research work regarding mechanical characterization of concrete and mortar with PCM incorporation

Other research work (authors)	Mortar / concrete mixture	Percentage of incorporated PCM in terms of total weight (%)	Average loss of compression strength (%)	Average loss of bending strength (%)
Zhengguo Zhang *et. al.*, [89]	Mortar with 1:3 ratio of cement and sand and water in ½ ratio of the weight of cement.	0.50	32.07	n.a
		1.20	41.35	n.a
		1.70	48.95	n.a
		2.50	55.70	n.a
Biwan Xu and Zongjin Li[90]	Mortar with 1:2 ratio of cement and sand and with water in ½ ratio of the weight of cement.	10.00*	26.80	13.04
		15.00*	28.90	8.70
		20.00*	43.60	27.54
		30.00*	48.70	47.50
M. Hunger *et. al.*, [66]	Self-compacting concrete	1.00	29.52	n.a
		3.00	52.79	n.a
		5.00	71.15	n.a
Present Study	Concrete	3.21	68.16	51.75

* - Relative percentage to the weight of cement of the mortar / concrete mixture | n.a – not available

Analysing Table 3.4 results, the average strength losses are comparable to other research work on cement mortars and concrete. The average loss of compression and bending strength for specimens with over 3.0% of incorporated PCM lead to more than 50% loss of the original strength capacity.

3.7 – Final remarks

The incorporation of microencapsulated PCM into concrete leads to a reduction in the concrete mechanical properties. Comparing the results attained between the concrete reference specimens and concrete incorporating PCM strength losses of 68% in compression, and 51% in bending were attained. With these strength losses, the concrete with PCM is still acceptable for application into concrete screed layer purposes. About the apparent densities of the concrete the PCM incorporation does not significantly change this property.

From the temperature chamber tests it was found that the addition of added quantity of PCM in the concrete slightly improves the thermal behaviour. Thus, PCM incorporated into the concrete screed layer, can reduce the indoor air temperature peaks and attenuates the daily temperature swing.

It is necessary to improve the mixing process of the PCM into concrete in order to achieve an increased knowledge of the features and issues responsible for the strength loss involved to the mixing process. Thus, it will be possible to provide more efficient mixing and production techniques to obtain lower loss of the mechanical properties.

From the results it is important to conclude that the mixing process and the water and binder relation must be optimised with higher control levels to reduce the high strength losses measured. Finally, from the assessment of the work developed, PCM provides a good potential on the thermoregulation effect, however special concerns on the mechanical properties should be taken in account.

This chapter presented and discussed the potential use of phase change materials. Thus, such materials will be studied further in chapter 5 and 6, for their thermal regulation effect and overheating reduction potential, in real case studies.

CHAPTER 4

PASSIVE HOUSE OPTIMIZATION FOR PORTUGAL: OVERHEATING EVALUATION AND ENERGY PERFORMANCE

Chapter outline

4. PASSIVE HOUSE OPTIMIZATION FOR PORTUGAL: OVERHEATING EVALUATION AND ENERGY PERFORMANCE

Work related to this chapter was published in the **Energy and Building** – An International Journal devoted to investigations of energy use and efficiency in buildings. Impact Factor: 2.88 DOI: 10.1016/j.enbuild.2016.02.034

Abstract Improving common constructive solutions and substituting HVAC systems for more efficient ventilation systems leads to significant opportunities to decrease energy demand for heating and cooling and for improving occupant's comfort. Passive House concept adapted to Southern European countries is regarded as a necessary strategy for reducing global energy consumption and greenhouse gas emissions at the building level. The present research, undertakes the Passive House concept optimization for the Portuguese climate, using a real building case, built according the national thermal code and classified as a plus building. The goal consists in complying with PH requirements through the definition of the external envelope solutions as well as the heating and cooling systems to be applied to new or refurbished buildings. The research starts for the Aveiro region climate (site built) and a broader analysis for different regions of Portugal mainland were performed. The building simulated is a detached house of contemporary architecture with the numerical model developed based on the original patented design solution and dynamic simulation realized with EnergyPlus® software. In a first approach and from the original model, sensitivity analysis and multi-objective optimization with an evolutionary algorithm were carried out in order to assess the reduction potential of the annual energy consumption. From the results long periods of thermal discomfort for the heating season (from 60 to 92%) were observed, as well as long periods of overheating during the summer (from 13 to 43%). Comparing one of the best solutions attained with the original case study, a reduction of 42% of the heating energy demand and the reduction of 64% of the cooling demand was achieved. Then, in a second approach the evolutionary algorithm was used to meet the compliant parameters defined by PH standards for different regions in Portugal mainland. The multi-objective optimization was developed to study the interaction between annual heating demand and summer thermal overheating rate objectives and assess their trade-offs. It was concluded that the Passive House concept is viable for the Portuguese climate; however it is essential to adapt and detail the technical and constructive solutions for different regions.

4.1 – Introduction

The International Energy Agency (IEA) collected data on world energy consumption which reveals that in the last decade, during the period between 1991 and 2012, the population has grown by 30% and the Total Primary Energy Supply (TPES) follows an evolution of three times the population growth (Figure 4.1). According to IEA the energy consumption trend in 2030 will be 23 TW (1.7 times 2012 data) based on current policies this value can be reduced to 19 TW if the policies under consideration are followed (1.4 times 2012 data).

Taking into account the rise of the total daily hours spent in buildings, a sustained threat of increasing of energy consumption and CO_2 emissions in the building sector, every day becomes more worrying. Population and economic growth, more strict indoor comfort levels and air quality, and the proliferation of air conditioning systems dependence turn the construction sector as one of the greatest energy consumers. It is estimated that this sector is responsible for consuming 20-40% of the total final energy consumption and considerable production of Green House Gases (GHG) [91, 92]. In the EU in 2010, buildings accounted for 40% of total primary energy consumption and released about 40% of total CO_2 emissions [93].

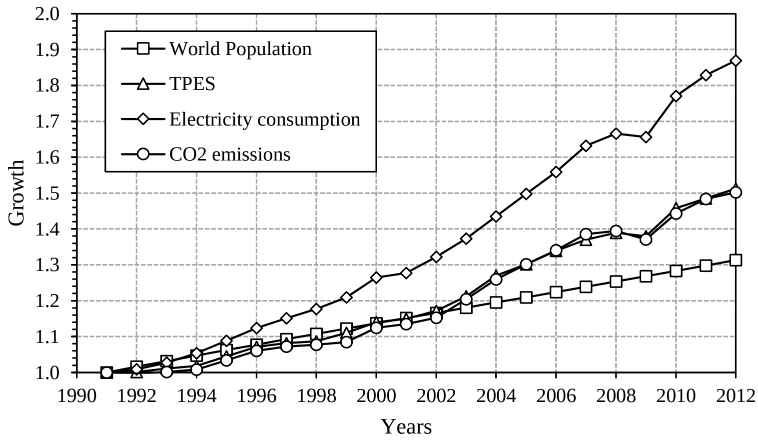


Figure 4.1 – World: indicators evolution (1991 to 2012). Source: International Energy Agency [94]

In Portugal, the Directorate General for Energy and Geology (DGEG) collected data that revealed a significant impact on the global energy demand with high quota related to the building sector [95]. Approximately 17% of the energy in 2009 is used in residential buildings. As a consequence, the development of higher efficiency energy buildings is a challenge at a global context due to the high impacts of the building sector on the energy consumption and on the environment worldwide. This goal concerns the energy efficiency and savings strategies issues as the priority objective for energy policies throughout the world. In Portugal the publication of the reviewed thermal code was the first step of the strategy to achieve the energy demand goal. To fulfil the EPBD goals (described in section 2.1) the Passive House concept is an essential premise for the strategy to reduce annual energy demand and achieve nZEB states. In spite of the PH concept established mostly for cold climates, new concerns on energy efficiency emerged in the Southern European countries with respect to the increase of cooling energy demand as described in section 2.1. Passive House concept was already described in section 2.1 however the following research studies are essential for this chapter framework and some these studies were taking into account the Portuguese climate.

Gonçalves and Brotas, following the Passive-On research have concluded that in Portugal it is estimated that the adjustment of the PH concept can reduce nearly 90% of thermal energy consumption in buildings [96]. Other studies regarding the PH concept application in Portugal mainland have been developed by the following authors without an optimization approach taking into account overheating risk. Ferreira and Pinheiro have studied the importance of bioclimatic measures in the scope of the EPBD implementation through the PH concept comparison (when the standard is applied to warm countries in Europe) [97]. Other important research work conducted by Jürgen Schnieders [46] was the parametric study of a row building (Hannover building typology) for Passive Houses in South West Europe, including Lisbon and Oporto, concluding that an annual heating and cooling demand requirements are reached for the most of locations in study. The levels of insulation can be considerably reduced; however the heat recovery system is necessary for almost all locations, except for the Oporto region. Another important conclusion is that the solar control (with shading elements or different windows solutions), wall to window ratio and the reduction of internal heat loads (such as lighting, equipment, etc) are critical. The global conclusion was that the task of designing Passive Houses in the South West Europe is more difficult than in central Europe, due to the hot and humid summers, that require additional measures to prevent overheating.

In sum and acknowledging that the amount of energy used in buildings is conditioned to local weather conditions, architectural design, energy systems for heating and cooling, electric appliances and lighting, are all essential to hold the need to adapt the construction features and active systems to specific climate zones.

4.2 – Simulation methodology for the PH optimisation

The goal consists in the definition of external envelope solutions as well as active systems needed to be applied to new or refurbished buildings in order to comply with PH comfort and energy requirements. To achieve this goal, dynamic thermal simulation of a detached building was carried out using EnergyPlus® 8.3.0 software.

The methodology starts with a hygro-thermal monitoring campaign of the building used to validate the numerical model. To record temperature and relative humidity thermo-hygrometer sensors were installed. In the second step a sensitivity analysis with passive features such as glazing type, orientation, bypass air flow rate, and insulation thickness was carried out. Seventy-two models were run in order to assess the thermal response of the case study and to analyse the effectiveness and improvement of the passive techniques. Once the improvements achieved, a smaller set of new simulations were carried out in order to define the best Passive House solution for the Aveiro region in Portugal mainland. The third step was performed with a multi-objective evolutionary algorithm. The parameters and objective functions were the same as the ones defined in the sensitivity analysis. The last step aims to optimise the found solutions by adding exterior shading devices to achieve passive house requirements for different regions in Portugal mainland without a common active cooling system during the summer season. This objective was fulfilled by removing the cooling system and adding the thermal comfort condition in the objective functions (binomial criteria: energy demand and comfort analysis using EN 15251 [29]). It is important to note that the parameters range was adapted in accordance with the energy demand limits and the discomfort conditions attained for each region.

The methodology described can be schematically depicted in Figure 4.2.

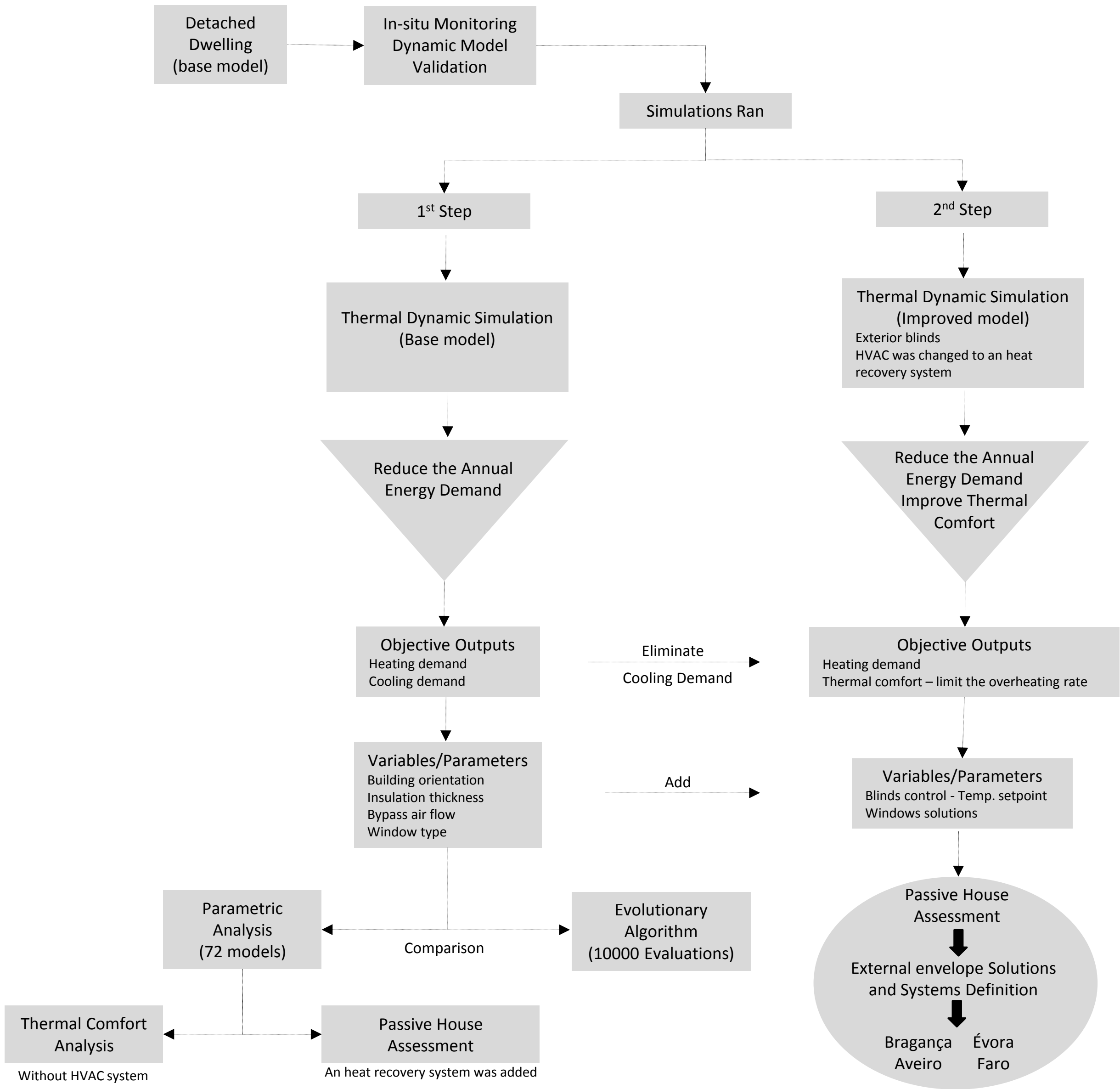


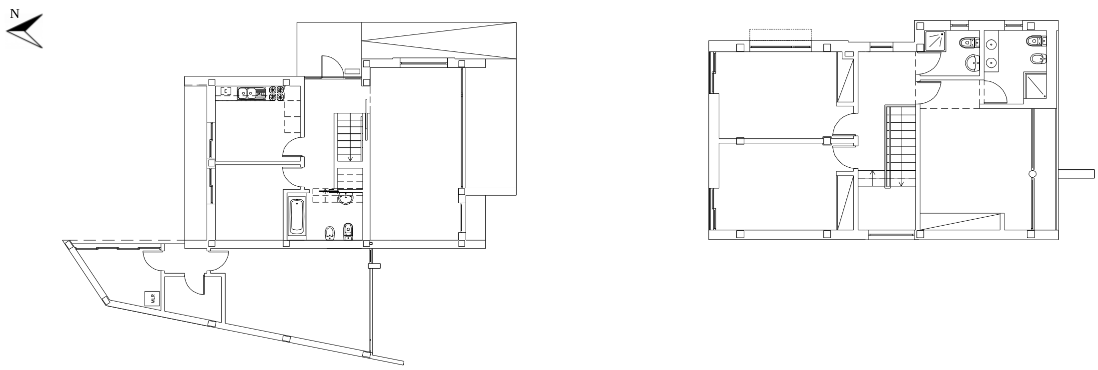
Figure 4.2 – Simulation methodology for the PH optimisation followed

4.3 – Case study

4.3.1 – Base model: general characterization

The base model under study is an existing contemporary architecture building, as shown in Figure 4.3. The ground floor entails the common living-space of the house and the first floor comprises the bedrooms and bathrooms. The house has 160 m^2 of treated floor area with a 405 m^2 of exterior surface area and the global percentage of glazing is about 24% of the opaque facade area. The building was oriented to take the maximum benefit from solar radiation during the heating season.

The building presents a simple box shape with highly glazed areas, with a form factor of 0.8 m^{-1} (A/V ratio; A – area; V – volume) [52].

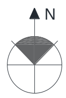
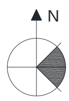
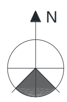
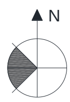


(a) (b)

Figure 4.3 – Architectural blueprints (no scale): (a) ground floor level; (b) elevated floor level

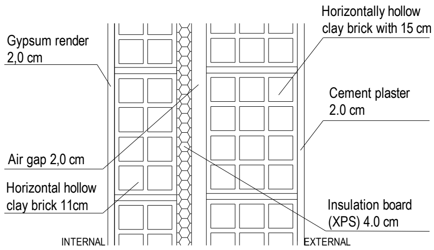
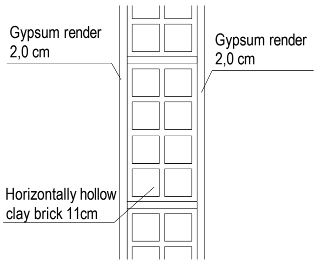
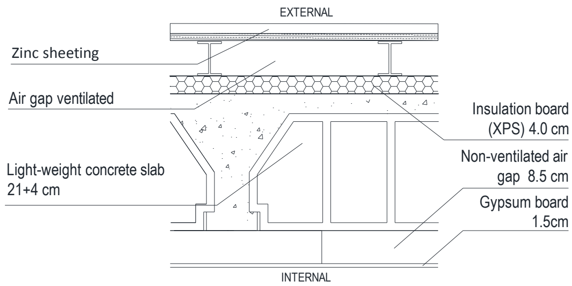
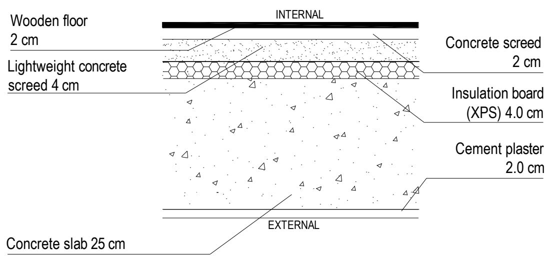
The glazing represents a relative percentage of 32% of the North facade, 54% of the South facade, 16% of the East facade and 1% of the West facade (see Table 4.1).

Table 4.1 – Window-wall ratio of the base model

	Total				
Gross wall (m^2)	192.03	41.69	64.21	41.69	44.44
Glazed (m^2)	46.70	13.52	10.32	22.87	0.71
Window-wall ratio (%)	24.32	32.43	16.06	54.85	1.04

The building's envelope walls are mainly composed of a double hollow clay brick with air gap and insulation thickness in the middle. The calculation method used to determine the thermal bridges depends on the type of bridge encountered (linear and punctual thermal bridges). In the present work the linear thermal bridges were estimated using the THERM® software and were taken into account in the model using an equivalent U_{value} for the thermal resistance for the opaque envelope (columns and beams). Table 4.2 lists the constructive solutions used.

Table 4.2 – Constructive solutions of the base model

Building element	Constructive solution	U_{value} (W/m^2 °C)
External walls		0.454
Internal partition walls		n.d
Flat roof		0.332
External floor slab		0.693

n.d - not defined

The thermal characteristics values used for windows were: thermal transmission coefficient ($U_{w,\ installed}$ = 1.77 W/(m^2°C)); Solar Heat Gain Coefficient (SHGC = 0.56); and external doors ($U_{w,installed}$ = 1.40 W/(m^2°C)). These values take into account the frame U_{value} (U_f) and glass edge thermal bridge (Ψ_g) in accordance with ISO 10077 [98] and the installation thermal bridge ($\Psi_{Install}$) in accordance with EN ISO 10211 [99]. In order to optimise the sensitivity analysis, an average value, $U_{w,installation}$, was used.

4.3.2 – Numerical modelling: monitoring and validation

In this section the hygro-thermal monitoring campaign performed in the building, fundamental for the validation of the numerical model, is exposed. To record temperature and relative humidity, thermo-hygrometer sensors were used: the temperature probe has an accuracy of 0.5ºC and a resolution of 0.1ºC and the humidity probe has 3% of accuracy and 0.1% of resolution.

The building was monitored during the last week of August (period from the 24th to 31st) and in the first week of December (period from the 3rd to 10th) 2013. The positioning of sensors inside of the compartments was defined in order to avoid direct sun exposure from the glazed areas. This distribution was done near to interior partition walls in accordance with ISO 7726 [100] to prevent the combined effect of solar radiation and exterior temperature of exterior walls. The numerical model was fed with weather data collected from a local weather station (2 km away from the local site). The monitored data was collected with a time step of 10 minutes and the parameters were: air temperature; relative humidity; solar radiation; wind speed and direction.

The comparison between measured and numerical data was done for the indoor air temperatures for the hall and the access to first floor spaces (sensor located at the ground floor and first floor) during the last week of August without occupation. To validate the model in accordance with the real use, some zones were monitored over a period of occupancy of the building in December 2013. Three main compartments (kitchen, living room and the first floor bedroom with South orientation) were monitored and the results are used to validate the numerical model with a real occupation profile accounting for internal gains. A real occupation schedule was defined by the residents themselves during this period under study resourcing to a data sheet created for this purpose. The resulting profile was used for the model validation.

The overlapping of results shows a fairly good agreement between numerical model and *in-situ* measurements. The difference between the temperature curves was approximately 1°C maximum (mainly due to temperature stratification) and a *CV RMSE* of 6.3% was attained.

With these slight differences in results and comparing *CV RMSE* with the values defined by guidelines ASHRAE [61], IPMVEP [62] and FEMP [63], the model was considered validated.

4.3.3 – Weather files used for numerical models

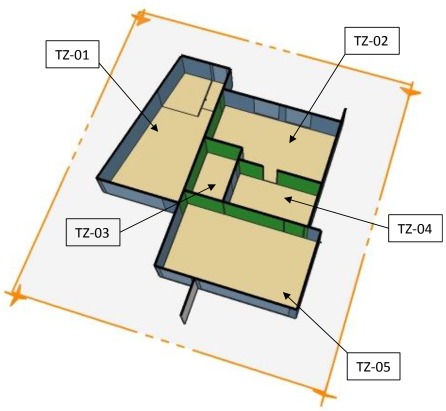
This point is completely detailed in section 2.2.2. The weather file parameters contained data of the regions in study in this chapter: air temperature; relative humidity; direct (solar) normal irradiance; and diffuse horizontal irradiance is resumed in Figure 2.5 and Table 2.3 in the Chapter 2.

In this chapter, two regions, representative of the interior North and South (Bragança and Évora) and two other near to the coast (Aveiro and Faro) were chosen.

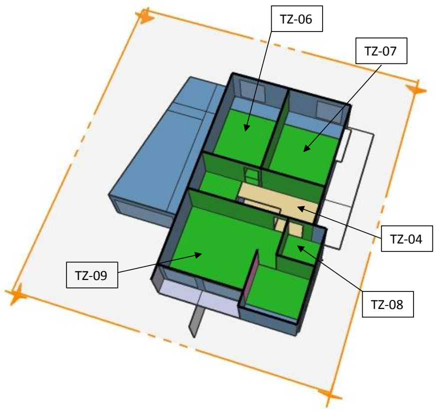
4.3.4 – Thermal building simulation: numerical model

Based on the parameters defined in previous sub sections (4.3.1, 4.3.2 and 4.3.3), a building model is developed resourcing to EnergyPlus® software as calculation engine. A SketchUp® tool with OpenSudio plugin, with a graphical interface, was used to reproduce the geometry of the model and some main features related to thermal zoning and constructive solutions definition.

A detached multi-zone model was assembled using nine thermal zones, corresponding to internal compartments of the building (see Figure 4.4). The ground floor has five thermal zones including the garage (unheated space), and the first floor has another five thermal zones. One of these five zones is common to both floor levels and includes the corridors and the staircase (TZ-04).



(a)



(b)

Figure 4.4 – Layout of the indoor spaces: (a) ground floor; (b) first floor. TZ-01 Garage; TZ-02 Kitchen; TZ-03 Bathroom; TZ-04 Hall; TZ-05 Living Room; TZ-06 Bedroom; TZ-07 Bedroom; TZ-08 Bathroom; TZ-09 Bedroom

During the summer season in an attempt to prevent overheating, internal blackouts were proposed and installed for the first floor windows and drapes at the ground floor.

The building was occupied by a family composed by two adults and two children (100% of occupation level/density) with a typical monthly agenda with a schedule routine presented in Table 4.3. Still with regard to Table 4.3, please note that during the remaining hours the presented zones are unoccupied.

Table 4.3 – Occupancy schedule by thermal zone TZ-i

Thermal Zone	Occupants Level* (%)	Profile: Week Day (On From)	Profile: Weekend (On From)
TZ-01	0	Always-off	Always-off
TZ-02	50	7.00 to 8.00	8.00 to 9.00
	100	8.00 to 9.00	9.00 to 10.00
	100	12.30 to 14.30	13.00 to 15.00
	50	19.00 to 20.00	19.00 to 20.00
	100	20.00 to 21.00	20.00 to 21.00
TZ-03	25	7.00 to 8.00	8.00 to 9.00
	25	19.00 to 20.00	19.00 to 20.00
TZ-04	0	Always-off	Always-off
TZ-05	100	21.00 to 22.00	21.00 to 23.00
	50	22.00 to 00.00	22.00 to 00.00
TZ-06	25	22.00 to 7.00	23.00 to 8.00
TZ-07	25	22.00 to 7.00	23.00 to 8.00
TZ-08	25	7.00 to 8.00	8.00 to 9.00
	25	19.00 to 20.00	19.00 to 20.00
TZ-09	50	00.00 to 7.00	1.00 to 8.00

* 100% represents 4 occupants

Energy consumption of the building is not only due to external envelope characteristics exterior boundary conditions or active heating/cooling systems. Indeed, a group of other features (occupancy, lighting and electric equipment) is responsible for the internal gains that come into play. In this case study, real schedules were defined for the occupancy, equipment and artificial lighting hours. The energy consumption was collected from the electricity bills and adapted per thermal zone in accordance with the technical details of the appliances/equipment and lighting installed.

4.4 – Sensitivity analysis - results

4.4.1 – Original building performance

Initially, the building was modelled with an HVAC system for assessing the annual energy consumption for heating and cooling. In a second approach, the building was modelled without HVAC system, however a 0.6 h^{-1} air change rate was ensured as a natural ventilation mode, including the building envelope infiltrations (without cooling or heating inputs). The indoor air quality requirements according to EN 15251 [29] should be satisfied by adopting in the numerical simulations a minimum ACR of 0.6 h^{-1}, assuming to comply with the requirements of Category II that should be used for new and refurbished buildings. Moreover, 0.6 h^{-1} is also the maximum admissible ACR imposed by the PH concept. The second approach without the active system allowed a passive thermal comfort assessment in accordance with the standard EN 15251 [29].

To assess the annual energy consumption for heating and cooling an ideal system air loads to control the indoor air temperature was defined. This system is operated by a thermostatic control for a specified temperature range with double function with a dead band for free running between 20 to 26ºC. Figure 4.5 shows the energy demand for cooling and heating.

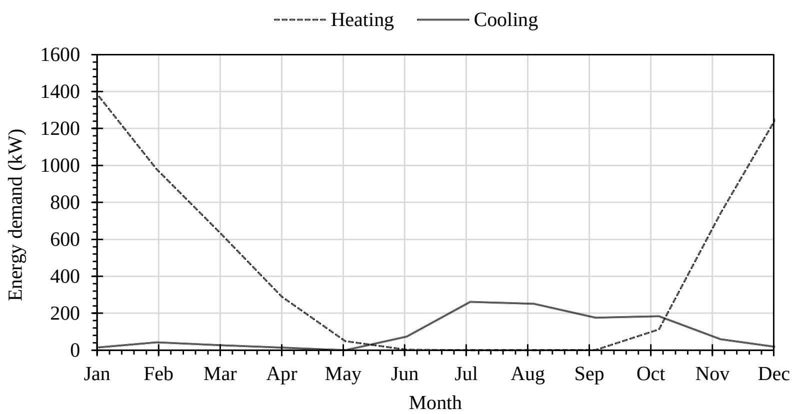


Figure 4.5 – Sensible cooling and heating demands

As expected, the period between June and September requires less auxiliary energy for indoor air comfort and the period from November to March leads to the highest energy consumption to maintain indoor air temperature above 20ºC. The overall energy demand for heating the building is 34.39 kWh/(m^{2}a) and for cooling is 6.96 kWh/(m^{2}a) considering that the temperature setpoint range is 20-26 ºC for all zones.

In the passive approach four thermal zones were selected as representative of the overall building behaviour (TZ-05, TZ-02, TZ-09, TZ-07). Two of these are oriented to South and the other two North oriented. The level of thermal comfort was assessed resourcing to the standard EN 15251 [29], which defines three categories of comfort I, II and III. The building under study fits on the category II, which refers to a normal comfort level adjusted to new and refurbished buildings.

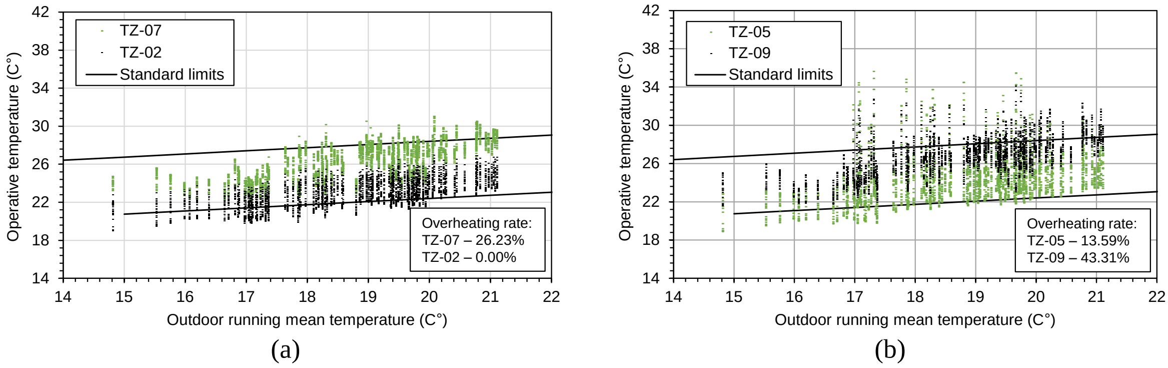


Figure 4.6 – Indoor air temperature for cooling season: (a) zones with North orientation; (b) zones with South orientation

From the analysis of Figure 4.6, it is possible to verify that the indoor air temperature for the zones with North orientation (see Figure 4.6(a)) for most of the cooling period are within the comfort zone. For the zones with South orientation (Figure 4.6(b)), it is worth to be noted an exceedance of the adaptive comfort limits above the upper limit curve for indoor air temperature, indicating long periods of overheating inside the thermal zones. On the ground floor, the living room (South oriented) presents short periods of overheating in comparison to the bedroom with North orientation because of the existence of a fin wall that shades partially the glazing.

For the heating season and analysing Figure 4.7 it is possible to assess that the indoor air temperature for all zones reveals a significant period below the lower limit of the indoor air temperature for comfort category II. For the bedroom and the kitchen (TZ-07 and TZ-02) with North orientation, it is possible to verify that the indoor air temperature during the heating season is most of the time below the lower limit of thermal comfort. The other two zones (see Figure 4.7(a)) and because they are South orientated with a highly glazed area, high overheating with frequency is revealed.

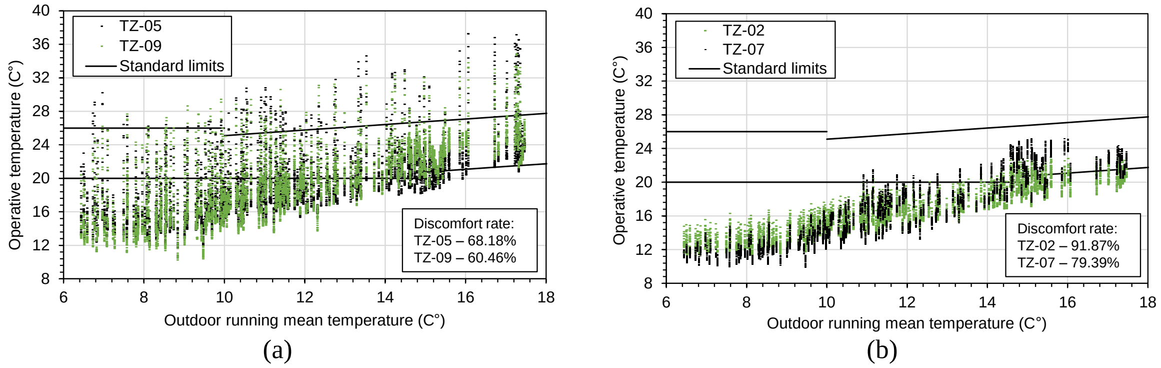


Figure 4.7 – Indoor air temperature for heating season: (a) zones with North orientation; (b) zones with South orientation

4.4.2 – Sensitivity analysis

A series of numerical simulations were carried out in order to analyse the effect and the improvements of the passive techniques. The main objective is to feature the advantage of the different strategies modelled to prevent overheating in summer and to reduce the annual energy demand attaining a high level of thermal comfort inside the building.

Different scenarios were defined to evaluate the thermal behaviour. These simulations, summarized in Figure 4.8, were performed for a rotation of the building with 0° (original position) 90°, 180°, and 270°, thus summing up to a total of 72 models to be analysed. The values of the additional air flow represent the bypass capacity expressed in h^{-1} for each thermal zone. In the cooling period the by-pass system is activated by differential dry bulb temperature, which means, the by-pass will activate and increase the outdoor air flow rate above the air change rate of $0.6h^{-1}$, when the outdoor air temperature is lower than the indoor air temperature.

The value of the thermal transmission coefficient used for the windows with triple glazing was Uw, installed = 1.18 W/(m^2°C) with a solar heat gain coefficient SHGC = 0.5.

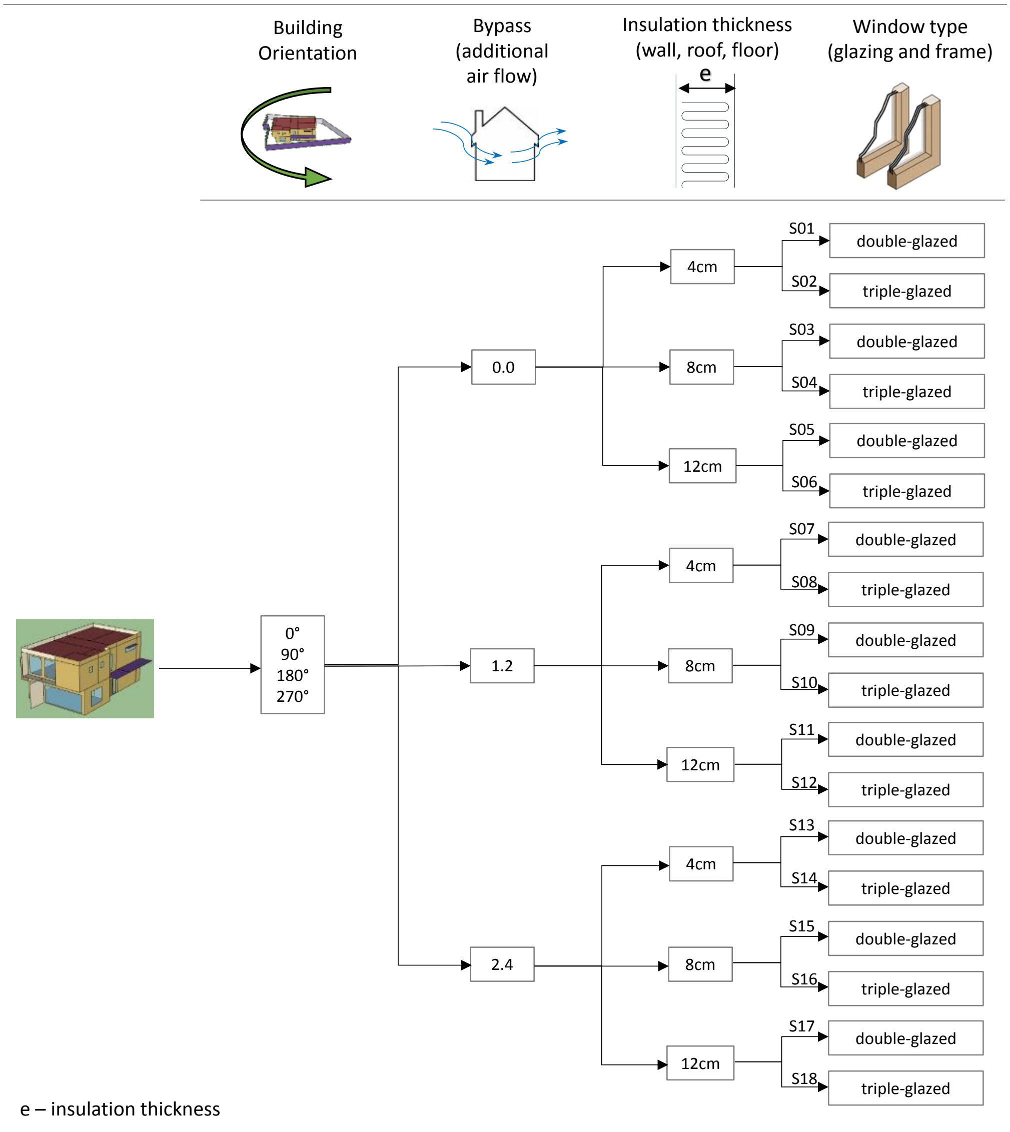


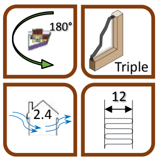
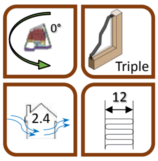
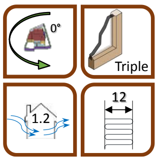
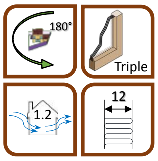
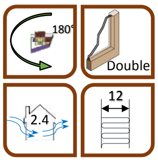
Figure 4.8 – Decision tree scenarios for sensitivity analysis

4.4.2.1 – Selected scenarios and results

From the simulations performed, the best scenarios were selected for further analysis. These were discussed in terms of energy demand for heating and cooling and the percentage of hours that the temperature drops outside of the comfort range defined (20º - 26°C).

Table 4.4 lists results for the five best simulations that lead to the best energy demand and thermal comfort performance. They represent the lowest combined heating and cooling energy demand for an annual simulation. To calculate the percentage of hours outside the comfort limits, the same simulations without defining active heating and cooling systems were performed. Simulation S54 represents the best scenario, in respect to the lowest energy demand. This scenario corresponds to a solution resourcing to a triple glazing, 12 cm of insulation for walls, roofs and floor, ACR equal to 0.6 h^{-1} with additional bypass (2.4 h^{-1}), and with the building rotated from the North by 180°C.

Table 4.4 – Best scenarios for minimum energy demand

Simulation n#		Energy demand (kWh/(m²a))			% discomfort hours (≥ 26°C)				% discomfort hours (≤ 20°C)			
		Heating	Cooling	Annual	TZ-05	TZ-02	TZ-09	TZ-06	TZ-05	TZ-02	TZ-09	TZ-06
S54		20.05	2.53	22.58	1.45	2.92	6.66	10.72	29.99	13.66	44.53	20.90
S18		19.14	3.78	22.92	5.45	0.23	10.75	8.73	29.85	39.59	19.05	43.14
S12		18.92	4.46	23.37	4.06	0.24	9.01	8.73	29.42	39.45	18.56	43.06
S48		20.02	3.36	23.37	1.51	1.78	6.61	9.90	30.00	13.58	44.51	20.89
S53		21.76	3.19	24.95	1.51	2.95	6.46	10.71	29.79	13.70	44.49	19.98

Compared with the original solution (34.39 kWh/m^{2}a), a reduction of 42% of the heating energy demand is obtained and the reduction in respect to cooling demand was 64%. In the approach without the active system, the frequency of overheating was acceptable (under 10% in average) for the cooling season however for heating season the discomfort rate was excessive.

4.4.2.2 – Passive House for Aveiro region

The best scenarios selected from the sensitivity analysis performed do not meet the Passive House requirements in terms of energy demand for heating. Thereby, a mechanical ventilation system with a heat recovery system (defined in accordance with the Passive House standard) was added only to the best simulation scenarios selected. The best solution (scenario S54) with a mechanical ventilation system with heat recovery leads to a 7.20 kWh/m^{2}a of heating and 2.42 kWh/(m^{2}a) of cooling demands. These values are below the requirements imposed by the Passive House standard. In order to obtain values of energy demand, closer to the Passive House limits (15 kWh/(m^{2}a)) a set of new simulations were performed. For the Aveiro climate zone the results reveal that the solution with double glazed windows, 0.6 h^{-1} without bypass system, 8cm insulation for the building envelope and rotated by 270º represents the best solution from the tree decision solution to meet the Passive House requirements with 13.73 kWh/(m^{2}a) for heating and 12.88 kWh/(m^{2}a) for cooling demands.

4.4.3 – Multi-objective evolutionary optimization

Optimization is an ongoing process of search and comparison of feasible solutions to a given problem until no better solutions can be found [101]. The multi-objective optimization is a problem where there are two or more usually conflicting goals. The main difference between the mono-objective optimization and the multi-objective approach is that for each problem instead of a single optimal solution there are a set of efficient solutions also known as Pareto-optimal solutions.

Since the development of green buildings has become a challenge at a global context, due to the high impacts of the building sector on the energy consumption and on the environment worldwide, many efforts have been made to assist designers in framing new solutions to achieve the goals desired. Currently, many real-world optimization problems in the construction sector involve multiple objectives optimisers. A review of some optimization studies developed in the last decade in the following topics is listed:

i. Heating and cooling [102, 103];
ii. Heating cooling and lighting energy [104];
iii. Energy consumption and life cycle cost [105];
iv. Primary energy, cost and thermal discomfort [106];
v. Primary energy, initial investment and annual emissions [107];
vi. Primary energy and investment cost [105, 108, 109];
vii. Total cost, carbon dioxide emissions and grid interaction index [110];
viii. Energy supply and demand at a district scale [111].

However, the optimization process is always a difficult task to find better design alternatives satisfying several conflicting criteria (cooling and heating demand to compare with attained sensitivity results and in other approach thermal comfort and heating demand – scope of this work). Herein is presented a multi-objective optimization using a hybrid evolutionary algorithm [112, 113] based on the Covariance Matrix Adaptation Evolution Strategies (CMA-ES) and Hybrid Differential Evolution (HDE) evolutionary algorithms.

In summary, a multi-objective evolutionary algorithm is employed to find optimal solutions with the parameters, constraints and objective functions defined in the following sub sections.

4.4.3.1 – Optimisation parameters

In an optimization process, the decision parameters reveal all set of alternative measures that are available for building design or retrofitting. Parameters allow a set of combinations of choices for the input database.

In the present study four types of decision parameters were used concerning the alternative choices. The parameters used in the optimization process were the same used in the manual trial and error approach of section 4.4.2 (sensitivity analysis). The input parameters considered and corresponding input method are shown in Table 4.5.

Table 4.5 – List of parameters action

Continuous variables		
Parameter id.	Designation	Box Constraints
x0	Envelope Insulation Thickness (cm)	4 – 12
x1 – x8 (by TZ)	Bypass Air flow rate (h^{-1})	0.00 – 2.40
x9	Building Orientation (º)	0 – 360
Discrete variables (strings)		
x10	Window Solution	U value = 1.77 (W/m^2 °C)[a] or U value = 1.18 (W/m^2 °C)[b]
x11		SHGC = 0.56[1] or SHGC = 0.50[2]

a) and b) represent coupled window solutions

Parameters defined as continuous variables (x0 to x9) can assume any value defined in the range of the box constraints limits. Discrete variables (x10 and x11) represent the parameters that can only take a value within a predefined set of values. The algorithm internally uses integer values to represent the choices. In this presented case, these choices are two different window solutions: double glazing (4|16|4 - Argon 90%) and triple glazing (4|12 | 4|12 | 4|12 - Argon 90%). The variables x10 and x11 represent respectively the U-value and the SHGC of the window. In order for the optimiser to propose only existing solutions, constraints were employed to force coupled solutions ({1.77, 0.56} and {1.18, 0.5}).

4.4.3.2 – Objective functions

The annual energy consumption of the building for heating and cooling was directly calculated by EP® software. The goal of the optimization problem in the present case study is the optimization of energy consumption for air conditioning resourcing composed of two objective functions (annual heating and cooling demand). In short the aim is to simultaneously minimize two conflicting objective functions.

4.4.3.3 – Results and comments

The results in this sub section contain the points on the Pareto front which represent a set of optimal solutions after 10.000 evaluations and the points from sensitivity analysis results.

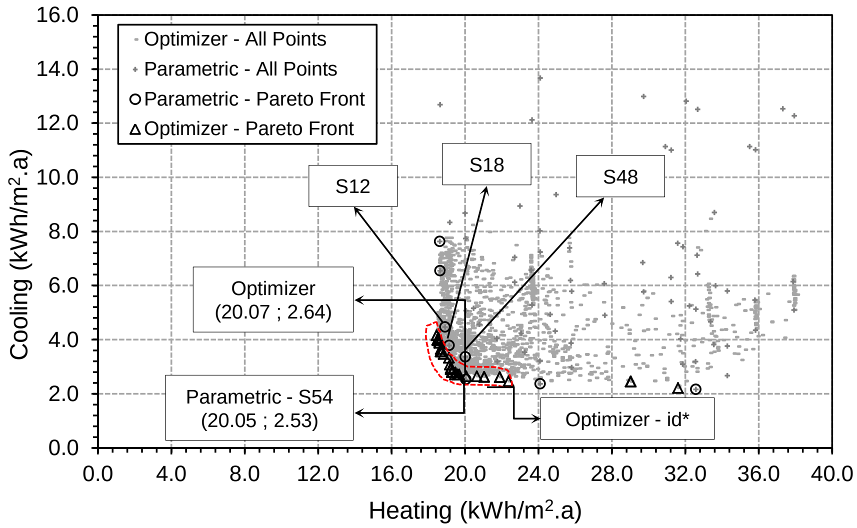
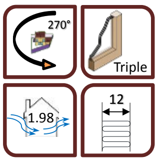
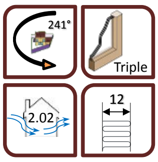
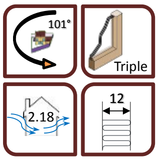
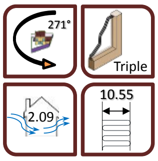
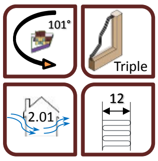


Figure 4.9 – Energy demand results: multi-objective optimization

Analysing the plot (Figure 4.9) it can be observed the best solutions (with lower annual energy demand) in the optimised Pareto front. In the plot it can be seen clearly that the heating and cooling demands are inversely proportional. Comparing the results of the sensitivity analysis with the results from the optimiser differences between 2% to 3% were observed in heating demand and differences between 3.5% and 17% were observed in cooling demand. The results were always better with the optimiser with the exception of the scenario S54 that represents a solution with all the parameters definition in the upper limit defined by constraints range. The differences observed between this scenario and the closest non-dominated scenario from the optimiser were 0.1% for the heating demand and 4.1% for the cooling demand.

Table 4.6 represents five of the best solutions taken from the optimised Pareto front.

Table 4.6 – Selected Pareto front solutions

Optimiser id#		Energy demand (kWh/m^2a) Heating	Energy demand (kWh/m^2a) Cooling	Annual
id 5811		20.07	2.64	22.71
id 3808		19.17	3.07	22.24
id 8682		18.49	3.98	22.47
id 6773		21.05	2.62	23.67
id 7584		18.45	4.16	22.61

From the results a set of conclusions can be pointed out:

i. For Aveiro region the energy for heating is on average five times higher than the energy for cooling;

ii. The best solutions for most of the cases were observed with the maximum insulation thickness and with triple glazed windows solution;

iii. The additional by-pass air flow is always close to 2 h^{-1} in all Pareto front solutions;

iv. The building orientation reveals that the zones with higher window to wall ratio were preferably orientated to the South (TZ-05 and TZ-09 for a building rotation angle at around 100º and the opposite zones TZ-02, TZ-07 and TZ-06 for a building rotation angle at around 270º).

It is important to note that the final decision can be made in agreement with the user's preferences referring to the solutions presented in the Pareto front.

4.5 – Passive House for different regions

The objective of this section is the PH evaluation for different regions in Portugal mainland. Starting from the base model with the reference parameters (U_{value} for opaque and translucent surfaces) defined by the national thermal code (REH) [52], improvements were applied to achieve the PH requirements in terms of energy demand and thermal indoor discomfort rate for summer season.

In this study the active cooling was removed and the discomfort rate during the summer season was calculated in each thermal zone of the building. A classification of summer thermal comfort (adapted from PHPP [40]), based on the frequency of overheating was performed. The measure of the frequency of overheating was defined as the rate in which indoor temperatures rise above the upper limit established by the EN 15251 [29] category II, expressed as a percentage of an annual period. The classification is defined as follows: between 0 and 2% is excellent; 2-5% is good; 5-10% is acceptable; 10-15% is poor and above 15% is catastrophic.

4.5.1 – Improvement measures to attain Passive House

During the summer season to prevent overheating (and to minimise the active cooling), exterior blinds with medium reflective slats (for Bragança, Aveiro and Evora regions) and with high reflective slats (for Faro region) were installed on both floors to attain a significant reduction of undesired solar gains. For the numerical model a schedule was created to control the blinds activation just in the summer season. It was defined between June 1st and October 31st and is triggered by the indoor temperature controller. The main characteristics of the blinds with medium reflective slats are the reduction of solar reflectance by 0.5, solar transmittance of 0.0 (with slats totally closed) and a thermal conductivity of 0.9 W/(m·K). The blinds with high reflective slats change the solar reflectance from 0.5 to 0.8.

4.5.1.1 – Optimiser parameters definition for different regions

In this sub section all the parameters used in the optimiser are presented (Table 4.7) for the different zones under consideration in this study.

Table 4.7 – List of parameters action

Parameter id.	Designation	Box Constraints used in each region	
x0	Insulation Thickness (cm)	B	6 - 12
		A	5 - 6
		E	3 - 6 walls 4.5 - 6 floor 3.5 - 6 roof
		F	2 - 4 walls 2 - 4.5 floor 2 - 4 roof
x1	Bypass Air flow rate (h^{-1})	AR	0.00 - 2.40
x2	Building Orientation (º)	AR	0 - 360
x3	Bypass activation temperature (ºC)	AR	21 - 26
x4	Slat angle (º)	AR	5 - 90
x5	Blinds activation temperature (ºC)	AR	21 - 50

B – Bragança | A – Aveiro | E – Évora | F – Faro | AR – All Regions

The parameters defined for each zone were combined with different windows solution scenarios (see Table 4.8) represented by an integer variable in the optimization process. The base case for each region starts with the windows solution defined by the Portuguese thermal code (reference solution according REH) [52]. The windows solutions were improved until achieving PH requirements. The Aveiro region was tested, in a second approach, without exterior blinds, achieving 100% comfort for scenario S1 (with exterior blinds).

Table 4.8 – Window Solution (W/(m^2 °C)) – Scenarios

Region	Scenario (Sx)	
Bragança	S1	U_{value} = 1.18 | SHGC = 0.50
	S2	U_{value} = 1.77 | SHGC = 0.56
	S3	U_{value} = 2.40 | SHGC = 0.63
Aveiro	S1	U_{value} = 2.60 | SHGC = 0.63
	S2	U_{value} = 2.60 | SHGC = 0.63 (without exterior blinds)
Évora	S1	U_{value} = 2.90 | SHGC = 0.63
Faro	S1	U_{value} = 2.90 | SHGC = 0.63
	S2	U_{value} = 1.77 | SHGC = 0.41

The goal of the optimization problem is to achieve a PH in these regions optimizing opposite objective functions heating demand and overheating (discomfort rate in summer season). A total of 10.000 runs were carried out for each curve of results.

4.5.1.2 – Bragança region

Bragança presents the most severe winter and summer climate. The methodology followed, started by verifying the PH requirements in accordance with the base model defined following the national thermal code. The objective was the definition of the optimum constructive solution and passive measures to apply in the building to achieve the PH requirements for this region.

The methodology starts by the compliance of the PH requirements with a solution with double glazed window (solution according to thermal code) using as insulation thickness a range between 6-12 cm (see Table 4.7 and Table 4.8). The lowest value (6 cm) was defined in accordance with the U_{ref} ($U_{exterior\ walls}$ = 0.35; $U_{ground\ slab}$ = 0.50; U_{roof} = 0.30; $U_{windows}$ = 2.40 W/(m^2°C)) presented in the national thermal code (REH) [52]. The results contain the points of the Pareto front for the solutions with three types of windows selected (see list of parameters defined in sub section 4.5.1.1).

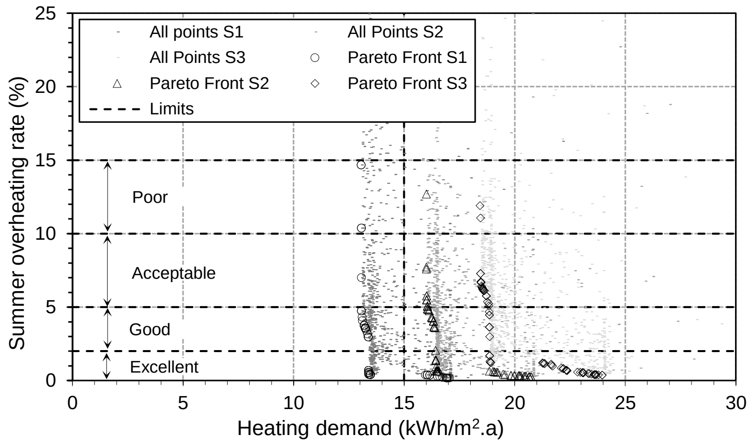


Figure 4.10 – Pareto front results for Bragança

Figure 4.10 shows the optimised solutions (with lower annual heating demand and overheating rate in the summer season) for the three optimised Pareto fronts. All points and Pareto Front represented by scenario S3 was the basis case for the simulations with the parameters defined in Table 4.7 combined with double glazing solution with an U_{ref} value defined by REH for this region. The results show an exceedance for the heating demand. The second scenario (S2) was performed with an improved double glazing windows solution. With this approach a reduction of 5 kWh/(m^2·a) of heating demand was achieved, however the passive house requirements were not fulfilled. The final approach (scenario S1) a triple glazed window solution was used and combined with the parameters initially defined. With this solution 14 kWh/(m^2·a) for heating demand was achieved.

4.5.1.3 – Aveiro region

Aveiro can be considered a region with a moderate climate. Achieving the PH requirements for heating and cooling in this region are not a very difficult task. Aveiro has humid wet temperate climate, coolish in the summer and moderately cold in winter. The rainy season claims itself during November, December, and January, while July and August are the driest months. Aveiro tends to have coastal winds, which provides good conditions to use natural ventilation as a passive way to reduce cooling demand. To this region the U_{ref} advised (REH) are ($U_{exterior\ walls}$ = 0.4; $U_{ground\ slab}$ = 0.50; U_{roof} = 0.35; $U_{windows}$ = 2.60 W/(m^2°C)).

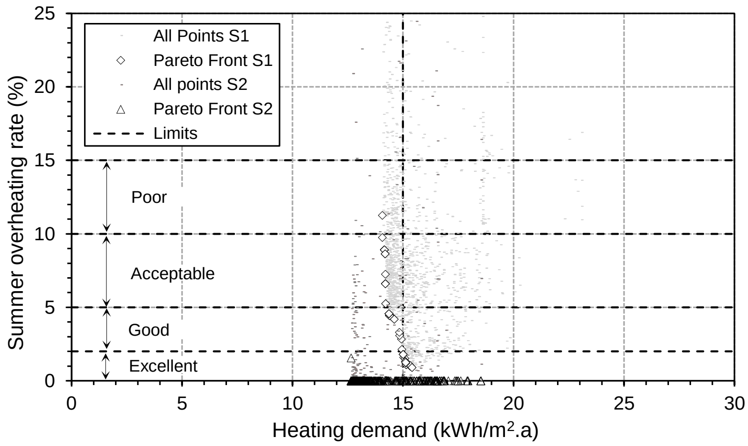


Figure 4.11 – Pareto front results for Aveiro

The first approach with exterior blinds revealed very good results in terms of summer discomfort overheating rate (see Figure 4.11). Scenario S2 led to 12.5 kWh/($m^2 \cdot a$) for the heating demand and 100% of comfort during the summer season. With such successful results, another scenario (S1) without exterior blinds was simulated. The new results reveal that it is possible to achieve excellent comfort conditions during the summer season without exterior blinds with an associated heating demand below the limit (15 kWh/($m^2 \cdot a$)). A list of predefined alternative external envelope solutions and systems is given in Table 4.9.

4.5.1.4 – Évora region

Évora is the region with higher temperatures, with an absolute maximum of 38.4ºC. The weather in this region is characterized as a hot mediterranean climate with warm to hot, dry summers and mild to cool, wet winters. Frosts in winter are uncommon and never severe. To this and Faro regions the U_{ref} values (REH) advised for the exterior envelope are the same and take the following values: $U_{exterior\ walls}$ = 0.4; $U_{ground\ slab}$ = 0.50; U_{roof} = 0.35; $U_{windows}$ = 2.60 W/(m^2°C).

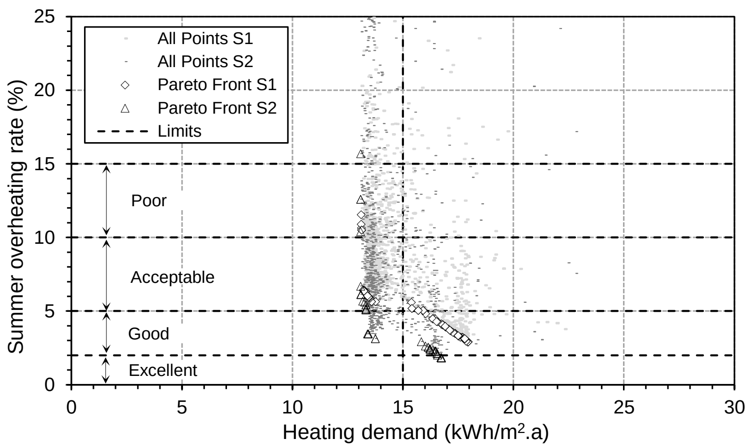


Figure 4.12 – Pareto front results for Évora

The results from the simulation for this region reveal that it is only possible to comply with the PH requirements for heating demand and get acceptable overheating rate with the first approach adopted (see Figure 4.12). To improve even better summer comfort conditions a second approach was tested resourcing to an improved window solution (Scenario S2). For this region, the use of exterior blinds and glazing with low solar heat gain coefficient is advised, to block out the undesired solar gains during the summer season.

4.5.1.5 – Faro region

Faro, near to the coast, is the region with the lowest temperature swing. This region is characterized by a long summer season (from March to November). Summers are warm to hot and sunny with higher average temperatures (above 30º). In this region the monthly average temperature never drops below 11º during all seasons. The rainfall mainly happens over the winter months and rain is very rare between June and September (summer season).

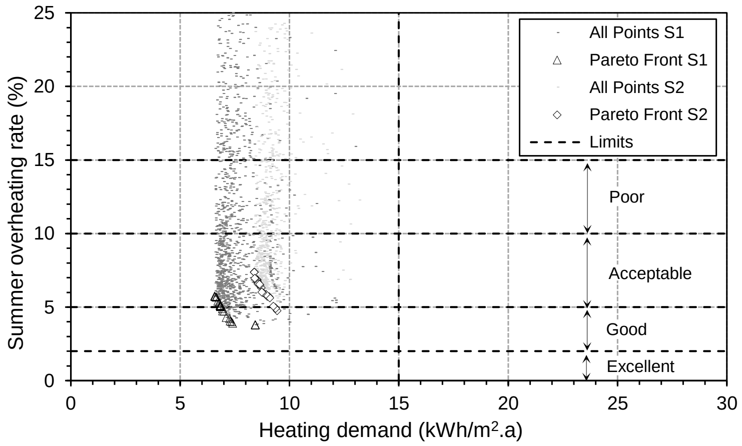


Figure 4.13 – Pareto front results for Faro

The parameters defined as reference (REH) combined with exterior blinds are enough to achieve acceptable summer comfort conditions. In this region the moderate temperatures felt during the winter season provides an easy way to comply with the heating demand limit defined by PH. To achieve good summer comfort conditions glazing with low solar heat gain coefficient was used (see Figure 4.13). The solution tested was the same used for Évora region.

4.5.2 – Results comparison and discussion

This section presents a table with a sum of the optimised solutions (see Table 4.9), energy demand for each region in study and the summer discomfort rate associated. It is also possible to evaluate the artificial lighting energy use in the case of the activation of the blinds during the occupancy schedule used. This value was evaluated with a daylight sensor placed in the kitchen and in the living room during the occupancy schedule. The illuminance was evaluated and the minimum admissible value considered was 150 lux. Below this value the activation of the internal lights (the lighting system installed only works with command on, off) was considered. In respect to illuminance and lighting requirements the European standards EN 12464 [114] and DIN 5035 [115] were followed.

Table 4.9 – Selected scenarios from the Pareto front

Optimiser. id#	Insulation Thickness (cm)			Building Orientation (degrees)	Bypass Air flow rate (h^{-1})	Bypass activation (ºC)	Blinds activation (ºC)	Slat angle (ºC)	Heating demand (kWh/m^2a)	Summer discomfort rate (%)	Extra Lighting (kWh)
	w	f	r								
Solutions with lower heating demand											
B – id1562		12.0		108	1.57	24.5	27.1	11	13.07	14.65	39.66
A – id1235		6.0		184	2.40	22.3	-	-	14.07	11.25	-
E – id2314	6.0	6.0	6.0	103	0.10	23.5	27.8	60	13.09	15.68	8.83
F – id2478	4.0	4.5	4.0	180	2.40	26	21	5	6.64	5.68	39.66
Solutions with lower summer discomfort rate											
B – id682		12.0		182	1.37	22.8	24.42	5	13.41	0.56	39.66
A – id5275		6.0		229	2.39	21.59	-	-	14.95	2.12	-
E–id10632	6.0	4.6	6.0	180	0.60	25.2	21.4	5	13.75	3.12	39.66
F – id2593	3.2	2.2	4.0	176	2.4	26	23	5	8.43	3.79	39.66
Balanced solutions											
B – id473		12.0		102	2.4	26	21	5	13.13	4.07	39.66
A – id2702		6.0		105	2.4	22.6	-	-	14.20	8.38	-
E – id2216	6.0	6.0	6.0	105	1.22	24.0	21.5	5	13.10	6.12	39.66
F – id963	4.0	3.7	4.0	187	1.31	21	23	5	6.81	5.27	39.66
Solutions nearest to the upper heating demand limit (15) and excellent summer comfort level											
B – id38		11		159	1.19	23.3	23.2	63	14.61	4.47	25.46
A – id3850		6		138	2.40	21.0	-	-	14.76	9.96	-
E–id11041	6.0	5.9	6.0	54.50	0.25	23.6	27.5	31.3	14.77	9.66	39.66
F – id4213	2.6	3.1	4.0	0	2.4	21.7	21	22.3	11.03	9.73	39.66

w – walls | f – floor | r – roof

4.6 – Final remarks

The results solidly prove the applicability of the PH concept, highly incentivized for Southern European climates.

To deepen and support this research a multi-objective optimization method using a hybrid evolutionary algorithm based on the CMA-ES and HDE was applied to a residential building case study. Using this evolutionary algorithm, each multi-objective simulation was performed with a computational time associated of approximately 10 hours undertaken with an Intel Core i7 4770K with 4 cores working at 3.5 GHz with 16GB of RAM.

Regarding the first part of this study it was observed that with a common building envelope solutions and construction materials, typically used in Portugal, simulations showed long periods of thermal discomfort for the heating season, as well as long periods of overheating during the summer. The sensitivity analysis provides an understanding of the impact of each parameter change on the building's overall performance. The multi-objective approach produces a wide range of non-dominated solutions, showing a great potential for building solution design, which can be used to aid design decisions.

In the second part of this chapter (Passive House evaluation for different regions) it was concluded that the Passive House concept is viable for Southern Europe climates, namely in Portugal (scope of this research), however it is essential to adapt and detail the technical and constructive solutions for different regions. This part of the study was deepened resourcing to the evolutionary algorithm with multi-objective function: heating demand and thermal comfort assessment for the summer season. Based on the results a set of conclusions can be taken:

i. Summer comfort can be achieved only resourcing to passive improvements, without any active cooling system;
ii. Bragança region requires triple glazing windows solution and 12cm of insulation thickness is required to achieve the PH requirements for heating demand;
iii. Aveiro, is the only region that can achieve good thermal comfort conditions during the summer season without exterior shading devices;
iv. With opaque envelope solutions recommended by the Portuguese thermal code (REH) only for the Faro region can a Passive House be achieved without exceeding the annual heating demand. However, for this region the values defined by REH for the transduced envelope are not enough to assure good thermal

comfort conditions during summer season. Double windows solution with low solar heat gain coefficient is advisable;

v. The energy used for lighting, as consequence of the exterior blinds use, is negligible when compared with the benefits provided by the exterior blind in terms of thermal comfort.

In the general framework of the thesis, Chapter 4 introduces a different methodology (comparing with the methodology used in the Chapter 2) to achieve the PH requirements for the Portuguese climate. Thus, and after the presentation of PCMs in Chapter 3 and the optimiser in Chapter 4, the case study presented in Chapter 2 will be used in the following chapter using a constructive solution including PCMs with the optimization goal of overheating rate reduction.

CHAPTER 5

OVERHEATING REDUCTION OF A COLD FORMED STEEL-FRAMED BUILDING USING A HYBRID EVOLUTIONARY ALGORITHM TO OPTIMISE DIFFERENT PCM SOLUTIONS

Chapter outline

5. OVERHEATING REDUCTION OF A COLD FORMED STEEL-FRAMED BUILDING USING A HYBRID EVOLUTIONARY ALGORITHM TO OPTIMISE DIFFERENT PCM SOLUTIONS

Work related to this chapter was published in the regional conference **Sustainable Built Environment (SBE)** 2016 – An International Conference for exchange between researchers and practitioners of the construction sector to foster system thinking in the built environment (indexed in Scopus).

Abstract Cold formed steel-framed constructions have been strongly disseminated with particular emphasis on the residential sector due to their fast execution, quality control and final cost. However, this construction typology presents a weakness associated to a low thermal inertia and consequential risk of overheating.

The present research addresses the overheating rate reduction of a cold formed steel-framed building located in the coastal region of mainland Portugal, a particular environment considering the combination of the high outdoor temperature amplitude and the lack of thermal inertia of such building typology. To overcome this weakness, different phase change materials solutions were incorporated into the partition walls and ceilings of south oriented compartments. Thus, thermal energy storage provided by the PCMs solutions play a crucial role in the indoor thermal regulation of the building by minimizing indoor temperature peaks and amplitude improving indoor thermal comfort with lower energy demand. To optimise the PCM solution in order to reduce the rate of overheating, a hybrid evolutionary algorithm was used in conjunction to the EnergyPlus® simulation engine, adapting a list of parameters. This study was extended to identify the best PCM solution to minimize, in some cases prevent, the overheating risk for different climate applications in Portugal mainland.

The results attained reveal the possibility to reduce up to 89% the overheating risk in highly glazed south faced compartments and 23% in north orientated compartments. In terms of heating energy demand, a reduction of 17% was also attained, triggered by the PCM storage effect.

5.1 – Introduction

In the pursuit of energy savings and thermal comfort, the implementation of new materials and constructive solutions are required in the construction sector. In order to investigate these further, this chapter explores how the optimization of the building features such as: bypass ventilation air flow capacity; bypass temperature activation; three different window solutions (including double and triple glazing) in combination with thirteen possible PCM solutions with different melting points and latent heat capacity for the partition walls and ceilings of internal compartments south oriented, can be used for overheating reduction.

5.2 – Simulation methodology for reducing overheating risk

The presented methodology consists on the use of a multi-objective evolutionary algorithm to optimise the buildings features with low thermal inertia, with overheating reduction as a goal. To fulfil this goal, dynamic thermal simulation of a cold formed steel-framed detached building was carried out using EnergyPlus® 8.3.0 software (a full description of the numerical model is observer in Chapter 2).

The first step starts by a building thermal performance characterization of the original constructive solution (without new features application). In the second step the following features were applied in the model and a thermal characterization was performed and compared with the results attained from the original solution:

i. A mechanical ventilation system with heat recovery capacity was specified;
ii. Three different windows solutions were tested;
iii. Natural ventilation with an air flow rate regulator in h^{-1} was specified;
iv. Ventilation by-pass air flow rate was controlled to react to a pre-defined indoor temperature value.

In the third step thirteen different PCM solutions were combined in the South orientated surfaces and ceiling. In this step the thermal performance was optimised and evaluated and finally, compared with the attained results from the first and second steps.

In the last step the influence of a mix PCM solution combining two PCMs with different melting temperature was evaluated.

5.3 – Case study characterization

A detailed description of the building is presented in the Chapter 2. However in this section some main features were presented for a better understanding in the chapter read.

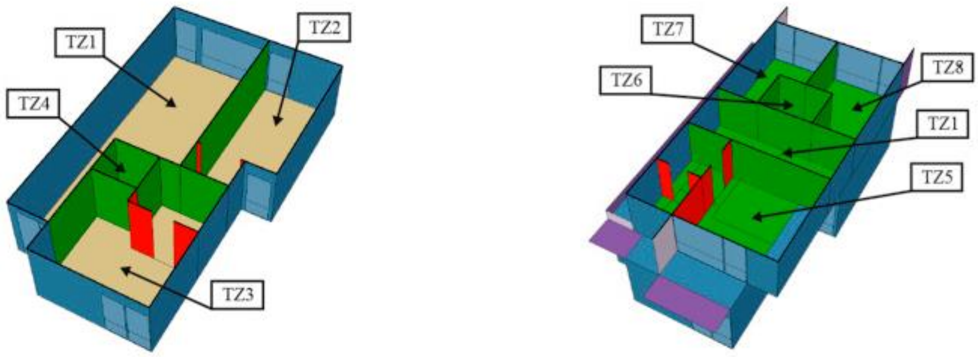
As referred in Chapter 2 the building consists of a two-story prefabricated cold formed steel-framed construction with a treated floor area of 148 m^2 and the global percentage of glazing of 16.4% in respect to opaque facade area. The glazing oriented to the Northeast represents a relative percentage of the total glazed area of 32.3%, and 58.7% to Southwest (see Figure 5.1).

Figure 5.1 – 3D view (real model with North view)

The building's external envelope is mainly composed of the followings elements: Ground floor slabs - U_{value} = 0.78 (W/m^2 ºC) and IT (insulation thickness) = 30 (mm); Facade walls - U_{value} = 0.33 (W/m^2 ºC) and IT = 60 (mm); Flat roof - U_{value} = 0.36 (W/m^2 ºC) and IT = 50 (mm). Windows modelled have a SHGC of 0.53 and U_{value} of 1.79 (W/m^2 ºC) for the glazing to the Northeast and U_{value} of 1.68 (W/m^2 ºC) to the Southwest.

5.4 – Dynamic thermal simulation model

The numerical model was presented in section 2.3. In this section, Figure 2.7 is repeated in Figure 5.2 in order to bring out a lighter and fluid reading. Thus, Figure 5.2 presents the internal partition division and thermal zoning.



(a) (b)

Figure 5.2 – Ground floor (a) and first floor (b) levels thermal zones, where: TZ1 – Hall, living room and staircase, TZ2 – Kitchen, TZ3 –Ground floor suite bedroom, TZ4 – Ground floor bathroom, TZ5 – First floor suite bedroom, TZ6 – First floor bathroom, TZ7 –First floor single room and TZ8 – First floor single room

5.5 – Results and general discussion

5.5.1 – Thermal behaviour characterization (1st step)

The original building was simulated considering an ideal air system that meets heating for a setpoint of 20 ºC as minimum indoor temperature to activate the system using an ACR of 0.6 h^{-1}. During the summer season the building characterization was evaluated in terms of overheating rate considering a mechanical ventilation system with the capacity to provide a constant air flow from the outdoor air of 0.6 h^{-1} without the capacity of air conditioning.

The results attained were 36.26 (kWh/m^2.a) for heating demand during the heating season and 15.23% of overheating in accordance with the EN 15251 standard during the summer season. These results were presented and detailed in Chapter 2 section 2.4.3.

5.5.2 – Thermal behaviour assessment - improvement and optimisation (2nd step)

As the original building demands in terms of energy and overheating are considerable, an optimization process was carried out in order to assess and achieve improved models with a better thermal response.

Passive and hybrid techniques were applied only by changing and optimizing the window solutions, adding a heat recovery air system with capacity to work in by-pass mode increasing the total air flow rate, and by-pass with a temperature control activation based on the indoor air temperature.

The improvements were applied to the model, resorting to an evolutionary algorithm that instructs the software used in the simulations. In the present study (in this step) the parameters used in the optimization process are defined as continuous and discrete variables (see Table 5.1).

As objective functions, heating demand and overheating rate were chosen to be minimized by the optimiser. Overheating rate was defined in EP in accordance with EN 15251(category II) and resourcing to Energy Management System (EMS) feature in EP that provides a way to develop custom control and modelling routines.

With this optimization (using the parameters defined in Table 5.1), higher reductions in heating demand and significant reduction in discomfort rate were achieved, when compared to the original solution. The energy and discomfort limits assigned in the plot are indicators of a building with high energy efficiency in accordance with PH standard.

Table 5.1 – List of parameters

Continuous variables		
Parameter id.	Designation	Box Constraints
x0	Bypass Air flow rate (h^{-1})	0.00 – 2.44
x1	Bypass activation temperature (ºC)	21 - 25
Discrete variables		
x2 (windows North orientated)	Window Solution (W/m² °C) ; SHGC	U_{value} = 1.79 SHGC = 0.53 U_{value} = 0.94 SHGC = 0.61 U_{value} = 0.70 SHGC = 0.42
x3 (windows South orientated)	Window Solution (W/m² °C) ; SHGC	U_{value} = 1.68 SHGC = 0.53 U_{value} = 0.90 SHGC = 0.61 U_{value} = 0.65 . SHGC = 0.42

From Figure 5.3 it is possible to depict the improvement attained in respect to the discomfort rate and heating demand reduction.

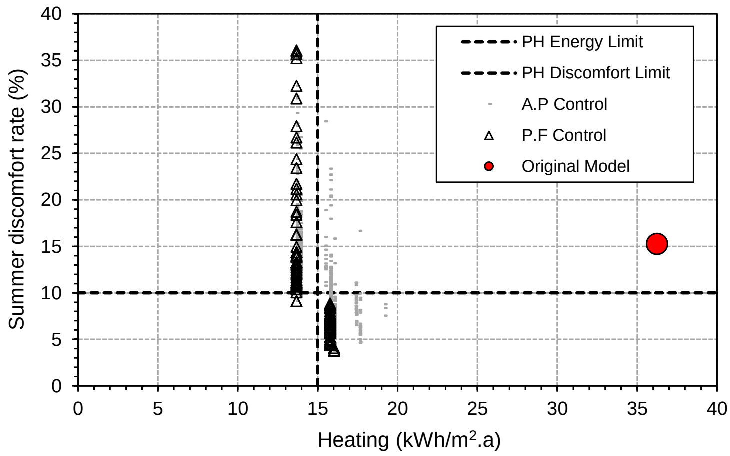


Figure 5.3 – Optimised results: 1st and 2nd step (A.P- All Points; P.F - Pareto Front)

The red circumference assigned in the plot represents the annual heating demand and summer overheating simulated and depicted in section 2.4.3.

5.5.3 – Thermal behaviour assessment – PCM solutions and optimisation (3rd step)

In this part of this study the initial priority was to prevent overheating during the summer period attaining simultaneously higher thermal comfort levels also using PCM in the constructive solutions.

A layer of PCM was incorporated into the partition walls and ceiling (positioned after the first layer in the wall solution) in the compartments with Southwest orientation (TZ1; TZ2; TZ7; TZ8). The following thirteen PCM solutions were implemented and tested:

i. Micronal® DS 5001 with a melting point of 21 ºC and an overall enthalpy capacity of 244960 (J/kg);
ii. BioPCM® series M27 with 21, 23, 25 and 27 different melting point and 289545, 300420, 322285, 322093 overall enthalpy capacity respectively;
iii. BioPCM® series M51;
iv. BioPCM® series M91.

The results presented in Figure 5.4 contain the points of the Pareto front (black triangles and black circular shapes markers) which represent a set of optimal solutions.

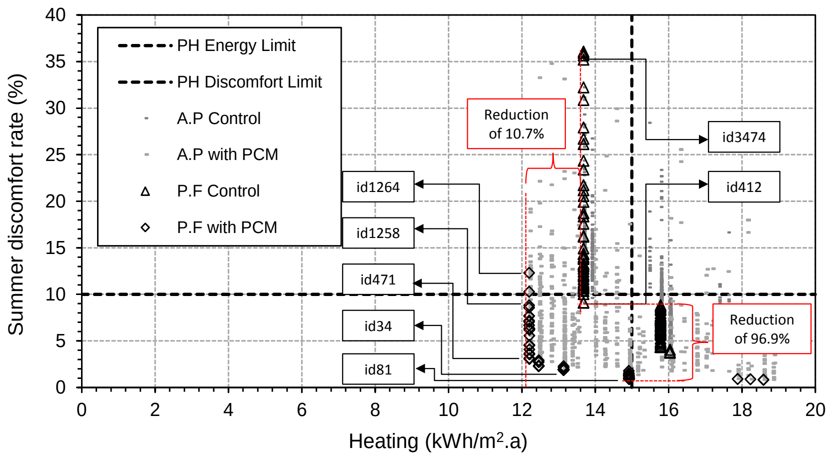


Figure 5.4 – Optimised results: 3rd step

Through the results, shown in Figure 5.4, it was observed that the use of PCM solutions has a significant impact during the summer season in the overall overheating reduction (67.1% of reduction). During the heating season, the PCM effect resulted in a heating demand reduction of 10.7%.

Table 5.2 and 5.3 list some of the best solutions after optimization analysis. From Table 5.2 the main conclusion is the direct relationship between the bypass air flow rate and activation temperature with the summer discomfort rate. A bypass system that works in anticipation (reacting to lower temperature) is a good solution for overheating reduction.

Table 5.2 – List of solutions in the models without PCM use

Optimiser. id#	Bypass Air flow rate (h^{-1})	Bypass activation (ºC)	Windows solution north (W/(m² °C))	Windows solution south (W/(m² °C))	Heating demand (kWh/m²a)	Summer discomfort rate (%)
Id3474	0.10	24.66	U_{value} = 0.94 SHGC = 0.61	U_{value} = 0.90 SHGC = 0.61	13.67	35.95
Id412	2.13	20.15	U_{value} = 0.94 SHGC = 0.61	U_{value} = 0.90 SHGC = 0.61	13.67	10.03

Table 5.3 shows that the best solution in terms of overheating reduction requires the bypass air flow rate at its maximum capacity with a temperature activation of 20.54 ºC using BioPCM type M91 with a melting point of 25 ºC. Other important conclusions are related with the windows solutions. When the main concern is the summer discomfort rate reduction, windows with low U_{value} and SHGC are required for south orientation. For the north orientation this requirement is more permissible to use higher U_{values}.

Table 5.3 – List of solutions in the models with PCM

Optimiser. id#	Bypass Air flow rate (h^{-1})	Bypass activation (ºC)	Windows solution north (W/(m² °C))	Windows solution south (W/(m² °C))	PCM type	Heating demand (kWh/m² a)	Summer discomf ort rate (%)
id1264	1.20	20.07	U_{value} = 0.94 SHGC = 0.61	U_{value} = 1.68 SHGC = 0.53	BioPCM M51/Q21/E0.021*	12.31	12.19
id1258	2.16	22.80	U_{value} = 0.94 SHGC = 0.61	U_{value} = 0.90 SHGC = 0.61	BioPCM M91/Q21/E0.037*	12.20	8.58
id471	2.44	20.00	U_{value} = 0.94 SHGC = 0.61	U_{value} = 0.90 SHGC = 0.61	BioPCM M91/Q21/E0.037*	12.21	3.07
id34	2.44	20.07	U_{value} = 0.94 SHGC = 0.61	U_{value} = 0.90 SHGC = 0.61	BioPCM M91/Q25/E0.037*	13.13	1.94
id81	2.44	20.54	U_{value} =1.79 SHGC =0.53	U_{value} = 0.90 SHGC = 0.61	BioPCM M91/Q25/E0.037*	14.92	1.11

* Nomenclature used: M (Btu thermal energy storage capacity); Q (peak melting temperatures in degrees Celsius); E (thickness).

5.5.4 – Thermal behaviour assessment – mix PCM solutions and optimisation (4th step)

Focusing on the issue of overheating risk and the fact that the PCM is not totally discharged (in a daily cycle), an additional analyse was carried out using a new constructive solution incorporating a mix of two PCMs with different melting points. Figure 5.5 presents the results from the optimization.

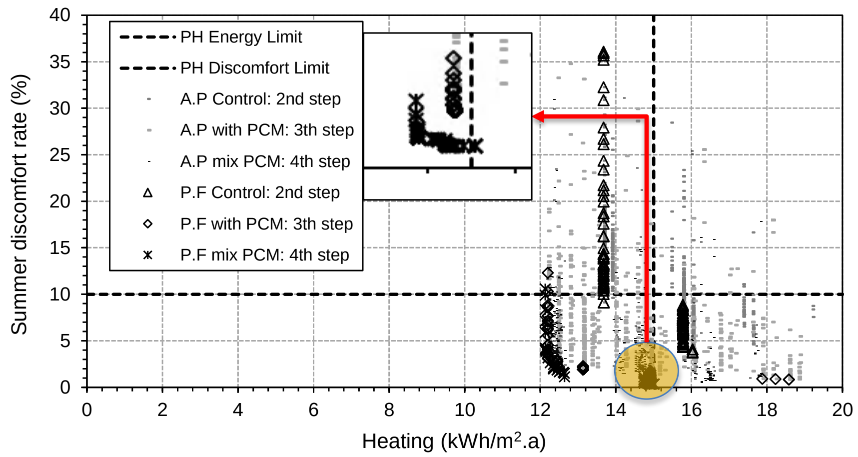


Figure 5.5 – Optimised results: 4th step

The use of PCM solutions with different melting points resulted in an improvement in the thermal comfort during the summer season. A reduction of 57% of the discomfort rate was achieved compared to the model with the lowest discomfort rate (0.82% of discomfort rate) from the optimization with PCM solutions with the model that uses a mixed PCM solution (0.35% of discomfort rate).

The optimised solution attained combines the bypass air flow rate of 2.44 h^{-1} with a temperature activation of 20 ºC using windows with U_{value} = 0.70 ($W/(m^2$ °C)) and SHGC = 0.53 north orientated and U_{value} = 0.65 ($W/(m^2$ °C)) and SHGC = 0.61 south orientated. This solution was combined with 62% of BioPCM type M91 with a melting point of 23 ºC and 38% of BioPCM type M91 with a melting point of 21 ºC.

5.6 – Final remarks

This study has tackled the overheating reduction issue in low thermal inertia buildings. Different PCM solutions were applied and optimised in the internal partitions and ceiling in the compartments with South orientation.

The main conclusions that can be taken are:

i. PCM provides a favourable thermal regulation effect with a high reduction of the thermal indoor discomfort rate;
ii. The selection of the melting point of the PCM is crucial to fully take advantage of the PCM (charging and discharging process on a daily cycle);
iii. Combining different solutions of PCM with different melting points is suitable since it increases the potential for overheating reduction. The annual overall thermal comfort is improved and cooling energy demand is reduced;
iv. The ventilation rate is essential to assure the discharging process of the PCM. The charging and discharging processes are only possible due to an effective combination of the PCM melting temperature selection and optimised ventilation rate.

Regarding the good results attained in this chapter with the use of PCM the optimiser approach and according with the thesis outline and sequence, Chapter 6 will present a case study that was monitored integrating phase change materials with the optimization approach to achieve the optimum thermal response.

CHAPTER 6

NUMERICAL AND EXPERIMENTAL STUDY ON CONSTRUCTIVE SOLUTIONS WITH PCM FOR THERMAL REGULATION

Chapter outline

6. NUMERICAL AND EXPERIMENTAL STUDY ON CONSTRUCTIVE SOLUTIONS WITH PCM FOR THERMAL REGULATION

The part of this chapter dedicated to describe the new calibration methodology is submitted for possible publication in the **Journal of Building Performance Simulation** – This, is the official journal of the International Building Performance Simulation Association (IBPSA). IBPSA is a non-profit international society of computational building performance simulation researchers, developers, practitioners and users, dedicated to improving the design, construction, operation and maintenance of new and existing buildings worldwide. Impact Factor: 1.62.

The experimental and numerical thermal evaluation is submitted for possible publication in the **Applied Energy** – This journal provides a forum for information on innovation, research, development and demonstration in the areas of energy conversion and conservation, the optimal use of energy resources, analysis and optimization of energy processes, mitigation of environmental pollutants, and sustainable energy systems. Impact Factor: 5.61.

Abstract Nowadays a correct thermal retrofit design has a strong global impact in the viewpoint of economies and energy-efficiency perspectives. Several aspects like architectonic design, building materials, construction systems and outdoor local climate determines thermal behaviour of buildings and their ability to provide indoor thermal comfort to occupants. The use of phase change materials in the construction systems is an opportunity that may reduce indoor air temperature fluctuation as well as overheating risk. This chapter presents the results of a study about indoor thermal comfort and the PCM behaviour when applied into constructive solutions, based on real data and numerical simulation of two rooms of a new University department. Monitoring of two rooms was carried out in which one has PCM panel's incorporated into the gypsum board partition wall and into a suspended ceiling. The monitoring campaign was used for indoor thermal characterization of the rooms and for numerical model calibration. Monitoring data measurements show that the indoor thermal comfort of the rooms present long periods in discomfort namely in overheating. However it was proved that the PCM application in one of the rooms, leads to an overheating reduction of 7.23% that represents a PCM efficiency of 35.49%.

Dynamic energy simulation tools are often used to predict the thermal performance of buildings (in the design stage) as well as to recommend energy retrofit package solutions for refurbishment. To reduce uncertainties in model inputs definition, the calibration of building energy simulation models assumes a crucial role in the accuracy of energy modelling. The monitoring campaign was used for the development of an approach to reduce the differences between building simulation and real monitored building data using a hybrid evolutionary algorithm. The results attained reveal a fairly good agreement between predicted and real data for the period defined.

After the model calibration a numerical study was conducted using an evolutionary algorithm to instruct the software EnergyPlus® simulation. In the scope of this optimization process, constructive solutions with the incorporation of different PCM solutions and different values of natural ventilation air flow rate were combined to assess the potential of these solutions for overheating reduction.

6.1 – Introduction

The optimum building design in respect to indoor thermal comfort should be based on passive techniques and is the first step towards the design of a low energy building. Indoor thermal comfort becomes a more challenging issue when the indoor spaces are offices or class rooms, with more concerns related with user's productivity and concentration. Recently this issue (thermal comfort in schools) has been receiving more attention by researchers with the publication of studies on this field. Some of them depict the relationship between the user's performance (including students and teachers performance) and the indoor thermal comfort conditions.

The use of PCMs in constructive solutions may be a good passive strategy for overheating reduction and to provide better conditions of the indoor thermal comfort (some of them evaluated in Chapter 3). Several studies have been developed around the PCM applications and integration in buildings, however full-scale applications in scholar buildings were not found in the existent scientific studies.

The possibility to use full scale models in research studies to characterize solutions is globally an advantage. In the scope of a research project, it was tested and monitored at the real scale a constructive solution incorporating PCMs in a recent built University department building, designated as CICFANO (already mentioned in Chapter 3). PCM panels were incorporated into the partition wall and ceiling. The building simulation using the software EP was calibrated. The PCM effect was evaluated by comparing the indoor thermal comfort in the two rooms, with and without PCM.

6.2 – Simulation methodology for PCM optimisation

The first goal of this study consists in assessing the indoor air temperature comfort as well as the PCM efficiency in the temperature control. The second goal is the development of a new methodology for dynamic model calibration. Finally, the goal is the optimization of the constructive solution with PCM, using different commercial PCM solutions, to attain the optimum indoor comfort conditions and energy efficiency. To achieve the first and second goal, real monitored data was collected and analysed. To comply with the third goal, dynamic thermal simulation of the department building was carried out using EP software.

The methodology starts with a hygro-thermal monitoring campaign of the two rooms, used to evaluate the indoor air temperature comfort according with EN 15251 [29]. A multi stage calibration approach for thermal dynamic building simulation with detailed models using an optimization procedure with an evolutionary algorithm is presented.

The second part of this approach it was carrying out of the optimization features using the multi-objective evolutionary algorithm. This step aims to increase the indoor thermal comfort and reduce heating demand by changing the existent constructive solutions with PCM with other solutions with different types of PCM (commercial based solutions) and combining the mechanical ventilation rate without cooling or heating inputs. The simulation methodology for the PCM optimisation is schematically depicted in Figure 6.1.

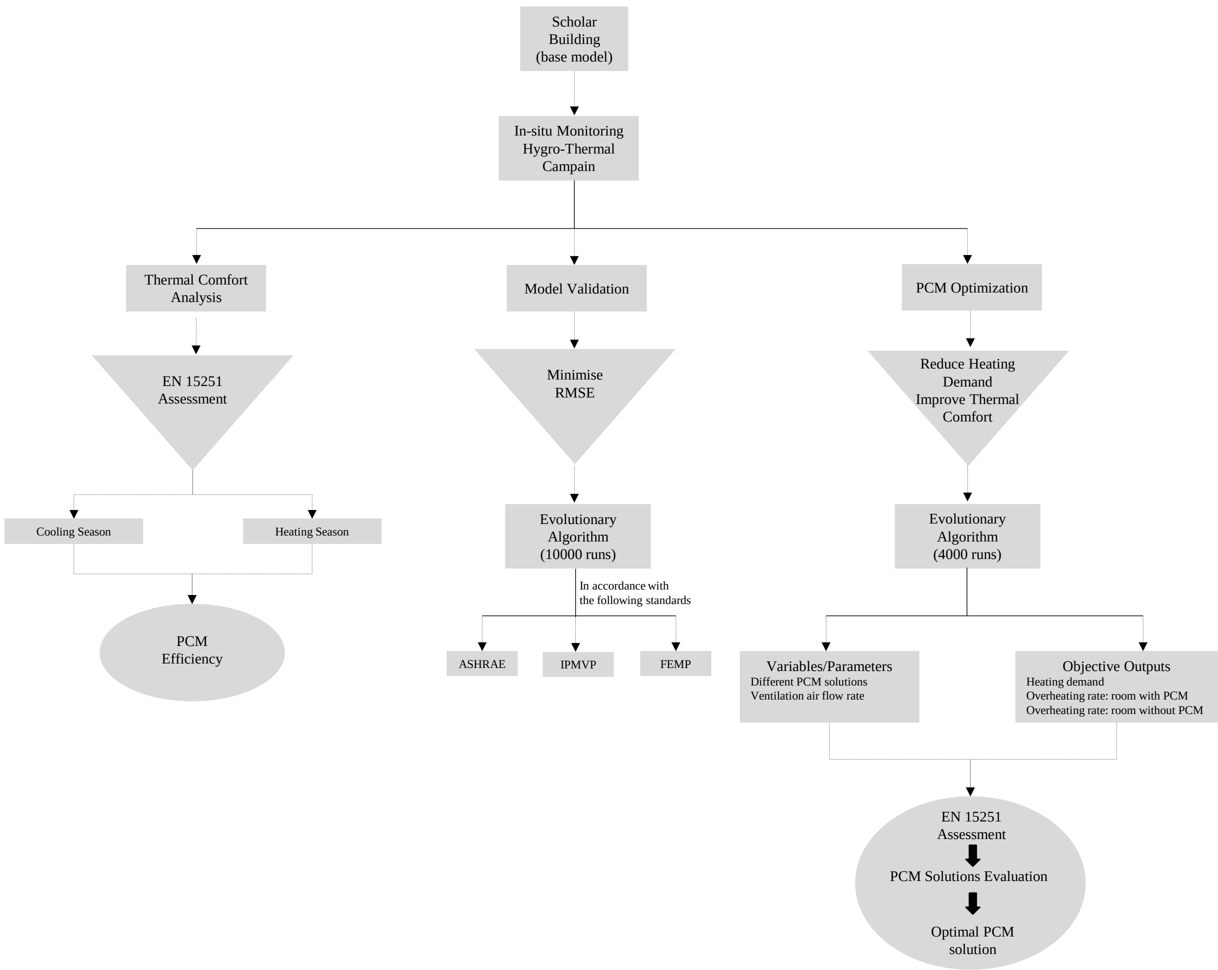


Figure 6.1 – Simulation methodology followed for PCM optimisation

6.3 – Case study: school building monitoring data collection

6.3.1 – Building location and general characterization

The university building was constructed four years ago (2012), in the university Campus of the city of Aveiro. It is located approximately at 10km from the Atlantic coast, in the central North of Portugal mainland. This building is representative of the architecture and constructive typology of the existent departments, and was built between two adjacent departments with similar geometry (see Figure 6.2).

(a)

(b)

Figure 6.2 – Case study: (a) location in the Aveiro University Campus (b) built department building

The building has a plan configuration with a rectangular shape with a gross floor area of 1600m^2 (see Figure 6.3). It is composed of three floors (ground floor and 2 elevated floors), and a technical floor at the rooftop level, that accommodates the active and air ventilation systems of the building.

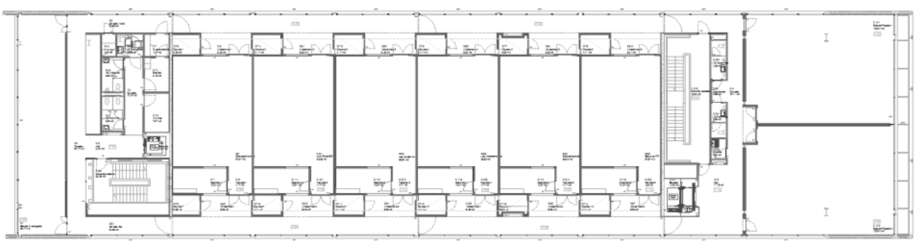
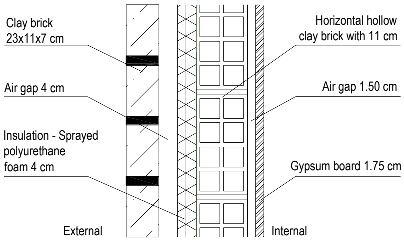
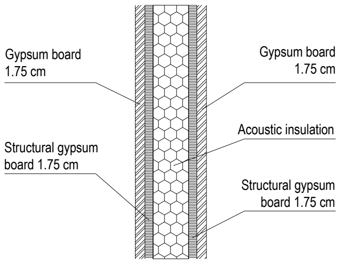
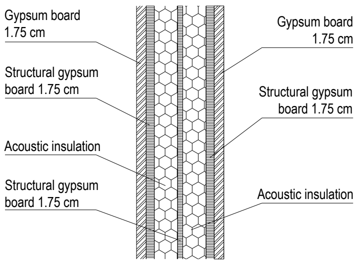
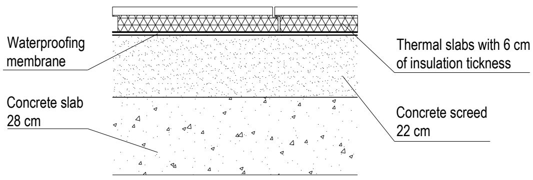
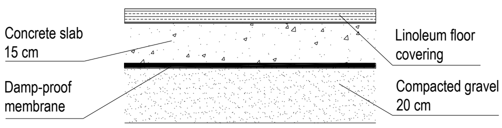


Figure 6.3 – 1st and 2nd or plans (no scale)

The ground floor entails the lobby and main secretary, laboratory rooms, technical areas and clean air block room. The first and second elevated floors entails the open space working rooms meeting rooms, offices, laboratories, computer rooms, class rooms, technical areas (duct and control spaces). The rooms located at the South corner of the building, were chosen as the test rooms. Finally the technical floor at the rooftop is dedicated to the air flow plant distribution system. The indoor air conditioning, is provided by two air handling units (AHU) located on the ground floor. Each system (AHU) has a water coil integrated to heat or cool supply air. The system uses a sensible heat recovery wheel of variable speed, for heat recovery in the heating season. The sensible heat recovery is possible whenever the exhaust air temperature is higher than the outdoor air temperature. For the cooling season, if the external thermal conditions are favourable, the system can act as a free cooling through a bypass valve.

Double brick wall with air gap partially filled with insulation was the constructive solution of the vertical opaque envelope of the building, covered by the internal surface with usual plasterboard. The envelope solutions of the test rooms are listed in Table 6.1.

Table 6.1 – Constructive opaque solutions of the base model

Building element	Constructive solution	U_{value} (W/m^2 °C)
External envelope walls		0.439
Internal partition walls type 1		n.d
Internal partition walls type 2		n.d
Flat roof		0.485
External floor slab		1.224

n.d - not defined

Regarding the translucent envelope the thermal characteristics of windows and doors are: thermal transmission coefficient ($U_{w,\ installed}$ = 2.40 W/(m^2°C)); solar heat gain coefficient (SHGC = 0.70). This values were determined taking into account the frame U_{value} (U_f), the glass edge thermal bridge (Ψ_g) in accordance with ISO 10077 [98]and the installation thermal bridge ($\Psi_{Install}$) in accordance with EN ISO 10211 [99]. In order to optimise the analyses presented in this chapter, the $U_{w,installed}$ value was used.

6.3.2 – Building region: local climate characterization

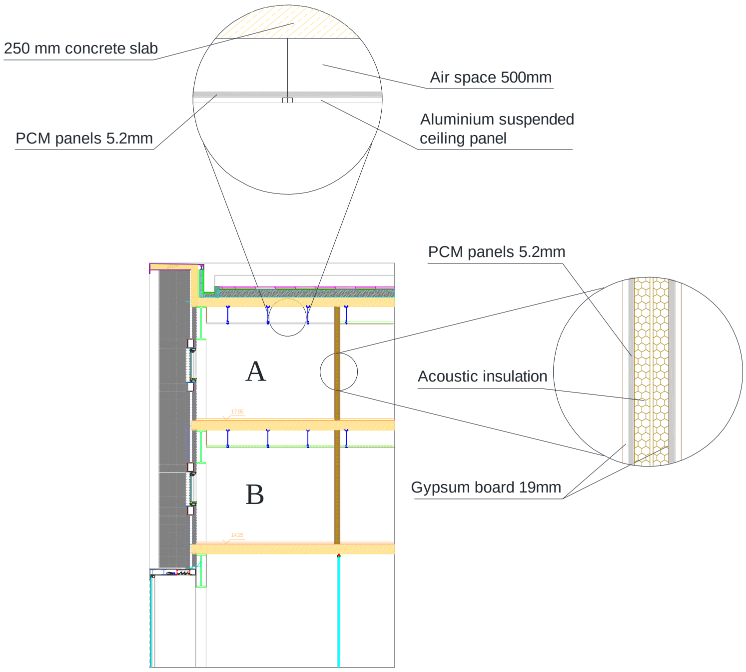
The assessed building is located in the city centre of Aveiro as the others case studies already presented. The local climate characterization was presented in section 2.2.2 in Figure 2.5.

6.3.3 – Monitoring strategy

In the scope of this research project, it was tested at real scale two constructive solutions incorporating PCMs applied in the building indicated in section 6.3.1. Two rooms with the same indoor space and geometry, orientation, opaque constructive solutions, glazed area and use, were monitored to be compared. One of the rooms has PCM panels installed in the partition wall and ceiling (A) and the other room, without PCM (B) is considered the reference room (see Figure 6.4a).

(a)

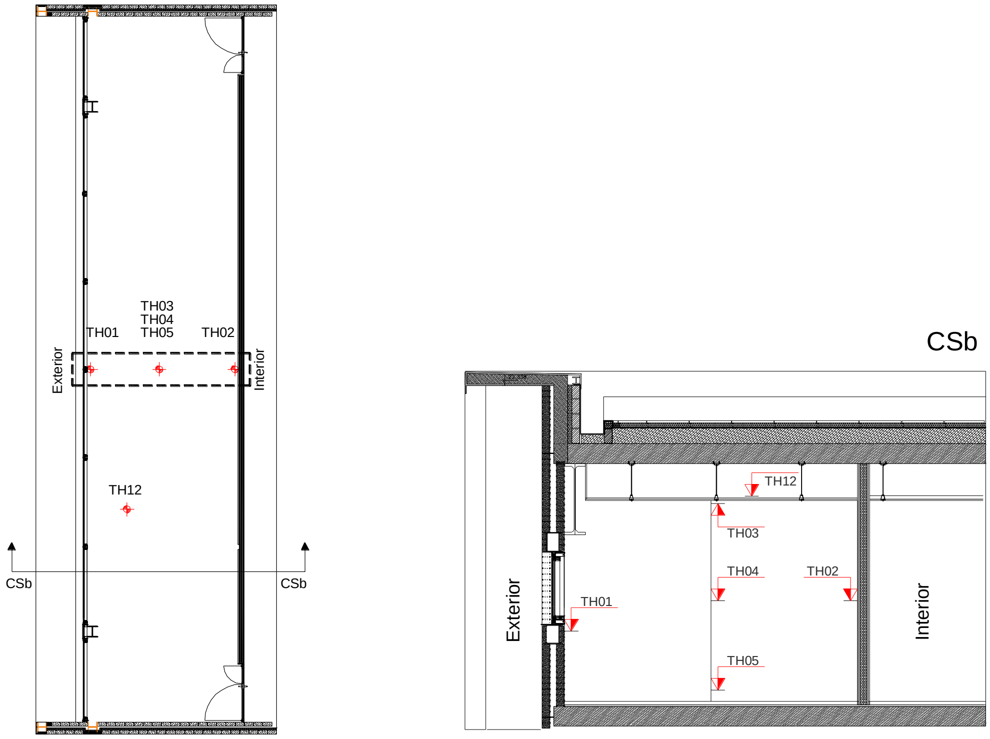
Figure 6.4 – Identification of the monitored rooms and the constructive solutions: (a) room with PCM assigned with the letter A and without PCM with the letter B; (b) representative section of the partition wall and suspended ceiling solutions (…)



(b)

Figure 6.4 – (…) Identification of the monitored rooms and the constructive solutions: (a) room with PCM assigned with the letter A and without PCM with the letter B; (b) representative section of the partition wall and suspended ceiling solutions

The monitoring of the rooms is essential to calibrate the numerical model that allows the simulation of the latent heat loads involved in the phase change process. The rooms were equipped with monitoring sensors that ensure a continuous recording of the temperature and relative humidity at several points. The positioning of sensors inside the rooms was defined in order to avoid direct sun exposure from the glazed areas in accordance with ISO 7726 [100]. Sensors were placed with a height distribution profile (vertically aligned) and also in the transversal direction (middle of the room). The monitoring acquisition system is logged at 10 minutes intervals and averaged hourly. Figure 6.5 shows the position of the thermo-hygrometer sensors in the test rooms, with the nomenclature "TH". It is worth mentioning that in the room without PCM the same sensors scheme is used.

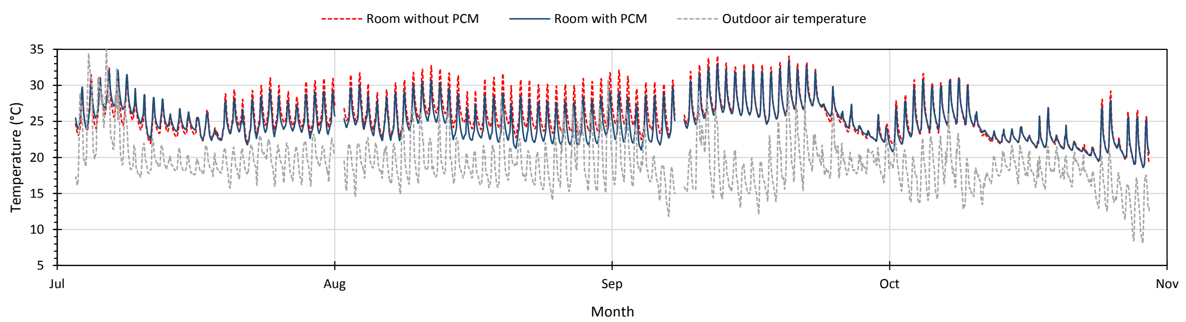


(a) (b)

Figure 6.5 – Temperature and relative humidity sensors layout (room A with PCM): (a) longitudinal view; (b) transversal cross section

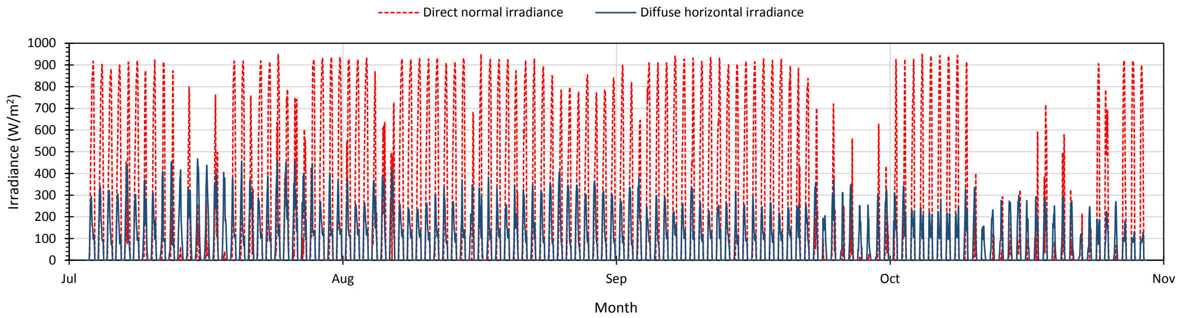
The air flow supply has been evaluated with discrete measurements directly at the ventilation grid outlets. The air flow rate, has a strong influence over the variation of the indoor air temperature, therefore it is very important to assess and monitor. This monitoring is of great support to define the initial value for the ACR for the calibration process.

The exterior weather data was collected at a local weather station located on the roof of a neighbouring building with same height, for the period under study (see Figure 6.6b). Global horizontal solar irradiance, outdoor dry-bulb temperature, relative humidity, wind direction and speed were collected hourly.



(a)

Figure 6.6 – Monitoring data for the calibration period: (a) indoor air temperature for both rooms and outdoor temperature; (b) direct solar normal and diffuse irradiance (…)



(b)

Figure 6.6 – (…) Monitoring data for the calibration period: (a) indoor air temperature for both rooms and outdoor temperature; (b) direct solar normal and diffuse irradiance

Direct and diffuse irradiance were converted from the monitored global horizontal solar radiance using the operational model developed by Perez *et al* [116].

6.4 – Original building performance

6.4.1 – Indoor air temperature data analysis

This section presents the monitored results of the temperature for the annual period. The temperature value depicted is an average value of all sensors in the room for the annual period monitored (see Figure 6.7).

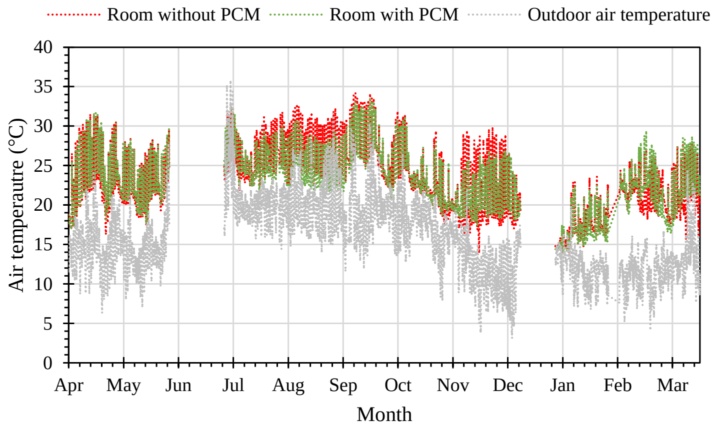


Figure 6.7 – Indoor and outdoor air temperature for both rooms

During the annual monitoring campaign there were periods in which data collected was lost due to acquisition software error.

The expected behaviour of the PCM is to buffer the temperature swing in the cooling season during the day, to avoid overheating and minimize the maximum indoor air temperature, and during the heating season to release the energy absorbed during the day in the night period, to avoid excessive temperature drop of the indoor air temperature.

Regarding Figure 6.7 it is possible to conclude that in the summer season both rooms showed large periods of overheating. The room without PCM showed excessive maximum indoor air temperature when compared with the room with PCM. From mid October until December the indoor air temperature in the room with PCM ranged inside the comfort limits. The room without PCM continued to have periods in overheating. During the heating season it has been found that the indoor air temperature peaks (inferior limit) are lower in the room without PCM.

To provide more detail and to show the PCM effect during an intermediate season it is shown in Figure 6.8 the PCM thermal regulation effect.

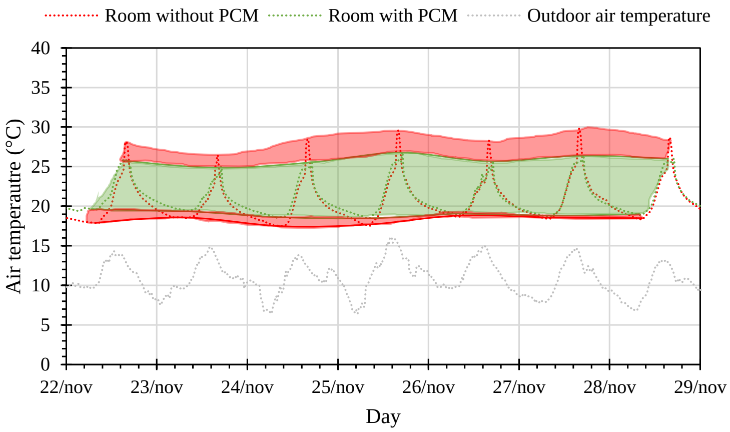


Figure 6.8 – Indoor and outdoor air temperature from the 22nd to 29th of November

During this week the daily temperature swing, allowed the PCM to charge during the day and discharge during the night. In this period, PCM promotes an average reduction of the indoor air temperature for the maximum peak of about 3 ºC, and in the minimum peak of 1 ºC (represented in the plot by the red contour). The PCM effect also allows a reduction of approximately 4 ºC if the indoor temperature amplitude.

Although the rooms have the same area and geometric form, the same use and orientation, they have a difference in the external envelope boundaries. The room with PCM (2º floor) has four exterior surfaces in direct contact with the exterior conditions, while the room without PCM (1º floor) has only three exterior surfaces (see Figure 6.9).

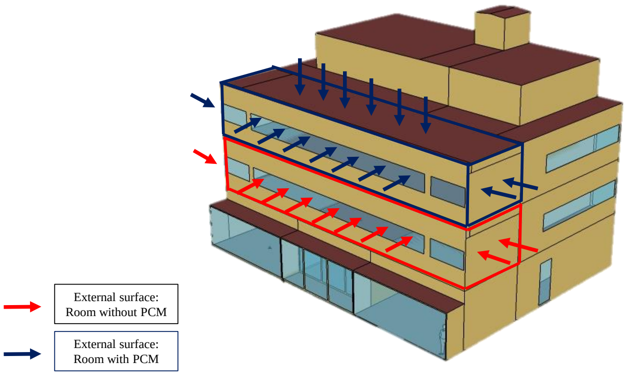


Figure 6.9 – External envelope surfaces

It is acknowledged that the position of the rooms (one over the other) has direct influence on its effective thermal performance, however the room with PCM has comparatively more heat losses in winter and heat gains in the summer period.

6.4.2 – Thermal comfort assessment in accordance to EN 15251: PCM effect evaluation

This section is divided into two subsections where the results are divided by heating and cooling seasons. The thermal comfort was evaluated in accordance with the standard EN 15251 [29] and the PCM performance was estimated according to the difference of percentage of indoor air temperature which is out of the comfort limit bounds defined by the standard for the heating and cooling period.

6.4.2.1 – Cooling season: recorded data

The period from the 1st of June until the 30th of September was considered the cooling season in accordance with the air conditioning and ventilation machine schedule (although, in this period under monitoring the active systems were turned off). Figure 6.10 represents the comfort assessment of the indoor air temperature in accordance with the standard EN 15251 for the cooling period monitored.

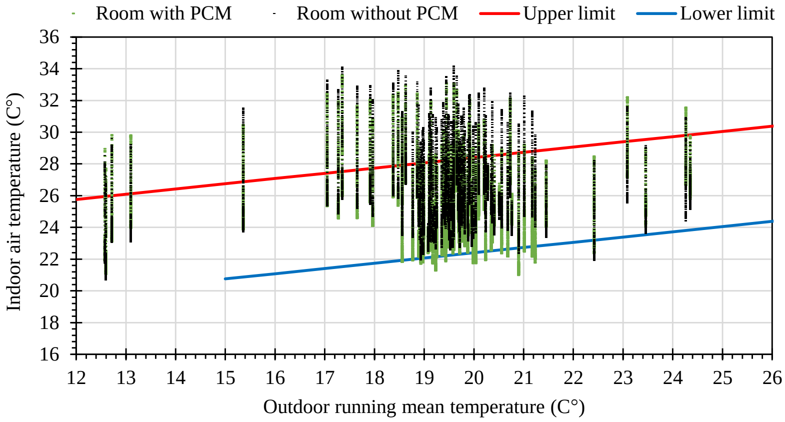


Figure 6.10 – Indoor air temperature for the cooling season (EN 15251 - Category II)

Note that the rooms have a high glazed surface South faced implying that the indoor air temperature is strongly influenced by the solar radiation, creating conditions for high overheating risk.

Figure 6.10 shows an extensive period above the upper limit for the indoor air temperature comfort, indicating periods of overheating inside both rooms. In terms of overheating percentage (points above the upper limit defined in the standard EN 15251 [29]) it was observed 20.37% of overheating in the room without PCM and 13.14% in the room with PCM. These values reveal a reduction of discomfort rate for cooling season in 7.23% for the correspondent period evaluated in the room with PCM. This reduction represents a PCM efficiency of 35.49% (relative percentage), between results of discomfort of the room with and without PCM.

The main conclusion observed in the plot is the fact of the minimum indoor air temperature in the room with PCM was for almost the whole period above 21.7ºC (melting point of the PCM used) indicating that the PCM during the night will never fully discharge the energy absorbed during the day (the same conclusion was observed in Figure 6.7).

6.4.2.2 – Heating season: recorded data

The period defined for the heating season was selected from the 1st of October until the 30th of May according to the air conditioning and ventilation machine schedule (although, in this period under monitoring the heating system was turned off).

Figure 6.11 represents the comfort assessment of the indoor air temperature in accordance with the standard EN 15251 [29] for the heating period monitored.

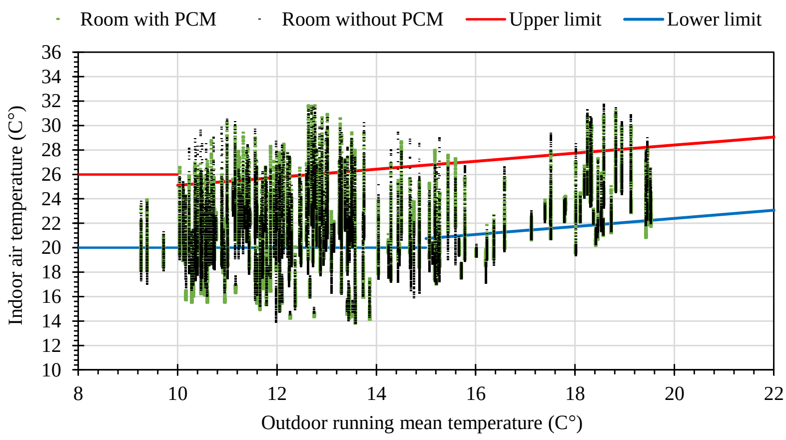


Figure 6.11 – Indoor air temperature for the heating season (EN 15251 - Category II)

Figure 6.11 shows that the overheating is still a substantial use during the heating season. Below the lower limit defined by the standard the indoor air temperatures present a large cloud of points that mean a higher discomfort rate during heating season. For this purpose, a reduction of discomfort for the heating season of 2.61% was measured in room with PCM (41.47% in discomfort) when compared with the same period for the room without PCM (44.55%). Regarding the PCM efficiency in attenuating the minimum indoor air temperature, it was yields in a relative percentage of 6.92%.

From the assessment of the discomfort time for the heating season it is possible to conclude that the PCM provides a potential thermal regulation effect, however the melting point chosen, was essentially driven for improving the indoor comfort in the cooling season.

Then, and after the monitoring data collection a new calibration methodology is proposed for model calibration and validation. Section 6.5 describes the calibration as an intermediate step before the dynamic model used for the constructive PCM solutions optimization.

6.5 – Building calibration: reducing the performance gap in dynamic building simulation using evolutionary algorithms

6.5.1 –Recent research on this topic

Thermal dynamic building simulation software are important tools to detail and to effectively evaluate the thermal behaviour in buildings [117]. Steady state methods do not provide detailed information required for making supported decisions on the best and optimal design options, neglecting thermal inertia and other assumptions. Energy simulation software allows to determine with high accuracy variables that can help designers to take decisions on the best measures to reduce the energy demand running costs and to improve indoor thermal comfort for users. However the assignment to attain these issues is a difficult task as it depends on many variables and parameters. In accordance with Balaras *et al.* [36] there are four main key factors with direct influence on the energy consumption of buildings, shown in Figure 6.12.

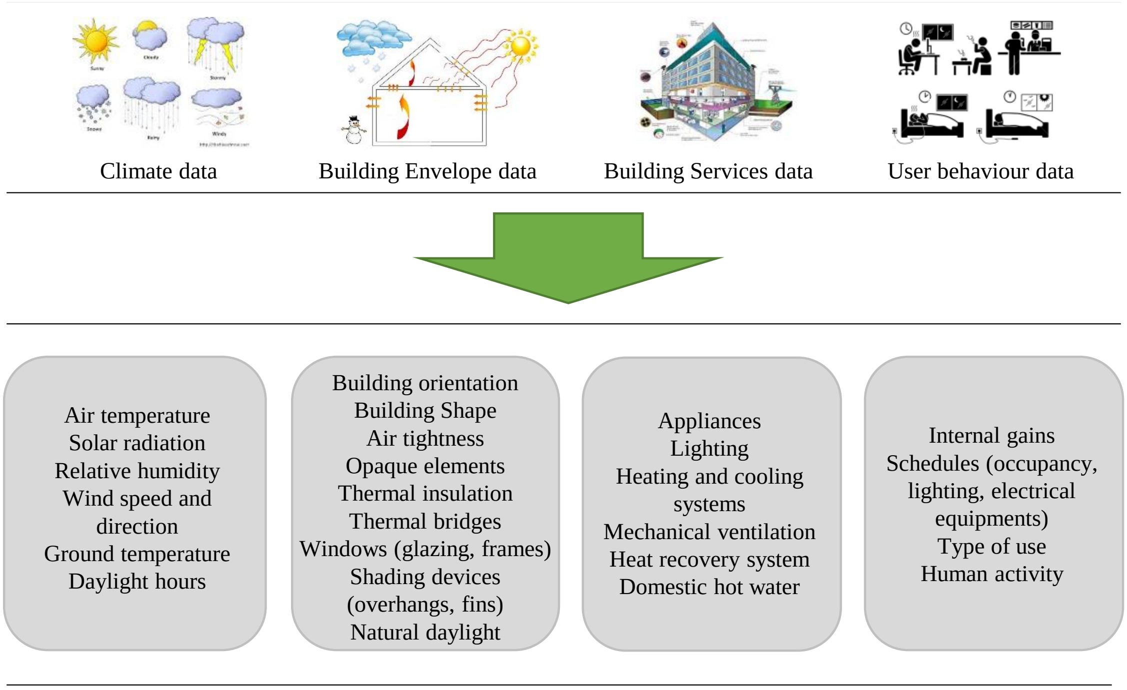


Figure 6.12 – Four main key factors with influence on the thermal dynamic simulation

Climatic data represents known design boundary conditions for a given location. It is important to stress that the typical meteorological yearly weather file for most of the cities does not have detailed and extensive climate data for the best accuracy of the results. Building envelope and services data have direct influence in buildings' thermal behaviour significantly affecting the energy performance of the building. Finally the human factor constitutes the most variable feature related to known design data involving high uncertainty, since the profile and the number of building occupants, as well human habits are not precisely known. In sum, the accuracy of these considerations, are the main keys factors to achieve a reliable energy efficient building with respect to the indoor thermal comfort and final energy demand. In this sense, model calibration is a fundamental process to ensure that the building thermal behaviour is accurate, allowing to optimise these refereed features.

The calibration process is defined across the input parameters variation and testing to reduce the difference between the real building behaviour and the simulated results. This process, usually obtained by trial error practice, is associated to an extensive and time consuming task to achieve a representative model of the real building thermal behaviour.

A review of current research on this field has revealed that it is impossible to identify the exact solution for the calibration process for Dynamic Building Energy Simulation models (DBES) and there is no generally implemented method for DBES calibration. Until 2008 three standard [61-63, 118] documents with methodologies based on manual refinement of the DBES models were created as guidelines for DBES calibration. ASHRAE guideline 14 [61] is proposed to be a guideline that provides a minimum acceptable gap in the measurement of energy demand savings from energy management projects applied to residential and service buildings. The International Performance Measurement and Verification Protocol [62] purpose is to “provide an overview of current best practice techniques available for verifying results of energy efficiency, water efficiency, and renewable energy projects”. One objective of this document is to be intended as a quick measurement and verification guideline including procedural outlines content checklists and option summary tables. The latter [63] provides a wide range of guidelines and approaches for measuring and verifying energy, water, and cost savings associated with federal energy savings performance contracts.

Recently, new frameworks and methodologies for calibration of DBES models have risen. Daniel Coakley and other researchers [119] in 2014 presented a detailed review on methods to match building energy simulation models with measured data. This work focused on the existent (in 2014) approaches for calibrations of DBES models, highlighting various combinations of analytical and/or mathematical and statistical techniques. From this brief review the main conclusions on this field were:

i. The calibration approach will be always an indeterminate problem with a non-unique solution;
ii. The limited measure data outputs, the sheer number of inputs and their uncertainties leads always the first problem in a calibration process;
iii. No consensus in a standard calibration definition to apply on a wide variety of buildings;
iv. Many of the approaches proposed for model calibration rely heavily on users and designers’ knowledge;
v. Most of existing approaches are based on trial and error practices.

The next section aims to further investigate the identified problem by introducing an original approach based on an evolutionary algorithm.

6.5.2 – Proposed calibration methodology

This research study proposes a multi stage calibration approach for thermal dynamic building simulation using an optimization procedure with the evolutionary algorithm. In this section is presented the same multi-objective optimiser that uses a hybrid evolutionary algorithm [112, 113] based on the CMA-ES and HDE evolutionary algorithms already exposed in Chapter 4.

The calibration approach itself systematically adjusts the values of the design variables (input parameters) and reduces the deviation Root Mean Square Error (*RMSE*) between predicted and measured indoor air temperature values. At the end of the process the overall Goodness Of Fit (*GOF*) indicator is assessed to classify the calibration accuracy. To minimise potential error sources due to boundary conditions, a real weather data file collected from a local meteorological station was used and the surrounding exterior shading obstacles were taken into account in the model definition.

Monitoring results of the building were used to calibrate the numerical model using as an objective function, the *RMSE*, between predicted and real data, adapting the uncertain input parameters. To reduce the unknown user behaviour, a period between July and December in which no occupants were present, was used to calibrate the model. This period comprehends heating and cooling seasons as well as a mid-season.

The proposed approach can be broken down into the following steps:

i. Gather building description information from the final technical building compilation and material specifications from manufacturers;
ii. Match check between the technical building compilation and the real building solutions;
iii. Evaluation of material property data sheets and creation of a list of parameters and definition of uncertainties;
iv. Gather building monitored data;
v. Design DBES model including the unknown input parameters as variables;
vi. Definition of the variables range according to the uncertainties;

vii. Run the set of simulations with the evolutionary algorithm linked to the software used (here in EnergyPlus® V8.3.0). In this step the software should be programed to systematically adjust the values of the design variables (input parameters defined as uncertainties) with an output to reduce the deviation *RMSE* between predicted and measured indoor air temperature values;

viii. Evaluate the performance of (*GOF*) of the temperature results.

This proposed calibration approach is presented in a graphical manner in Figure 6.13.

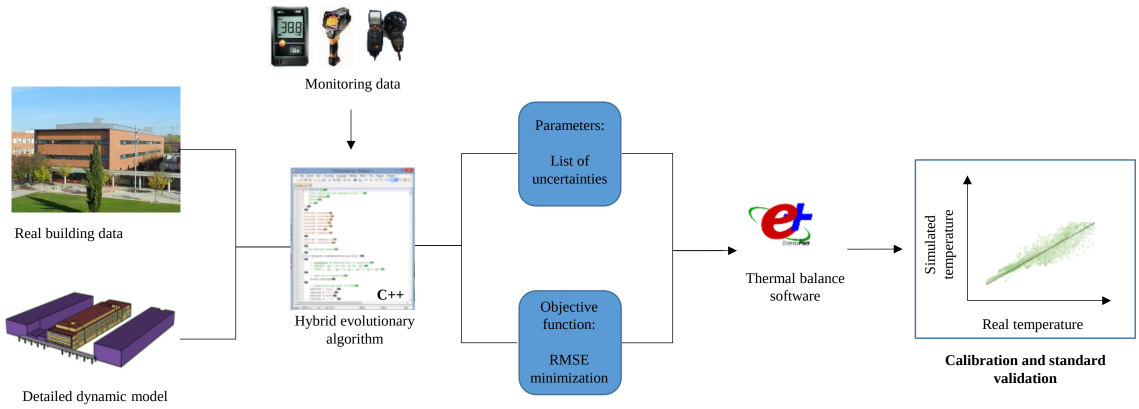


Figure 6.13 – Proposed approach for model calibration

6.5.3 – Numerical model definition

Based on the envelope solution (constructive solutions and materials thermal characteristics), a building model is developed resourcing to EnergyPlus® software as a calculation engine. Conduction finite difference model algorithm for the surface heat balance calculation is mandatory when using PCMs. A SketchUp® tool with OpenSudio plugin, with a graphical interface, was used to reproduce the geometry of the model and main features related to thermal zoning and constructive solutions definition (see Figure 6.14).

The model was assembled using twenty-four thermal zones, corresponding to the main internal partitions. The ground floor has six main thermal zones with another four zones that correspond to the lift and staircases which are common thermal zones to all floor levels. First and second elevated floors have similar internal arrangement however, the first floor has five thermal zones and the second floor has six thermal zones, both with another four thermal zones as common zones to all floor levels. The third elevated floor has three thermal zones. During the monitoring campaign the building was unoccupied and had no external or internal shading devices. All the exterior building conditions, namely the presence of adjacent buildings and other structures were included in the EP model definition as shading surfaces.

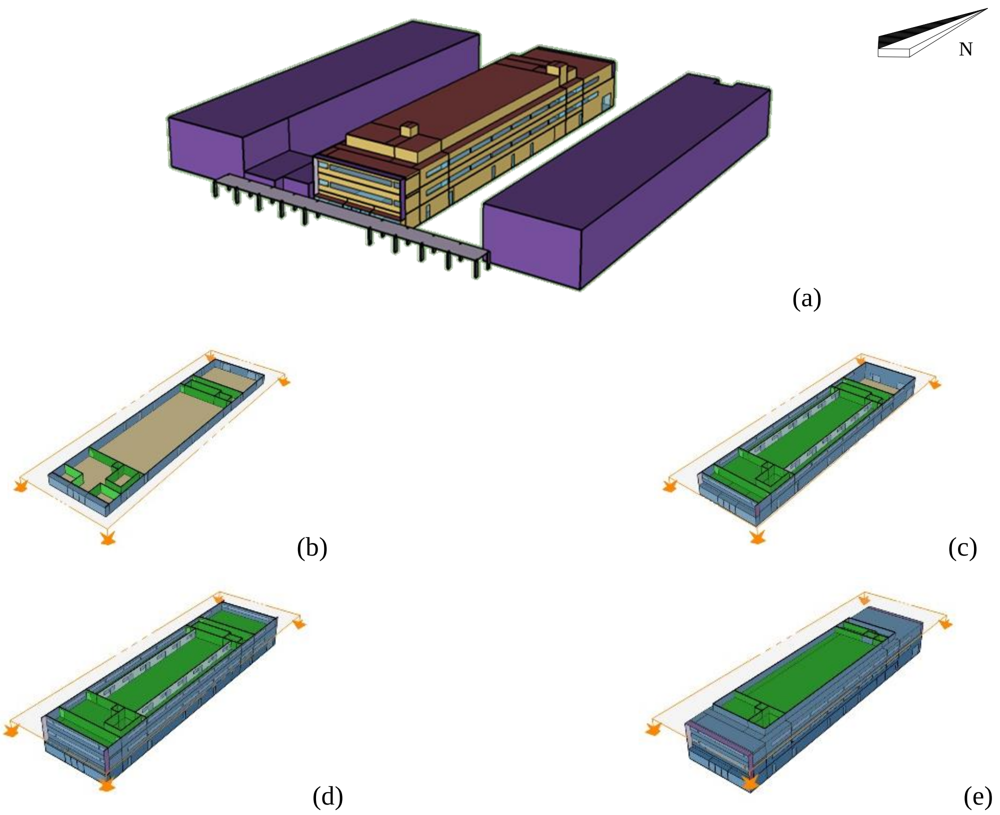


Figure 6.14 – Building energy model definition: (a) full exterior view; (b) ground floor internal partitions; (c) 1st floor; (d) 2nd floor; (e) technical floor

During the monitored period the building has been unoccupied, however, all the simulations in the optimization process, in order to represent the real building behaviour, were simulated under scheduled condition of occupation, lighting and equipment use detailed in section 6.6.1.

6.5.4 – Uncertainty analysis and definition of the unknown parameters range

The *GOF* and coefficient of variation of the root mean square error (*CV RMSE*) were the selected criteria to validate the models accuracy. *GOF* indicator is related to the calculation of the following dimensionless indexes for the optimised model. The methodology followed involves the following equations:

i. *RMSE* – root mean square error

This index was the objective function used in the optimization process with an evolutionary algorithm. *RMSE* is a measure of the variability of the data. In this present study the difference in paired data points is calculated and squared hourly.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - S_i)^2} \tag{6.1}$$

Where M_i and S_i represents measured and simulated data points for each instance "$_i$" (hourly values) and "*n*" is the total number of data points at the interval considered.

ii. *NBME* (%) – Normalized mean bias error

$$NMBE = \frac{\sum_{i=1}^{n}(M_i - S_i)}{n \times \overline{M_\iota}} \times 100 \tag{6.2}$$

Where $\overline{M_\iota}$ is the average of the measured data values for the considered period "*n*".

iii. *CV RMSE* (%) – Coefficient of Variation of the Root Mean Square Error

This index quantifies how well a model fits the data by capturing offsetting errors between measured and simulated data.

$$CV\ RMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - S_i)^2}}{\overline{M_\iota}} \times 100 \tag{6.3}$$

iv. *GOF* (%) – Goodness of Fit

$$GOF\ (\%) = \frac{\sqrt{2}}{2} \times \sqrt{NMBE^2 + CV\ RMSE^2} \tag{6.4}$$

To attain the estimation of *RMSE* coefficient (the programming language is called E+ runtime language (Erl)) it was programmed as an output using the energy management system application in EnergyPlus®. Using this output as an objective function, it was possible to identify, easily, the most accurate models. After the *GOF* indicator calculated, in which lower values represent the parameters that provide a closer match between measured data and simulated results.

The definition of the best unknown input parameters values was developed based on the three first points described in the methodology approach. In this case study the main unknown sources are related to the following parameters listed in Table 6.2.

Table 6.2 – Range of variation of the unknown input parameters

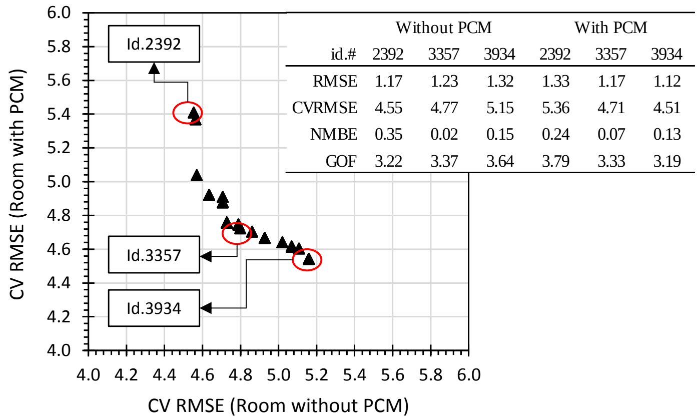
Continuous variables		
Parameter id.	Designation	Box Constraints
x0 – x10 (by thermal zone and from the monitored schedules)	Ventilation air change rate (h^{-1})	1.500 – 5.500
x11	Windows SHGC	0.550 – 0.750
x12	Infiltration air change rate (h^{-1})	0.050 – 0.200
x13	Wall insulation thickness (m)	0.035 – 0.040
x14	Roof insulation thickness (m)	0.050 – 0.080

Parameters from x0 to x10 represent the air change rate (h^{-1}) provided by the HVAC system for the thermal zones. The air flow supply, was evaluated directly from the ventilation grid (referred in the monitoring strategy, section 6.3.3) and the obtained results ranged between 1.5 and 5.5 h^{-1}. Moreover, during the monitored period the system works with different daily schedules, which led to use ten parameters to match simulated and real monitored schedule. Parameter x11 is related to SHGC, indicated by technical manufacture information as 0.65. Even though the information provided by the manufacturers considered reliable, uncertainty was considered as a box constraint in the optimizer with the range defined in Table 6.2. The parameter x12 (infiltration air change rate) has a significant impact on the indoor air temperature, as well as on the space heating or cooling energy use in buildings. In this case study the range defined (0.05 to 0.20 h^{-1}) was based on *in-situ* tests developed by Almeida [120] during his research work developed in similar buildings. Almeida [120] evaluated in school buildings the ACR considering only the air infiltration without mechanical ventilations systems. To evaluate infiltration rates, Almeida used the leak testing with tracer gas (in this study SF_6 was used) using the leak methodology. Other studies developed by Curado [121] resourcing to the blower door tests revealed similar values. Finally, parameters x13 and x14 were added as uncertainty variables to take into account the thermal bridges. These parameters were identified as the most sensitive inputs that revealed significant influence over the models results.

6.5.5 – Results and discussion

The simulation and optimisation were ran using a server with 32 Intel® Xeon® CPU E5-2665 0 @ 2.40 GHz. The optimiser was defined to minimize the objective function (*RMSE*) while finding a trade-off between the input design parameters (defined as variables) and the monitored indoor air temperatures.

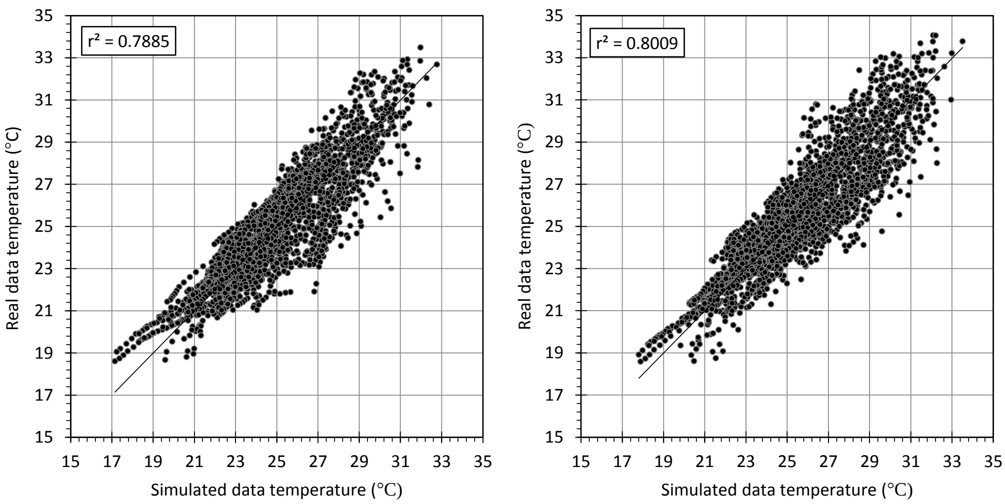
Figure 6.15 shows the results for the optimised solutions identified by the optimiser, matching real data and simulated results in both rooms separately using EP software. In the optimization process the index *RMSE* was minimised however to compare with the standard values *CV RMSE* is presented in the plots (Figure 6.15). Furthermore, a table with the main index resulting values used in the calibration process is also presented.



	Without PCM			With PCM		
id.#	2392	3357	3934	2392	3357	3934
RMSE	1.17	1.23	1.32	1.33	1.17	1.12
CVRMSE	4.55	4.77	5.15	5.36	4.71	4.51
NMBE	0.35	0.02	0.15	0.24	0.07	0.13
GOF	3.22	3.37	3.64	3.79	3.33	3.19

Figure 6.15 – Definition of the Pareto front for the best results

Figure 6.16 shows the graphical correlation factor r^2 on top of a scatter plot with real data and simulated results for the indoor air temperature. For the temperatures between 17 to 21°C it is observed that the indoor air temperature simulated is always lower when compared with real data. From 21 to 33°C the observed deviation can be considered reasonable.



(a) (b)

Figure 6.16 – Scatter plot of monitored versus simulated temperatures for the calibration period (4th July to 31st October – id 3357): (a) room without PCM; (b) room with PCM

Figure 6.17 presents the indoor air temperature for the calibration period. In the plot, a similar temperature swing behaviour of the real and simulated curves can be observed.

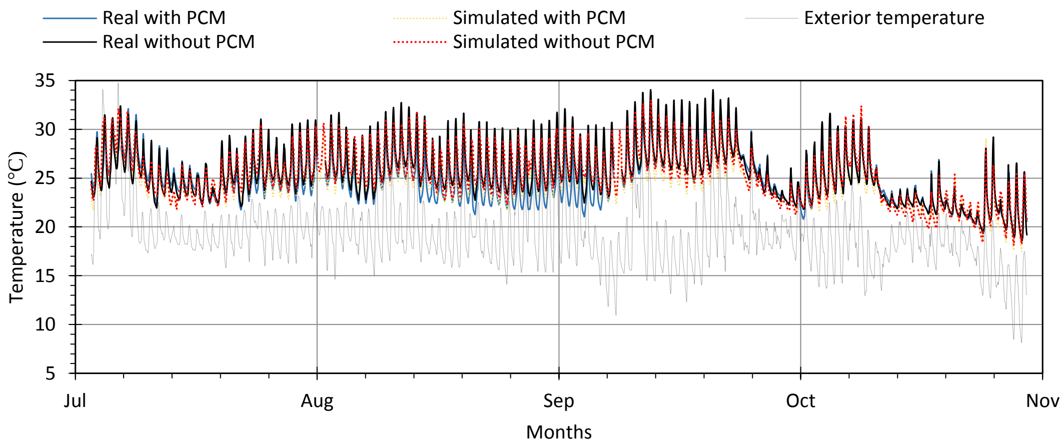
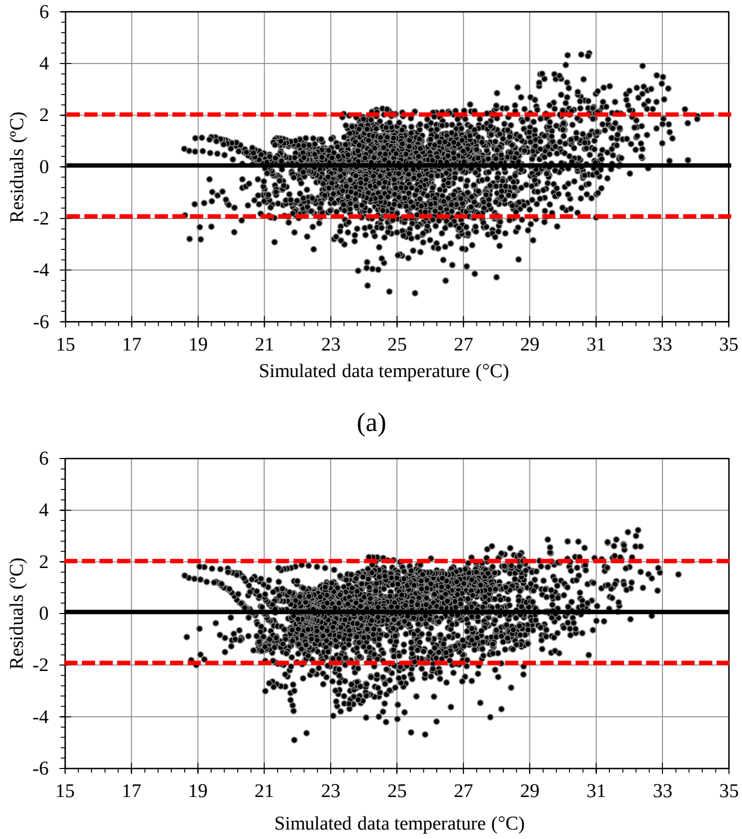


Figure 6.17 – Indoor air temperatures: monitored data and simulated results

In Figure 6.18, the residuals (difference between the monitored and simulated values) versus indoor air temperature are displayed. As shown, the residuals are concentrated mostly in the temperature range between -2 to 2 °C. However, it can also be observed that there are some peaks in the temperature curves whose error values are approximated to +4 and -4°C.



(b)

Figure 6.18 – Residuals values for the period under calibration (4th July to 31th October – id.3357): (a) room without PCM; (b) room with PCM

Figures 6.20 and 6.21 outlines the comparison in the period from 8th to the 14th of August of the measured and simulated temperatures using Box Whisker Mean plots (BWM). The whiskers plots show the 2nd and the 3rd quartiles for the real data and simulated results respectively. The circles and the triangles connected with a black line are overlaid and represent the mean daily values and finally, the exterior marks represent the maximum and the minimum values.

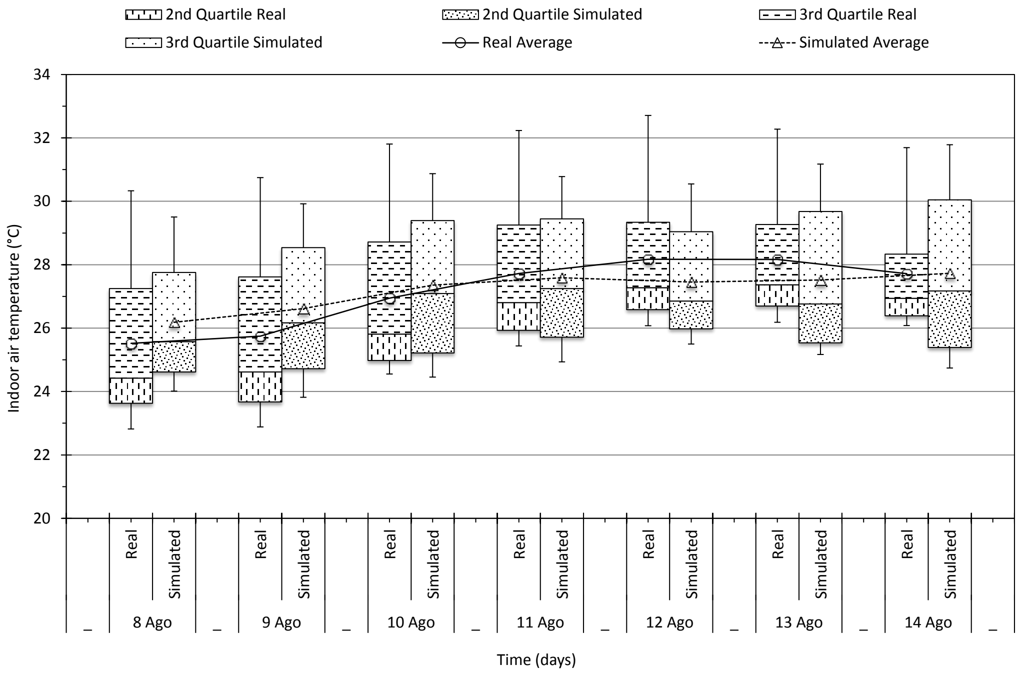


Figure 6.19 – BWM plot of measured and simulated temperatures in the room without PCM (8th to the 14th August – id.3357)

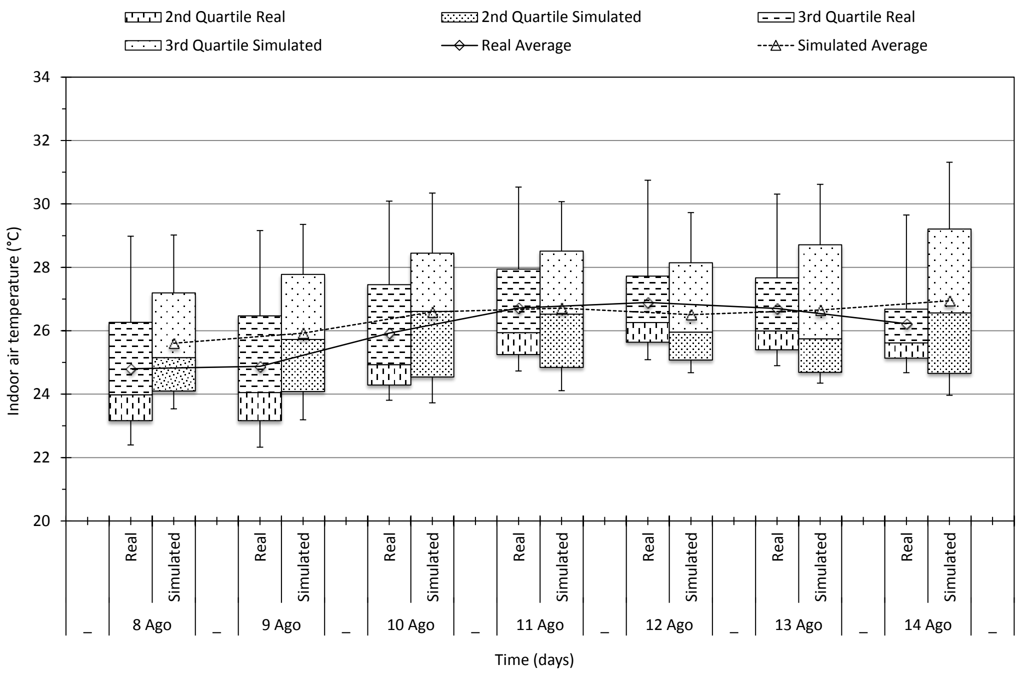


Figure 6.20 – Hourly BWM plot of the measured and simulated indoor air temperatures in the room with PCM (8th to the 14th of August – id.3357)

From the mean values a maximum difference of 1°C was observed between measured data and simulated results and when comparing the maximum and minimum values, small differences were observed in both rooms. Furthermore, the room with PCM shows more similar minimum and maximum temperatures and presents a good agreement for each day. Analysing the results of the 2nd quartile for both rooms, the simulated results reveals more points for this quartile than the real data. The 3rd quartile results, shows a good agreement between the simulated results and real data with an exception for the 14th of August.

In summary, the *CV RMSE* values attained are below the limit values referred in the existing standards or guidelines in respect to the calibration model results (see Table 6.3).

Table 6.3 – Acceptance criteria for calibration (hourly criteria %)

Standard / Guideline	*CV RMSE* limit	Calibration results	*CV RMSE*	
			Room without PCM	Room with PCM
ASHRAE Guideline [61]	30	Multi-stage approach used	From 4.55 to 5.15	From 4.51 to 5.36
IPMVP [122]	20			
FEMP [63]	30			

The *GOF* index depicted in the ASHRAE Guideline [61] recommends a *GOF* value below 11% for trials acceptance, however Cipriano *et al* [123] for free floating conditions suggests a *GOF* below 3%. In the presented work the attained *GOF* is very near to the limit value suggested by [123] however the unknown input parameters definition is different in both methodologies.

6.5.6 – Calibration methodology: lessons learned

This methodology aims to locate the best simulated performance points that are the nearest to the real measured data, changing pre-identified inputs as variables. To achieve this goal an evolutionary algorithm was used with multi-objective capacity. This calibration process was applied in the calibration of two rooms of a university department building (case study presented in this chapter) using hourly measured data.

The results show that this methodology can be used in buildings with a high level of detail using a calibration approach per thermal zone. The correlation with the measured and simulated hourly indoor air temperature data is good, demonstrating the effectiveness of the methodology. However, due to the number of the uncertainties existing in the model inputs and the limited available monitored values, the calibration process can be a problem with a non-unique solution, and the final decision will have to be chosen by the designer.

Using evolutionary algorithms connected and instructing dynamic building software used for simulations, in an automatic process, increases its efficiency to find the best solution reducing the *CV RMSE* (avoiding the user using trial and error practice) increasing the reliability of the calibration process.

6.6 – PCM optimization using a hybrid evolutionary algorithm

A final model was simulated after the calibration methodology application. The main goal of this point is the overheating reduction optimizing different PCM solutions changing the ventilation rate. Based on the calibrated model and using the weather file from LNEG (see section 3.2) all the simulations ran for a yearly period (with an hourly frequency). First the model was simulated using the model resulting from the calibration with the original PCM constructive solutions. The thermal building characterization was evaluated in accordance with the standard EN 15251 [29] considering a mechanical ventilation system with capacity to provide a constant air flow from the outdoor air without the capacity of air conditioning (natural ventilation without cooling inputs) during the summer season. During the heating season the indoor air conditioning is provided by the mechanical ventilation system with an activation trigger that reacts to the indoor air temperature (activated when the temperature decreases bellow to 20ºC). In the second step a hybrid evolutionary algorithm was used to instruct the software in order to combine different PCM solutions with variations in the air flow rate and attain the best compromise between PCM solution and ventilation rate without heating or cooling inputs.

6.6.1 – Simulated building performance

The results presented in this section result from the first simulation with the original solution (model id.3357 provided from the calibration process and presented in Figure 6.15). This characterization, using simulated data will be used in the comparison of the results attained in the optimization process.

During the calibration process some envelope solutions suffered minor adjustments (thermal properties of layers) with the RSME (between monitored and simulated data) minimization goal. Thus, Table 6.4 sums up the main simulation details and assumptions considered in the final model after calibration.

Table 6.4 – Simulation details and assumptions

Simulation details		
Designation	Properties	Observation
Exterior walls	U value = 0.453 (W/m^2 °C)	Provided from the calibration
Flat roof	U value = 0.468 (W/m^2 °C)	Provided from the calibration
External floor slab	U value = 1.224 (W/m^2 °C)	Equal to original model
Exterior windows	U value = 2.4 (W/m^2 °C) SHGC = 0.74	Provided from the calibration
ACR	1.125h^{-1}	For an occupation of 1 persons per 8m^2 (10 persons in each room in study)
Infiltration	0.116h^{-1}	Provided from the calibration
Electrical equipment*	8.61 W/m^2	Computers and other devices
Lighting*	13.30 W/m^2 – Offices 7.10 W/m^2 - Corridors	Illumination in offices and corridors
Occupation* (activity level)	122 W	10 Persons in offices in study 2 Persons in corridors
Run period	Annual	Hourly step
Summer season	Without cooling inputs	Natural ventilation
Winter season	Heating when indoor temperature drops below 20 ºC	HVAC system

*See the correspondent schedule in Figure 6.21

In this part of the work all the simulations were performed in order to simulate the PCM effect in the building under real conditions (occupation and all other internal gains were added). Figure 6.21 shows the schedules defined and used for occupation, electrical equipment and devices and lighting. The information in Table 6.4 should be simultaneously read with the schedules presented in Figure 6.21. Infiltration and ventilation rates were considered always on and constant without cooling and heating inputs in the original building thermal performance analysis.

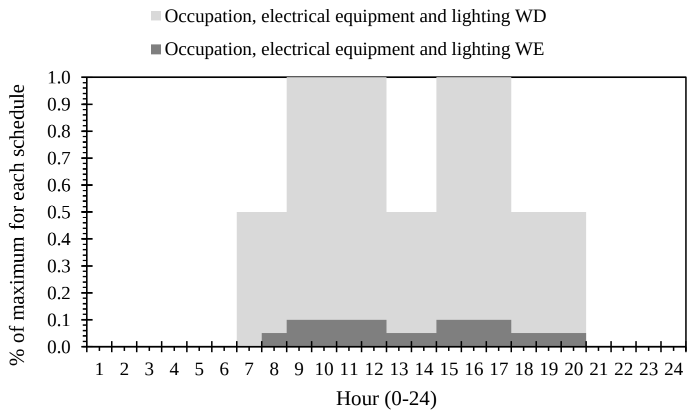


Figure 6.21 – Occupancy, lighting and electrical equipment schedules (WD: week day; WE: weekend)

Simulations without resourcing to an active system for the summer season allow a passive thermal comfort evaluation according with the standard EN 15251 [29]. The building under study fits into category II (EN 15251 defines three categories of comfort), which refers to a normal comfort level adjusted to new and refurbished buildings. The heating season behaviour was characterized by the energy demand to keep the indoor air temperature above 20 ºC.

As previously mentioned the goal of this work consists in the PCM solutions optimization for overheating reduction and for heating demand assessment, for that, only the rooms presented in Figure 6.4 are used to present overheating results.

6.6.1.1 – Original building thermal performance after calibration: summer season

The building performance was characterized evaluating the overheating rate during the summer season and heating energy demand during the winter season.

Figure 6.22 presents the overall thermal performance in accordance with EN 15251 [29] of the rooms with and without PCM, for the cooling season (from the 1st June to 30th September).

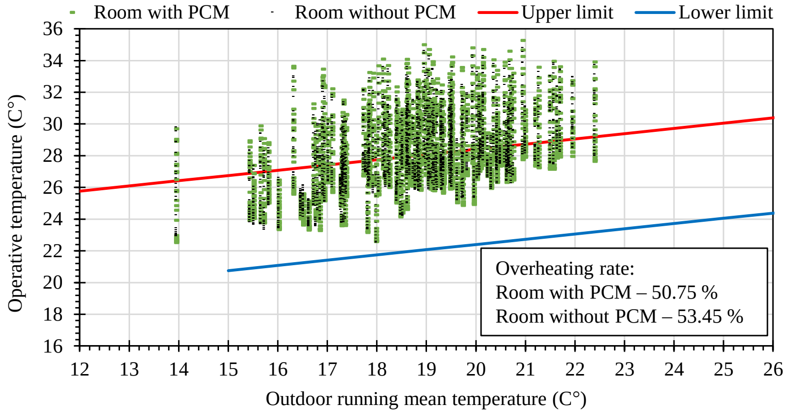


Figure 6.22 – Indoor air temperature for the cooling season (EN 15251 - Category II)

Resulting from the analysis of Figure 6.22, it is possible to observe that the indoor air temperature shows an exceedance of the adaptive comfort limits above the upper limit, indicating a period of overheating of 50.75% for the room with PCM and 53.54% for the room without PCM. This results represent a PCM efficiency of 5.05%.

6.6.1.2 – Original building energy performance after calibration: heating season

To assess the energy consumption for heating an ideal system air loads to control the indoor air temperature was defined. This system is operated by a thermostatic control for a specified temperature trigger. In this case the dead band for free running is defined to operate above 20ºC.

The energy demand for heating determined was 60.18 kWh/m^{2}a considering all net conditioned building area, and 5.43 kWh/m^{2}a exclusively for the room without PCM and 7.10 kWh/m^{2}a for the room with PCM. Note that the exterior envelope is different for the rooms with and without PCM (see section 6.4.1).

6.6.1.3 – Original building thermal performance after calibration: full season free flow

This sub section presents the thermal behaviour (without inputs for cooling and heating) on an annual basis to evaluate the PCM effect and the differences caused by the external envelope boundary.

Figure 6.23 presents the overall thermal performance of the original building for the real purpose of use (according to Table 6.4). The results show an exceedance of the operative temperature outside the standard limits (upper and lower limits) of 63.86% in the room without PCM and 64.91% in room with PCM.

To evaluate the influence of the envelope differences in the results comparison between the room with and without PCM a new model was developed without PCM in both rooms (see results in Figure 6.24). Figure 6.24 shows an exceedance of the operative temperature outside the standard limits of 63.87% in room without PCM and 65.64% in room with PCM.

Overheating and underheating is presented in the plots of Figure 6.23 and Figure 6.24 respectively.

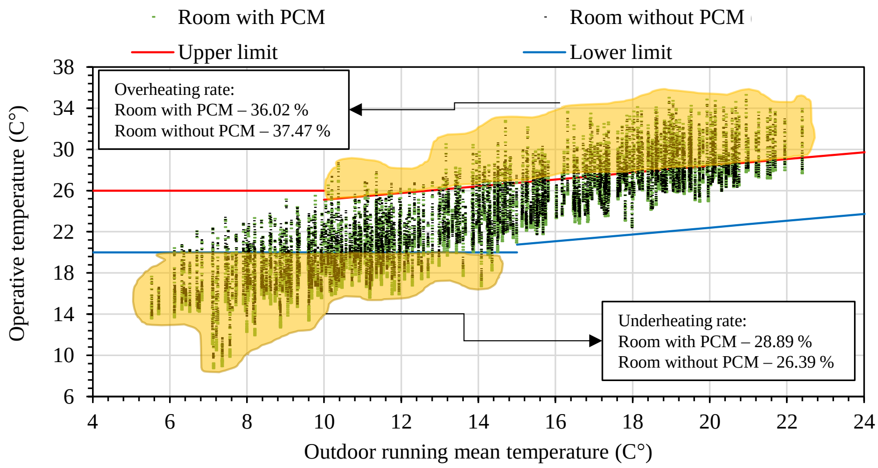


Figure 6.23 – Original building: full season thermal performance according to EN 15251 - Category II

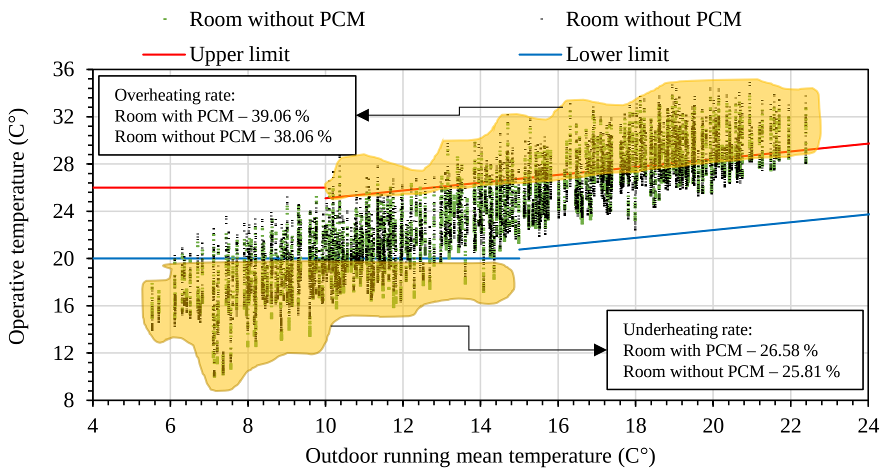


Figure 6.24 – Building without PCM: full season thermal performance according to EN 15251 – Category II

On an annual analysis, results show the same percentage of the global discomfort for the room without PCM and a slight reduction for the room with PCM. Considering a local analyses (in overheating and underheating rate) it was observed that the use of PCM works better tackles the overheating reduction. Comparing results from models with room with PCM (Figure 6.23) and the same room but without PCM, (Figure 6.24). Note, that the PCM performance is affected by the differences of the external envelope boundary conditions.

6.6.2 – Overheating and heating demand reduction using different PCM solutions

In this section a multi-objective evolutionary algorithm is used to find an optimal solutions using different types of PCM with overheating and heating demand reduction as a goal. The optimiser is a hybrid evolutionary algorithm based on the CMA-ES and HDE that was introduced in Chapter 4.

A comparison between the original model (with heating inputs) and the improved model (combining different PCM solutions and ventilation rate for summer and winter seasons), resulted from the optimization process is presented.

6.6.2.1 – Optimisation parameters

Different types of PCM were used and combined in the existent constructive solutions. The strategy consists in changing the layer with PCM panels by different types of PCM (melting point and latent heat capacity) in the existent partition wall and suspended ceiling.

In the present optimization process, PCM solutions represent all the set of alternative measures that are under study for overheating and heating demand reduction. Thus, parameters allow a set of chosen combinations for the input database.

In the present study thirteen types of PCM solutions (decision parameters) were used concerning the alternative choices. The different types of PCMs (Micronal® DS 5001 and BioPCM® series M27, M51 and M91) incorporated in the constructive solutions were the same presented in section 5.5.3. The PCM solutions represent discrete variables in the inputs, with the possibility to combine different types of PCM in the partition wall and suspended ceiling.

Ventilation air flow rate was also used as a variable, however in this case, the ventilation rate was used as a continuous variable with a box constrain limited in the range of $1.125h^{-1}$ to $5.5h^{-1}$. Ventilation air flow was separated by season period to enable different air flow rates optimization for summer and winter.

6.6.2.2 – Objective functions

As objective functions, heating demand and overheating rate were chosen to be minimized by the optimiser. Overheating rate was defined in EP in accordance with EN 15251(category II) and resourcing to EMS feature in EP that provides a manner to develop custom control and modelling routines.

Heating demand was added in order to find the optimum compromise between the conflictual issue, the ventilation rate during the summer and winter season.

6.6.2.3 – Results: multi-objective approach

Figure 6.25 shows the optimum results of the triple-objective minimization in the form of a three-dimensional points with projection on the axis plans.

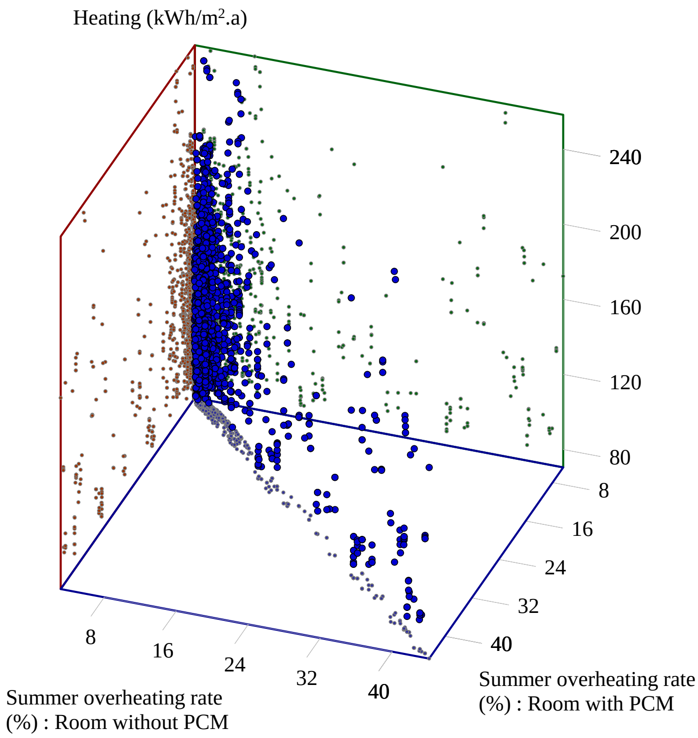


Figure 6.25 – Optimised results (overheating for both rooms separately and heating demand minimization)

The results of the optimization problem point out that based for the original model (sub section 6.6.1.1), the overheating rate during the summer season decreases about 90% in the room with PCM and about 87% in the room without PCM while the global annual heating demand increases about 14%.

From Figure 6.26 it is possible to depict the coupled result of the improvement attained in respect to the discomfort rate for both rooms separately and the annual heating demand. The results contain the points of the Pareto front (black triangles and black circular shapes markers), which represent a set of optimal solutions. Black triangles represent the Pareto front of the ordinated pair, annual heating demand and overheating rate of the room with PCM and the circular marks represent the Pareto of the ordinated pair, annual heating demand and overheating rate of the room without PCM.

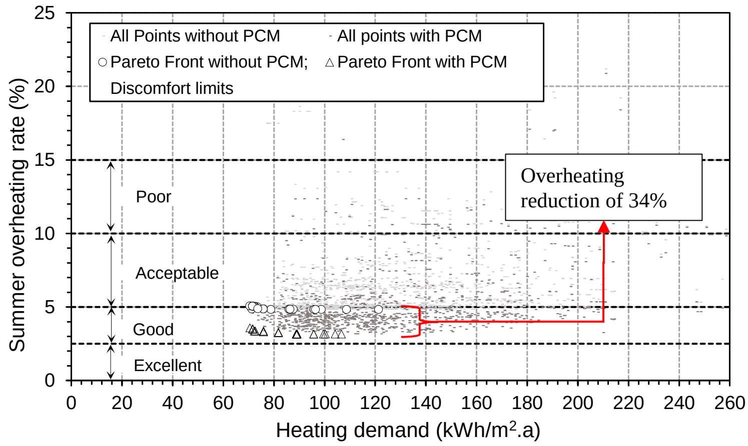


Figure 6.26 – Optimised results (overheating for each room independently and energy heating demand minimization)

Pareto front solutions are composed by all the optimum points given from an optimization process that creates an archive of the tested configurations (a detailed description is presented in section 4.4.3). Through the results, shown in Figure 6.26, it was observed that the use of PCM solutions has a significant impact during the summer season in the overall overheating reduction. Comparing the attained results of the overheating rate between both rooms a reduction of about 34% was achieved by the use of PCM in one of the rooms.

Table 6.5 lists some of the optimal solutions after optimization analysis. Results shows that the optimum solution in terms of overheating reduction requires the air flow rate at its maximum capacity using BioPCM with a melting point of 23 ºC. The overheating reduction attained using a PCM with higher heat storage capacity (from M51 to M91) is insignificant (see Table 6.5). Thus, it is possible to conclude that BioPCM® M51/Q23_0.021 could be one of the optimal solutions regarding the thermal efficiency in overheating reduction and cost (M91 costs approximately 1.5 times more when compared with M51 cost).

Table 6.5 – List of optimised solutions

Optimiser. id#	Air flow rate (h^{-1}) Winter season	Air flow rate (h^{-1}) Summer season	PCM type	Global heating demand (kWh/m^2 a)	Summer discomfort rate (%) Room with PCM	Summer discomfort rate (%) Room without PCM
id2897	2.07	5.50	BioPCM® M51/Q23_0.021	71.61	3.49	5.05
Id3734	2.55	5.50	BioPCM® M91/Q23_0.037	81.78	3.25	4.88
Id3737	2.19	5.50	BioPCM® M91/Q23_0.037	95.74	3.16	4.87
Id3661	2.37	5.50	BioPCM® M91/Q23_0.037	106.63	3.16	4.87

* Nomenclature used: M (Btu thermal energy storage capacity); Q (peak melting temperatures in degrees Celsius); E (thickness).

6.6.3 – PCM payback analysis on cooling reduction

This sub section brings out information about the payback period when PCM is incorporated in the constructive solutions (partition walls and suspended ceiling) with the goal to persuade householders and building sector to adopt PCM solutions in new buildings or refurbishment.

An economic analysis was performed to estimate the payback period for the PCM constructive solutions used in the study. The model used to estimate the PCM investment evaluation was the Net Present Value (NPV) method. The NPV method consists in the difference between the present value of cash inflows and the present value of cash outflows, enabling the analyses of the profitability of the projected investment made with the PCM application (see equation 6.1).

$$NPV = \sum_{t=0}^{n} \frac{NCF_t}{(1+r)^t} \tag{6.1}$$

Where:

NPV – Net Present Value;

NCF_t – Net Cash Flow generated by the PCM application in year t;

r – discount rate.

Table 6.6 resumes the PCM market cost according to the suppliers.

Table 6.6 – PCM cost (supplier price including installation)

PCM type	M27	M51	M91	Micronal® DS 5001
Melting point (ºC)	Price (€/m^2)			
21	139.16	201.23	315.48	35.00
23	133.75	198.13	316.60	-
25	122.53	175.16	279.11	-
27	49.93	64.23	102.34	-

In this case study the room with PCM included in the partition wall and suspended ceiling have a surface area of 56.89 m^2 and 70.78 m^2 respectively. The floor area of this room is 77.16m^2.

To assess the energy consumption for heating and cooling the model presented in sub section 6.6.1.2 was used and it was operated by a thermostatic control for a temperature trigger between 20ºC to 26ºC. An additional model was created removing PCM from the constructive solution to be compared. Thus, the electricity consumption was computed considering 0.50 €/kWh cost and a corresponding annual inflation rate of 2.80 %. Successively, the energy saving (for cooling) comparing the models with and without PCM solutions were obtained, and the payback period is attained when the difference between energy savings accumulated over the years and the PCM additional investment inflated with an interest rate of 1.31%.y^{-1} equals zero.

The annual energy demand results attained are presented in Table 6.7 as well as the payback time.

Table 6.7 – Payback time for the cooling season

Installed solution	Total initial cost (€)	Room with PCM (kWh)	Annual energy cost saving (€)	Payback time (years)
Original building without PCM	-	3114.97	-	-
Dupont Energain (Micronal® DS 5001)	4468.45	2977.47	22.83	41
BioPCM® M51/Q23_0.021 (id 2897)	25295.25	921.07	1096.99	18
BioPCM® M91/Q23_0.037 (id 3661)	40420.32	904.68	1105.15	26

The solution with Dupont Energain with Micronal® DS 5001 (installed solution) shows a higher payback time when compared to other models (see Table 6.7). A possible explanation for this result is that the weather data in Aveiro region has a hotter summer season. Thus, the outdoor temperature is higher than PCMs melting range which keeps them to stay in their liquid state. As a result, in the afternoon due to higher solar radiation, PCM with lower melting point (in this case approximately 21ºC) does not drop below its melting range, losing the capacity to discharge absorbed energy.

Summer energy performance results showed that BioPCM® M51/Q23_0.021, model id2897 obtained the best cooling energy payback time. Solution id3661 with BioPCM® M91/Q23_0.037 allows a higher annual energy cost saving, however the initial investment cost is impracticable leading to a payback time of 26 years.

Saffari [124] developed similar studies in office buildings using PCM solutions from Rubitherm, CSM PCM-Panel. The payback time achieved in this study was in the range of 6 to 132 years. Thus the best payback time attained in this present study is more than twice if compared with Saffari's research work. However, the methodology used to estimate the payback time is different in both approaches.

6.7 – Final remarks

This study has tackled the overheating and heating demand reduction issue for a typical room in a university department building. In the experimental work, a layer of PCM was incorporated into the partition wall and suspended ceiling in the form of panels in one room of the building. The two rooms were monitored during a complete year. Thermal comfort and the PCM influence were quantified using the standard EN 15251 [29]. Finally the monitoring data base was also used for the development of a new methodology for dynamic models calibration. Thus, a numerical approach, evaluation different PCM solutions was applied and optimised. In the presented optimization problem, a multi-objective optimization was performed using a hybrid evolutionary algorithm based on the covariance matrix adaptation evolution strategies and hybrid differential evolution. EnergyPlus® outputs were programmed using EMS application estimate *RMSE* coefficient and overheating rate according to EN 15251 [29]. The design parameters were 13 different types of PCM and ventilation rates for summer and winter seasons separately. In addition, three objective function were taken into account, enclousing the annual heating demand and the overheating rate for the summer season for the two rooms of the building. The results of the optimization problem were compared with the original building with the features attained after the calibration process. Finally the achieved optimum solutions from the multi-objective optimization problem were reported in a 3D plot and as Pareto optimal fronts in a 2D plot. To conclude this chapter an economic analysis was performed on the payback period in years for the PCM constructive solutions used and optimised.

In sum with the results attained the general conclusions regarding the developed work are outlined in the following:

i. The use of PCM as a thermal regulator, leads to a reduction of the overheating rate during the summer season of 7.23% (corresponding to a PCM efficiency of about 35%). Moreover, during this monitored period there was no occupation and internal gains in the building;

ii. In the numerical simulation, the PCM efficiency attained was similar to the experimental results. However, with the corrected melting point chosen and using the ventilation air flow rate optimised to promote PCM charging and discharging process the overheating rate was reduced from 36% to 3%.

iii. PCM provides a favourable thermal regulation effect with a high reduction in the thermal indoor overheating rate;

iv. The selection of the melting point of the PCM is crucial to fully take advantage of the PCM (charging and discharging process on a daily cycle);

v. The ventilation rate is essential to assure the discharging process of the PCM. The charging and discharging processes are only possible due to an effective combination of the PCM melting temperature selection and optimised ventilation rate;

vi. A real problem using multi-objective minimization may lead to a compromise in which one of the objectives increases and other decreases simultaneously;

vii. To reduce the PCM payback time the melting point should be previously optimised using dynamic simulation to increase the PCM efficiency.

CHAPTER 7

FINAL REMARKS AND FUTURE WORK

Chapter outline

7.1 – Brief description of the research work

7.2 – Final comments

7.2.1 – Chapter 2 – Thermal comfort and energy performance: sensitivity analysis to apply the Passive House concept to the Portuguese climate

7.2.2 – Chapter 3 – Mechanical and thermal characterization of concrete with incorporation of microencapsulated PCM for applications in thermally activated slabs

7.2.3 – Chapter 4 – Passive House optimization for Portugal: overheating evaluation and energy performance

7.2.4 – Chapter 5 – Overheating reduction of a cold formed steel-framed building using a hybrid evolutionary algorithm to optimise different PCM solution

7.2.5 – Chapter 6 – Numerical and experimental study on constructive solutions with PCM for thermal regulation

7.3 – Future developments

7. FINAL REMARKS AND FUTURE WORK

Abstract This chapter presents a general overview of the research work developed throughout the thesis program and summarises the main conclusions, stated in the previous chapters. As a last subsection, possible future research guidelines and activities are outlined.

7.1 – Brief description of the research work

As exposed in Chapter 1, the main goal of this research work is to contribute to the knowledge related to energy saving in buildings through the use of new buildings solutions with phase change materials and ambitious energy compliance criteria, as the case of the PH standard. This goal was accomplished with the performed work through the development and characterization of the thermal performance of indoor rooms with applications of constructive solutions with PCM and the adaptation and compatibility with the Passive House concept for Southern European climate. Three case studies were under scope in the presented thesis, aimed essentially at three main goals: i) adaptability of the Passive House requirements to Portugal, balancing the thermal comfort analysis according to EN 15251 with the energy demand resourcing to optimization of buildings features and systems; ii) mechanical and thermal characterization of concrete screed with the incorporation of microencapsulated PCM of a thermally activated slab; iii) use of PCMs as potential thermal regulator of indoor spaces of service buildings with inherent energy saving potential.

This document was structured into seven sections. Firstly in Chapter 1 a brief introduction of the broader scope of this work was made, and some general considerations were underlined. The global methodology was outlined to present in an intelligible manner the work. The second chapter is dedicated to thermal comfort and energy performance assessment for the PH concept application to the Portuguese climate. To this end, in the first approach, a real case study was modelled and characterized according with the original constructive solutions and then a sensitivity analysis with building features improvement was performed until achieving the PH compliance criteria. This study was applied for different regions of Portugal creating a first building physics database in respect to building envelope characteristics for each climate zone in study. Chapter 3 presents a study regarding the characterization of concrete incorporating microencapsulated PCM. A mechanical and thermal characterization were carried out in laboratory conditions. Then, in Chapter 4 an evolutionary algorithm was used to optimise building features and equipment (cooling and heating) for the PH assessment for Southern European climate. After exploring PCM use and the optimiser, the case study presented in Chapter 2 was used and optimised in the Chapter 5 for overheating reduction resourcing to constructive solutions with different PCM melting points. As the last case study, an University department building, all the techniques and strategies studied in previous chapters were applied. The building was monitored and the recorded data was used for a thermal characterization and for numerical model calibration, including the development of a new methodology tool for dynamic model calibration. The efficiency of the PCM solutions over the overheating reduction was optimised and the investment payback was also evaluated.

7.2 – Final comments

The detailed conclusions obtained were discussed throughout the previous chapters and the main conclusions are summarized in the following subsections.

7.2.1 – Chapter 2 – Thermal comfort and energy performance: sensitivity analysis to apply the Passive House concept to the Portuguese climate

In what regards to the thermal dynamic simulation and sensitivity analysis with different constructive solutions and active equipment to meet Passive House requirements (thermal comfort and energy compliant targets), four conclusions can be taken:

i. With common building envelope solutions and construction materials, typically used for light steel frame structures in Portugal, dynamic simulations revealed long periods of thermal discomfort for the heating season, as well as long periods of overheating during the summer;

ii. The Passive House concept is obviously viable for Southern Europe climates specifically in the case of light steel frame typology, namely in Portugal however it is essential to adapt and detail the technical and constructive solutions for different regions;

iii. Significant reduction of the energy demand for Aveiro region was attained, over 60% for heating and 70% for cooling;

iv. The opaque building envelope solutions for Bragança and Lisbon require the highest levels of insulation thickness and triple glazing windows solutions.

Coimbra, Évora and Faro regions require double glazing windows and small thickness of thermal insulation. Finally the Oporto region requires intermediate levels of insulation and double glazing windows solutions;

v. The thermal inertia increase through the use of an extra interior mortar of light steel frame buildings, attenuates the temperature swing and reduces both maximum and minimum temperature peaks;

vi. The use of external shading protection systems, activated automatically with a temperature control trigger is advisable for overheating control.

7.2.2 – Chapter 3 – Mechanical and thermal characterization of concrete with incorporation of microencapsulated PCM for applications in thermally activated slabs

The laboratory tests described in Chapter 3, were carried out aiming at studying and characterizing the mechanical and thermal behaviour of concrete with the incorporation of microencapsulated PCM. Following the work developed in this chapter, the principal conclusions were taken:

i. The incorporation of microencapsulated PCM into concrete leads to a strength losses of 68% in compression and 51% in bending (ratio between PCM and concrete was 3.21% by weight of the total mass);

ii. The incorporation of PCM did changed slightly concrete density;

iii. Taking into account the significant strength loss, concrete with PCM could be used for applications of concrete screed layer purposes;

iv. The mixing process has a significant influence over the final mechanical properties;

v. Regarding the thermal characterization, PCM incorporation into concrete slightly improves the thermal behaviour, therefore expected, when applied as a constructive solution can reduce the indoor air temperature peaks and attenuates the daily temperature swing.

7.2.3 – Chapter 4 – Passive House optimization for Portugal: overheating evaluation and energy performance

Chapter 4 presents a pioneering and valuable approach, through buildings physics and active equipment optimization for the Passive House concept application for Portugal mainland. Bearing in mind such goals, the following conclusions should be underlined:

i. The use of a multi-objective optimization yields a wide range of non-dominate solution, showing a great potential for building solution design;
ii. The optimization outputs has proven that the applicability of the PH concept for Southern European climates should be incentivated;
iii. The overheating issue can be solved only resourcing to passive features without an active cooling system;
iv. The additional energy needed for lighting resulting from the exterior blind activation is insignificant when compared with the benefits achieved in the overheating reduction.

7.2.4 – Chapter 5 – Overheating reduction of a cold formed steel-framed building using a hybrid evolutionary algorithm to optimise different PCM solution

As described in Chapter 5, the case study presented in Chapter 2 was used for PCM constructive solutions testing in the overheating reduction goal. On this subject three main conclusion can be taken:

i. The annual overall thermal comfort is upgraded and the overheating rate is reduced, however it is crucial a correct selection of the PCM melting point;
ii. The increase of the ventilation rate with favourable exterior temperature conditions is essential to assure the total discharging of the PCM energy stored during the day;
iii. The use of different solutions of PCM with different melting points increases the potential for the overheating reduction.

7.2.5 – Chapter 6 – Numerical and experimental study on constructive solutions with PCM for thermal regulation

Chapter 6 presents a real case study with the application of PCM constructive solutions for overheating reduction. This study lead to an innovative approach for dynamic model calibration. Thus and regarding this chapter, the following is worth to be pointed out:

i. In the calibration methodology developed, it was demonstrated a high precision on the attained results, namely in *CV RMSE* statistical index, increasing in this way the reliability of the calibration process of thermal dynamic models;
ii. The challenging issue in a calibration process is the uncertainties identification and in the most of cases the limited monitored data used;
iii. The real data recorded reveals a reduction of the overheating rate during summer season of 7.23% through comparing the discomfort rate between the room with and without PCM;
iv. In the numerical work after the PCM and ventilation rate optimization the overheating rate was reduced from 36% to 3% for the room with PCM;
v. The combination between the ventilation rate and the PCM melting point selection is a fundamental issue to ensure the optimum overheating reduction;
vi. The best model using PCM as a constructive solution leads to a payback time of 18 years;
vii. Constructive solutions containing PCM are advisable as a good solutions for overheating reduction in Southern European climates.

7.3 – Future developments

Research work in modelling and optimization of energy efficient buildings and new constructive solutions is steady evolutive and growing trend. As a result of the research work performed herein many other opportunities were identified for further exploration. Thus, the following topics would be of value in the short term to give more strength to the work performed:

i. Incorporation and modelling of renewable energy systems to decrease energy demand of buildings supported on the PH premise, aiming at the PH plus and PH premium design strategies;

ii. Development of new laboratory campaign to improve the mixing process of the PCM into concrete and deepening knowledge of the features and issues responsible for the strength loss;
iii. Performing Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) of the constructive solutions with PCM herein used;
iv. Consideration of the water vapour transfer phenomenon in the numerical simulations carried out;
v. Numerical models to study and optimise building in respect to external envelope and orientation at the urban scale scenario;
vi. Simulation of these case studies for future climate scenarios, showing the impact of climate change on the building thermal behaviour;
vii. Development of strategies for an energy hub model to apply in buildings to collect stock and redistribute energy from free energy carriers like geothermal, wind and solar energy;
viii. Study and definition of public policies and incentives for highly efficient buildings and districts and the development of guidelines for optimal building design.

Highlight Chapter 6 and considering that the work developed was used to quantify (experimental work) and to optimise (numerical work) the overheating rate reduction using PCM solutions, it is expected to use this study to optimise the solutions costs, aiming not only the energy reduction during the building exploration but also to optimise other important solutions taking into account the investment costs. Therefore, more design solutions (more parameters in the optimiser) should be considered in the case of the new goals to cover these objectives in future research works.

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