Ricardo Manuel Mafra Barbosa
Mestre

Staying Cool: Towards an Integrated Vulnerability Approach to Climate Change in Southern Europe Housing

Dissertação para obtenção do Grau de Doutor em
Alterações Climáticas e Politicas de Desenvolvimento
Sustentável, especialidade Ciências do Ambiente

Orientador: Doutor Rui Jorge Fernandes Ferreira dos Santos, Professor Associado, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa
Co-Orientador: Doutor Romeu da Silva Vicente, Professor Associado, Departamento Engenharia Civil, Universidade de Aveiro

Júri:

Presidente:	Doutor António S. Câmara, Professor Catedrático da Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa
Arguentes:	Doutor Fililpe Duarte Branco da Silva Santos, Professor Catedrático da Faculdade de Ciências, Universidade de Lisboa Doutor Vasco Manuel Araújo Peixoto de Freitas, Professor Catedrático da Faculdade de Engenharia da Universidade do Porto
Vogais:	Doutora Maria Júlia Fonseca de Seixas, Professora Auxiliar com Agregação da Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa Doutor José António Raimundo Mendes da Silva, Professor Associado da Faculdade de Ciências e Tecnologia da Universidade de Coimbra.

FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE NOVA DE LISBOA

Outubro 2016

“If it is true that the buildings and furnishings, which we describe as beautiful evoke of happiness, we might nevertheless ask why we find such evocation to be necessary. It is easy enough to understand why we would want such qualities as dignity and clarity to play a role in our lives, less clear is why we should also need the objects around us to speak to us of them. Why should it matter what our environment has to say to us? (…) Why are we so vulnerable, so inconveniently vulnerable, to what the spaces we inhabit are saying?

We need a home in a psychological sense as much as need one in the physical: to compensate for vulnerability. We need a refugee to shore up our states of mind, because so much of the world is opposed to our allegiances. We need our rooms to align us to desirable versions of ourselves and to keep alive the important, evanescent sides of us.”

Alain de Botton “The Architecture of Happiness”

Declaração dos direitos de cópia

Titulo da Tese: Staying Cool: Towards an Integrated Vulnerability Approach to Climate Change in Southern Europe Housing

O autor desta tese foi apoiado financeiramente por uma bolsa de doutoramento da Fundação para a Ciência e Tecnologia (FCT) (Referência SFRH/BD/ 70395/ 2010).

Declaro que compus esta tese e que nenhuma parte foi submetida noutra Universidade. Todas as fontes de informação foram especificamente referenciadas.

A Faculdade de Ciências e Tecnologia e a Universidade Nova de Lisboa têm o direito, perpétuo e sem limites geográficos, de arquivar e publicar esta dissertação através de exemplares impressos reproduzidos em papel ou de forma digital, ou por qualquer outro meio conhecido ou que venha a ser inventado, e de divulgar através de repositórios científicos e de admitir a sua cópia e distribuição com objetivos educacionais ou de investigação, não comerciais, desde que seja dado crédito ao seu autor e editor.

Ricardo Barbosa

Ricardo Barbosa.

October 3, 2016

Lisboa, Portugal

Acknowledgements

I would like to express my gratitude to my supervisor, Professor Rui Santos, for providing me with the opportunity to write this study and for challenging me to always keep pushing my boundaries and be at the highest standard in my writing.

I am deeply appreciated for the valuable technical and moral support provided also by my co-supervisor Professor Romeu Vicente, in particular in the work related with monitoring and thermal modelling and simulations. His guidance and availability, as well as the motivation that he gave me in every discussion were fundamental for the completion of this thesis.

I would also like to thank the rest of my thesis committee Professor Paula Antunes and Professor Ricardo Aguiar for insightful comments and hard questions, which encouraged me to widen the research to several perspectives. I also thank Professor Ricardo Aguiar for developing and providing the climate change scenarios used in Chapter 5 and for useful advice and support in developing the questionnaire presented in Chapter 4.

I am very grateful to Alice Ramos for her patience and valuable contributions to the statistical analysis. I learned a lot during our lunches and meetings.

I would also like to thank the occupants of the monitored dwellings in Lisbon, who patiently assisted in the research and allowed for the development of fieldwork, as well as Pedro Viterbo, from IPMA, Pedro Garret from CCIAM and Rita Cardoso from Instituto D. Luiz for the help and interesting discussions around downscaling techniques and climate projections.

The completion of this work would not be possible without the friendship and support of my dear friend and cousin Ana Maria Ferreira for always encouraging and inspiring me to keep going. I would also like to deliver a word of gratitude to my friends at CENSE, for listening, for lunches and for valuable discussions. I have made what I think are life-long friendships with colleagues during this journey and I am also thankful for that.

Thanks to all my friends and family for the patience, especially in my absences.

Finally, I have to thank Ana, for her continuous support throughout the years of research and for helping me to keep perspective of what is really important in life. I am very fortunate to be married to such a generous and beautiful soul, who besides being the love of my life and an excellent mother to our (now not so) little Emi, is also an outstanding reviewer.

I would like to dedicate this work to my daughter Emília. I hope that you always stay cool.

Resumo

As alterações climáticas são crescentemente aceites e reconhecidas como uma realidade que exige ação, por académicos, decisores políticos e pela sociedade em geral. Para além de uma subida nas temperaturas médias, os modelos climáticos indicam um aumento na frequência e gravidade de fenómenos extremos, como as ondas de calor. As condições interiores de conforto térmico nos edifícios residenciais existentes podem assim mudar significativamente, decorrentes destes fenómenos, uma vez que estes não foram projetados para tais condições. Estas mudanças poderão comprometer a sua capacidade de moderar as temperaturas exteriores, principalmente em regiões onde estes edifícios ainda são, na sua maioria, naturalmente ventilados, como é o caso do Sul da Europa.

O presente trabalho aborda esta problemática integrando duas interpretações distintas de vulnerabilidade – vulnerabilidade resultante e contextual, com o objetivo de apoiar a decisão no desenho e aplicação de instrumentos de política e no desenvolvimento de intervenções de reabilitação. Com recurso a um caso em Lisboa, Portugal, quatro estudos foram desenvolvidos com base em diferentes metodologias, incluindo a aplicação da modelação térmica dinâmica e a realização de questionários.

Os resultados da modelação dinâmica sugerem que o tipo de construção parece ser determinante na capacidade de adaptação às alterações de temperatura exterior. Conclui-se ainda que é possível anular o efeito do aumento das temperaturas exteriores ou reduzi-lo significativamente de forma custo-eficaz, através da implementação de medidas passivas na envolvente externa dos edifícios.

Algumas características não físicas, relacionadas com o comportamento dos ocupantes dos edifícios, como o período de ocupação e o horário de abertura de janelas, têm também uma importância significativa à escala da habitação, permitindo uma redução de até 91% nas horas de desconforto. Contudo, e apesar de útil, esta interpretação não reflete todas as facetas da vulnerabilidade às altas temperaturas, porque o comportamento simulado não traduz a diversidade de práticas que os ocupantes dos edifícios adotam nem o contexto onde estas ocorrem.

Por essa razão, técnicas estatísticas, como a análise fatorial e análise de variância, foram aplicadas aos dados obtidos resultantes de um questionário a ocupantes de edifícios, e que permitiram caracterizar o comportamento dos ocupantes em dois tipos de práticas adaptativas individuais - pessoais e ambientais. Os resultados sugerem uma variância estatisticamente significativa de fatores sócio-demográficos, pessoais e contextuais em relação à adoção de práticas. Em particular, as características dos edifícios, assim como a idade e o sexo dos ocupantes, parecem ter relevância no comportamento adoptado com vista à obtenção de condições de conforto.

A integração dos resultados relativos às duas interpretações, nomeadamente em termos de relação entre o ocupante e o edifício, fundamentam a defesa de uma perspetiva sócio-técnica de conforto e salientam a importância da consideração de uma visão sistémica da vulnerabilidade para o planeamento de intervenções de reabilitação no edificado e para o desenho de políticas de adaptação, onde se inclui o uso de vários instrumentos combinados e conciliação com outros setores.

Palavras chave: Conforto térmico, Vulnerabilidade, Adaptação, Alterações Climáticas, Reabilitação Energética, Práticas adaptativas, Medidas de Adaptação

Abstract

Climate change is increasingly recognized as a reality that requires action, not only by society in general but also by policy decision-makers and scholars. In addition to the increase in mean temperatures, climate models indicate an increase in frequency and severity of extreme events, such as heatwaves. Therefore, indoor environmental conditions in existing residential buildings can be significantly affected, since these were not initially designed to endure such conditions. These changes may compromise their ability to moderate outdoor temperatures, particularly in regions such as Southern Europe, where most buildings still rely on natural ventilation.

This work aims to approach this topic by integrating two different interpretations of vulnerability – outcome and contextual vulnerability –, with the purpose of providing information to support policy design and decision-making, and also the development of retrofit interventions. Using a case study from Lisbon (Portugal), four studies were developed independently based on different methodologies, including thermal modelling and questionnaires.

Results from thermal simulations suggest that construction type seems to be determinant in defining the building"s ability to moderate high outdoor temperature. Findings also indicate that it is possible to offset or reduce the effect of the increase in temperatures by means of cost-effective passive measures applied to the building envelope. Some non-physical characteristics such as occupancy and window control are also significant, allowing up to a 91% reduction in discomfort hours. Although useful, this view does not reflect all facets of vulnerability to high temperatures, as simulated behavior cannot illustrate the diversity of practices adopted by occupants nor the context where they occur, For this reason, statistical techniques such as factor and variance analysis were applied to data obtained from a survey to buildings" occupants and allowed to characterize occupant behavior in two main types of practices – personal and environmental. Results suggest a statistically significant variance of socio-demographic, personal and contextual factors in relation to the individual adoption of adaptive practices. In particular, building characteristics, age and sex of occupants seem to be relevant in terms of behaviour towards the provision of comfortable conditions.

Integration of results regarding the two interpretations, namely regarding the relation between occupant and the building, support the socio-technical perspective of comfort and highlight the need for a systemic view over high-temperature vulnerability in planning retrofit interventions and designing adaptation policy instruments, including the use of policy mix and integration with other sectors.

Keywords: Thermal Comfort, Vulnerability; Adaptation; Climate Change; Energy Retrofit; Adaptive Practices; Adaptation measures.

TABLE OF CONTENTS

1 CHAPTER 1 - INTRODUCTION 1
  1.1 Relevance of the study 3
  1.2 Outset 4
    1.2.1 The case for comfort in existing residential buildings in Southern Europe 4
    1.2.2 Vulnerability and Social-Technical Systems 5
  1.3 Case study – The city of Lisbon, Portugal 7
  1.4 Thesis scope and research questions 9
  1.5 Structure of the thesis 11
  References 11
2 CHAPTER 2 – RESEARCH CONTEXT AND METHODS 15
  2.1 Framing thermal comfort in a changing climate 17
    2.1.1 The expected change: Heatwaves and Climate Change 17
    2.1.2 Overview on thermal comfort assessment models 22
    2.1.3 Existing buildings and climate change 28
    2.1.4 Adaptation and high temperatures adaptation policy 31
    2.1.5 Integrating vulnerability through a socio-technical background 34
  2.2 Methods 40
    2.2.1 Research Approach 40
    2.2.2 Research Design 40
  References 42
3 CHAPTER 3 – COMFORT AND BUILDINGS: CLIMATE CHANGE VULNERABILITY AND STRATEGIES 49
  3.1 Introduction 52
  3.2 Methodology 53
    3.2.1 A vulnerability framework for thermal comfort 53
    3.2.2 Materials and methods 54
  3.3 Vulnerability factors influencing impacts on thermal comfort in dwellings 55
  3.4 Strategies and interventions for increased adaptive capacity 59
  3.5 Implications for policy and building design 63
  3.6 Conclusions 65
  References 66
4 CHAPTER 4 - CLIMATE CHANGE AND THERMAL COMFORT IN SOUTHERN EUROPE HOUSING: A CASE STUDY FROM LISBON. 71
  4.1 Introduction 73
  4.2 Methodology 76
    4.2.1 Case study 76
    4.2.2 Materials and Methods 78
  4.3 Results 85
    4.3.1 Climate 85
    4.3.2 Monitoring 87
    4.3.3 Calibration 87
    4.3.4 Simulations variants 88
  4.4 Discussion 92
  4.5 Conclusions 93
  References 94
5 CHAPTER 5 - VULNERABILITY AND ADAPTATION MEASURES TO HIGH TEMPERATURES IN A SOUTHERN EUROPEAN CONTEXT - A BOTTOM UP APPROACH FROM LISBON RESIDENTIAL DWELLINGS 99
  5.1 Introduction 102
  5.2 Methodology 105
    5.2.1 Targeted dwellings 105
    5.2.2 Building model and settings 106
  5.3 Results 114
  5.4 Discussion 117
  5.5 Conclusion 120
  References 121

6 CHAPTER 6 - EXPLORING VULNERABILITY FACTORS AND INDIVIDUAL ADAPTIVE PRACTICES TO HIGH TEMPERATURES IN BUILDINGS: INSIGHTS FROM A CASE STUDY IN LISBON 129
  6.1 Introduction 132
  6.2 Individual adaptive practices to achieve comfort as a response to vulnerability 133
    6.2.1 Occupant Behavior for Thermal Comfort – from actions to practices 133
    6.2.2 Factors influencing vulnerability 136
  6.3 Methodology 136
    6.3.1 The study area 136
    6.3.2 Sample 137
    6.3.3 Questionnaire 138
    6.3.4 Data analysis 139
  6.4 Results 139
  6.5 Discussion 142
  6.6 Conclusions 145
  References 146
7 CHAPTER 7 - DISCUSSION 153
  7.1 Integrating two interpretations of vulnerability 155
  7.2 Policy towards climate adapted housing 160
  References 163
8 Chapter 8 – Conclusion 167
  8.1 Possible future research developments 170
9 Appendices 171
  9.1 Appendix 1 - Diary Sheet used for Monitoring Period 173
  9.2 Appendix 2– Comfort Practices and Vulnerability Survey 177

List of Publications

This thesis is based on the work contained in the following papers:

Peer reviewed journal papers:

Barbosa, R., Vicente, R., Santos, R. (2015) "Climate change and thermal comfort in Southern Europe housing: A case study from Lisbon". *Building and Environment* 92, 440-451.

Barbosa, R., Vicente, R., Santos, R. (2016) "Comfort and buildings: climate change vulnerability and strategies"*, International Journal of Climate Change Strategies and Management*, 8:5, 670-688.

Barbosa, R., Vicente, R., Santos, R. (2016) "Vulnerability And Adaptation Measures To High Temperatures In A Southern European Context - A Bottom Up Approach From Lisbon Residential Dwellings", Submitted on July 2016 to Energy and Buildings

Peer reviewed conference papers:

Barbosa, R., Vicente, R., Santos, R. (2014) "Framework for thermal performance assessment of buildings in a changing climate – an illustrative study in Lisbon". *Proceedings of 40th World Congress on Housing - Sustainable Housing Construction*, IAHS, Funchal, Madeira, Portugal.

Barbosa, R., Vicente, R., Santos, R. (2015) "Methodology for thermal performance assessment in a changing climate – a case Study from Lisbon", *Euro-Elecs 2015 - Conferência Latino-americana e Europeia sobre Edificações e Comunidades Sustentáveis*.

Other conference papers:

Barbosa, R., Vicente, R., Santos, R. (2014) "Climate Change and Thermal Comfort", *IV National Congress on Climate Change*, Universidade de Aveiro, Portugal.

List of Figures

Figure 1.1 - Evolution and classification of construction characteristics in Lisbon buildings. Source: Cóias (2006). 8
Figure 2.1- Lisbon 2003 Heatwave temperatures 18
Figure 2.2- Multi-model Average temperature increase in relation to significant SRES scenarios. Source: (IPCC, 2007) 20
Figure 2.3 - Diagram of Fanger analytical model of comfort. Source: (Fanger, 1970) 25
Figure 2.4 – Design values for non-conditioned buildings in the cooling season, as a function of outdoor temperature running mean. Source: CEN (CEN, 2007) 27
Figure 2.5 - Feedback Loop between the adoption of mechanical cooling, energy use and climate change. Source: Adapted from original figure of Fergus Nicol presented in Roaf et al. (2009) 31
Figure 2.6 - Typology of adaptation measures. Source: Funfgeld and McEvoy (2011) 32
Figure 2.7 – Comparison between adaptation and extreme events policy measures. Source: adapted from EEA (2014). 34
Figure 2.8 – Integrated vulnerability framework considering thermal comfort as a socio-technical issue. Adapted from Chappin and van der Lei (2014); O´Brien et al., 2007 and Iwama et al., 2016 38
Figure 2.9 - Multi-level perspective on transitions. Source: Geels and Schot (2007) 39
Figure 3.1 – Vulnerability framework – Source: Allen Consulting Group (2005) 54
Figure 4.1 - Case study building: West Elevation; Section and Floor Plan with temperature sensor positioning 77
Figure 4.2 - Methodology for thermal comfort vulnerability assessment 78
Figure 4.5 – Configuration of simulation variants 83
Figure 4.6 – Design values for STAT and ADPT models of comfort, as a function of outdoor temperature running mean. Source: adapted from CEN (2007) and REH (2013) 85
Figure 4.7 – Summer Design Week and Heatwave Period – Temperature frequency 86
Figure 4.8 - TMY and Climate Change Scenarios - Temperature Frequency 86
Figure 4.9 – Monitoring period – Temperature frequency 87
Figure 4.10 - Calibration results for zone B_LR 88
Figure 4.11- Percentage of Discomfort Hours for S01 simulation for Heatwave Period 89
Figure 4.12 - Percentage of Discomfort Hours for S01 simulation for Climate Change 89
Figure 4.13 - Percentage of Discomfort Hours for S02 and S03 simulation for Heatwave period 89
Figure 4.14 - Percentage of Discomfort Hours for S02 and S03 for Climate Change 89
Figure 4.15 - Comfort criteria comparison 90
Figure 4.16 - Effect of insulation on percentage of discomfort hours – Heatwave period and climate change scenarios 91
Figure 5.1 - Percentage of dwellings regarding building age . Source: INE (2012) 106
Figure 5.2 - Layout of base case dwelling used in this study 108

Figure 5.3 - Air temperature Frequency of Weather and Climate Data considered in this study 111
Figure 5.4 - Configuration of performed simulations 113
Figure 5.5 - Design values for EN15251, as a function of outdoor temperature running mean. Source: adapted from CEN (2007) 114
Figure 5.6 - Results for percentage of discomfort hours by age category and orientation in relation to heatwave period 115
Figure 5.7 - Results regarding variation of values of percentage of discomfort hours for 2030, 2050 and 2080 climate scenarios 116
Figure 5.8 - Relation between decrease in discomfort hours effect and cost of adaptation measure for heatwave period 117
Figure 6.1 - Percentage of Frequency regarding respondents" cooling actions 140

List of Tables

Table 1.1 - Structure of the thesis 11

Table 2.1 - The ten most deadly events in Portugal in the last 100 years (source: EM-DAT: The OFDA/CRED INternational Disaster Database, 2016) 18

Table 2.2- Data available for the three A2 scenario data sets Source: adapted from Jentsch et al. (2013) and IPCC (2010) 20

Table 2.3 - Characteristics of RCP scenarios and SRES equivalent. Source: adapted from Rogelj et al. (2012) 22

Table 2.4- Parameters affecting comfort. Main Sources: (Matias, 2010; McIntyre, 1980; Paciuk, 1990; Baker and Standeven, 1996; Brager and De Dear, 1998; Nikolopoulou and Steemers, 2003) 24

Table 2.5 - Examples of adaptation measures. Adapted from Funfgeld and McEvoy (2011) . 33

Table 3.1 - Synthesis of vulnerability factors and major sources of evidence 60

Table 4.1 - Building and dwelling characteristics. 80

Table 4.2 - Occupancy, shading and ventilation profiles during the monitored period 80

Table 4.3 – Typical internal gains (adapted from Canha da Piedade et al (2009)) 81

Table 4.4 - Cost and effect on discomfort decrease in insulation measures on the thermal comfort in heatwave period 91

Table 5.1 - Location and form parameters for the base case dwelling (source: Climaco, 2012; Bragança et al. 2007) 108

Table 5.2 - Age categorization and constructive characteristics (sources: Santos and Matias , 2006; DOE, 2011; INE, 2011) 109

Table 5.3 - Adaptation measures . (Source for reference values:REH, 2013; Porrit et al., 2012; van Hooff et al., 2014) 112

Table 5.4 - Mean decrease in discomfort hours by measure and age category regarding climate change scenarios 118

Table 6.1 - Vulnerability factors and sources of evidence 137

Table 6.2 - Questionnaire contents 138

Table 6.3 - Principal Component Analysis (varimax rotation) and classification of practices 141

Table 6.4 - Descriptive and variance analysis for Socio Demographic factors 141

Table 6.5 - Descriptive and variance analysis for Personal factors 142

Table 6.6 - Descriptive and variance analysis for Contextual factors 143

1 CHAPTER 1 - INTRODUCTION

INTRODUCTION

1.1 Relevance of the study

Evidence for consequences of climate change is increasingly consistent and alarming, ranging from drastic changes in sea levels to the increase in mean air temperatures in some parts of the globe.

According to the Intergovernmental Panel for Climate Change (IPCC) and depending on the emissions scenario, an increase in global mean surface temperature that ranges from 0.3˚C-0.7˚C to 2.6˚C-4.8˚C can be expected until 2100, in relation to a 1986-2005 baseline (IPCC, 2013). Moreover, in Europe, a higher probability in heatwave occurrences is also projected (Barriopedro et al., 2011) with the possibility of longer duration and increased intensity (Fischer and Schar, 2010; IPCC, 2013). Heatwaves are considered to be life-threatening events. During the so-called 2003 European heatwave – which became a reference for its intensity, duration and spatial extension (IPMA, 2013) –, countries like France, England and Portugal registered an increased number of deaths at home which had been related to abnormal high temperatures inside dwellings (60% in France, 17% in England and Wales and a 40% increase in Portugal) (Kovats and Hajat, 2008).

Cities are at the forefront of this climate challenge, due to their significant energy consumption and accountability for greenhouse gas emissions. In developed nations, it is estimated that about 25%-40% of energy-related anthropogenic emissions of carbon dioxide can be attributed to buildings (Eurostat, 2010). In acknowledgement of this fact, mitigation of further consequences for the climate has been included in both the political and technical European agenda, mainly by promoting energy efficiency of buildings. With an increasing concern for the rational use of energy, in particular by focusing on energy used in heating, legal measures and regulations were adopted in order to establish minimum levels of thermal performance in both new and existing buildings alike.

However, whether due to slowly changing climatic conditions or more frequent, sudden extreme events such as heatwaves, buildings (and their occupants) will most likely have to cope with conditions for which they are not initially designed, and thus, in particular regarding events concerning temperature, their ability to act as “climate moderators” (Roaf et al., 2009), can be compromised. This question is pertinent not only because of the mortality associated with high temperatures inside buildings, but also from the perspective of sustainability. Discomfort is a fundamental factor in mechanical cooling adoption, leading to potentially higher energy consumption by buildings (Stern, 2007). These arguments are even more important when framed in the context of summer fuel poverty (Hills, 2012), which has been reported to occur predominantly in Eastern and Southern European countries (Thomson and Snell, 2013).

1.2 Outset

1.2.1 The case for comfort in existing residential buildings in Southern Europe

In most regions, and particularly the ones with the most established building stocks, existing buildings will still be in use for many decades to come. In fact, it is estimated that about 70% of the dwellings occupied in 2050 have already been built (Boardman et al., 2005), and the vast majority of these buildings were not designed to deal with the range of projected temperatures (Roaf et al, 2009).

Buildings stocks, typically consisting mainly of residential buildings, are strongly marked by regionalisms in terms of materials used, which arise from local availability and traditional techniques. These traditional techniques were later influenced by industrialization and globalization, resulting in the construction techniques used in recent buildings (Climaco, 2012), which makes each building stock unique. This uniqueness, combined with local conditions and projected changes makes climate change impacts very distinctive from region to region.

In addition to being a climatologically vulnerable region (Santos and Miranda, 2006), Southern Europe's building stock has already been characterized as having significant proportions, as well as being stable and aging significantly (Eurostat, 2010). However, most research regarding adaptation in residential buildings is focused in Northern Europe and Australia, while Southern Europe has been receiving less attention in this context. This can easily be translated as a research gap that needs to be addressed, and some specificities can further highlight the interest in improving the knowledge regarding this region. Firstly, most of the Southern Europe has a relatively low adoption of air-conditioning devices and still relies on the so-called traditional techniques for achieving comfortable conditions in the cooling season in dwellings, using energy mainly for heating purposes (Fonseca, 2013). Furthermore, existing residential buildings – which are widely recognized as the greatest challenge for sustainable development (Hamilton et al., 2002) –, are mainly being retrofitted with the objective of promoting energy efficiency. Because of the focus on reducing energy consumption for heating on building codes and standards, these retrofit interventions are likely to increase thermal insulation and air-tightness, which, even in current conditions, have been associated with overheating in some regions (Mulville and Stravoravdis, 2016). Therefore, in such context, if the objective is to understand how buildings would be impacted (and the effect of retrofit interventions in that impact), the question can be identified as being primarily related with thermal discomfort, and not only as an energy consumption issue, as interpreted by other studies.

Thermal comfort is a complex subject. Although modern times have been treating the subject of comfort as an industrialized asset which can be achieved by pressing a button, an adaptive approach to comfort – backed by sustainability concerns - seems to be making its way into the field, mainly due to the recognized potential of behavioral adaptation as a response to outdoor temperatures (Coley et al., 2012). Being so, while the essential role of building, constructive characteristics and technological adaptation in the provision of thermal comfort in the face of climate change is highlighted in literature (e.g. Roaf et al, 2009), there is increasing evidence that the way people behave and react inside buildings is of the utmost importance when dealing with high temperatures, namely at the dwelling scale. However, taking such a perspective of thermal comfort can lead to increased complexity, because behavior regarding the provision of comfort is extremely dynamic and not restricted to window control operation (Nicol and McCartney, 2000), despite being the only parameter usually considered in technical studies.

It can be argued that, when faced with high temperatures, people not only tend to adapt through behavior but also by making incremental adaptive changes in their homes, autonomously. Nonetheless, due to the intensity and extension of the projected changes, some authors argue for a more comprehensive and collective approach to adaptation, namely through implementation of public policy (Williams et al., 2013).

Public policy addresses high temperatures in mainly two distinct ways - one concerns extreme events and the other is related with gradual climate change. They additionally present considerable differences regarding the policy approaches taken. While extreme events are extensively treated within the epidemiological and social tradition, with relevance to personal and behavioral factors of occupants regarding vulnerability, climate change literature is mainly technical and focused on buildings. While taking into account that adaptation to extreme events can serve as a “starting point” for the reduction of vulnerability to climate change (Burton et al., 2004), a view on adaptation through thermal comfort can stress the need to consider a perspective to public policy that considers behavioral and technological adaptation together. It is argued here that it also has the potential to conciliate both existing policy approaches.

1.2.2 Vulnerability and Social-Technical Systems

The two policy approaches addressed in the previous section correspond to different views on vulnerability. Vulnerability or the “propensity to be adversely affected” (IPCC, 2013) is widely treated in both climate change and natural disasters literature and usually defined as the result of sensitivity, exposure and adaptive capacity of a system. Nevertheless, it can be interpreted from different perspectives. O´Brien et al (2007) make a distinction between two approaches: “outcome vulnerability” and “contextual vulnerability”. Outcome vulnerability is the result of the projected impacts of whatever hazard is considered in the analysis (in this case, climate change and extreme events). It is associated with the analysis of the effect of different climate scenarios as well as the technological adaptations necessary to offset these impacts over the “exposure unit” (O´Brien et al., 2007). On the other hand, contextual vulnerability analyses are multidimensional. In this view, hazards are considered to occur in a given context and factors from personal and social dimensions influence the exposure and also the responsiveness to change.

The complex interaction between the occupant and the indoor environment is determinant to thermal performance and to assess projected impacts. However, it also been argued to be important regarding the contextualization of comfort (Roaf et al., 2009) because how occupants behave regarding the provision of comfort is sought to be connected with climate and the building. In fact, existing research suggests physical infrastructure and embedded technology as one of the most important factors influencing occupant behavior (e.g. Maller and Strengers, 2011; White-Newsome et al., 2011). This rationale stresses the importance of the interaction between social and technical dimensions when looking at comfort from a systemic perspective.

Socio-technical systems (STS) are a concept developed by Trist (Trist and Bamforth, 1951), with the purpose of studying behavioral issues in the introduction of new technologies. The work developed was based on the assumption that technology and social agents are "intertwined in a complex web of mutual causality. In the language of E.A. Singer they were co-products of each other" (Trist, 1980), and in this view, the performance of such systems is dependent on these two dimensions.

Several fields soon absorbed and adapted this theoretical perspective in order to address different types of engineering systems with distinctive levels of interacting agents (Ottens et al., 2006). Thermal comfort was no exception and the concept is addressed under a STS perspective in several studies (e.g. (Shove, 2003; Maller and Strengers, 2011). The STS perspective is distinctive because, it considers agency to be distributed throughout the system. This agency is being shared between human and non-human actors, which some authors argue can provide the potential for technological lock-ins in terms of shaping actions towards comfort (e.g. Hinton, 2010). The studies addressing comfort under a STS lens also offer interesting perspectives on how cultural and technological variations influence occupants" comfort practices (Wilhite et al., 1996) and highlight the need to consider the fact that thermal comfort and in particular, indoor thermal expectations, are historically and socially specific and have to be assessed with that in mind (Shove et al., 2008).

These questions are crucial in relation to adaptive capacity and can be influential in term of designing and choosing effective policy instruments (Maller and Strengers, 2011). Therefore when socio-technical dynamics are considered, information from both outcome vulnerability and contextual vulnerability has to be contemplated in order to formulate more effective policies. In this study, the two interpretations of vulnerability are integrated using a STS perspective as a common background. It is argued here that it can potentially trace new ways of designing adaptation practice and policy. In particular, it can make it possible to identify additional adaptation potential, not only by acknowledging different interactions occupants have with buildings and their effects on technological adaptation, but also by taking into consideration the context where the variety of adaptive practices are adopted at the dwelling scale.

1.3 Case study – The city of Lisbon, Portugal

In this study, the two interpretations of vulnerability are explored in the context of existing residential buildings in a Southern European context – the city of Lisbon, Portugal.

With a registered increase in average temperature of 0,5˚C per decade, Southern Europe is considered to be more vulnerable to climate change than Northern Europe (Santos and Miranda, 2006). Exemplary of a southern European city, Lisbon presents a Mediterranean climate with mild winters and hot and dry summers with high levels of solar radiation. The hottest month is August, with an average temperature of 23.5˚C. In terms of climate extremes, the highest registered absolute temperature was 42˚C, during the 2003 heatwave (IPMA, 2013). Additionally, it presents a significant urban heat island effect in the most densely constructed areas with an average intensity of 3°C, which in a projected context of warming temperatures, is expected to also increase (Alcoforado et al., 2009).

In addition, in the last decade, in at least half the years, a heatwave was recorded, occasionally more than once a year, associated with significant damages in terms of loss of human lives and disruption of well being (ARSLVT, 2012). Despite this context, adoption of mechanical cooling instruments in residential buildings are surprisingly low (INE, 2011), indicating that occupants of buildings still rely on adaptive behavior and the so called “traditional techniques” (Fonseca, 2013) in order to alleviate vulnerability.

The region of Lisbon is the most populous in Portugal (INE, 2012) and an important socio-economic center in the country. Lisbon Municipality is home for an estimated 53191 buildings containing almost three hundred thousand dwellings (INE, 2012), 70% of which were built previous to the first thermal regulations in 1990 (INE, 2012), which raises concerns regarding both adequate thermal performance and energy efficiency.

The building stock in Lisbon is in fact a mix of buildings of different ages, originally built from local or nearby materials and later progressively incorporating other materials, regardless of the distance to the construction site. The first buildings are therefore strongly marked by regionalism, whereas the most recent ones enjoy the “universality of industrialization” in terms of both construction techniques and materials (Climaco, 2012).

The most consensual classification of buildings regarding their constructive characteristics was developed with the objective of seismic vulnerability assessment and divides residential buildings in seven main groups (Figure 1.1.)

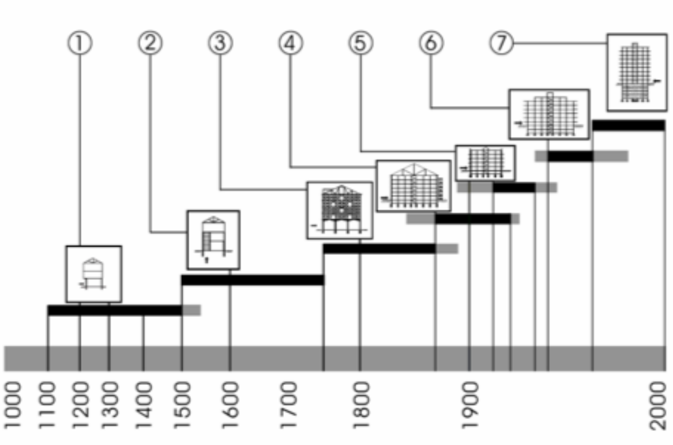


Figure 1.1 - Evolution and classification of construction characteristics in Lisbon buildings. Source: Cóias (2006).

The first group concerns constructions prior to the 1755 earthquake, mainly constituted by masonry structure. This classification defines the second group of buildings as built between 1755 and 1880, commonly designated as “Pombalinos”. These are buildings erected after the earthquake that practically devastated the entire built environment of the city and are constituted by a combination of masonry and wood structure, designed to resist a similar phenomenon. The third group, known as “Gaioleiros”, is formed by buildings built between 1880 and 1930. Buildings in this group are related with the urban expansion of the city in the last quarter of 19th century. Between 1930 and 1940, construction started to transition from wood to concrete and these buildings present mixed structures of these materials. They form the fourth group of the classification. The first phase of concrete construction in the city (and in Portugal) concerns buildings between 1940 and 1960 (fifth group). The sixth group is related with constructions taken place between 1960 and 1985 and considered to be the second phase of concrete, before seismic regulation. Structures built after 1985, with reinforced or pre-stress concrete post-regulation are included in the seventh and last group. Even if this classification is not indented to characterize thermal performance of buildings, it is useful to understand constructive differences, which influence significantly thermal performance (Mavrogianni et al., 2012).

In Lisbon building stock there is a clear predominance of buildings from 60s and 70s decades of the 20th century. There is a historic reason for the fact that buildings from this age can be found in a considerable number. A massive migratory flux from rural areas was registered in Portugal and greatly felt in Lisbon in the 60s. In search of better living conditions, the rural population moved not only to other countries but also to the major cities, where opportunities for work were abundant (Barata Salgueiro, 1992). Their need for housing caused a major development of new construction in these cities, some of it illegal and, especially, unplanned (Consiglieri et al., 1993). As a result, about 23% of the present building stock still stems from that period. Even more significantly, 60s and 70s typology represents 32% of the existing dwellings in the city area (INE, 2012).

Besides being predominant, these buildings are also the ones presenting the most significant rehabilitation needs (INE, 2012). In fact, the 50s decade is considered by several authors to mark the transition from structural masonry to steel reinforced beams and pillars (Almeida et al., 2004). This era also represents the start of a gradual distancing from vernacular architecture features. However, with insufficient technical knowledge about new construction techniques and no adequate regulation – the first Portuguese thermal regulation only took place in 1990 (DL. 40/90 of February 6th) –, buildings from the following two decades were generally built with deficiencies, both from the structural and thermal perspectives, In fact, despite the fact that modern techniques represented an improvement in building skin thermal transmittance, problems from the thermal as well as structural point of view are known to be present (Santos and Matias, 2006).

Considering their significant share and their low state of conservation, the 60s and 70s buildings – which take on a significant role in the first part of this study – will be relevant in the overwhelming task of retrofitting the city as well as the country. Nevertheless, technical interventions should be contextualized and adaptation policies should be designed taking into consideration the actual behavior of building occupants in relation to high temperatures. While some technical-driven studies can be found in Northern Europe contexts, interventions focusing on Southern European building stocks are fairly ignored in both scientific literature and adaptation policy regarding adaptation to high temperatures. Furthermore, due to the predominance of naturally ventilated buildings there is the need to better understand the actions dwellings occupants take in order to moderate vulnerability to high temperatures, namely regarding extreme events, and use that knowledge to inform adaptation policy.

1.4 Thesis scope and research questions

The study investigates vulnerability at the dwelling scale in Lisbon, integrating outcome and contextual approaches using a socio-technical background. The objective of the study is to use insights to support recommendations for retrofit interventions and adaptation policy regarding high temperatures. Being so, one main aim is to assess vulnerability of the most common dwellings in Lisbon residential stock, as well as the effect of technological adaptation, taking human behavior into consideration – i.e. the effect of different occupancy typologies and window-opening schedules. The other goals are to explore the relation between contextual factors influencing vulnerability and the comfort practices used in response to change and improving knowledge about the actual individual adaptive practices.

To address these broader goals, the thesis is divided into four independent chapters, followed by a discussion reporting the main findings and a concluding chapter. Five main research questions are identified:

1. What are the main relevant factors influencing vulnerability and adaptive capacity in Lisbon buildings in relation to thermal comfort?
2. What is the effect of different occupancies and behavior in vulnerability assessment of residential building of Lisbon?

3. What is the effect of technological passive adaptations on residential buildings in Lisbon?
4. What – and how significant – are the differences regarding practices of comfort in relation to factors influencing vulnerability?
5. How can the study of occupant behavior, infrastructures and the relation between the two improve retrofit interventions and adaptation policy in southern European housing?

The research questions are approached using Lisbon as a case study. Case studies are useful in order to address research, which are dependent on the context (Yin, 2009). There is a long history in using case studies in climate change research and it is considered adequate to develop place-based vulnerability research that focus on a particular exposure unit (Ford et al., 2010).

The study includes methodologies from different research areas in order to combine interdisciplinary results about vulnerability and adaptation in a Southern Europe housing context (see Table 1.1).

The methodologies used are explained in detail in the appropriate chapters. The thesis is structured in a paper style format and suitable for publication. Being so, each of the chapters presenting empirical work here has its own independent structure – Introduction, Methodology, Results, Discussion, Conclusions and References – with the exception of Chapter 1, Chapter 2, Chapter 7 and Chapter 8. As a result of this structure, some repetition is also likely to occur.

Hopefully, this work will contribute to an improved understanding of vulnerability by bringing together two distinctive interpretations to a common background. Departing from the central role of the building in a socio-technical perspective on thermal comfort, and using the dwelling as the exposure unit, this thesis makes a conciliatory approach between two different views on vulnerability. Lessons learned from the case study will allow to expand knowledge about the challenges of integrating different but complementary perspectives on vulnerability and on the ways it can be promoted and reproduced to other similar contexts. It can also provide insights on diversity of forms in which adaptive capacity can be manifested and the significance of contextual conditions. From the theoretical perspective, results from this study can assist in discussing socio-technical transitions to a more resilient and sustainable built environment and cities in general. It can also contribute to a better understanding of the dependence on technological pathways and potential lock-ins of this approach in terms of adaptation to climate change.

From the practical point of view, this study aims at investigating vulnerability and adaptation to high temperatures in a Southern European urban context with the main objective of informing and clarifying policy formulation and choice of instruments regarding heat management and adaptation policies, as well as providing insights and informing construction practice regarding effective technological interventions in existing residential buildings.

1.5 Structure of the thesis

The study is divided into three parts. The first part contains the outset of the research, the background on which it can be contextualized, as well as the questions guiding the research (Chapter 1). Chapter 2 details the context of the research. This chapter also presents the approach taken in the study and research design. In the second part of the study (Chapters 3 -6), results of empirical work with residential dwellings in Lisbon are presented in the form of four research papers. In the third part, Chapter 7 discusses results of the research papers in terms of integration of the main findings and theoretical and practical contributions of the empirical work. The concluding chapter reviews the findings and reflects on further developments of the research.

Table 1.1 - Structure of the thesis

Part of the study	**Objective**	**Methods**	**Results**
Paper I – Chapter 3	What are the most important factors influencing vulnerability in buildings?	Literature review	Extraction of main factors influencing vulnerability of thermal comfort in interdisciplinary literature.
Paper II – Chapter 4	What is the influence of behavior in assessing vulnerability? Analyses of retrofit interventions impact on future performance.	Case study/ Monitoring/ Thermal dynamical simulation	Development of a vulnerability assessment methodology. Evidence on the importance of different types of occupant behavior in vulnerability assessment.
Paper III – Chapter 5	Can technological adaptation alone moderate vulnerability in residential buildings? A view on outcome vulnerability.	Thermal dynamical simulation	Identification of the most effective adaptation measures considering the existing dwellings in Lisbon building stock.
Paper IV – Chapter 6	Is there a difference in comfort practices in relation to known vulnerability factors? Analysis of the factors presented in Paper I in contextual vulnerability.	Case study/ Questionnaire	Identification of key comfort practices in relation to Socio Demographics, Personal and Contextual factors of vulnerability.
Discussion – Chapter 7	What are the implications for practice and policy of such an approach?	Reflection on findings in Paper I-IV	Deeper discussion of theoretical and practical relevance of the study

References

Alcoforado, M.J., Andrade, H., Lopes, A. and Vasconcelos, J. (2009) “Application of climatic guidelines to urban planning: The example of Lisbon (Portugal)”, *Landscape and Urban Planning*, vol. 90, no. 1-2, pp. 56-65.

ARSLVT (2012) “Alterações Climáticas e Saúde Humana - Gestão do Risco para a Saúde da População da Região de Lisboa e Vale do Tejo”, Lisboa: Administração Regional de Saude de Lisboa e Vale do Tejo.

Barata Salgueiro, T. (1992) *A cidade em Portugal. Uma Geografia Urbana*, Edições Afrontamento.

Barriopedro, D., Fischer, E., Luterbacher, J., Trigo, R.M. and Garcia-Herrera, R. (2011) “The hot summer of 2010: Redrawing the temperature record map of Europe”, *Science,* vol. 332 (6026), pp. 220-224.

Boardman, B., Darby, S., Killip, G., Hinnells, M., Jardine, C.N., Palmer, J. and Sinden, G. (2005) *40% House*, Environmental Change Institute, University of Oxford.

Burton, I., Malone, E. and Huq, S. (2004) *Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures*, Cambridge University Press.

Climaco, N. (2012) *Energy Efficient retrofit of Residential Buildings*, Lisboa: Universidade Técnica de Lisboa - Instituto Superior Técnico.

Coley, D., Kershaw, T. and Eames, M. (2012) “A comparison of structural and behavioural adaptations to future proofing buildings against higher temperatures”, *Building and Environment,* vol. 55, pp. 159-166, Available: doi:10.1016/j.buildenv.2011.12.011.

Consiglieri, C., Ribeiro, F., Vargas, J. and Abel, M. (1993) *Pelas freguesias de Lisboa. O termo de Lisboa*, CML.

Eurostat (2010) “EU Energy in Figures 2010 – Greenhouse Gas Emissions by Sector”, Luxembourg: Office for Official Publications of the European Communities.

Fischer, E.M. and Schar, C. (2010) “Consistent geographical patterns of changes in high-impact European heatwaves”, *Nature Geoscience*, no. 3(6), pp. 398–403.

Fonseca, S. (2013) *Agência e estrutura nas práticas sociais de uso eficiente da energia* – a construção social da eficiência energética no sector doméstico, Lisboa: Phd Dissertation-ISCTE-IUL.

Ford, J., Keskitalo, E., Smith, T., Pearce, T., Berrang-Ford, L., Duerden, F. and Smit, B. (2010) “Case study and analogue methodologies in climate change vulnerability research”, *Wiley Interdisciplinary Reviews: Climate Change*, vol. 1, pp. 374-392, Available: DOI : 10.1002/wcc.48.

Hamilton, A., Mitchell, G. and Yli-Karjanmaa, S. (2002) “The BEQUEST toolkit: a decision support system for urban sustainability”, *Building Research & Information*, vol. 30, no. 2, pp. 109-115.

Hills, G. (2012) “Getting the measure of fuel poverty”. Final Report of the fuel poverty review.

Hinton, E. (2010) *Review of the literature relating to comfort practices and socio-technical systems* - Environment, Politics and Development Working Paper Series, [Online], Available: http://www.kcl.ac.uk/schools/sspp/geography/research/epd/working.html [2014].

INE (2011) *Estatísticas da Construção e Habitação 2010*, Lisbon: Instituto Nacional de Estatistica.

INE (2012) *Anuário Estatístico da Região de Lisboa 2011*, Lisbon: Instituto Nacional de Estatistica.

INE (2012) *Censos 2011 Resultados Definitivos - Portugal*, Lisbon: Instituto Nacional de Estatistica.

IPCC (2013) “Summary for Policymakers”, in Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (ed.) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPMA (2013) *Instituto Portugues do Mar e Atmosfera* , [Online], Available: www.ipma.pt [February 2013].

Kovats, R. and Hajat, S. (2008) “Heat Stress and Public Health: A Critical Review”, *Annual Review of Public Health*, no. 29, pp. 41-55.

Maller, C.J. and Strengers, Y. (2011) “Housing, heat stress and health in a changing climate: promoting the adaptive capacity of vulnerable households, a suggested way forward”, *Health Promotion International* , vol. 26, no. 4.

Mavrogianni, A., Wilkinson, P., Davies, M., Biddulph, P. and Oikonomou, E. (2012) “Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings”, *Building and Environment*, no. 55, pp. 117–130, Available: doi:10.1016/j.buildenv.2011.12.003.

Mulville, M. and Stravoravdis, S. (2016) “The impact of regulations on overheating risk in dwellings”, *Building Research and Information*, March, Available: The impact of regulations on overheating risk in dwellings.

Nicol, F. and McCartney, K. (2000) *Smart Controls ad Thermal Comfort (SCATs) Project*. Final Report., Joule III Project (Contract JO3-CT97-0066).

O´Brien, K., Eriksen, S., Nygaard, L. and Schjolden, A. (2007) “Why different interpretations of vulnerability matter in climate change discourses “, *Climate Policy*, vol. 7, pp. 73-88.

Ottens, M., Franssen, M., Kroes , P. and Van De Poel , L. (2006) “Modelling infrastructures as socio-technical systems “, *International Journal of Critical Infrastructures* , vol. 2, no. 2, pp. 133-145.

Roaf, S., Crichton, D. and Nicol, F. (ed.) (2009*) Adapting Buildings and Cities for Climate Change*, Architectural Press.

Santos, C. and Matias, L. (2006) *Coeficientes de Transmissão Térmica de elementos da envolvente dos edifícios*, Lisboa: Laboratório Nacional de Engenharia Civil.

Santos, F.D. and Miranda, P. (ed.) (2006) *Alterações Climáticas em Portugal. Cenários, Impactos e Medidas de Adaptação— Projecto SIAM II*, Lisboa: Gradiva.

Shove, E. (2003) *Comfort, Cleanliness and Convenience: The social organisation of normality*, Oxford: Berg.

Shove, E., Chappells, H., Lutzenhiser, L. and Hackett, B. (2008) “Comfort in a lower carbon society “, *Building Research & Information* , vol. 36, no. 4, pp. 307-311.

Stern, N. (2007) *The Economics of Climate Change: The Stern Review*, Cambridge University Press.

Thomson, H. and Snell, C. (2013) “Quantifying the prevalence of fuel poverty across the European Union”, *Energy Policy*, vol. 52, pp. 563-572.

Trist, E. (1980) “The evolution of socio-technical systems”, Conference on organizational design and performance, Pennsylvania, US..

Trist, E.L. and Bamforth, K.W. (1951) “Some social and psychological consequences of the longwall method of coal-getting: an examination of the psychological situation and defences of a work group in relation to the social structure and techno- logical content of the work system. “, *Human Relations* , vol. 4, no. 1, pp. 3-38, Available: http:// dx.doi.org/10.1177/0 0187267510 040 0101..

White-Newsome, J.L., Sanchéz, B.N., Parker, E., Dvonch, T., Zhang, Z. and O´Neill, O. (2011) “Assessing heat-adaptive behaviors among older, urban-dwelling adults”, *Maturitas*, vol. 70, no. 1, pp. 85–91, Available: doi:10.1016/j.maturitas.2011.06.015.

Wilhite, H., Nagakami, H., Masuda, T., Yamaga, Y. and Haneda, H. (1996) “A cross cultural analysis of household energy use behaviour in Japan and Norway”, *Energy Policy*, vol. 24, no. 9, pp. 795-803.

Williams, K., Gupta, R., Hopkins, D., Gregg, M., Payne, C., Joynt, J. and Bates-Brkljac, N. (2013) “Retrofitting England’s suburbs to adapt to climate change”, *Building Research & Information*, no. 41(5), pp. 517-531, Available: doi:10.1080/09613218.2013.808893.

Yin, R. (2009*) Case Study Research*, Sage Publication.

2 CHAPTER 2 – RESEARCH CONTEXT AND METHODS

RESEARCH CONTEXT

2.1 Framing thermal comfort in a changing climate

2.1.1 The expected change: Heatwaves and Climate Change

Heatwaves and the gradual increase in temperatures concerning climate change are generally treated in distinctive research fields. However, in climate change studies and due to a recognized urgency in dealing with the issue of temperature increase and its impacts, the study of the two phenomena are gradually connecting to a common ground. Some authors argue that adaptation to extreme events can serve as a "starting point" for vulnerability reduction to gradual climate change (Burton et al., 2004). This is not unrelated with the fact that, even from a technical perspective, there is some recognition that certain episodes of high temperatures which already took place, such as the 2003 summer heatwave, closely resemble the projections of regional climate models until the end of the century (Beniston, 2004).

While there is no accepted universal definition, the World Meteorological Organization suggests that a heatwave consists of more than five consecutive days where the maximum temperature exceeds the average historical maximum temperature by 5 °C (Frich et al., 2002). Europe has been experiencing devastating heatwaves recently. The extent and severity of 2003 and 2010 heatwaves, which broke the seasonal records held for 500 years in most of Europe´s territory, are even referred to as "mega-heatwaves" (Barriopedro et al., 2011). Models project that the probability of occurrence of these "mega heatwave" events will increase by a factor of 5 to 10 within the next 40 years (Barriopedro et al., 2011), which is worrying considering mortality figures of the 2003 heatwave. Over 30000 deaths can be attributed to the European summer heatwave of 2003 (WHO, 2004). While France suffered the most damaging losses in terms of human lives (with an estimated 15000 deaths), other countries like Germany, Holland, United Kingdom, Spain, Italy and Portugal also reported significant losses (WHO, 2004; Grynszpan, 2004). In Portugal, in particular, the impact was estimated on more than 50% increase in mortality (Trigo et al., 2009).

Southern Europe and in particular Mediterranean climates seem to be especially vulnerable to this kind of phenomena. Considered to be recurrent, heatwaves in Mediterranean climates are conditioned essentially by the synoptic regional conditions (Cunha, 2012). The phenomena can be further exacerbated or moderated by specific regional or local factors such as the geographical characteristics and the use of soil (Lopes, 1998), as is the case of urban areas, where impacts seem to be augmented (Alcoforado et al., 2009).

Heatwaves are complex events with serious consequences in terms of high temperature ranges and increasing air pollutants, but maximum temperatures seem to be the main cause for mortality (Trigo et al., 2005).

In Portugal, heatwaves have been reported as one the most consequential "natural" disaster, with the 2003 summer heatwave being the event that caused more deaths (Table 2.1).

The arguments stated above make it imperative to analyze a heatwave period in the context of this study. Being so, real weather data from a heatwave period (July 29th to August 15th 2003) was collected from recordings made at Gago Coutinho meteorological station (IPMA, 2013). Data was subsequently processed and in the case of missing data necessary for model simulation, interpolated typical weather data from IPMA (2013) for the same year period was assessed.

Table 2.1 - The ten most deadly events in Portugal in the last 100 years (source: EM-DAT: The OFDA/CRED INternational Disaster Database, 2016)

Event	Date	Number of Deaths
Heatwave	Aug 2003	2696
Flooding	Nov 1967	462
Flooding	Feb 2010	43
Heatwave	Jul 2006	41
Flooding	Dec 1981	30
Storm	Oct 1997	29
Flooding	Jan 1979	19
Flooding	Nov 1983	19
Forest Fire	Jun 1986	15
Forest Fire	May 2005	15

Figure 2.1 shows the profile of air temperature for the heatwave period considered here in terms of frequency of temperatures.

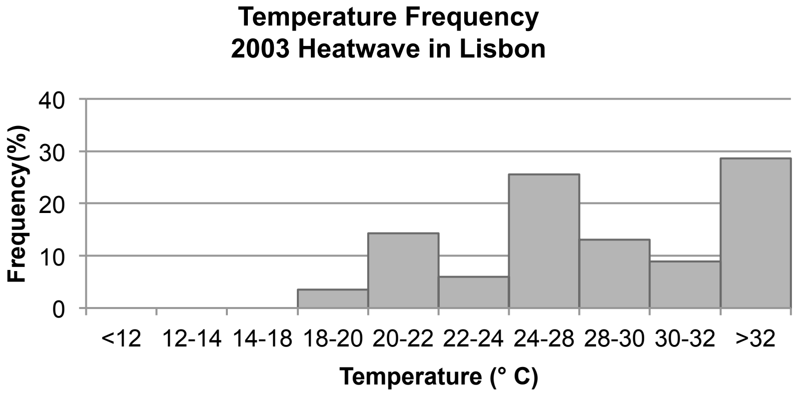


Figure 2.1- Lisbon 2003 Heatwave temperatures

Despite being useful to understand vulnerability, data regarding extreme events is not sufficient to prepare existing building stocks to high temperatures. Increasingly, and in all sectors, the world is trying to understand what the impacts of climate change are throughout the whole year or at least during the cooling season. In the case of infrastructure and buildings in particular, which are designed taking into account historical normalized data (namely in the form of Typical Meteorological Years (TMY[1]), knowledge is of particular interest and can only be obtained through building simulation using modified climate files. Being so, there is a considerable effort to obtain useful and adequate scaled projections to be used with this purpose.

Global changes in climate are assessed through the use of General Circulation Models (GCM) that cover worldwide location but with a wide coarse grid (IPCC, 2014). The information obtained from GCM can be further detailed in Regional Climate Models, which typically provide the spatial and temporal resolution that is appropriate for building simulation (Jentsch et al., 2008). However, this kind of models is not readily available for every location in the world. Trustful and viable downscaling methods are generally required in order to represent 50 km or less grid scales. Hacker et al. (2009) make an extensive review of the existing downscaling methodologies used to develop hourly weather data from climate projections. In this study, two types of downscaling methodologies are used in order to generate hourly weather data for dynamical thermal simulation.

The majority of the work in the field of climate change adapted weather data was centered in the United Kingdom[2]. Noteworthy are the reports addressing the subject by Chartered Institution of Building Services Engineers (CIBSE) (Hacker et al., 2009), as well as, the UK Climate Impacts Programme (UKCIP) (UKCIP, 2011), that have been delivering consistently updated and innovative climate change scenarios up until the latest probabilistic approach. As a result of early modeling from UKCIP, Belcher et al. (2005) developed a methodology to combine “present day” data (i.e. TMY) with hourly time steps and monthly projections of climate change into future hourly weather data. It adds the predicted absolute changes to the original weather data (a process designated as shift calculation), multiplies it by the predicted fractional change (stretch calculation) or combines the two approaches. The attractiveness of the method resides in the fact that the downscaling calculations are done using as basis-measured data of a determined station to deliver Typical Meteorological Year 2 (TMY2) and EnergyPlus/ESP-r (EPW) formats. Furthermore, it requires low computation power (Jentsch et al., 2008). The method is commonly designated as “morphing” and further evolved to be used in other locations outside the UK, through the development of a tool designated as “CCWeatherGen tool” (Jentsch et al., 2013).

Following its fourth assessment, IPCC released a set of “emissions scenarios” that were used to drive models (Nakicenovic and Swart, 2000). These scenarios became known as SRES scenarios (Special Report Emissions Scenarios) and are based on future developments including technological, economic, social and demographic factors.

---

[1] Typical Meteorological Years basically compiles data of 30 years of real weather data in order to represent long term weather patterns (IPMA, 2013).

[2] For detailed information on work developed in UK on on climate adapted files, Mylona (2012) provides an embracing review.

[3] Radiative forcing is, according to Word Meteorological Organization, “the change in balance between

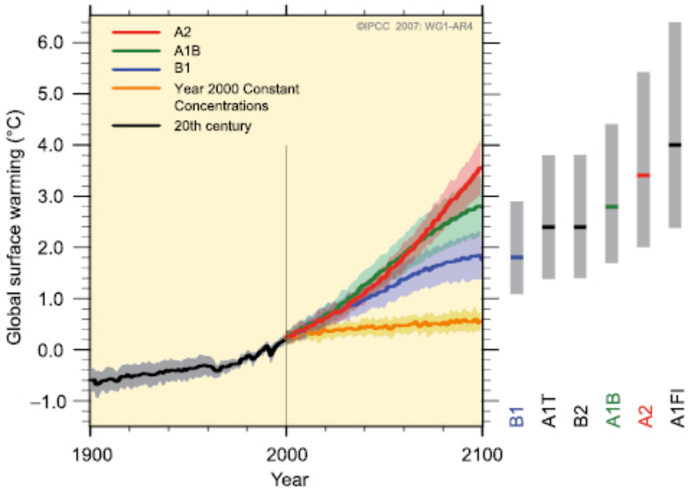


Figure 2.2- Multi-model Average temperature increase in relation to significant SRES scenarios. Source: (IPCC, 2007)

Each scenario family - A1, A2, B1 and B2 – corresponds to an expected increase in global average temperatures in relation to the 1990 baseline that can range from 1.1-2.9 °C to 2.4-6.4 °C, depending on the emissions scenario (IPCC, 2007), as demonstrated in Figure 2.2. The "CCWeatherGen tool" so far, can only use SRES scenarios. Therefore, in order to take into account climate change effects on weather files, Hadley Centre Coupled Model, version 3 (HadCM3) summary data was used. In particular, for the simulations presented in this study using this methodology and following Jentsch (2013), the HadCM3 A2 model output was considered to be suitable to develop the work in this research for the following reasons:

1. The HadCM3 A2 results are the only ones containing all the necessary data for morphing calculations, which is possible by combining outputs of the 3 data sets. (see Table 2.2)

Table 2.2- Data available for the three A2 scenario data sets Source: adapted from Jentsch et al. (2013) and IPCC (2010)

Climate parameter	**HadCM3 experiment**		
	A2a	A2b	A2c
Total downward shortwave flux	x	x	x
Total cloud in long wave radiation		x	x
Precipitation rate	x	x	x
Mean temperature	x	x	x
Daily minimum temperature	x	x (2020 and 2080 only)	x
Daily maximum temperature	x	x (2020 and 2080 only)	x
Relative humidity	x	x	x
Mean sea level pressure	x		
Wind speed	x	x	x

2. Because A2 represents a business as usual scenario, and can be considered a valuable and likely development path with significance for the built environment.

Although useful, in particular for locations where other downscaling methodologies are not easily available, some limitations are recognized to this methodology, which have been previously discussed by Belcher et al. (2005) and also in Jentsch et al. (2013). The most relevant appear to be related with uncertainties (in relation to the representativeness of GCM data or of the TMY data in relation to the specificities of location) and the apparent linearity of the application of a simple shift or scaling calculation. However, the widespread use of the methodology in several studies and in particular its uptake by an experienced and credible institution such as CIBSE, as also argued by Jentsch et al. (2013), is reason for a fair degree of confidence. Furthermore, a study by Eames et al. (2011) also compared data resulting from this methodology to another originated from a statistical tool and concluded that results are generally consistent in the two approaches.

IPCC has lately released its fifth assessment report (AR5), where a new concept of scenarios pathways – designated Representative Concentration Pathways (RCP) - is introduced (IPCC, 2014). While the new scenarios represent a clear divergence from SRES scenarios and in particular from the use of socioeconomic narratives - RCP are projections of the components of radiative forcing[3] – some similarities are recognized (Rogelj et al., 2012). Table 2.3 shows the radiative forcing considered in each scenario, as well as the median temperature anomaly (over pre-industrial levels) and SRES equivalent.

It was possible, in a latest stage of the research, to consider RCP scenarios in building simulation. Two scenarios originating from the 5th Assessment Report from IPCC (IPCC, 2014) - Representative Concentration Pathways (RCP) - were considered here. RCP 4.5 corresponds to a pathway in which the increase in greenhouse gas emissions is controlled and therefore corresponds to the least burdensome scenario. On the other hand, RCP 8.5 represents a significant increase in emissions during the 21st century (Meinshausen et al., 2011).

In order to generate the two climate change scenarios for Lisbon, a “weather generator” using historical data from 1971-2000 (IPMA, 2013) and Coupled Model Intercomparison Project Phase 5 (CMIP5) (CMIP5, 2012) information was prepared by means of the analysis of anomalies found through the difference between historical and CMIP5 data. Besides air temperature, climate data considers solar radiation, relative humidity and wind, even if no anomaly is calculated for wind. The same methodology was used to inform Building Energy Certification Scheme in Portugal regarding climate change data. More information can be found in Aguiar (2013).

---

[3] Radiative forcing is, according to Word Meteorological Organization, “the change in balance between incoming and outgoing radiation to the atmosphere caused primarily by changes in atmospheric composition” (WMO, 2015)

Table 2.3 - Characteristics of RCP scenarios and SRES equivalent. Source: adapted from Rogelj et al. (2012)

Scenario	**Radiative forcing**	**CO^2 equiv (ppm)**	**Temperature anomaly (°C)**	**Pathway**	**SRES Temperature anomaly equiv**
RCP8.5	8.5Wm^2 in 2100	1370	4.9	Rising	A1F1
RCP6.0	6 Wm^2 post 2100	850	3.0	Stabilization without overshoot	B2
RCP4.5	4.5 Wm^2 post 2100	650	2.4	Stabilization without overshoot	B1
RCP2.6	3Wm^2 before 2100, declining to 2.6 Wm^2 by 2100	490	1.5	Peak and decline	None

2.1.2 Overview on thermal comfort assessment models

It is not possible or desired to explain in a comprehensive manner, the complexity involved in understanding and assessing thermal comfort. However, it is necessary to address the most important issues in order to provide a framework for the analysis that follows.

The search for shelter and comfortable environments in the face of adverse climate has been a constant in human history. Already in century 1 BC, Vitruvius included the need to consider the climate in the design of the building for health and comfort reasons in the first ever known complete architecture treaty. From industrialization to present time, a greater emphasis on achieving the ideal indoor conditions of thermal comfort has been pursued. Matias (2010) sees it as a consequence of the "demanding evolutionary tendency of mankind".

Thermal comfort in buildings has been a subject of research since the start of the twentieth century, mainly motivated by innovation in building construction and the advent of acclimatization systems, with the objective of improving indoor conditions (Edholm, 1978).

Its complexity comes primarily from the dependence of multiple factors – physical, physiological and psychological. Fanger (1970) defined it as "the state of mind expressing satisfaction with the thermal environment". The definition presupposes immediately that it is not only a physiological state (even if Fanger´s own work tends to focus mainly on the physiological factors), but it is also influenced by individual preferences, particular cultural aspects and both social and organizational factors (Matias, 2010; Nicol and Stevenson, 2013; Shove et al., 2008).

If is true that certain physiological conditions must be observed, namely those related with the balance of the thermo-regulation system of human body with the surrounding environment, this balance was also found to be variable, depending on local climate and individual adaptation capacity (Nicol and McCartney, 2000). However, it may be important to understand the physiological mechanisms through which the human body interacts with the environment, at least as the starting point to understanding thermal comfort. The human body produces energy through synthesizing food according to the so-called metabolism rate (M). This rate depends on the individual organism, on activities performed and on the conditions where these activities are performed. The metabolism can be determined according to equation 1 (Fanger, 1970).

$$M=H+W \; [W/m^2] \qquad \text{(Eq.1)}$$

From the energy produced, just a small fraction is used to work (W), the rest being dissipated in the form of heat (H) (Fanger, 1970). The way as an individual “feels” the thermal environment is mainly the result of the conditions in which the heat exchanges between the body and the environment are made. These exchanges can be made in several ways: convection, radiation, conduction or evaporation, the latter being the only that does not depend of thermal gradient direction, occurring whenever there is a heat loss in the human body. While thermal balance does not mean the same as thermal comfort, it is related to a significant concept in terms of assessing comfort, designated as “thermal neutrality” in which an individual reports feeling neither cold nor hot.

This physiological process of maintaining balance between the body and the environment is the one designated by thermo-regulation, and considers that for comfort and well being, the internal body temperature has to be around 37˚C ±0,8˚C (ASHRAE 55, 2004). The process of thermo-regulation triggers a series of physical reactions (like sweating) with the purpose of restoring balance when exposed to stress. Those reactions can be complemented with voluntary actions i) affecting the individual: like changes in clothing and change in activity levels or ii) affecting environmental conditions, if possible: by opening windows or turning on mechanical cooling devices.

It has already been mentioned that there are several parameters that can influence the perception of thermal comfort. Matias (2010) divided them into two major groups: Physical parameters and Subjective parameters. Table 2.4 attempts to synthesize the main variables affecting these parameters according several authors.

If the physical parameters are relatively straightforward when assessing comfort, the need to consider subjective parameters makes comfort assessment significantly complex. There are two main approaches regarding thermal comfort assessment in buildings: the analytical models, where research based on the results of experiments in climate chambers focuses on the physical parameters, and the adaptive models that allow for the consideration of the real context in existing variability in (free-running) buildings. These last models are based in field studies and consider subjective parameters as well.

Table 2.4- Parameters affecting comfort. Main Sources: (Matias, 2010; McIntyre, 1980; Paciuk, 1990; Baker and Standeven, 1996; Brager and De Dear, 1998; Nikolopoulou and Steemers, 2003)

Physical parameters	Environmental	Air temperature Average radiant Temperature Air Humidity Air velocity
	Individual	Activity Clothing
Subjective parameters	Individual Perception of Comfort* Individual Sensorial stimulus response	*Perception depending on: Acclimatization Expectations Past experience Exposure time

The analytical model

In the work developed by Fanger (1970), the focus is clearly physiological and comfort is calculated by the physical heat transfer, where the individual is considered only as a recipient of the thermal stimulus (Kwok and Rajkovich, 2010).

According to Fanger, three main conditions have to be verified in order to obtain thermal comfort (McIntyre, 1980):

1. The human body has to be in thermal balance, in a way that the loss of heat is equal to the production of heat, which implies a stationary environment;
2. The superficial skin temperature is paramount to the thermal sensation and therefore its value has to be appropriate for a comfort situation;
3. There is a preferred rate of perspiration associated with the metabolism.

With these principles in mind, Fanger (1970) pursued relationships between skin temperature, desired perspiration and metabolic activity, which were combined with the heat balance equation. The result is a complex equation with four environmental variables and two individual variables (the physical parameters in Table 2.4). In a clear breakthrough for its time, combinations of the parameters that can be classified as being comfort conditions were obtained. Figure 2.3 shows an example of one diagram of the combinations.

By relating these conditions with thermal chamber experiments, Fanger was able to establish a Predicted Mean Vote (PMV), which allows to estimate the mean value of the vote in a thermal sensation scale of an extensive number of people in established combinations of variables.

Despite some criticism over this approach – mainly due to the disconnection between type of buildings, the climate where buildings are located and the specificities of occupants (De Dear et al., 1997) –, the analytical model was adopted by several international standards (e.g. (ASHRAE 55, 2004)).

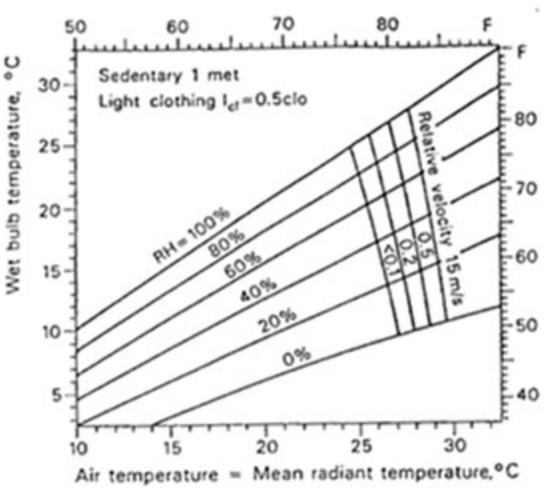


Figure 2.3 - Diagram of Fanger analytical model of comfort. Source: (Fanger, 1970)

Importantly for this study, it also forms the basis for the establishment of reference conditions for a significant number of thermal regulations in Europe for air-conditioned and naturally ventilated buildings. Spain and Finland, for example, have a single value specified for the reference temperature of comfort – 20˚C and 21˚C respectively (DB-HE, 2007; National Building Code of Finland, 2002). The approach taken by Portugal, by adopting a range of acceptable values for reference temperatures (18˚C to 25˚C) in which a building is considered to be comfortable (REH, 2013) is more common regarding regulations and building codes throughout Europe.

The adaptive model

The adaptive model, unlike the thermal balance approach, takes into consideration the fact that people have a response to change and are willing to act in order to restore thermal comfort conditions, extending their comfort zone beyond the one considered in the analytical model. In this sense, the adaptive model is physical, but also behavioral (Nicol and Stevenson, 2013). It builds on the adaptive principle drawn by Nicol et al. (2012):

“If a change occurs such as to produce discomfort, people react in ways, which tend to restore their comfort.”

The idea of relating outdoor climate with comfort temperatures goes as far as 1950 with Olgyyay and Yaglou (Arens et al., 1986). However, it was in the 70s decade that several adaptive models began to be proposed, as a consequence of field studies, where first it was noted that comfort was obtained under very different circumstances and then, that comfort temperature in naturally ventilated buildings was closely related with outdoor temperature.

The adaptive principle recognizes the interaction of humans with the environment they are occupying – whether adapting to the environment or adapting the environment to their own requirements. This recognition contextualizes comfort. In particular, it connects comfort temperature to three important contextual variables: the Climate, the Building and Time (Roaf et al., 2009). Climate is important in cultural terms, influencing both thermal attitude of occupants and buildings. Recognizing the building as a context is recognizing the central role of infrastructures. It plays a significant part in understanding responses in relation to comfort. The adaptive approach assumes that the comfort temperature is continuously changing. Therefore, time is also an important variable regarding the achievement of comfort conditions. Within the framework of adaptive comfort, three different processes regarding individual adaptations to temperatures can be considered (Peeters et al., 2009):

1. Physiological adaptation, corresponding to the adaptation of human body to the environment and its properties of thermoregulation. Acclimatization is also considered here.
2. Psychological adaptation, refers to the consideration that the perception of comfort can be modified by past experiences or expectation of thermal conditions regarding a particular indoor environment;
3. Behavioral adaptation, in what regards the changes made in local environment, like handling or adjusting clothing, body movement or objects, like windows opening or redirecting fans.

Besides the recognition of the dynamical nature of comfort conditions, the adaptive approach distinguishes itself from the one delineated by Fanger (1970) by additional reasons. The analytical model allows to consider behavioral adaptation, by taking into account clothing and air velocity, but it does not consider acclimatization nor expectation of comfort conditions (Matias, 2010).

Several models are considered to be important to the adaptive approach, as understood today. Of relevance, in this context, is the pioneer work developed by Nicol and Humphreys (1973), Humphreys (1976) and Auliciems (1981). The first comprehensive study dedicated to the development of an adaptive model of comfort was the study by De Dear, Brager and Cooper (De Dear et al., 1997) in 160 buildings. Responses of the occupants in relation to thermal sensations and preferences and results from buildings monitoring were analyzed and a linear regression was calculated in a way that it is possible to obtain comfort temperature by the outdoor conditions. Following this study, a European project designated Smart Controls and Thermal Comfort (SCATs) (Nicol and McCartney, 2000) was promoted between 1997 and 2000. The project was developed in several countries in Europe, including Portugal. While the main objective was the development of an adaptive algorithm for climatized buildings, it extended significantly previous knowledge by considering the outdoor temperature as an exponential weighted mean of the exterior temperatures.

Two relevant Portuguese studies in this scope should be mentioned here. Correia Guedes (2000) demonstrated the influence of the behavioral adaptation on thermal comfort in office buildings occupants and Matias (2010) developed an adaptive model for Portugal.

The adaptive model developed in SCATS, was later adopted in the European Standard EN 15251 (CEN, 2007). This model in particular was considered adequate in order to assess comfort in the scope of this study. It uses data from Portugal, and although the data originates mainly from office buildings (as all other adaptive models also do), the temperature range applicability is appropriate for different buildings (Lomas and Giridharan, 2012) and the use in residential contexts can also be found (Porrit et al., 2012).

The model allows for determination of the operative temperature of comfort T_{oc}, depending on exterior conditions, calculated through Eq. (2). Exterior conditions are considered in the form of the weighted running mean exterior temperature, T_{rm}, which also accounts for temperatures recorded in previous days.

$$\boldsymbol{T_{oc}} = \mathbf{0,33}.\boldsymbol{Trm} + 18,8 \ (^\circ\mathrm{C}) \quad (\mathrm{Eq.2})$$

Figure 2.4 demonstrates the relation between comfort temperature and running mean outdoor temperature considered by the model. It also allows to understand the effect of the type of building. For the temperatures defined by this equation, it is suggested, in the standard, that the effect of the type of building should be considered. This is operationalized by the use of categories that can be translated in acceptability limits. Three categories are accounted for and each category defines a determined range of temperatures a user may find comfortable, depending on the type of building and thereby defining an upper and lower threshold. Category I is the most demanding and used for indoor spaces with special requirements (like hospitals) and the range of temperatures considered here is narrower than the other two categories (90% acceptability limits). Category II corresponds to the normal level of expectation for new buildings and renovations (80% acceptability limits). Buildings studied in the scope of this thesis are considered to be in category III, the one with the broader range of acceptable temperatures (±3 °C), applicable to existing and non-retrofitted buildings (65% acceptability limits).

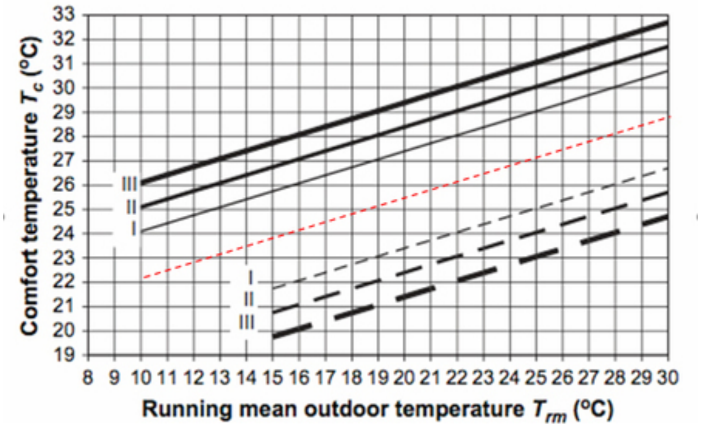


Figure 2.4 – Design values for non-conditioned buildings in the cooling season, as a function of outdoor temperature running mean. Source: CEN (CEN, 2007)

This knowledge, in particular behavioral adaptation, has been increasingly connected with climate change adaptation (Nicol and Stevenson, 2013). The concern with the provision of healthy and comfortable indoor spaces, not only now, but in an uncertain and more likely warmer future has led researchers to adopt adaptive thinking while trying to predict the impacts of climate change in comfort conditions at the same time that a likely increase in energy consumption from conditioned cooling in buildings has to be mitigated. Buildings physical characteristics play a significant part in the way exterior temperatures are reflected indoor and thus it is important to deepen this matter further.

Discomfort regarding high temperatures is generally quantified in terms of overheating threshold and is currently the subject of intense debate (Porrit et al., 2012). Overheating assessment approaches are normally comprised of determining a number beyond that the discomfort is no longer acceptable and there is no evidence that the number studied now would be the same as in the future (Shove et al., 2008). Some studies determine 1% of the occupied time as the limit of discomfort hours (CIBSE, 2005), as others assume 5% (Gupta and Gregg, 2012). This study assumes vulnerability as relative and uses it to compare different conditions. Being so, it considers the percentage of discomfort hours as the main metric.

2.1.3 Existing buildings and climate change

Human adaptability to various climates, as well as the significant range of temperature humans can endure, are well-researched issues. Both physiological and behavioral differences, which can be found in different cultures, have been developed as a consequence of distinctive climates and contexts. From a physiological perspective, the human body can adapt to higher (or lower) temperatures in a matter of days (Nicol and McCartney, 2000).

Physical infrastructure is much slower to respond to expected changes in climate (Kovats and Jendritzky, 2005). Overtime, humanity has been adapting lifestyles and buildings to different climate contexts and at the light of the knowledge produced so far, new buildings can be designed in order to be prepared for the change ahead in the future. However, whether due to slowly changing climatic conditions or frequent, sudden extreme events, existing buildings (and their occupants) will most likely have to cope with conditions for which they were not initially designed, and thus, their ability as “climate moderators” (Roaf et al., 2009) may be compromised. For Hamilton et al. (2002), the adaptation of the existing built environment in a way that continuously supports sustainable living patterns is at the core of what can be considered sustainable development.

Concerning the existing built environment, the majority of buildings are of residential nature (BERR, 2007; INE, 2012). If an average stock turnover of 1% a year is considered (TRCGG, 2008), a high percentage of the buildings existing in 2050 have already been built today. For the UK, for example, this percentage has already been estimated at 70% ((SDC, 2007).

Buildings from several ages constitute building stocks with significant differences in terms of external envelope solutions and therefore different thermal performance. Regarding changes in climate and extreme events, research done so far shows that, generally speaking, vernacular buildings take into account the prevailing climate and importantly, provide occupants with the opportunity to adapt (Roaf et al., 2009). In climates where high temperatures are expected, these buildings generally have high levels of exposed thermal mass, low levels of airtightness and high ceilings (Porrit et al., 2012). While being recognized as an outcome of the efforts of sustaining a living environment with reduced available resources and local constraints (Fernandes et al., 2014), this view created a branch in literature dedicated to studying what knowledge can be drawn from this type of construction in relation to preparing buildings for future conditions (e.g. Rubio-Bellido et al., 2015; Fabbri and Tronchin, 2006). In fact, these characteristics point towards adequate climate moderation. However, modifications and further adaptations to refurbishing buildings to modern lifestyles, as well as to providing healthy environments throughout the year, raise concerns regarding thermal performance in the future (Porrit et al., 2012).

In addition, several authors have observed the poor quality of modern buildings, highlighting a strong disconnection from the prevailing climate, which makes the use of mechanical cooling not only necessary, but also imperative (Roaf et al., 2009; Roberts, 2008). In this context, Roaf et al. (2009) argue about the relative freedom of Modern Movement architects to test new construction materials and techniques after the Second World War, where an “increasing numbers of buildings were built using new methods of construction and materials, which were often innovative, untried and apparently unquestioned.” The new methods allowed for quick and very large projects, which amplified the effect of this type of construction. As an epitome of such movement, the notorious architect Le Corbusier once claimed that he could build anywhere in the world with what he called “une respiration exacte” (Le Corbusier, 1983), a complex ventilation system which controlled temperature indoors while also guaranteeing air quality. While trusting the newly developed concrete structure, the so-called “modern building” used lightweight partitions and extensive glass cladding, because they were no longer limited by the structural qualities of external walls. Moreover, this new approach is founded on the belief in the availability of cheap fuels and limitless energy, which are not compatible with the new world context. The considerable share of modern buildings in major European Cities led to several studies focusing on these buildings in the context of climate change (e.g. van Hooff et al., 2014)

The most recent buildings, taking into consideration regulations driven by energy efficiency concerns, have lower airtightness standards and are better insulated, which also raises questions in relation to overheating (Orme and Palmer, 2003). In fact, buildings have, in general, evolved to providing thermal comfort for the most uncomfortable seasonal conditions experienced (Hacker et al., 2005), as in the case of Northern Europe and the recognized need for high levels of insulation. As a consequence, buildings in countries with mild winters tend to offer less protection against the cold. In the same way, the ones situated in regions with temperate climates, as in the case of Portugal, may fail to protect occupants from extreme heat (Riberon et al., 2006), in particular when the majority of buildings still rely on natural ventilation and traditional techniques for cooling (Fonseca, 2013).

Assuring a future adequate thermal performance of existing buildings is not only important regarding mortality, as already stated above. This kind of serious condition is situated at one extreme of the range of possible impacts of increased outdoor temperatures inside dwellings. Even if is considered a less dangerous condition, avoiding discomfort in residential buildings can be of significance in terms of health, but also regarding well being. Additionally, one major question regarding this issue is the concern about an overreliance on the provision of mechanical cooling in order to act against extreme conditions (Roaf et al., 2009). This situation can lead to an increase in the use of fossil fuels energy, exacerbating climate change even more (Stern, 2007) and potentially increasing future summer fuel poverty contexts (Figure 2.5). Fuel poverty is an emerging subject in literature and recent research shows that it is already occurring with prevalence in Eastern and Southern European countries (Thomson and Snell, 2013).

The existing research literature reflects the importance of adaptation to buildings and is dedicated to investigating the way impacts can be avoided. The predominance of technically driven studies is noticeable. An overwhelming number of studies regarding adaptation in buildings in Northern Europe (United Kingdom in particular) and Australia (namely regarding heatwaves) point out the broad direction of the use of technical passive measures, which allow occupants to maintain comfortable temperatures while avoiding the environmental (and economic) costs of adopting mechanical ventilation. These measures generally consist of reducing internal gains, promoting natural ventilation and preventing solar gains through fabric and glazing and have distinctive effects depending on the type of buildings considered, the construction techniques used and the location (Roberts, 2008), which stresses the need for assessing the impact of these measures in several locations, including Southern European, where it is not explored.

Additionally to these technical measures, the role of behavior regarding adaptation to heat is being recognized as having the same potential (Coley et al., 2012) and needs to be further explored. Technical studies usually consider occupancy, use of available controls and typified window-opening profiles as a way to take the interaction with the building into consideration (e.g. Porrit et al., 2012), but the effect of these parameters in the assessment of vulnerability is yet to be detailed. Furthermore, occupants take actions beyond window control that are extremely dynamic, can hardly be expressed using fixed parameters (De Dear, 2006) and are influenced by an interaction between individuals and the systems of power, infrastructures, technologies, society and culture (Guy, 2006; Maller and Strengers, 2011).

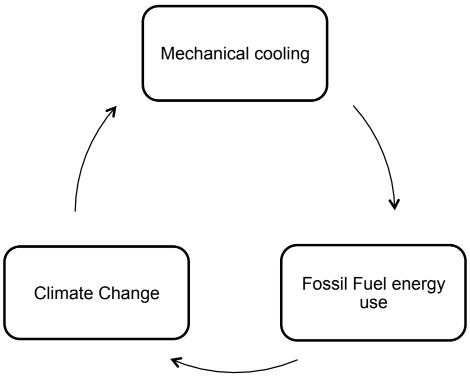


Figure 2.5 - Feedback Loop between the adoption of mechanical cooling, energy use and climate change. Source: Adapted from original figure of Fergus Nicol presented in Roaf et al. (2009)

2.1.4 Adaptation and high temperatures adaptation policy

While historical reasons have been pointed out for the prevalence of mitigation approaches, adaptation has been gaining increasing recognition in the policy realm as equally significant and, more importantly, as a much needed complementary perspective (Pelling, 2011). The recognition of the costs involved is not oblivious to this interest. Stern´s (2007) estimates suggest that adaptation costs will be 5 to 200 times superior to the costs of mitigating climate change.

Adaptation, as it has been defined by IPCC, relates with adjustments in natural and human systems as a response to the projected climatic stimulus or their effects, moderating harm and exploiting potential opportunities (IPCC, 2014). It can be argued that societies have been adapting to the impacts of weather and climate since the dawn of times. However, the increasing evidence of an anthropogenic climate change represents an abrupt event, which poses new risks when seen in the context of historical experience. Furthermore, while it is admitted that the most effective adaptation is done autonomously (Fankhauser et al., 1999; OECD, 2008), actions regarding adaptations are considered to be “neboulous” and intertwined with responses undertaken in social and environmental contexts (OECD, 2008). Additionally, because of the range of societal consequences and the scale of the challenge, governments are called in order to provide a suitable environment, allowing agents to make timely and efficient adaptation decisions. In fact, as argued by Fankhauser et al. (1999), adaptation decisions have to be made within informational, budgetary and other constraints, as well as to avoid maladaptation. For that purpose, individuals and organizations have to be incentivized in the right direction and also possess the resources, knowledge and skills to pursue these decisions.

Adaptation measures have been classified by scope (local versus regional; short term versus long term); timing (anticipatory; reactive) and purposefulness (autonomous versus planned) as well as in relation to the type of agent (individuals versus collective; private vs. public) (Fankhauser et al., 1999). Funfgeld and McEvoy (2011) propose a typology regarding temporal, spatial and administrative scope and timing of actions (Figure 2.6). Five categories of measures are defined – behavioral measures, institutional capacity building, technological measures and financial and regulatory measures – all of which can be implemented by using different types of policy instruments. In practice and by definition, planning to adapt involves a form of anticipatory adaptation and any measure implemented with a medium to long-term goal is expected to be anticipatory to a certain impact. Additionally, for long-term transformations, acting on the different levels of governance also plays an important role, as also highlighted by the Figure 2.6.

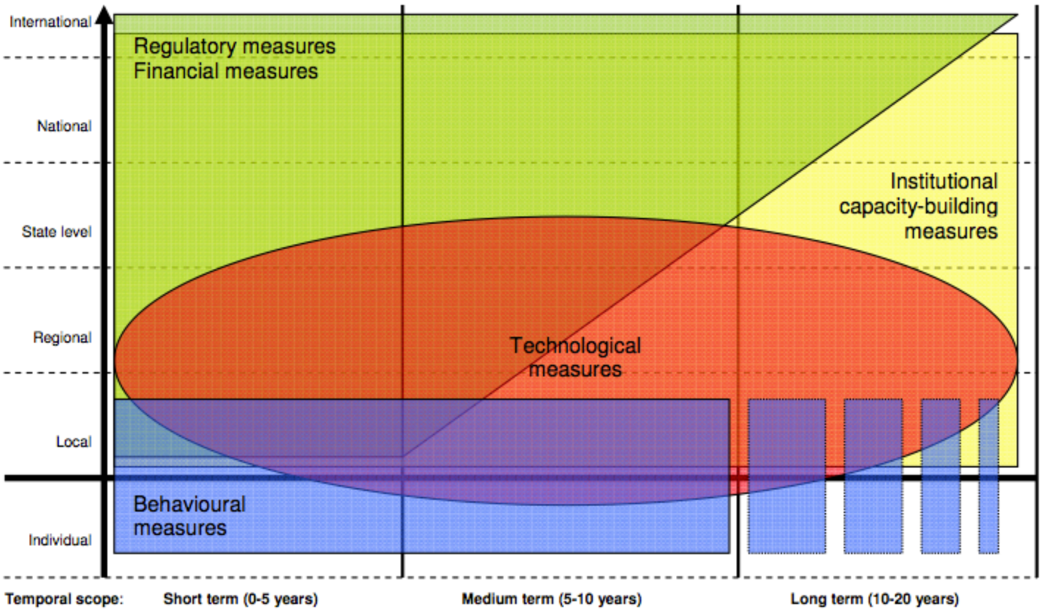


Figure 2.6 - Typology of adaptation measures. Source: Funfgeld and McEvoy (2011)

Table 2.5 provides some examples of measures in the five categories for the case of increased temperatures. For the authors, regulatory measures are considered to be more effective when they are coherent across all levels of government.

Technological adaptation, which is of particular interest for this study, is best applied at the local and regional scale, responding to particular and contextualized impacts. Behavioral measures, which include information provision instruments, are usually intended for short and medium term, and focused on phenomena such as heatwaves, while it can be expected that some measures will lead to a stable behavioral change.

Although the scope and timing of measures is clear and well identified in this typology, policy implementation faces significant barriers. Amongst the most significant barriers for the implementation of adaptation measures identified in literature are uncertainty and cost of adaptation (Fankhauser et al., 1999). Actors have to make decisions without being certain of the exact impacts and the best timing for implementation. An established approach to deal with this issue is by taking an economic perspective of adaptation measures also considering costs and benefits drawn with the implementation of such measures. Several studies have shown that some measures (including infrastructural measures) can be implemented at low cost or with a high cost/benefit ratio (e.g. (Porrit et al., 2012)).

Table 2.5 - Examples of adaptation measures. Adapted from Funfgeld and McEvoy (2011)

Type of adaptation measure	**Examples**
Regulatory	Amending planning schemes and legislation to take climate change into consideration Mandating the development of heatwave response strategies
Financial	Providing funding to climate change local impacts assessment and research
Technological	Retrofitting buildings to protect from increased temperatures
Institutional Capacity building	Local government staff training in climate change science Conducting scenarios planning exercises Devising a local process to develop an adaptation plan
Behavioral	Information provision on appropriate behavior Awareness raising program on heat wave response

The role of human behavior is, however, mostly neglected in the majority of these accounts, which can lead to bias towards more costly and inappropriate measures (LCCP, 2009).

According to Strengers and Mallers (2011) there is also a verified tendency to separate “behavioral” and “technical” policy responses. Furthermore, policy responses are promoted by separate public sectors such as health and housing. For example, policies regarding heat-stress related mortality e.g. heatwave planning and evaluation, dissemination of information to health providers and provision of information to households on how to prepare (including the appropriate use of air conditioning) are left at the responsibility of public health institutions. On the other hand, policies, which include potential modifications to buildings and implementation of technical measures, are mainly promoted by institutions related with housing and energy. Examples of these policy instruments include building codes and economic incentives for uptake of technological measures.

Analyzing the issue for Europe, the most used adaptation policy instruments is in the form of provision of information, followed by actions plans and for last, financial incentives (EEA, 2014).

The water sector is admittedly a priority in terms of adaptation and is, consequently, a front-runner in the implementation of adaptation policy, followed by health aspects (Reckien et al., 2014). Being so, most of the instruments are used in this context. By contrast, in relation to buildings for example, only a few policy instruments have been reported to be in use. Portugal is a good example of reporting a number of instruments already in place (EEA, 2014), including, and in particular, the national adaptations plan (where strategic planning is delineated but no action is specified). Although synergies are recognized, measures regarding extreme events are normally accounted for in a separate way (EEA, 2014), but included in strategic plans such as adaptations plans. Figure 2.7 shows the relation between number of adaptation policy measures and the ones related with extreme events regarding temperature in the most significant European contexts.

There is evidence that supports that people are more motivated to act when faced with events perceived as immediate risks and that adaptation can go further when it is rebranded as reduction of vulnerability (or resilience) to extreme weather (Porter et al., 2015).

In short, despite the emphasis in recent research literature and the evidence that local governments are already planning for adaptation, adaptation policy is fragmented and is still in its early stages, in particular when compared with mitigation purposes (Shapiro, 2016). Additionally, the separation between behavioral measures focusing on extreme events, in particular, and other type of policy measures stresses the need for both approaches to be addressed in a complementary and integrated way.

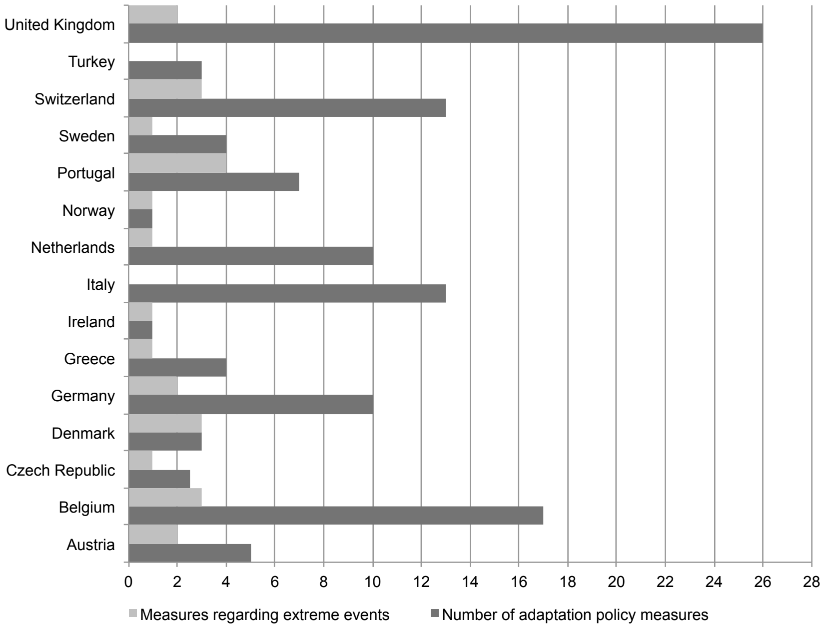


Figure 2.7 – Comparison between adaptation and extreme events policy measures. Source: adapted from EEA (2014).

2.1.5 Integrating vulnerability through a socio-technical background

Research done so far suggests that a system-oriented perspective is needed in order to understand how to adapt to high temperatures (Maller and Strengers, 2011) as well as to drive policy responses.

Vulnerability, following the IPCC definition, is “the propensity or predisposition to be adversely affected” (IPCC, 2014), which considers it to be a function of the magnitude and character of the climate variation and change, its exposure, sensitivity and adaptive capacity.

For IPCC, exposure is related with “the presence of people (…) infrastructure or economic social or cultural assets in places that could be adversely affected” (IPCC, 2014). It can be seen here as being “in the wrong place at the wrong time” (Liverman, 1990.). Sensitivity is defined as “the degree to which a system (….) is affected (…) by climate variability or change” (IPCC, 2014). Finally, adaptive capacity can be defined as “the ability of systems, (…) to adjust to potential damage (…) to respond to consequences” (IPCC, 2014). The three components are a relatively common characteristic of the framework and help to structure it. Vulnerability represents a well-researched and mature approach to understanding a system's response to change, despite the well-documented variety of definitions and approaches found in literature, resulting from the various fields in which the concept is addressed. (Miller et al., 2010).

Being so, there is no lack of studies looking to define and classify different views on vulnerability (e.g. O´Brien et al., 2004; Adger, 2006; Fussel, 2007). However, according to O´Brien et al. (2004), two main different interpretations of vulnerability can be recognized in literature. These interpretations are shaped by different scientific discourses and therefore represent different approaches to vulnerability and resulting policy responses. These two interpretations – designated as outcome vulnerability and contextual vulnerability – can be distinguished by the point where looking at vulnerability, as explored by Kelly and Adger (2000). Outcome vulnerability is prone to be seen as an end-point approach, where vulnerability is the result of a "sequence of analyses" (Kelly and Adger, 2000) with results that can usually be quantitatively considered. Technical approaches such as Gupta and Gregg (2012) are exemplary of such a perspective. On the other hand, contextual vulnerability can be seen as "the starting-point approach" (Kelly and Adger, 2000), where vulnerability is inherent to the system as a result of its contextual conditions, such as in epidemiological approaches to high temperatures (e.g. Vandentorren et al., 2006). Such a view of vulnerability and of the climate change problem assumes contextual conditions as an influence over the exposure and potential responses to the hazard. Being so, if in outcome vulnerability the adaptive capacity of the system is capable of influencing vulnerability, the contextual vulnerability perspective considers that vulnerability can influence adaptive capacity (Iwama et al., 2016). Studies using this perspective are interested in what subjects are in fact most vulnerable to climate changes and extreme events and how this vulnerability relates with the actions taken to reduce it. The two interpretations of vulnerability are complementary views and Miller et al (2010) argue about the need to integrate the concept in terms of vulnerability studies. Regarding this framework in particular, integration of the two interpretations has already been used in a recent study from Iwama et al (2016) in order to study environmental change and vulnerability in the Northern Coast of Sao Paulo, Brazil.

If the objective is the reduction of vulnerability regarding thermal comfort in existing residential dwellings and recognizing what was addressed in section 1.2.1, then and following Strengers and Maller, 2011, the problem should be recognized as a socio-technical issue, in the way that it considers infrastructures and technologies as central to moderating and mediating what people do in order to achieve comfort conditions.

The concept of socio-technical systems was developed following work conducted at the Tavistock Institute regarding the need to address issues related with coal mining machinery and the influence of behavioral issues in the introduction of new technologies (Trist and Bamforth, 1951). The framework has since evolved to several fields, from work design to infrastructures (Davis et al., 2014). The subject of thermal comfort has already been explored from a socio-technical perspective: while the most notable research regarding this topic is most definitely the work of Shove (e.g. Shove, 2003; Shove and Walker, 2010), other authors have explored this perspective, mainly from a social practice theory approach, such as Gram-Hanseen (2010) and Strengers and Maller (2011).

This perspective is distinctive from other approaches to thermal comfort – such as the ones favoring technical or psychological positions on comfort – as it considers that agency is distributed throughout the system, instead of being centered in just one actor or type of actor (Hinton, 2010). For example, physiological approaches tend to view the individual as having the majority of agency in choosing the actions to achieve comfort, while sociological approaches theorize agency as a shared concept between individuals and society. In a STS view of comfort, these elements are part of a socio-technical assemblage, sharing agency between human and non-human actors and shaping the actions, at different levels, that are taken to achieve comfortable conditions. From this perspective, comfort can then be seen as an "achievement" (Hinton, 2010), which is being continually negotiated with the available socio-technical assemblage. The concept is therefore close to the adaptive principle delineated by Nicol et al. (2012) and the adaptive model of comfort is coherent with a socio-technical perspective.

The building and the immediate technical surroundings of an individual dwelling (including building controls) is obviously of the utmost importance in the perspective of a socio-technical view on comfort. Buildings are considered to have co-evolved with society and therefore their context can be socially and historically situated. Being so, some authors argue that the change undertaken in buildings in recent decades and this material agency could have provided the potential for the co-evolution (and "lock-in" (Hinton, 2010)) of a determined set of comfort practices. This perspective on the provision of comfort is therefore pertinent in terms of climate change. Future socio-technical assemblages should provide (or assure that they continue to provide) the context for adequate and sustainable comfort practices.

The concept of practices is central in the socio-technical perspective of comfort. Rather than focus on individual actions, it is argued that the focus should be on practices, characterized by having a social nature (Jackson, 2005). Following Strengers (2009), practice is defined here as being a "coordinated entity of elements (practical knowledge, material infrastructures and common understanding), as well as a performance carried out by individuals who actualize and sustain the practice". A complementary vision is the one claimed by Ropke (2009), where "in continual flow of activities (or actions) it is possible to identify clusters or blocks of activities where coordination and interdependence make it meaningful for practitioners to conceive them as entities".

The rationale delineated above reflects an understanding of governance of infrastructures where "social elements and technological elements cannot be fully separated" (Chappin and van der Lei, 2014). While recognizing social and technical as being intricately connected, a socio-technical approach focusing on practices is also bound to bridge distinctive policy sectors and to integrate measures (Strengers and Maller, 2011). However, the role of practices has not yet been sufficiently explored in the context of driving change in these systems (Shove and Walker, 2010) or in policy-making (Strengers and Maller, 2011).

In fact, while considerable research is dedicated to understanding the complexity associated with comfort practices, studies translating implications of the approach to policy domain are scarce. Notably, Shove's work (Shove and Walker, 2010), in particular, has been arguing for a move of the policy focus on technology efficiency (such as the improvement of air conditioning efficiency). Her work stresses the need for regional and climate specific policies where practices are debated and incorporated, while questioning regulations and standards considering fixed comfort "zones". In the same direction, Guy and Shove (2000) analyzed the building industry and argued for the consideration of infrastructures as non-human actors, to be acknowledged by policy makers, in a way representing an attempt to bridge technology-behavior policy separation. Strengers and Maller (2011) argue that, in order for this to happen it is also necessary that policy responses are framed around a problem that is common, rather than its effects (e.g. mortality). The view of the problem of comfort as a socio-technical issue – by focusing on shared agency and interdependency - highlights the need for an integrated approach that on the one hand considers the extent of the problem in terms of physical vulnerability of existing dwellings, and on the other hand acknowledges the factors of various natures influencing inherent vulnerability of comfort and the diversity of responses from occupants.

In this context, Figure 2.8 illustrates an integrated vulnerability framework for the study presented here which is outlined around the problem of thermal comfort in the face of climate change and extremes as a socio-technical issue. The framework highlights the central role of the building and available controls for the provision of comfort and facilitating comfort practices, but also considers occupant behavior to be influenced by other factors as part of a socio-technical assemblage. For an integrated approach to the problem, which can potentially provide a more holistic set of policy measures and intervention strategies to adaptation to climate change, the problem should be examined using both interpretations of vulnerability. Contextual vulnerability highlights a qualitative type of research, which addresses the variety of occupant behaviors directly. Outcome vulnerability, by contrast, assumes a very objective and quantitative approach in order to address the extent of the problem in terms of vulnerability of existing infrastructure (i.e. in this case, residential dwellings). The problem is presented as a common background to the study, which means that the vision of the system is inherent to both interpretations.

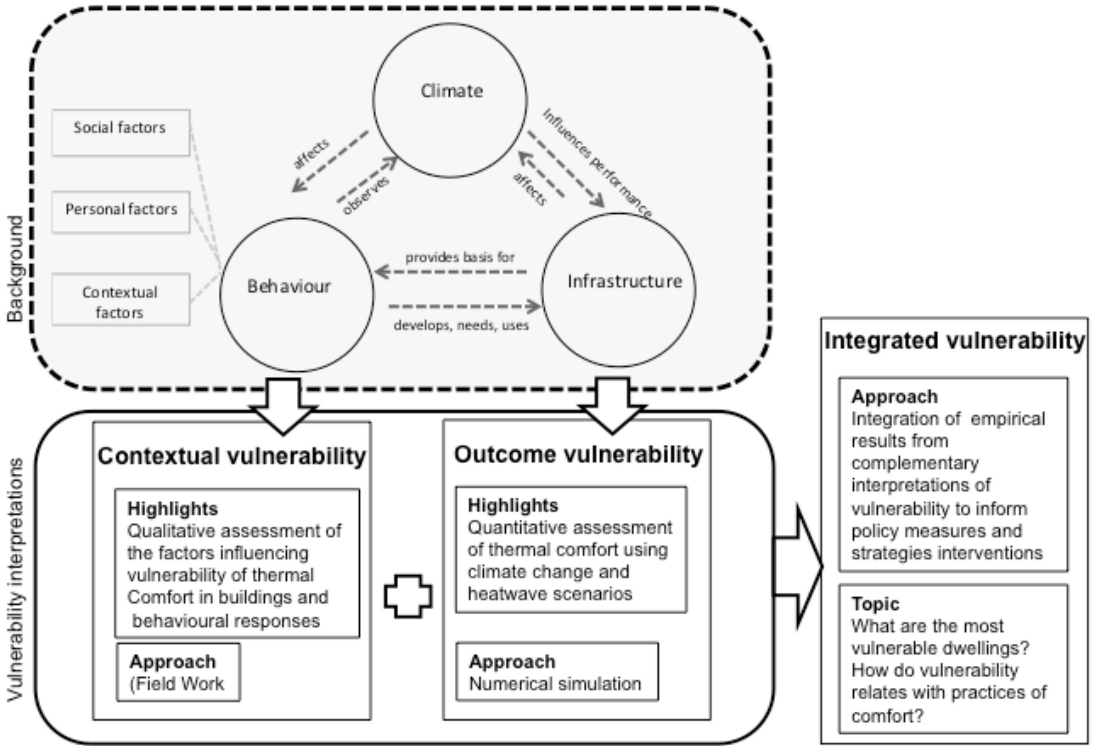


Figure 2.8 – Integrated vulnerability framework considering thermal comfort as a socio-technical issue. Adapted from Chappin and van der Lei (2014); O´Brien et al., 2007 and Iwama et al., 2016

This study aims at contributing to the discussion of the implications of an integrated vulnerability approach using a socio-technical background to the adaptation policy domain. For Chappin and van der Ley (2014), adaptation in these systems suggests “making purposeful changes” to one or various elements. While this can be seen as a simplistic view, it stresses the need for changes to be promoted in more than one way in order to adapt. A useful perspective of how change is conducted in socio-technical systems is provided by the Multi-Level Perspective (MLP) (Geels, 2004), consisting of three levels: landscape; regime and niches. Figure 2.9 illustrates the structure of change proposed within the MLP. The macro level – the landscape, corresponds to understanding the broader context (at a macro level, such as climate change) and is important in the sense that it puts pressure on regimes and creates windows of opportunities for responses (Geels and Schot, 2007). Niches have a particular role in STS, because the most significant changes in regimes emerge from this level, by providing opportunity for new and innovative technologies, ideas and concepts, considered unsustainable if not provided by this kind of small structures (Geels, 2002).

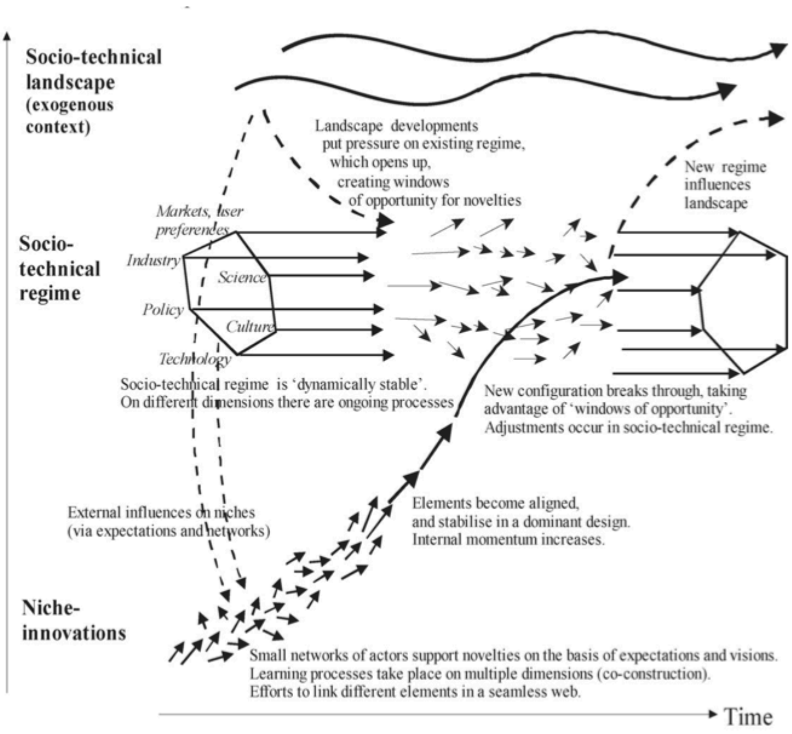


Figure 2.9 - Multi-level perspective on transitions. Source: Geels and Schot (2007)

Regimes, on the other hand, are influenced by policy, markets, user preferences and industry and represent accommodation of a broad community of social groups and their alignment of activities. It has been argued to be the structure of socio-technical systems responsible for stabilizing trajectories in several ways: cognitive routines that blind engineers to developments outside their focus, regulations and standards, adaptation of lifestyles to technical systems, sunk investments in machines, infrastructures and competencies (Geels and Schot, 2007). However, it is at this level that changes are perceived and operationalized and therefore in order to design effective policies to change it is necessary to understand regimes. Similarly to a theatrical stage, regimes are the place where the actions unfold. In that way, practices are representations of regimes, in the sense that they are produced and changed at this level. So in order to understand regimes, it is necessary to understand practices better.

While various levels of change are admitted in literature, Pelling (2011) argues that in order for a system to be adapted, a transition is necessary. This view stresses that in order to drive change in socio-technical regimes, multi-level and multi-sectorial regime changes are required and integrated policies necessary.

2.2 Methods

The research takes on the subject of vulnerability and adaptation of residential dwellings to high temperatures in a Southern European context. Central to the study is the knowledge about the degree of vulnerability in existing residential dwellings in terms of thermal comfort, as well as the way occupants adapt to the increase in temperatures in a Southern European context.

2.2.1 Research Approach

In this research, a case study approach was used. This kind of approach is considered useful when context is significant and when a *how* question is being asked (Yin, 2009). Following Stake´s work in relation to the application of the case study to scientific enquiry, the study is closer to instrumental case study, in the sense that it uses a particular case – in many instances, considered typical – to gain a broader knowledge of an issue (Stake, 1995). In opposition to experimental design that focuses on manipulation of the environment in order to test a given hypothesis, this approach intends to capture information in an explanatory manner when a naturalistic understanding of the problem is pursued (Crowe et al., 2011). The case study approach is also considered useful in order to generate information for policy and good practices, as well as knowledge transfer to other contexts (Burton et al., 2004).

The approach is usually connected with the collection of data from multiple sources of evidence, commonly using a range of quantitative and qualitative methodologies. Klein (1990) also suggests that the use of interdisciplinarity tends to convergence or integration. This is also the core of the framework presented in section 2.1.5. Therefore, following this rationale, this research applies methodologies from different fields of knowledge in order to collect and analyze data.

Interdisciplinary research is also part of the very foundation of the climate change field (Cornell and Parker, 2010) and many authors argue for a much-needed integration between physical and social sciences in the field (e.g. Fussel, 2007). The research presented in this study combines the two approaches throughout the articles where the empirical work is presented in order to produce insights to both theory and practice.

2.2.2 Research Design

The study was initiated with a literature review that included, besides vulnerability frameworks and conceptualization, vulnerability assessments in buildings, climate policy, climate change scenarios and downscaling techniques as well as empirical studies on human behavior and actions towards comfort. The objective was to realize the most comprehensive literature review to gain background knowledge on the research topic. An additional goal was to assert the most important vulnerability factors influencing buildings, which would serve as backbone of the empirical work.

The information collected was organized and is partly included in section 2.1 and in Paper I (Chapter 3), where the aim is to classify the most significant vulnerability factors influencing thermal performance of buildings in the face of climate change and extreme weather found in literature. Despite being centered on the physical structure of the building, the review also allowed for the extraction of important parameters used in both Paper II (Chapter 4) and consequently in Paper III (Chapter 5) (in order to define the most important attributes to be used in the assessment methodology) and in Paper IV (Chapter 6) (where they were used as part of the factors used in the variance analysis).

The framework presented in Figure 2.8 guides the main empirical work presented in this study. Because the timeline of qualitative research demanded more time dedicated to data collection phase, the research starts by addressing outcome vulnerability. In Chapter 4, the aim was to develop an adequate vulnerability methodology with the potential to help to understand the most important parameters at the dwelling scale, including occupant behavior and occupancy, and its effects on vulnerability of residential dwellings. Due to its importance in Lisbon building stock (as described in section 1.3), two dwellings in a 60s building were monitored, and simulated using thermal dynamical modelling in order to explore the effects of increasing temperature regarding both climate change and heatwaves episodes. An additional goal was to test the methodology in order to study the effect of implementation of energy retrofitting measures, in particular increased insulation. The case presented in this study provided a valuable example of the parameters influencing vulnerability at this scale. However, it was not representative of the reality presented in Lisbon building stock in terms of construction techniques. In order to manage high temperature related risks, information is required, namely concerning the identification of the most vulnerable buildings, as well as the adaptation measures to be targeted by policy instruments. The methodology developed in Paper II was used to provide an image of the vulnerability of the residential dwellings existing in Lisbon building stock. Therefore, the objective of Chapter 5 (Paper III) was to assess vulnerability of different construction techniques found in the building stock and to evaluate the effectiveness of technological adaptation measures in preventing overheating regarding climate extremes and gradual expected change.

While the actions taken by occupants are thought as part of the adaptive model of comfort considered in the methodology of vulnerability assessment, knowledge about the particular actions taken is limited. In Chapter 6 (Paper IV), an interpretation of contextual vulnerability is explored. The article reports an exploratory survey-based study that, by using statistical analysis techniques, intends to clarify the characterization of comfort practices used in the urban context and their relation with vulnerability factors. Besides the development of the conceptualization of practices to be used in the analysis, results present important relations with previous chapters, in particular regarding Paper III (Chapter 4).

Chapter 7 is dedicated to discussing these relations, as well as the main findings in each chapter. Insights from the case study were used for a discussion regarding theoretical and practical implications of the research.

Finally, chapter 8 presents the conclusions. Main results are summarized and possible further developments of the work are presented.

References

Aguiar, R. (2013) *Climatologia e Anos Meteorológicos de Referência para o Sistema Nacional de Certificação de Edifícios (versão 2013) - Relatório para ADENE - Agência de Energia*, Laboratório Nacional de Energia e Geologia, I.P.

Adger, W.N. (2006) “Vulnerability”, *Global Environmental Change*, vol. 16, pp. 268-281.

Alcoforado, M.J., Andrade, H., Lopes, A. and Vasconcelos, J. (2009) “Application of climatic guidelines to urban planning: The example of Lisbon (Portugal)”, *Landscape and Urban Planning*, vol. 90, no. 1-2, pp. 56-65.

Arens et al. (1986) *Thermal comfort under an extend range of environmental conditions*, ASHRAE TRANSACTIONS, SF-86-01, Nº2.

ASHRAE 55 (2004) *Thermal environmental conditions for human occupancy*. ANSI/ASHRAE Standard 55-2004, AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS.

Auliciems, A. (1981) “Towards a psychophysiological model of thermal perception”, *Int J Biometeorology*, vol. 25, pp. 109-122.

Barriopedro, D., Fischer, E., Luterbacher, J., Trigo, R.M. and Garcia-Herrera, R. (2011) “The hot summer of 2010: Redrawing the temperature record map of Europe”, *Science*, vol. 332 (6026), pp. 220-224.

Belcher, S.E., Hacker, J.N. and Powell, D.S. (2005) “Constructing design weather data for future climates”, *Building Services Engineering Research and Technology* , vol. 26, pp. 49-61.

Beniston, M. (2004) “The 2003 heat wave in Europe: A shape of things to come? An analysis based on Swiss climatological data and model simulation”, *Geophysical Research Letters*, vol. 31, Available: DOI: 10.1029/2003GL018857.

BERR (2007) *Digest of United Kingdom Energy Statistics 2007 (DUKES),* [Online], Available: www.berr.gov.uk/energy/statistics/publications/dukes/page39771.html.

Burton, I., Malone, E. and Huq, S. (2004) *Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures*, Cambridge University Press.

CEN (2007) *Indoor Environmental input parameters for design and assessment of energy performance of buildings-addressing indoor air quality, thermal environment, lighting and acoustics*. EN 15251:2007.

Chappin, E. and van der Lei, T. (2014) “Adaptation of interconnected infrastructures to climate change: A socio-technical systems perspective”, *Utilities Policy* , vol. 31, pp. 10-17.

CIBSE (2005) *TM36 Climate change and the indoor environment: impacts and adaptation*, London: The Chartered Institution of Building Services Engineers.

CMIP5 (2012) *Coupled Model Intercomparison Project Phase 5* , [Online], Available: http://cmip-pcmdi.llnl.gov/cmip5/index.html [November 2015].

Coley, D., Kershaw, T. and Eames, M. (2012) “A comparison of structural and behavioural adaptations to future proofing buildings against higher temperatures”, *Building and Environment*, no. 55, pp. 159–166.

Cornell, S. and Parker, J. (2010) “Critical realist interdisciplinarity: a research agenda to support action on global warming”, in Bhaskar, R., Frank, C., Hoyer, K., Naess, P. and Parker, J. (ed.) *Interdisciplinarity and Climate Change*, Routledge.

Crowe, S., Cresswell, K., Robertson, A., Huby, G., Avery, A. and Sheikh, A. (2011) “The case study approach”, *BMC Medical Research Methodology* , vol. 11, no. 100.

Cunha, L. (2012) “Riscos climáticos no Centro de Portugal. Uma leitura geográfica “, *REVISTA GEONORTE* - Edição Especial, vol. 4, no. 4, pp. 105-115.

Davis, C.D., Challenger, R., Jayewardene, D. and Clegg, C. (2014) “Advancing socio-technical systems thinking: A call for bravery “, *Applied Ergonomics* , vol. 45, pp. 171-180.

DB-HE, C. (2007) *Código Técnico de la Edificacion (CTE). Documento Basico. Ahorro de Energia*, Madrid: Ministerio de Fomento.

De Dear, R. (2006) “Adapting buildings to a changing climate: but what about the occupants?,”, *Building Research & Information*, no. 34:1, pp. 78-81, Available: DOI: 10.1080/09613210500336594.

De Dear, R., Brager, G. and Cooper, D. (1997) *Developing an Adaptive Model of Comfort and Preference,* ASHRAE RP-884.

Eames, M., Kershaw, T. and Coley, D. (2011) “On the creation of future probabilistic design weather years from UKCP09.”, *Building Services Engineering Research and Technology* , vol. 32, pp. 127-42.

Edholm, O.G. (1978) *Man-Hot and Cold,* London: Edward Arnold.

EEA (2014) *National adaptation policy processes in European countries*, Copenhagen: Environmental European Agency.

European Commission (2013) *Adapting infrastructure to climate change* - Commission Staff Working Document, Brussels: European Commission.

Fanger, P. (1970) *Thermal comfort Analysis and applications in environmental engineering*, McGraw-Hill.

Fankhauser, S., Smith, J.B. and Tol, R.S.J. (1999) “Weathering climate change: some simple rules to guide adaptation decisions “, *Ecological Economics* , vol. 30, pp. 67-78.

Fernandes, J., Dabaieh, M., Mateus, R. and Bragança, L. (2014) “The influence of the Mediterranean climate on vernacular architecture: a comparative analysis between the vernacular responsive architecture of southern Portugal and north of Egypt”, World SB 14, Barcelona.

Fonseca, S. (2013) *Agência e estrutura nas práticas sociais de uso eficiente da energia – a construção social da eficiência energética no sector doméstico*, Lisboa: Phd Dissertation-ISCTE-IUL.

Frich, P., Alexander, L.V., Della-Marta, P., Gleason, B., Haylock, M., Klein Tank, A.M.G. and Peterson, T. (2002) “Observed coherent changes in climatic extremes during the second half of the twentieth century. “, *Climate Research*, vol. 19, pp. 193-212.

Funfgeld, H. and McEvoy, D. (2011) *Framing Climate Change Adaptation in Policy and Practice*, Victorian Centre for Climate Change Adaptation Research.

Fussel, H.-M. (2007) “Vulnerability: A generally applicable conceptual framework for climate change research “, *Global Environmental Change* , no. 17, pp. 155-167.

Geels, F.W. (2004) “From sectoral systems of innovation to socio-technical systems - Insights about dynamics and change from sociology and institutional theory “, *Research Policy*, vol. 33, pp. 897-920.

Geels, F. and Schot, J. (2007) “Typology of socio-technical transition pathways “, *Research Policy*, vol. 36, no. 3, pp. 399-417.

Gram-Hanseen, K. (2010) “Residential heat comfort practices: understanding users”, *Building Research and Information*, vol. 38, no. 2, pp. 175-186.

Grynszpan, D. (2004) “Lessons from the French Heatwave”, *Lancet*, vol. 362, pp. 1169-1170.

Gupta, R. and Gregg, M. (2012) “ Using UK climate change projections to adapt existing English homes for a warming climate”, *Building and Environment*, no. 55, pp. 20–42.

Guy, S. (2006) “Designing urban knowledge: competing perspectives on energy and buildings “, *Environment and Planning C-Government and Policy* , vol. 24, pp. 645-659.

Hacker, J.N., Belcher, S.E. and Connell, R.K. (2005) *Beating the Heat: keeping UK buildings cool in a warming climate*.UKCIP Briefing Report., Oxford: UKCIP.

Hacker, J., Capon, R. and Mylona, A. (2009) *Use of Climate Change Scenarios for Building Simulation: the CIBSE Future Weather Years*, London: Chartered Institution of Building Services Engineers.

Hamilton, A., Mitchell, G. and Yli-Karjanmaa, S. (2002) “The BEQUEST toolkit: a decision support system for urban sustainability”, *Building Research & Information* , vol. 30, no. 2, pp. 109-115.

Hinton, E. (2010) *Review of the literature relating to comfort practices and socio-technical systems,* [Online], Available: http://www.kcl.ac.uk/schools/sspp/geography/research/epd/working.html.

Humphreys, M.A. (1976) “Field studies of thermal comfort compared and applied”, *Inst. Heat. & Vent. Eng*, vol. 44, pp. 5-27.

INE (2012) *Censos 2011 Resultados Definitivos* - Portugal, Lisbon: Instituto Nacional de Estatistica.

IPCC (2007) *Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*., Cambridge, UK and New York, NY, USA: Cambridge University Press.

IPCC (2014) “Summary for policymakers”, in Field, C.B., Barros, R., Dokken, D.J., Mach, K.J., Mastrandea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCraken, S., Mastrandea, P.R. and White, L.L. (ed.) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPMA (2013) *Instituto Portugues do Mar e Atmosfera* , [Online], Available: www.ipma.pt [February 2013].

Iwama, A., Batistella, M., Ferreira, L., Alves, D. and Ferreira, L. (2016) “Risk, Vulnerability and Adaptation to Climate Change: An Interdisciplinary Approach”, *Ambiente & Sociedade*, vol. 19, no. 2, Available: http://dx.doi.org/10.1590/1809-4422ASOC137409V1922016.

Jackson, T. (2005) *Motivating sustainable consumption: a review of evidence on consumer behaviour and behavioural change*, University of Surrey.

Jentsch, M.F., Bahaj, A.S. and James, P.A. (2008) “Climate change future proofing of buildings e generation and assessment of building simulation weather file”, *Energ Build* , no. 40.

Jentsch, M.F., James, P.A., Bourikas, L. and Bahaj, A.S. (2013) “Transforming existing weather data for worldwide locations to enable energy and building performance simulation under future climates”, *Renewable Energy*, no. 55, pp. 514–524, Available: doi:10.1016/j.renene.2012.12.049.

Kelly, P.M. and Adger, W.N. (2000) “Theory and practice in assessing vulnerability to climate change and facilitating adaptation”, *Climatic Change*, vol. 47, pp. 325-352.

Klen, T.J. (1990) *Interdisciplinarity. History, Theory & Practice*, Detroit: Wayne State University.

Kovats, R.S. and Jendritzky, G. (2005) “Heat waves and human health,”, in Menne, B. and Ebi, K.L. (ed.) *Climate Change and Adaptation Strategies for Human Health*, Steinkopff Verlag.

Kwok, A.G. and Rajkovich, N.B. (2010) “Addressing climate change in comfort standards”, *Building and Environment*, no. 45(1), pp. 18–22, Available: doi:10.1016/j.buildenv.2009.02.005.

LCCP (2009) *Economic Incentive Schemes for Retrofitting London”s Existing Homes for Climate Change Impacts*, London: Greater London Authority.

Le Corbusier (1983) *Armée du Salut, Cité de Refuge*, New York: Garland Publishing.

Lomas, K.J. and Giridharan, R. (2012) “Thermal comfort standards, measured internal temperatures and thermal resilience to climate change of free-running buildings: A case-study of hospital wards”, *Building and Environment*, no. 55, pp. 57-72, Available: doi:10.1177/0143624411432012.

Lopes, A. (1998) “Contrastes térmicos noturnos e acumulação de ar frio em áreas urbanas do sul da Península de Lisboa “, *Finisterra*, vol. 66, pp. 25-40.

Maller, C.J. and Strengers, Y. (2011) “Housing, heat stress and health in a changing climate: promoting the adaptive capacity of vulnerable households, a suggested way forward”, *Health Promotion International* , vol. 26, no. 4.

Matias, L.M.C. (2010) *Desenvolvimento de um modelo adaptativo para definição das condições de conforto térmico em Portugal*, Lisbon: Laboratório Nacional de Engenharia Civil.

McIntyre, D. (1980) *Indoor Climate*, Applied Science Publishers.

Meinshausen, M., Kainuma, M., Kainuma, M.T., Lamarque, J.-F., Matsumoto, K., Montzka, S.A., Raper, S.A., Riahi, K., Thomson, A., Velders, G.J.M. and van Vuuren, D.P.P. (2011) “The RCP greenhouse gas concentrations and their extensions from 1765 to 2300”, *Climatic Change,* vol. 109, no. 213, November, Available: 10.1007/s10584-011-0156-z.

Miller, F., Osbahr, H., Boyd, E., Thomalla, F., Bharwani, S., Ziervogel, G., Walker, B., Birkmann, J., van der Leeuw, S., Rockstrom, J., HInkel, J., Downing, T., Folke, C. and Nelson, D. (2010) “Resilience and vulnerability: complementary or conflicting concepts?”, *Ecology and Society* , no. 15(3).

Nakicenovic , N. and Swart, R. (2000) *Special report on emissions scenarios. A special report of working group III of the intergovernmental panel on climate change*, Cambridge, UK and New York, NY, USA: Cambridge University Press.

National Building Code of Finland (2002) *Thermal Insulation in a building. Regulations 2003*, Helsinki: Ministry of Environment - C3 National Building Code of Finland.

Nicol, J.F. and Humphreys, M.A. (1973) “Thermal comfort as part of a self-regulating system.”, *Building Research and Practice* , vol. 6, no. 3, pp. 191-197.

NIcol, F., Humphreys, M.A. and Roaf, S. (2012) *Adaptive therma comfort: principles and practice.* , Abingdon: Routledge, Taylor and Francis Group.

Nicol, F. and McCartney, K. (2000) *Smart Controls ad Thermal Comfort (SCATs) Project*. Final Report., Joule III Project (Contract JO3-CT97-0066).

Nicol, F. and Stevenson, F. (2013) “Adaptive comfort in an unpredictable world”, *Building Research & Information*, no. 41(3), pp. 255–258, Available: doi:10.1080/09613218.2013.783528.

O´Brien, K., Eriksen, S., Nygaard, L. and Schjolden, A. (2007) “Why different interpretations of vulnerability matter in climate change discourses “, *Climate Policy*, vol. 7, pp. 73-88.

O´Brien, K., Eriksen, S., Schjolden, A. and Nygaard, L. (2004) “What’s in a Word? Conflicting Interpretations of Vulnerability in Climate Change Research.”.CICERO Working Paper, Oslo Norway

OECD - Organisation for Economic Co-Operation and Development (2008) *Economic Aspects of Adaptation to Climate Change - Costs, benefits and policy instruments*, OECD.

Orme, M. and Palmer, J. (2003) *Control of overheating in future housing, Design guidance for low energy strategies*, Hertfordshire, UK: Faber Maunsell Ltd.

Peeters, L., De Dear, R., Hensen, J. and D´haeseleer, W. (2009) “Thermal comfort in residential buildings: Comfort values and scales for building energy simulation.”, *Applied Energy*, vol. 86, no. 5, pp. 772-780.

Pelling, M. (2011) *Adaptation to Climate Change: From resilience to transformation*, London and New York: Routledge.

Porrit, S.M., Cropper, P.C., Shao, L. and Goodier, C.I. (2012) “Ranking of interventions to reduce dwelling overheating during heat waves”, *Energy and Buildings*, no. 55, pp. 16–27, Available: doi:10.1016/j.enbuild.2012.01.043.

Porter, J.J., Demeritt, D. and Dessai, S. (2015) “The right stuff? informing adaptation to climate change in British Local Government”, *Global Environmental Change*, vol. 35, November, pp. 411-422, Available: doi:10.1016/j.gloenvcha.2015.10.004.

Reckien, D., Flacke, J., Dawson, R.J., Heidrich, O., Olabazal, M., Foley, A., Hamann, J.J.-P., Orru, H., Salvia, M., De Gregorio Hurtado, S., Geneletti, D. and Pietrapertosa, F. (2014) “Climate change response in Europe: What´s the reality? Analysis of adaptation and mitigation plans from 200 urban areas in 11 countries”, *Climatic Change*, vol. 1-2, no. 122, pp. 331-340.

REH (2013) *Regulamento de Desempenho Energético dos Edifícios de Habitação*. Decreto-Lei n.º 118/2013 de 20 de Agosto. Diário da República n.º159 – 1.ª série, pp 4988 a 5005, Lisboa: Ministério da Economia e do Emprego.

Riberon, J., Vandentorren, S., Bretin, P. and et al. (2006) “Building and urban factors in heat related deaths during the 2003 heat wave in France”, *Proceedings of Healthy Buildings 2006*, vol. V, , Lisbon, 323-326.

Roberts, S. (2008) “Altering existing buildings in the UK “, *Energy Policy*, vol. 36, pp. 4482-4486.

Roberts, S. (2008) “Effects of climate change on the built environment “, *Energy Policy*, no. 36, pp. 4552–4557.

Rogelj, J., Meinshausen, M. and Knutti, R. (2012) “Global warming under old and new scenarios using IPCC climate sensitivity range estimates”, *Nature Climate Change*, vol. 2, pp. 248-253, Available: doi:10.1038/nclimate1385.

SDC (2007) Sustainable Development Commission, *Stock Take:Delivering Improvements in Existing Housing* [Online], Available: http://www.sd-www.sd-commission.org.uk/publications/downloads/Stock_Take_UK_Housing.pdf.

Shapiro, S. (2016) “The realpolitik of building codes: overcoming practical limitations to climate resilience”, *Building Research and Information*, vol. 44, no. 5-6, pp. 490-506, Available: DOI:10.1080/09613218.2016.1156957.

Shove, E. (2003) “Converging conventions of comfort, cleanliness and convenience “, *Journal of Consumer Policy* , vol. 26, pp. 395-418.

Shove, E., Chappells, H., Lutzenhiser, L. and Hackett, B. (2008) “Comfort in a lower carbon society “, *Building Research & Information* , vol. 36, no. 4, pp. 307-311.

Shove, E. and Walker, G. (2010) “Governing transitions in the sustainability of everyday life “, *Research Policy* , vol. 39, pp. 471-476.

Stake, R.E. (1995) *The art of case study research*, London: Sage Publications,Ltd.

Stern, N. (2007) *The Economics of Climate Change: The Stern Review*, Cambridge University Press.

Strengers, Y. (2009) *Bridging the divide between resource management and everyday life, smart metering, comfort and cleanliness* - PHD Thesis, Melbourne: RMIT University.

Strengers, Y. and Maller, C. (2011) “Integrating health, housing and energy policies: social practices of cooling”, *Building Research and Information*, vol. 39, no. 2, pp. 154-168, Available: http://dx.doi.org/10.1080/09613218.2011.562720.

Strengers, Y. and Maller, C. (2011) “Integrating health, housing and energy policies: social pratices of cooling”, *Building Research and Information*, vol. 39, no. 2, pp. 154-168.

Thomson, H. and Snell, C. (2013) “Quantifying the prevalence of fuel poverty across the European Union”, *Energy Policy*, vol. 52, pp. 563-572.

TRCGG (2008) Three Regions Climate Change Group, [Online], Available: www.london.gov.uk/trccg/docs/pub1.pdf [March 2014].

Trigo, R., Garcia-Herrera, R., Diaz, J., Trigo, I. and Valente, M. (2005) “How exceptional was the early August 2003 heatwave in France?”, *Geophysical Research Letters*, vol. 32, Available: doi:10.1029/2005GL022410.

Trigo, M., Ramos, A.M., Nogueira, P.J., Santos, F.D., Garcia-Herrera, R., Gouveia, C. and Santo, F.E. (2009) “Evaluating the impact of extreme temperature based indices in the 2003 heatwave excessive mortality in Portugal”, *Environmental Science & Policy*, vol. 12, pp. 844-854, Available: doi:10.1016/j.envsci.2009.07.007.

Trist, E.L. and Bamforth, K.W. (1951) “Some social and psychological consequences of the longwall method of coal-getting: an examination of the psychological situation and defences of a work group in relation to the social structure and techno- logical content of the work system. “, *Human Relations* , vol. 4, no. 1, pp. 3-38, Available: http:// dx.doi.org/10.1177/0 0187267510 040 0101..

UKCIP (2011) UK Climate Impacts Programme, [Online], Available: http://www.ukcip.org.uk [November 2014].

van Hooff, T., Blocken, B., Hensen, J.L.M. and Timmermans, H.J.P. (2014) “On the predicted effectiveness of climate adaptation measures for residential buildings* “, *Building and Environment*, vol. 82, pp. 300-316, Available: http://dx.doi.org/10.1016/j.buildenv.2014.10.006.

Vandentorren, S., Bretin, P., Zeghnoun, A., Mandereau-Bruno, L., Croisier, A., Cochet, C., Ribéron, J., Siberan, I., Declercq, B. and Ledrans, M. (2006) “August 2003 heat wave in France: risk factors for death of elderly people living at home.”, *Eur J Public Health*, vol. 16, no. 6, December, pp. 583-91.

WHO (2004) *Heat waves: risks and responses*. Health and Global Environmental Change. Series No. 2., WHO.

Yin, R. (2009) *Case Study Research,* Sage Publication.

3 CHAPTER 3 – COMFORT AND BUILDINGS: CLIMATE CHANGE VULNERABILITY AND STRATEGIES

Paper I – Published in International Journal of Climate Change Strategies and Management

Full reference:

Barbosa, R., Vicente, R., Santos, R.(2016) “Comfort and buildings: climate change vulnerability and strategies”, *International Journal of Climate Change Strategies and Management*, 8:5, 670-688.

Comfort and Buildings: Climate Change Vulnerability and Strategies

Ricardo Barbosa [1], Romeu Vicente [2], Rui Santos [1]

[1] CENSE – Center for Environmental and Sustainability Research, Departamento de Ciências e Engenharia do Ambiente, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Campus da Caparica, 2829-516 Caparica, Portugal

[2] Departamento de Engenharia Civil, Universidade de Aveiro

Abstract

This paper aims to investigate vulnerability factors that influence thermal comfort in residential buildings in the context of climate change and variability, as well as adaptive strategies that can be adopted. There is a need for research that systematically addresses factors influencing thermal comfort in the context of climate change.

Using a vulnerability framework, this paper reviews existing literature in order to identify factors driving impacts to comfort as well as strategies to increase adaptive capacity in buildings. Data was collected from several sources including international organizations, scientific journals and government authorities, following an initial web-based subject search using Boolean operators.

Significant impacts can be expected in terms of thermal comfort inside buildings depending on four vulnerability factors – Location; Age and Form; Construction Fabric and Occupancy and Behavior. Despite the fact that the majority of the existing studies are technically driven and spatially restricted, there is strong evidence of interdependencies of scales in managing vulnerability and adaptive capacity.

Results from this review emphasize the importance of balance mitigation with adaptation regarding new building design as well as when retrofitting old buildings. The factors identified here can also be used to assist in construction of simplified tools such as a vulnerability index that helps to identify the most vulnerable buildings and dwellings and assist in retrofit decisions. The paper offers critical insight regarding implications in building design and policy in a vulnerability framework.

Keywords: Residential Buildings, Thermal Comfort, Vulnerability, Adaptation, Climate Change, Heatwaves

3.1 Introduction

Climate change is recognized as a global key challenge for the 21st century. According to the Intergovernmental Panel for Climate Change (IPCC), an increase in the global mean surface temperature is expected, ranging from 0.3˚C to 4.8˚C until 2100, in relation to a 1986-2005 baseline (IPCC, 2013). Moreover, a higher probability in the occurrence of more frequent and severe heatwaves is also projected (Barriopedro et al., 2011). Heatwaves are considered to be life-threatening events and are an object of concern regarding adaptation (EEA, 2012). During the 2003 European heatwave, still seen as a reference due to its intensity, duration and geographical extension (IPMA, 2013), countries like France, England and Portugal registered an increased number of deaths related to abnormal high temperatures inside dwellings (Vandentorren et al., 2006).

Whether due to slowly changing climatic conditions or more frequent, sudden extreme events, existing buildings (and their occupants) will likely have to cope with conditions for which they were not initially designed, and thus, their ability as “climate moderators” (Roaf et al., 2009) may be compromised. For Hamilton et al. (2002), the adaptation of the existing built environment in a way that continuously supports sustainable living patterns is at the core of what can be considered sustainable development.

In Europe, the majority of residential buildings still rely on natural ventilation (Eurostat, 2010). Therefore, understanding the response of buildings to climate change is closely related to how deeply thermal comfort will be impacted and not (yet) as an energy consumption issue. However, there is the concern that, in response to future expectations of temperature change, the installation of mechanical cooling systems will increase, which would impose a greater energy demand of buildings (Stern, 2007), making the study of these issues significant both from the energy and well-being perspective.

Even though the impacts of change (in particular in the case of extreme events) on health and well-being are well addressed through epidemiological research, studies focusing on thermal comfort issues are scarce. In particular, few studies focus on a systematic review of the factors influencing thermal comfort impacts on buildings and the adaptation options adequate to offset or minimize these impacts. With Europe registering, since 2000, nine of the ten hottest years ever recorded (WMO, 2014), it is timely to review the existing body of knowledge related to thermal comfort and climate change with the aim to identify evidence of parameters influencing vulnerability and adaptive capacity. This will, hopefully, contribute to provide useful insights to both building design and policy-making with the goal of preparing the built environment for a warmer future in Europe.

3.2 Methodology

3.2.1 A vulnerability framework for thermal comfort

The concept of comfort, because it results from human sensations, is of difficult definition and depends on multiple factors – physical, physiological and psychological (McCartney and Nicol, 2002). It can be defined as “the state of mind expressing satisfaction with the thermal environment” (ASHRAE, 2004).

Two generally contrasting approaches and views are distinguished, resulting in different models for thermal comfort assessment. The analytical model, mainly derived from the work of Fanger (1970), though often criticized for considering individuals as a mere recipient of the thermal stimulus (Kwok and Rajkovich, 2010), has been the basis for the definition of reference conditions of a significant number of thermal codes throughout Europe, establishing fixed limits for comfort temperature. Contrasting with this approach, the adaptive model, developed following field studies (e.g. Nicol , 1993), considers that people have a response to change and are willing to act in order to restore thermal comfort conditions. This approach is consistent with the perspective of “comfort as achievement” (Hinton, 2010), which recognizes the agency of individuals to devise their own strategies in order to achieve comfort.

If a systemic socio–technical approach to comfort is considered, the dwelling, as a unit of accommodation, can be seen as a system, involving the physical environment, the occupants and the rules and institutions regulating how occupants interact with available opportunities in order to achieve comfortable conditions (Chappels and Shove, 2005), and avoiding potentially overheating situations, as expected in the future.

Vulnerability represents a well-researched and mature approach to understanding a system’s response to change (Miller et al., 2010). Rooted in the fields of geography and natural hazards, the dissemination of the concept makes a rigorous and homogeneous definition very hard to obtain (Fussel, 2007). In this study, the concept is approached following the IPCC definition as “the propensity or predisposition to be adversely affected” (IPCC, 2014). It considers it to be a function of the magnitude and character of the climate variation and change, its exposure, sensitivity and adaptive capacity. Exposure is related with “the presence of people (…) infrastructure or economic social or cultural assets in places that could be adversely affected” (IPCC, 2014). On the other hand, sensitivity is defined as “the degree to which a system (….) is affected (…) by climate variability or change” (IPCC, 2014). It can be considered then, that the vulnerability of a dwelling or building is determined by the combination of the sensitivity and exposure factors -the vulnerability factors- as well as the projected change.

On the other hand, adaptive capacity, which can be considered as “the ability of systems, (…) to adjust to potential damage (…) to respond to consequences” (IPCC, 2014), is seen here, as being capable of influencing the inherent system vulnerability. Changes in adaptive capacity are materialized through the implementation of adaptation strategies. Following Gupta and Gregg (2012), adaptations are actions taken to eliminate or reduce the risk. Figure 3.1 presents a graphical representation of the framework considered here.

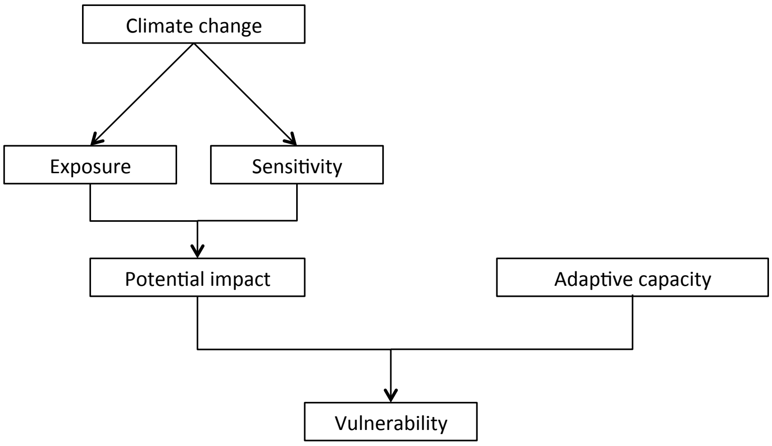


Figure 3.1 – Vulnerability framework – Source: Allen Consulting Group (2005)

3.2.2 Materials and methods

The objective of the study is twofold: to understand the vulnerability factors concerning the impacts of climate change on thermal comfort and to capture evidence of strategies and interventions to deal with those impacts, improving the adaptive capacity of the system. The principal sources of literature include: International organizations such as the *International Energy Agency*; Major databases of scientific journals; Government and institutional authorities such as *The Chartered Institution of Building Service Engineers*; Research Institutes such as *Arup Research and Development*.

In order to execute the search in literature, a list of keywords was used in Google Scholar (GS) search engine. The keywords include: climate change, thermal comfort; thermal performance; heatwave; overheating; climate projections; dwelling; adaptation and adaptation strategies. The keywords were selected from the ten most cited articles, following an initial subject search using Boolean operators in GS interface.

The focus of the literature reviewed concerns impacts on thermal comfort regarding residential buildings in Europe. However other regions of the world were also considered, depending on the relevance of the study. Relevance was assessed by comparing citations results for each keyword. This resulted in 121 initial references, which were then evaluated for evidence extraction regarding variables or parameters influencing vulnerability and adaptive capacity in buildings. Following this evaluation, 65 articles and reports were selected to be reviewed in this study.

3.3 Vulnerability factors influencing impacts on thermal comfort in dwellings

The majority of the studies on this field are conducted through modelling exercises, using dynamic thermal simulation packages. The most frequent approach is the identification of overheating situations, through the establishment of a time limit of exceedences of comfort temperatures (e.g. CIBSE, 2006).

Of relevance for the topic of study is the underlying discussion relating to the adequacy of thermal comfort standards and models in assessing indoor conditions in the future (Nicol and Stevenson, 2013) and the kind of climate projections to be used (Jentsch et al., 2008). Climate models can have a significant and obvious influence on modelling results. For use at the building scale, General Circulation Models (GCM) data has to be downscaled into more detailed regional models. Hacker et al. (2009) provides an extensive review of downscaling methodologies used to develop hourly weather data from climate projections. For building simulation purposes, two major approaches can be distinguished in the reviewed studies. The first to be developed is considered to be more deterministic. It uses a simple methodology developed by Belcher et al. (2005) – commonly designated as "morphing" - in order to transform historic weather files according to climate change GCM scenarios. It was developed following the work of 2002 UKCIP (United Kingdom Climate Impacts Programme) (UKCIP, 2002), which provided predictions for 2020, 2050 and 2080 and carbon emission scenarios derived from IPCC projections. Upon realization that the majority of the work done in this field was concentrated in the UK, the tool was further developed, enabling the morphing methodology to be used for other locations (Jentsch et al., 2013). More recently and with the need to reflect the uncertainty inherent to climate projections, a probabilistic approach was adopted. The second generation of UKCIP projections published in 2009 (UKCIP, 2009), alongside a finer spatial resolution, also included distribution range of climate variables. However, this type of approach is not readily available in most countries.

Predicting future climate is an important source of uncertainty, but it is not the only one present in modelling studies. De Wilde and Tian (2012) alert for uncertainties regarding the "definition of the object under investigation, in this case, the building and its subsystems.", but also the ones regarding occupant behavior and retrofit interventions, all of which can be represented by a unlimited number of combinations and parameters.

Despite these uncertainties, significantly common and consensual issues arise from the reviewed studies concerning the most important factors that influence the vulnerability of dwellings.

Location

Findings from the existing literature indicate that the location of the building is a significant factor influencing climate change impacts on thermal comfort. In that context, a study related to Portugal analysed thermal loads of a typical single-family house and an apartment for several locations (Aguiar et al., 2002). Results indicate that a reduction in heating requirements is expected, but it would not compensate entirely for the increase in air conditioning demand in summer, which suggests a considerable impact on the thermal performance of buildings, in particular in the South and center inland of the country. In a CIBSE report (CIBSE, 2005), dwellings were simulated for three geographical locations - London, Manchester and Edinburgh. The results of the research suggest that the south of UK is more likely to face risk of overheating by mid-century. Another study argues that this risk is influenced by the expected increase in solar radiation and air temperature in that region (Sanders and Phillipson, 2003). According to Jenkins et al. (2008) study, there is a projected 14% difference regarding global radiation between London and Edinburgh in 2030, which is suggested to be in the origin of the significant overheating risk faced by London when these two locations are compared (Peacock et al., 2010)

The location of the building within the city is also found to be of significance. With the projected increase in temperatures, Urban Heat Island effect (UHI) in already dense urban centers, such as London, Peterborough or Southampton will most likely be intensified. In particular, this increase is thought to produce a substantial impact on the possibility of night-time ventilation, which depends on the significant difference of pressure between indoor and outdoor conditions (ARUP, 2008). Evidences from studies under the umbrella of Adaptation and Resilience in a Changing Climate in UK (ARCC, 2011) are indicative of the importance of urban setting characteristics in the vulnerability of the built environment, such as the impact of street "canyons". Observations from Manchester, UK, indicated a 2°C increase in temperatures within an urban "canyon", that was already demonstrating a difference of 5°C from a nearby rural setting (ARCC, 2011). Also, in this context, existence and proximity of green and blue areas (areas with water) is indicated as determinant (Smith and Levermore, 2008).

Evidence from several sources suggests that dwelling location within the building can also be a determinant factor. Porrit et al. (2012), for example, found a difference of up to 100% in discomfort hours between dwellings of the same typology with different orientations. Additionally, findings from various modelling studies indicate that dwellings located on top floors in multi-residential buildings are more vulnerable to overheating, when compared to dwellings on other floor levels in the same building (Orme and Palmer, 2003; CIBSE, 2005).

Other studies, however, devalue the importance of the urban setting and location, suggesting other features, such as age and built form, as more determinant in overheating control (Oikonomou et al., 2012).

Age and form

Age of the building is a factor generally identified as important in modelling studies. However, considerations relating to age are subjacent and directly connected, although not exclusively, with typical building envelope for the time of construction and spatial configuration of dwellings. Accordingly, results from several studies suggest that dwellings built around 1960 are more likely to overheat due to lack of thermal protection from poorly or non-insulated slabs (Orme and Palmer, 2003, Hacker et al., 2009). On the other hand, while some studies (e.g. Young et al. (2007)) suggest that new buildings (characterized by being highly insulated) have more potential to overheat than older ones, others, in particular in Australia (BRANZ, 2007), seem to indicate that recent buildings - i.e. complying with national building codes - are more capable of dealing with gradual projected changes.

Dwelling form and size is inherently taken into account in the design of modelling exercises, and it is considered to be significant for the thermal response of a dwelling (Coley et al., 2012). Age and form were also found to be responsible for a determinant variation in temperature in Mavrogianni et al. study (2012) at the point of being suggested as “predictors” of risk.

Occupancy and Behavior

Despite the current recognized importance of occupants in thermal modelling, earlier studies (e.g. CIBSE (2005)), only considered one type of occupancy – a working family. While suggesting that occupancy profile influences the effectiveness of the building envelope, Porrit et al. (2012) ran simulations for two occupancy profiles (occupants” schedules and the room they occupy at a particular time of day), including an elderly couple, and found it to be significant.

The effect of the type of room most occupied, was also subject of research in other studies. Orme and Palmer (2003) suggest that spaces with high internal gains like kitchens are likely to overheat in such conditions. Other type of spaces, like bedrooms, present reduced adaptive opportunities (due to the fact that occupants are most likely sleeping most of the occupied time), which is also object of concern in the literature. In this context, the work of Peacock et al. (2010) and the introduction of “number of cooling nights” in a year, as a metric of comfort in this type of rooms, are worthy of note.

In free-running buildings, behavior is strongly connected with adaptive opportunities, which are mostly related with the ability of controlling the temperature through ventilation. A building relying on natural ventilation was found to be more frequently overheating in a UK study (up to 3.7% for a modern mixed use building for 2020 and from a 5% to 25% increase for a 1960 building in 2080) (Hacker and Holmes, 2007). Other studies had also indicated a certain level of risk associated to ventilation and in particular to expected night-time elevated temperatures (Lomas and Ji, 2009).

Building Fabric

Several authors point out the characteristics of the building fabric as the most important factor regulating indoor thermal comfort. This is basically the approach taken in purely technical studies, such as CIBSE (2005) and Mavrogianni et al. (2012). The perspective presented in ARUP (2008) study is exemplary of the rational behind the recognition of this importance in the context of climate change. Since projections indicate that temperatures in UK can be similar to Mediterranean climates, the issue lies in the fact that existing buildings do not have the same characteristics as buildings in those countries, such as “small, shuttered windows on south and southwest facing walls (…) often painted white to reflect heat” (ARUP, 2008). This claims for an assessment of existing components under new climate conditions.

Evidence found in studies suggests that thermal mass is important because of the capacity of thermally massive buildings to absorb heat in times of higher gain, which is re-emitted with a delay - a property which is usually termed thermal capacity. In the four dwelling archetypes considered for four residential buildings in CIBSE study (CIBSE, 2005), for UKCIP02 Medium High scenarios in 2020, 2050 and 2080, the research concluded that most of the buildings would overheat, in particular the ones with lightweight construction. Additionally, the ones performing the best in those conditions were the ones presenting high thermal mass. Evidences from other studies, such as Hacker (2008) and Kendrick et al. (2012) corroborated these findings for UK.

Coley and Kershaw (2010) followed a more comprehensive approach and focused on developing an amplification coefficient – allowing for a simplification of how the building transforms exterior temperature into indoor conditions. Architectural parameters considered in the analysis included a significant range of thermal capacity (from 10 $kJ/m^2°C$ to 230 $kJ/m^2°C$), but also thermal resistance, the fraction of glazing in the envelope, orientation and the maximum angle windows can open, together with air infiltration rate. Lightweight construction was found to amplify exterior temperatures and, in opposition, the lowest values in the amplification coefficient are for heavyweight building.

The study from Mavrogianni et al. (2012) aimed to study the influence of building characteristics on their propensity for overheating in dwellings in London. It also deepened knowledge on insulation positioning, namely in cases of retrofit interventions, and its influence on the potential to overheat. There are several sources indicating the level of insulation, and, as importantly, its positioning in the wall, to be determinant in terms of overheating risk (Peacock et al., 2010; Mavrogianni et al., 2012). Orme and Palmer (2003) investigated the overheating risk in super insulated houses using modelling archetypes for flats and houses, which showed that a lightweight well insulated house, even with natural ventilation, can amplify a 29°C external temperature to an internal temperature of 39°C.

Insulation has a clear relationship with energy efficiency in buildings. In this context, conflicting views could be found regarding the impact of climate change on energy-efficient building types (in some cases, also depending on active systems features). Crawley (2008), for instance, argues, that energy-efficient buildings present less sensitivity to change, while Wang et al. (2010) argues the opposite for the case of Australia. A report for the same country suggests that buildings that comply with energy-efficiency requirements and the national construction code can reasonably withstand the effects of expected climate changes, but not the impacts of extreme events (BRANZ, 2007). Other energy-efficiency related measures such as air-tightness standards is thought to also cause overheating situations in buildings subjected to future climate, both in new construction and building retrofit (NHBC, 2012). Other studies, however, point out that this parameter is beneficial because it is an enabler of effective control of ventilation (CIBSE, 2005).

The compilation of evidence made possible by the review can be framed according to the vulnerability framework already presented in section 3.2.1. Additionally it is also possible to identify, from the literature, which variables could be used to calculate the factor and sub-factor influence on the system. Results are synthetized in Table 3.1 .

3.4 Strategies and interventions for increased adaptive capacity

The vulnerability factors presented and discussed in the previous section make clear that the system should be adequately designed and adapted. This section intends to focus on evidences of strategies taken to increase adaptive capacity. Three major scales were identified – Urban, Building and Occupant scale.

Urban scale

Implementation of green and blue areas is considered to be an essential tool for both mitigation and adaptation by the European commission, which calls for integrated approaches in spatial planning for multi-functional areas (European Commission, 2012). The increase in this kind of areas or “infrastructures” in an urban context are pointed out in the literature as common adaptation measures at this scale (Gill et al, 2007) and interpreted in a very similar fashion, independently of the urban context (Wamsler et al., 2013). These areas consist of evaporation areas which have the potential to reduce air and surface temperature as well as to increase humidity, through evapotranspiration and shading (Muller et al,2014).

Green areas enjoy a more significant exposure in literature and are considered as being thermally more comfortable than blue areas (Klemm et al.,2015). However, the combination of both is essential in providing a solid ground for adaptation to climate change (Muller et al. 2014; Voskamp and de Ven, 2015) while also providing recreational areas and adding value for urban contexts (Wamsler et al, 2013).

Furthermore, their impact is considered to be significant. A study modelling changes of surface area in Manchester region in the context of climate change, found that, under a high emission scenario for 2080, an increase of 10% of green areas could maintain maximum surface temperatures as the 1961-1990 considered baselines conditions. On the contrary, if a 10% decrease in green areas is considered, the surface temperature could increase as much as about 8°C (Gill et al., 2007). Another study suggests that doubling the green spaces in London could decrease exterior temperature as much as 0.3° C (Met Office, 2015).

However, the increase of such areas, especially in denser consolidated urban locations, can be a complex task and its effectiveness has to be considered. Gromke et al (2015) study concludes in a study for the Netherlands that using avenue trees is the most effective strategy for reducing air temperature, in comparison with green roofs and façade greening.

Table 3.1 - Synthesis of vulnerability factors and major sources of evidence

Vulnerability component	Vulnerability factor	Sub-factors	Variables	Major sources of evidence
Sensitivity	Location	Urban Climate	Air Temperature (°C)	(CIBSE, 2005) (ARUP, 2008) (Sanders & Phillipson, 2003) (ARCC, 2011)
			Solar radiation	(Sanders & Phillipson, 2003) (Peacock et al., 2010)
		Building/Dwelling positioning	Orientation (degree)	(Coley & Kershaw, 2010) (Porrit et al., 2012)
			Building Floor	(Orme & Palmer, 2003) (CIBSE, 2005) (Mavrogianni et al., 2012) (Olkonomou et al., 2012)
	Age and Form	Age	(combination of factors)	(Orme & Palmer, 2003) (Sanders & Phillipson, 2003) (Hacker et al., 2009)
		Size	Interior Area (m^{2})	(Coley et al., 2012) (Porrit et al., 2012) (Mavrogianni et al., 2012) (Gupta & Gregg, 2012)
			Exterior Surface area (m^{2})	(Coley & Kershaw, 2010) (Mavrogianni et al., 2012)
	Building Fabric	Walls and structure opaque composition Glazing	Thermal capacity (kJ/m^{2}°C)	(CIBSE, 2005) (Hacker, 2008) (Kendrick et al., 2012) (Coley & Kershaw, 2010)
			Thermal resistance (W/m^{2}.year)	(Coley & Kershaw, 2010) (Mavrogianni et al., 2012) (Peacock et al., 2010) (Porrit et al., 2012)[65]
			Glazing to floor ratio (%)	(Coley & Kershaw, 2010) (Mavrogianni et al., 2012) (Porrit et al., 2012)
			Air tightness (ach/h)	(Coley & Kershaw, 2010) (Lomas & Ji, 2009) (NHBC, 2012)
			Surface albedo	(Gupta & Gregg, 2012) (Porrit et al., 2012)
Exposure	Occupancy and behavior	Occupancy	Time spent indoors (h)	(Porrit et al., 2012) (Gupta & Gregg, 2012)
			Occupied time of the day (0-24h)	(Porrit et al., 2012) (Gupta & Gregg, 2012)
			Type of occupied room	(Orme & Palmer, 2003) (Peacock et al., 2010)
		Behavior	Allowed ventilation (ventilation strategy) (ac/h)	(Porrit et al., 2012) (Hacker & Holmes, 2007) (Lomas & Ji, 2009)
			Internal gains (W/m2.year)	(Orme & Palmer, 2003) (Holmes & Hacker, 2007)

Due to scarcity of space most cities have to deal with, green roofs were found to give a significant contribution in terms of cooling effect and heat island effect reduction (Wilby, 2007), in the same way as reflective coatings and lighter colors in roofs increasing albedo on urban surfaces (Porrit et al., 2012).

Building scale

There is no shortage of literature addressing adaptation to climate change from a technical perspective. CIBSE (2005) defines four principles guiding adaptation strategies at a building scale: switch off (reducing additional heat gains); absorb (thermal mass); blow away (a intelligent ventilation strategy) and finally, cool (active cooling). In a similar approach, De Dear (2006) also classifies the possible adaptations as “the four principles of cooling”.

The recommendation for active cooling deserves a special note. Although several authors acknowledge the need for air-conditioning as adaptation in extreme cases (Sanders & Phillipson, 2003; Brown & Walker, 2008), it is consensual that, for most cases, passive measures have the potential to maintain comfortable indoor conditions, without having the need for the increased energy consumption implied in active cooling (Roberts, 2008). In fact, regarding heat waves, the World Health Organization advises that a “climate adapted building and energy efficient design should be stressed over air-conditioning” (WHO, 2004). With that in mind, only passive measures were considered here.

Evidence regarding limiting and reducing gains refers to employing shading (using blinds, slates, awnings, overhangs and recessed windows) (Gupta and Gregg, 2012), reducing the lightning and appliance density or power and also reduce ventilation to a minimum during warmer periods of the day (Porrit et al., 2012; Peacock et al., 2010). In this context, systems like automatic shading and glazing with electrochromic properties, can provide a step further in the future (ARUP, 2008). Other measures include increasing the reflectivity of terraces, roofs and facades (Porrit et al., 2012), or taking advantage of soil mass in ground floors, through concrete, wood and ceramic floors (Capon & Hacker, 2009).

Insulation is a popular and well-funded measure regarding mitigation and is indicated in literature as a possible protective measure, but one that has to be implemented with caution, depending on the expected climate (Peacock et al., 2010). Porrit et al. (2012) found the external insulation to be the most effective intervention to reduce heat gains, regarding heatwave events, but with significant distinctive results according to the occupancy. For example, in a house occupied by a family (working couple and children at school), indoor temperatures would benefit from external wall insulation because both bedroom and living room are mainly occupied in a later part of the day allowing for a time-lag in heat release. In opposition, internal wall insulation can potentially increase the risk of overheating in a dwelling occupied by an elderly couple that spends most of the time at home. For Mavrogianni et al. (2012), however, insulation of the building envelope may be negative, regardless of occupancy.

Better insulation – i.e. the reduction of thermal transmittance of the building envelope – can be achieved on both opaque and glazed elements. Glazing is the least insulating part of the envelope. Typically the heat loss coefficient is four to ten times higher for this element than for opaque elements (UNEP, 2007). Several possible advances in glazing insulation are worth considering and are reviewed in Roberts (2008). The most important include translucent fillers, vacuum-insulated windows and “smart windows” which include thermochromic properties as well as the ability to alter transmittance in response to temperature.

Adding thermal capacity to walls is an important strategy to offset high temperatures in buildings (Coley et al., 2012). Evidence indicates that buildings with a high thermal mass get to be between 4˚C and 6˚C cooler than the peak summer temperatures during the day (Roberts, 2008), but some caution has to be taken regarding the storage of unnecessary gains (Sanders and Phillipson, 2003). Phase change materials was already suggested as a viable solution, although acknowledging the need for further research and cost reduction (ARUP, 2008; Roberts, 2008).

The third "principle of cool" – Ventilation – is consensually recognized as an effective adaptation strategy. However, in Peacock et al. (2010) study for London houses, window opening does not appear to be an effective strategy for reducing overheating from 2030s onwards, but makes the difference between lightweight and heavyweight buildings less apparent. In that sense, Sanders and Phillipson (2003) discusses the need for designing or re-designing internal spaces that could maximize the benefits of natural ventilation and strategies such as "stack effect", even if there is the concern that temperature increase may compromise the possibility of using ventilation to dissipate heat. The same concern exists regarding night ventilation (CIBSE, 2005).

In a study originating from the Netherlands, van Hooff et al. (2015) explored the effectiveness of six climate adaptation measures in residential buildings. Their results suggest that different measures should be considered depending on the age of the building. The need for specificity and complementarity in adaptation measures applied to buildings is consistent in other relevant studies. Peacock et al. (2010) found that, for a building to perform well year round, it needs to present a high thermal mass and low thermal resistance. Mavrogianni et al. (2012) suggests the advantages of combined measures of insulation (such as roof/loft or windows) in decreasing internal temperatures. The example described by Porrit et al. (2012) is also worthy of note. Focusing on heat waves, the author considers interventions that have the dual objective of reducing energy heating needs and managing high temperatures induced in buildings indoor conditions in the UK. Results from the study suggest that measures such insulation, shading and ventilation have to be considered together for a successful retrofit, concerning both performance and cost.

Gupta and Gregg (2012) agrees with the ranking of interventions proposed by the latter study, but their results concerning suburban houses suggest that even combined measures would not avoid overheating for 2080 scenarios.

The case for ventilation as a complementary measure is transversal in literature. There are evidences suggesting that both exposed thermal mass buildings and strongly insulated ones should be appropriately ventilated in order to perform at its best (Orme and Palmer, 2003; CIBSE, 2005). Not focusing on overheating, but with the objective of reducing cooling loads in 50%, Capon & Hacker (2009) argue for the need for night ventilation combined with fans in order to increase air circulation and restriction of solar gains during the day using adequate shading. This is intricately related with occupant behavior.

Occupant scale

Occupants take a number of actions known to increase the adaptive capacity of the system. The response of occupants to change was already defined in three distinctive levels in thermal comfort literature: 1) Unconscious physiological changes (e.g. shivering, sweating) 2) behavioral changes and 3) use of controls available in the building (Roaf et al., 2009). While all levels are dependent on the subjective parameters of comfort of the individual(s) occupying the space, the last two levels are of interest for the context considered here.

Behavioral change can range from personal strategies - changes in clothing, reduction of activity to slow down metabolism or intake of water - to a degree of interaction with the environment – moving either inside the building to cooler areas or even abandoning it (Coley et al., 2012). These actions are extremely dynamic and can hardly be expressed using fixed parameters (De Dear, 2006). However, existing research suggests the emergence of patterns and a relationship between behavior and type of dwelling. For example, windows are less likely to be opened in flats or in older dwellings (Dubrul, 1987).

The use and availability of controls (e.g. operating windows) is indicated in literature as a factor inducing tolerance to high temperatures independently of the characteristics of occupants (Nicol and Stevenson, 2013) making the case for robust and simple systems (Roberts, 2008). Results from the CREW project (Porrit et al., 2012) argue for a 30% reduction in “overheating exposure” if windows are opened only when the outside temperature is lower than inside temperature. Hence, the effectiveness of this strategy relies not only on the availability of controls, but on the way they are used. In this context, Coley et al. (2012) argues about a similar potential in “behavioral” adaptation measures and “structural” ones regarding managing overheating.

3.5 Implications for policy and building design

One clear and general finding from literature review is related with the geographical distribution of the studies, showing a clear predominance of research in Australia and the United Kingdom. Approaches to impacts on indoor conditions are similar, with Australia giving special attention in research to extreme events (i.e. heatwaves) and non-technical adaptation in relation to projected climate change. The differentiated results in relation to European studies are also exemplary of the importance of context and specificities of construction techniques used in different parts of the world. For more on this subject, Wamsler et al (2013) provides an interesting perspective on similarities and differences regarding urban adaptation in different parts of the world. The case for the predominance of UK studies, even if some heat extremes events have been registered, is not evident. De Wilde and Tian (2012) discuss some of the subjacent reasons, with particular emphasis in the availability of downscaled climate models. Of interest for the subject at hand, though, is the general lack of studies in other regions already identified as particularly vulnerable and with a significant existing building stock, as Southern Europe (Santos and Miranda, 2006).

In fact, with only 30% of the existing building stock in 2050 to be constructed post-2006 (ARUP, 2008) the mismatch between the projected changes operated in climate and existing building characteristics seems to be the main problem to be addressed. Additionally, even though the mechanisms that cause a building to gain heat are reasonably well known, the uncertainty surrounding both projections and occupant behavior, the non-linearity of climate parameters and the particularities of each location and built environment can cause impacts to be very distinct.

One key issue brought up by the review of vulnerability factors driving impacts and strategies for improving adaptive capacity of the system is that its comprehension requires that interdependencies from different scales should be taken into account, a question that has already been discussed conceptually by Hufschmidt (2011), regarding the vulnerability of a system.

These aspects are structural in discussing implications of the review for both policy and building design. They highlight the limited knowledge obtained so far and the urgent need for further comprehensive studies exploring more of the complexity and diverse forms of the relationship between different climates, urban space, buildings, dwellings and occupants. This urgency has two major time frames that are closely related to impacts– The shorter term concerns serious implications to heatwave-related mortality. The longer term, with relation to the gradual increase in temperatures, claims for an adequate physical environment with no need for mechanical cooling and capable of maximizing opportunities to adapt in a sustainable manner, with implications regarding energy-intensive use of energy and fuel poverty in the future.

In terms of building design, the effect of energy efficiency measures such as the increase in insulation appears to be a significant discussion arising from the review and further research could provide significant input to practice. This matter stresses the need to integrate mitigation and adaptation in retrofit design. In this context, it is also important to understand how different dwelling features affect behavior. An interesting research in that field is the behavioral algorithm developed by Tuohy et al. (2007). The key point in this argument is that behavior is not independent of building design, despite the fact that there are many more features affecting it. Due to its significance in terms of comfort, several adaptation studies argue for the need for buildings to be designed taking into consideration the way occupants should behave and not the other way around (Roaf et al., 2009; Nicol and Stevenson, 2013; Porrit et al., 2012).

Regarding policy, a clear point that can be taken from literature is that the main instruments regulating new construction and retrofit interventions – building codes and standards which are designed around historic climate data – should integrate climate projections and uncertainty which could provide additional adaptive capacity to buildings when designed or intervened, as already argued in other studies (Gangolells and Casals, 2012; ABCB, 2010).

Additionally it is also considered here that information policies, namely the ones focusing in emergency management regarding heatwaves can benefit from simplified approaches using vulnerability factors such as the ones identified in this review. Urban areas or cities with dwellings and buildings identified as being more vulnerable can be directly targeted by these kind of policies.

3.6 Conclusions

Results from the review suggest that climate change and variability, in the form of gradual change of climate conditions or extreme weather occurrences can have significant impact on thermal comfort inside buildings. The review allowed for verification that, independently of the approach chosen by each study, there is consensus in recognizing vulnerability as involving a combination of several factors. The evidence found in literature was synthesized in four factors within a vulnerability framework - Location; Age and Form; Construction Fabric and Occupancy and Behavior - and some implications of the evidences found were discussed.

Northern Europe, and in particular the UK, have been particularly active in terms of research on the topic. However, a significant lack of homogeneity in the availability of evidence regarding impacts on thermal comfort in Europe can be implied from the review. In particular, studies focusing on already identified vulnerable regions, such as Southern Europe, with a distinctive building stock from the UK, are lacking and considered here to be important.

Additionally, there is a significant focus on technical studies and the discussion around the future effect of retrofit measures, especially in Europe, such as insulation, and other energy efficiency measures, is worthy of note. In fact, there is some divergence regarding the implementation of measures with the objective of improving energy efficiency in buildings, indicating that a balance between adaptation and mitigation is needed.

This context can be seen in relation of the identified need for simplified approaches that can help policy making. One such approach is the development of an index tool, for which the result of this study can be useful, regardless of the need for specifying the weights of different factors. Variables inferred here can also be used to structure a dynamic model construction for thermal comfort, essential to understand the vulnerability of the building stock and effects of retrofit interventions.

While the role of occupants, and their behavior, is already recognized as significant regarding adaptation in buildings, in Europe this is generally restricted to actions concerning interaction with the controls of the building and does not reflect the totality of actions occupants perform when dealing with extreme temperatures. In this context, qualitative methodologies and statistical analysis of observations could help provide a deeper understanding of the individual adaptive strategies in tackling extreme temperatures and inform technical studies, as well as contribute to comprehend the role of infrastructure and other contextual factors in the choice of strategies. This kind of study would require an interdisciplinary research view on the topic.

Acknowledgments

To the National Foundation for Science and Technology, Portugal (Contract SFRH / BD / 70395/ 2010) for funding the research. The authors would like to thank two anonymous reviewers for their helpful comments and suggestions.

References

ABCB (2010) “An Investigation of Possible Building Code of Australia (BCA) Adaptation Measures for Climate Change”, Australian Building Codes Board, Canberra.

Aguiar, R., Oliveira, M. and Gonçalves, H. (2002) “Climate change impacts on the thermal performance of Portuguese buildings. Results of the SIAM study”, *Building Services Engineering Research and Technology*, vol. 23, pp. 223-231, Available: doi: 10.1191/0143624402bt045oa.

ARCC (2011), “Adaptation and Resilience in a Changing Climate”, Available at: http://www.ukcip-arcc.org.uk/ (Accessed December 2014).

ARUP (2008) *Your home in a Changing Climate - Retrofitting Existing Homes for Climate Change Impacts*, Greater London Authority, London.

ASHRAE (2004) “ASHRAE Standard 55 – 2004 - Thermal environmental conditions for human occupancy*”,* American Society of Heating, Refrigerating and Air-conditioning Engineers Inc.,Atlanta.

Barriopedro, D., Fischer, E., Luterbacher, J., Trigo, R.M. and Garcia-Herrera, R. (2011) “The hot summer of 2010: Redrawing the temperature record map of Europe”, *Science*, vol. 332 (6026), pp. 220-224.

Belcher, S.E., Hacker, J.N. and Powell, D.S. (2005), “Constructing design weather data for future climates”, *Building Services Engineering Research and Technology* , vol. 26, pp. 49-61.

BRANZ (2007)*, “*An Assessment of the Need to Adapt Buildings for the Unavoidable Consequences of Climate Change”, BRANZ for AGO. Dept of the Environment and Water Resources, Canberra.

Brown, S. and Walker, G. (2008), “Understanding heat wave vulnerability in nursing and residential homes” , *Building Research & Information* , vol. 36 (4), pp. 363-372, Available: DOI: 10.1080/09613210802076427.

Capon, R. and Hacker, J.N. (2009), “Modelling climate change adaptation measures to reduce overheating risk in existing dwellings”, in IBPSA (ed.) *Building Simulation*, IBPSA, Glasgow.

Chappels, H. and Shove, E. (2005), “Debating the future of comfort: environmental sustainability, energy consumption and the indoor environment”, *Building Research & Information*, vol. 33(1), pp. 32-40.

CIBSE (2005), “TM36 Climate change and the indoor environment: impacts and adaptation”, The Chartered Institution of Building Services Engineers, London.

CIBSE (2006), “CIBSE Guide A, 7th edn - Thermal comfort: annotated definitions of main thermal parameters”, Chartered Institution of Building Services Engineers, London.

Coley, D. and Kershaw, T. (2010), “Changes in internal temperatures within the built environment as a response to a changing climate” , *Building and Environment* , vol. 45, pp. 89-93, Available: 0.1016/j.buildenv.2009.05.009.

Coley, D., Kershaw, T. and Eames, M. (2012), “A comparison of structural and behavioural adaptations to future proofing buildings against higher temperatures”, *Building and Environment*, vol. 55, pp. 159–166.

Crawley, D.B. (2008), “Estimating the impacts of climate change and urbanization on building performance”, *Building Perform Simulation*, vol. 1, pp. 91-115.

De Dear, R. (2006), “Adapting buildings to a changing climate: but what about the occupants?”, *Building Research & Information*, vol 34(1), pp. 78-81, Available: DOI: 10.1080/09613210500336594.

de Wilde, P. and Tian, W. (2012), “Management of thermal performance risks in buildings subject to climate change”, *Building and Environment*, vol. 55, pp. 167-177, Available: doi:10.1016/j.buildenv.2012.01.018.

Dubrul, C. (1987), “IEA Annex VIII: Inhabitants” behaviour with respect to ventilation”, Air Infiltration and Ventilation Centre, Conventry.

EEA (2012), “Urban Adaptation to climate change in Europe – Challenges and Opportunities for cities together with supportive national and European policies – EEA report”, European Environment Agency, Copenhagen.

European Commission (2012), “Green Infrastructure”, Available at: http://ec.europa.eu/environment/nature/ecosystems/index_en.htm (Accessed November 2014).

Eurostat (2010), “EU Energy in Figures 2010 – Greenhouse Gas Emissions by Sector”, Office for Official Publications of the European Communities, Luxembourg.

Fanger, P. (1970), *Thermal comfort Analysis and applications in environmental engineering*, McGraw-Hill.

Fussel, H.-M. (2007), “Vulnerability: A generally applicable conceptual framework for climate change research” , *Global Environmental Change* , no. 17, pp. 155-167.

Gangolells, M. and Casals, M. (2012) “Resilience to increasing temperatures: residential building stock adaptation through codes and standards”, *Building Research & Information* , vol. 40, no. 6, pp. 645-664, Available: http://dx.doi.org/10.1080/09613218.2012.698069.

Gill, S.E., Handley, J.F., Ennos, A.R. and Pauleit, S. (2007), “Adapting Cities for Climate Change: The Role of the Green Infrastructure” , *Built Environment* , vol. 33, pp. 115-133.

Gromke, C. Blocken, B., Janssen, W. Merema, B., van Hooff, T., Timmermans, H. (2015) “CFD analysis of transpirational cooling by vegetation: Case study for specific meteorological conditions during a heat wave in Arnhem, Netherlands”, *Building and Environment,* vol.83, pp.11-26

Gupta, R. and Gregg, M. (2012), “Using UK climate change projections to adapt existing English homes for a warming climate”, *Building and Environment*, vol. 55, pp. 20–42.

Hacker, J.N. (2008), *Climate change in London: implications for passive and active cooling of dwellings*, ARUP, London

Hacker, J., Capon, R. & Mylona, A. (2009), “Use of Climate Change Scenarios for Building Simulation: the CIBSE Future Weather Years”, Chartered Institution of Building Services Engineers, London

Hacker, J.N. and Holmes, M.J. (2007), “Thermal Comfort: Climate Change and the Environmental Design of Buildings in the United Kingdom”, *Built Environment* , vol. 33, pp. 97-114.

Hamilton, A., Mitchell, G. and Yli-Karjanmaa, S. (2002), ”The BEQUEST toolkit: a decision support system for urban sustainability”, *Building Research & Information* , vol. 30 (2), pp. 109-115.

Hinton, E. (2010), “Review of the literature relating to comfort practices and socio-technical systems”, Available at: http://www.kcl.ac.uk/schools/sspp/geography/research/epd/working.html (accessed December 2014)

Holmes, M.J. and Hacker, J.N. (2007), ”Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century” , *Energy and Buildings*, vol. 39, pp. 802-814, Available: doi:10.1016/j.enbuild.2007.02.009.

Hufschmidt, G. (2011), “A Comparative Analysis of Several Vulnerability Concepts”, *Natural Hazards*, vol. 58, no. 2, pp. 621-643.

IPCC (2013), “Summary for Policymakers”, Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (ed.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2014), “Summary for policymakers”, Field, C.B., Barros, R., Dokken, D.J., Mach, K.J., Mastrandea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCraken, S., Mastrandea, P.R. and White, L.L. (ed.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPMA (2013) “Instituto Portugues do Mar e Atmosfera”*,* Available at: www.ipma.pt (accessed February 2013).

Jenkins, D., Liu, Y., Peacock, A.D. (2008, “Climatic and internal factors affecting future UK office heating and cooling requirements”, *Energ Build,* no 40, pp.874-881

Jentsch, M.F., Bahaj, A.S. and James, P.A. (2008), “Climate change future proofing of buildings e generation and assessment of building simulation weather file”, *Energ Build* , no. 40.

Jentsch, M.F., James, P.A., Bourikas, L. and Bahaj, A.S. (2013), “Transforming existing weather data for worldwide locations to enable energy and building performance simulation under future climates”, *Renewable Energy*, no. 55, pp. 514–524, Available: doi:10.1016/j.renene.2012.12.049.

Kendrick, C., Ogden, R., Wang, X. and Baiche, B. (2012), “Thermal mass in new build UK housing: A comparison of structural systems in a future weather scenario”, *Energy and Buildings*, vol. 48, pp. 40-49, Available: doi:10.1016/j.enbuild.2012.01.009.

Klemm, W., Heusinkveld, B., Lenzholzer, S. Jacobs, M. Van Hove, B. (2015), “Psychological and physical impact of urban green spaces on outdoor thermal comfort during summertime in The Netherlands”, *Building and Environment,* vol.83, pp.120-128

Kwok, A.G. and Rajkovich, N.B. (2010), “Addressing climate change in comfort standards”, *Building and Environment*, vol. 45(1), pp. 18–22, Available: doi:10.1016/j.buildenv.2009.02.005.

Lomas, K.J. and Ji, Y. (2009), “Resilience of naturally ventilated buildings to climate change: advanced natural ventilation and hospital wards”, *Energy Build*, vol. 41 (6), pp. 629-653.

Mavrogianni, A., Wilkinson, P., Davies, M., Biddulph, P. and Oikonomou, E. (2012), “Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings”, *Building and Environment*, no. 55, pp. 117–130, Available: doi:10.1016/j.buildenv.2011.12.003.

McCartney, K.J. and Nicol, J.F. (2002), “Developing an Adaptive Control Algorithm for Europe: Results of the SCATs Project. *Energy and Buildings*, vol 34(6) pp 623-635.

Met Office (2015), “MET OFFICE”, Available at: http://www.metoffice.gov.uk/climate-guide (accessed January 2015).

Miller, F., Osbahr, H., Boyd, E., Thomalla, F., Bharwani, S., Ziervogel, G., Walker, B., Birkmann, J., van der Leeuw, S., Rockstrom, J., HInkel, J., Downing, T., Folke, C. and Nelson, D. (2010), “Resilience and vulnerability: complementary or conflicting concepts?”, *Ecology and Society* , vol. 15(3).

Muller, N., Kuttler, W., Barlag, A. (2014), “Counteracting urban climate change: adaptation measures and their effect on thermal comfort”, *Theor Appl Climatol,* vol.115, pp.243-257

NHBC (2012), *Overheating in new homes - a review of the evidence*, HS BRE Press on behalf of the NHBC Foundation.

Nicol, F. (1993), *Thermal Comfort - A Handbook for Field Studies Toward an Adaptive Model*, University Of East London, London.

Nicol, F. and Stevenson, F. (2013), “Adaptive comfort in an unpredictable world”, *Building Research & Information*, vol 41 (3), pp. 255–258, Available: doi:10.1080/09613218.2013.783528.

Oikonomou, E., Davies, M., Mavrogianni, A., Biddulph, P., Wilkinson, P. and Kolokotroni, M. (2012), “Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London”, *Building and Environment*, vol. 57, pp. 223–238, Available: doi:10.1016/j.buildenv.2012.04.002.

Orme, M. & Palmer, J. (2003), *Control of overheating in future housing, Design guidance for low energy strategies*. Faber Maunsell Ltd., Hertfordshire, UK

Peacock, A.D., Jenkins, D.P. and Kane, D. (2010), “Investigating the potential of overheating in UK dwellings as a consequence of extant climate change”, *Energy Policy*, no. 38, pp. 3277-3288, Available: doi:10.1016/j.enpol.2010.01.021.

Porrit, S.M., Cropper, P.C., Shao, L. and Goodier, C.I. (2012), “Ranking of interventions to reduce dwelling overheating during heat waves”, *Energy and Buildings*, no. 55, pp. 16–27, Available: doi:10.1016/j.enbuild.2012.01.043.

Roaf, S., Crichton, D. and Nicol, F. (ed.) (2009) *Adapting Buildings and Cities for Climate Change*, Architectural Press.

Roberts, S. (2008), “Altering existing buildings in the UK”, *Energy Policy*, vol. 36(12), pp. 4482–4486, Available: doi:10.1016/j.enpol.2008.09.023.

Roberts, S. (2008) “Effects of climate change on the built environment” , *Energy Policy*, vol. 36, pp. 4552–4557.

Sanders, C.H. and Phillipson, M.C. (2003), “UK adaptation strategy and technical measures: the impacts of climate change on buildings”, *Building Research and Information*, vol. 31 (3-4, pp. 210-221.

Santos, F.D. and Miranda, P. (ed.) (2006) *Alterações Climáticas em Portugal. Cenários, Impactos e Medidas de Adaptação" — Projecto SIAM II*, Gradiva, Lisboa.

Smith, C. and Levermore, G. (2008), “Designing urban spaces and buildings to improve sustainability and quality of life in a warmer world”, *Energy Policy*, vol. 36 (12), pp. 4558-4562, Available: doi:10.1016/j.enpol.2008.09.011.

Stern, N. (2007) *The Economics of Climate Change: The Stern Review*, Cambridge University Press, Cambridge.

Tuohy, P.G., Rijal, H.B., Humphreys, M.A., Nicol, J.F., Samuel, A.A. and Clarke, A. (2007) “Comfort driven adaptive window opening behaviour and the influence of building design” , *Proceedings of Building Simulation 2007, 10th IBPSA Conference.*

UKCIP (2002), “United Kingdom Climate Impact Programme”, Available at: http://www.ukcip.org.uk/ukcp09/ukcip02/ (accessed 15 July 2014).

UKCIP (2009), “United Kingdom Climate Impact Programme Projections”, Available at: http://ukclimateprojections.defra.gov.uk/ [accessed 16 July 2014].

UNEP (2007), *Buildings and Climate Change: Status, Challenges and Opportunities*, United Nations Environment Programme.

van Hooff, T., Blocken, B., Hensen, J.L.M. and Timmermans, H.J.P. (2015), “Reprint of: On the predicted effectiveness of climate adaptation measures for residential buildings” , *Building and Environment*, vol. 83, pp. 142-158, Available: http://dx.doi.org/10.1016/j.buildenv.2014.10.006.

Vandentorren, S., Bretin, P., Zeghnoun, A., Mandereau-Bruno, L., Croisier, A., Cochet, C., Ribéron, J., Siberan, I., Declercq, B. and Ledrans, M. (2006), “August 2003 heat wave in France: risk factors for death of elderly people living at home”, *Eur J Public Health*, vol. 16 (6), December, pp. 583-91.

Voskamp, I.M., Van de Ven, F.H.M. (2015), “Planning support system for climate adaptation: Composing effective sets of blue-green measures to reduce urban vulnerability to extreme weather events”, *Building and Environment,* vol.83, pp.159-167

Wamsler, C., Brink, E., Rivera, C. (2013), “Planning for climate change in urban areas: from theory to practice”, *Journal of Cleaner Production,* vol.50, pp.68-81

Wang, X., Chen , D. and Ren, Z. (2010), “Assessment of climate change impact on residential building heating and cooling energy requirement in Australia”, *Building and Environment*, vol. 45, pp. 1663-82.

WHO (2004), *Health and Global Environmental Change: Heat Waves: Risks and Responses*, World Health Organisation.

Wilby, R.L. (2007), “A Review of Climate Change Impacts on the Built Environment”, *Built Environment* , vol. 33, pp. 31-45.

WMO (2014), “World Meteorological Organization-backed study confirms 2014 on track to be Europe’s warmest year on record”, Available at: http://www.wmo.int/pages/mediacentre/news/europeswarmestyearonrecord.html (Accessed 13 February 2015).

Young, A.N., Pathan, A. & Oreszcyn, T.(2007), “Domestic air conditioning - occupant use and operational efficiency, Final Report”, University College London, London, UK.

4 CHAPTER 4 - CLIMATE CHANGE AND THERMAL COMFORT IN SOUTHERN EUROPE HOUSING: A CASE STUDY FROM LISBON.

Paper II – Published in Building and Environment

Full reference:

Barbosa, R.,Vicente, R., Santos,R.(2015) “Climate change and thermal comfort in Southern Europe housing: A case study from Lisbon”, *Building and Environment 92*, 440-451

Climate Change and Thermal Comfort in Southern Europe Housing: a Case Study from Lisbon

Ricardo Barbosa [1], Romeu Vicente [2], Rui Santos [1]

[1] CENSE – Center for Environmental and Sustainability Research, Departamento de Ciências e Engenharia do Ambiente, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Campus da Caparica, 2829-516 Caparica, Portugal

[2] Departamento de Engenharia Civil, Universidade de Aveiro

Abstract

The world has been experiencing a significant increase in daily average temperatures per decade and climate change scenarios are projecting high probability of more frequent heat waves. In vulnerable regions, like Southern Europe, where most of the residential buildings still rely on natural ventilation for cooling, impact on thermal comfort can be significant in terms of health, well-being and also energy consumption. The question is particularly important for the existing building stock, which was not designed considering the projected future climate conditions and is prone to be subjected to interventions with the purpose of improving thermal performance. The study presents a vulnerability framework and methodology for the assessment of thermal comfort in existing dwellings in the context of climate change. Results relating to a 1960s typical building case study in Lisbon, Portugal, suggest that specific dwelling characteristics, such as orientation, and occupancy profiles are relevant when assessing vulnerability, suggesting significant differences, of up to 91% in discomfort hours on a annual basis. Furthermore, increased insulation seems to be effective in decreasing discomfort, as the best results (48% in discomfort hours decrease) stem from a context of external insulation for a heatwave situation. The methodology can be useful for assessing vulnerability in existing dwellings and its specific conditions. It can also contribute to understanding the effect of energy retrofitting measures in future climate conditions, assisting energy efficiency policies and decision-making regarding retrofit interventions.

Keywords: Thermal Comfort, Vulnerability, Adaptation, Climate Change, Energy Retrofit

4.1 Introduction

As the world experiences a progressive increase in temperature, climate change is recognized as a global key challenge for the 21st century. According to the Intergovernmental Panel for Climate Change (IPCC), an increase in the global mean surface temperature is expected to range from 0.3˚C-0.7˚C to 2.6˚C-4.8˚C until 2100 in relation to a 1986-2005 baseline (IPCC, 2013). Moreover, results from modelling studies indicate a 5 to 10 factor increased probability in the occurrence of more frequent and severe heatwaves in a 40-year timeframe (Barriopedro et al., 2011). Heatwaves are considered to be life-threatening events and are an object of concern regarding adaptation (EEA, 2012). During the 2003 European heatwave, still seen as a reference due to its intensity, duration and geographical extension fields (IPMA, 2013), countries like France, England and Portugal registered an increased number of deaths related to abnormal high temperatures inside dwellings (Vandentorren et al., 2006) .

Cities are at the forefront of this challenge. It is estimated that, for a developed nation, about 25%-40% of energy-related anthropogenic emissions of carbon dioxide can be attributed to buildings (Eurostat, 2010). Acknowledging this fact, energy efficiency of buildings has been promoted as an important mitigation factor in the political and technical European agenda. With a focus on the concern about the rational use of energy and associated reduction of emissions, legal measures and regulations were adopted in order to establish minimum levels of thermal performance for both new and existing buildings.

However, whether due to slowly changing climatic conditions or more frequent, sudden extreme events, existing buildings (and their occupants) will most likely have to cope with conditions for which they were not initially designed, thus compromising their ability as “climate moderators” (Roaf et al., 2009). These views combined suggest there is a need to balance mitigation and adaptation to a changing climate. In Europe, the vast majority of residential buildings still remain naturally ventilated (Eurostat, 2010), therefore proving relevant the discussion in literature about the factors motivating the increasing uptake of home air conditioning devices (Peacock et al., 2010). A core argument is that, in response to future expectations of change in temperature, the installation of such devices is likely to increase, which would lead to a greater energy demand from buildings (Stern, 2007). This line of thinking is important to the extent that studies point out high levels of fuel poverty occurring already in Europe, predominantly in Eastern and Southern European countries (Thomson and Snell, 2013) and that the most vulnerable households may not afford the increasingly high fuel costs in summer, leading to interesting discussions around the concept of summer fuel poverty in those countries (Hills , 2012).

The study of these issues is therefore significant not only from a perspective of human well-being but also from an energy savings and efficiency point of view. Several studies suggest that there are potential significant impacts to be expected in terms of discomfort as a result of climate change and extreme events, differing according to the geographical location, building type and function (Lomas and Giridharan, 2012), as well as constructive characteristics (Mavrogianni et al., 2012). For this reason, thermal comfort and adaptation studies are being conducted on a common ground, with an underlying discussion regarding the adequacy of thermal comfort standards in assessing indoor conditions in the future (Nicol and Stevenson, 2013) and which kind of climate projections to use (Jentsch et al., 2008). The review highlights the fact that Northern Europe and United Kingdom in particular, have been the most active in research on impacts and adaptation to a changing climate in buildings, either from monitoring and/or modelling (de Wilde and Tian, 2012), but studies focusing on Southern Europe are scarce in comparison. In that context, a study worth of note related to Portugal, is Aguiar et al. (2002), devoted to thermal loads of a typical single-family house and an apartment. Results indicate that a reduction in heating requirements is expected, but it would not compensate entirely for the increase in air conditioning demand in summer, which suggests a considerable impact on the thermal performance of buildings. The study was part of a broader research regarding scenarios, impacts and adaptation in Portugal (Santos and Miranda, 2006) concerned with impacts on the energy sector and assisting the preparation of the National Adaptation Plan. National Adaptation Plans are generally considered the backbone of regulation and strategies regarding adaptation, although approaches for implementing and evaluating the proposed strategies seem to be lacking (Biesbroek et al., 2010). This gap is acknowledged by Gangolells et al. (2012) while exploring the impacts of the Spanish stock of buildings to climate and summer overheating. It argues for the role of regulatory instruments, until now focusing strongly on mitigation, as well as the very constitution of the existing building stock, concerning age and physical quality. In fact, Southern Europe is characterized by a stable and aging building stock of significant proportions, mainly built prior to the implementation of thermal regulations (Eurostat, 2010), which has been already been identified as a major challenge regarding sustainable development (Hamilton et al., 2002). In existing buildings, adequate thermal performance is mainly promoted through retrofitting actions, prone to increase thermal insulation and air-tightness, and several authors have already suggested that a heating-reduction driven policy and decision-making regarding measures such as insulation, can have unexpected effects if considered in a climate change context (CIBSE, 2005; Gangolells and Casals, 2012; Mavrogianni et al., 2012). These studies also stress the fact that most literature dedicated to adaptation regarding thermal comfort is technically focused and driven to understand adaptation measures to be applied to buildings (Lomas and Giridharan, 2012; Porrit et al., 2012; van Hooff et al., 2015). In comparison to building design, attention given to the role of occupants and their behavior while operating naturally ventilated building controls in reviewed studies across Europe, is limited (Roetzel and Tsangrassoulis, 2012; Coley et al., 2012).

This paper contributes to this body of work briefly presented above, by focusing on the influence of insulation measures in building envelopes, particularly in residential buildings and at the scale of dwellings, where occupant behavior and ventilation strategies can be determinant in avoiding indoor discomfort. Consequently, an examination of prevailing thermal comfort standards and their usefulness in assessing comfort in a changing climate context, is also a key aspect of this study.

Additionally, this study conceptualizes the problem as a vulnerability issue. Vulnerability represents a well-researched and mature approach to understand a system's response to change, despite the variety of definitions and approaches found in literature (Miller et al., 2010). The IPCC definition, as "the propensity or predisposition to be adversely affected"

(IPCC, 2014) consider it to be a function of the magnitude and character of the climate variation and change, its exposure, sensitivity and adaptive capacity. While recognizing the generic nature of this definition, vulnerability here is approached from a biophysical perspective (Fussel, 2007) and the dwelling, as a unit of accommodation, is seen as a system, encompassing the physical environment, the occupants and the rules and institutions regulating how occupants interact with building controls in order to achieve comfortable conditions (Chappels and Shove, 2005). The above-cited definition presupposes exposure as related with "the presence of people (…) infrastructure or economic social or cultural assets in places that could be adversely affected" (IPCC, 2014). Furthermore, sensitivity is defined as "the degree to which a system (….) is affected (…) by climate variability or change" (IPCC, 2014) and adaptive capacity is considered to be "the ability of systems, (…) to adjust to potential damage (…) to respond to consequences" (IPCC, 2014). From this viewpoint, adaptive capacity is not a direct component of vulnerability, as generally interpreted (Gallopin, 2006). Instead, it is operationalized as a property of the system, capable of offsetting or reducing vulnerability, through the implementation of adaptation strategies.

A methodology is proposed to assess relative effectiveness of changes in thermal comfort vulnerability and is illustrated and developed through its application on two dwellings in Lisbon (Portugal).

4.2 Methodology

The main objective of this study is to develop a methodology to assess thermal comfort vulnerability in residential buildings for Portugal, taking into consideration potential changes, namely those regarding levels of insulation and occupancy. This section presents the materials and methods used and elaborate on the particularities of the case study used to develop the methodology.

4.2.1 Case study

With a recorded increase in average temperature of 0,5˚C per decade, Southern Europe is considered to be more vulnerable to climate change than Northern Europe (Santos and Miranda, 2006). As an example of dense Mediterranean cities with a significant heat island effect (Alcoforado, 2006), Lisbon has mild winters and hot and dry summers with high levels of solar radiation. According to the monthly climate data for Lisbon, the hottest month is August, with an average temperature of 23.5˚C. The highest absolute temperature ever registered was 42˚C, during the 2003 heatwave (IPMA, 2013). During the last decade, heatwaves were recorded in at least half the years, occasionally more than once a year, and lead to significant losses in terms of human lives and well-being (ARSLVT, 2012).

Most of Lisbon buildings constructed after 1950 used reinforced concrete (INE, 2011) at a time when specific building codes and thermal regulation were still lacking - the first Portuguese thermal regulation only came in place in 1990 (DL. 40/90 of February 6th). With the gradual neglect of vernacular architecture features and insufficient knowledge about new construction techniques, buildings constructed in these decades are the ones which now present the most significant structural and thermal retrofit needs (INE, 2011; Climaco, 2012), although the more modern techniques represented an improvement in terms of thermal transmittance in the building envelope (Santos and Matias, 2006). This context is meaningful, considering that the 60´s and 70´s decades were a booming era of concrete construction in Lisbon and about 23% of the present city building stock dates from that period. In terms of dwellings, the 60"s and 70´s typology represents 32% of the existing dwellings in the city area, making it far more representative of the building stock than simply considering number of buildings (INE, 2011).

The building chosen as a case study was built in 1960 and is located on a central avenue in the city of Lisbon - Avenida Almirante Reis. It has two exposed façades – East and West oriented. The building is partially elevated in the West façade, allowing for a recessed entrance and commercial spaces on the ground floor. Each floor of the building has four dwellings. Each dwelling consists of a living/dining room, a bedroom; a kitchen and a bathroom with an average area of 75 sqm (Figure 4.1). Each dwelling has only one front and does not present the possibility of cross ventilation.

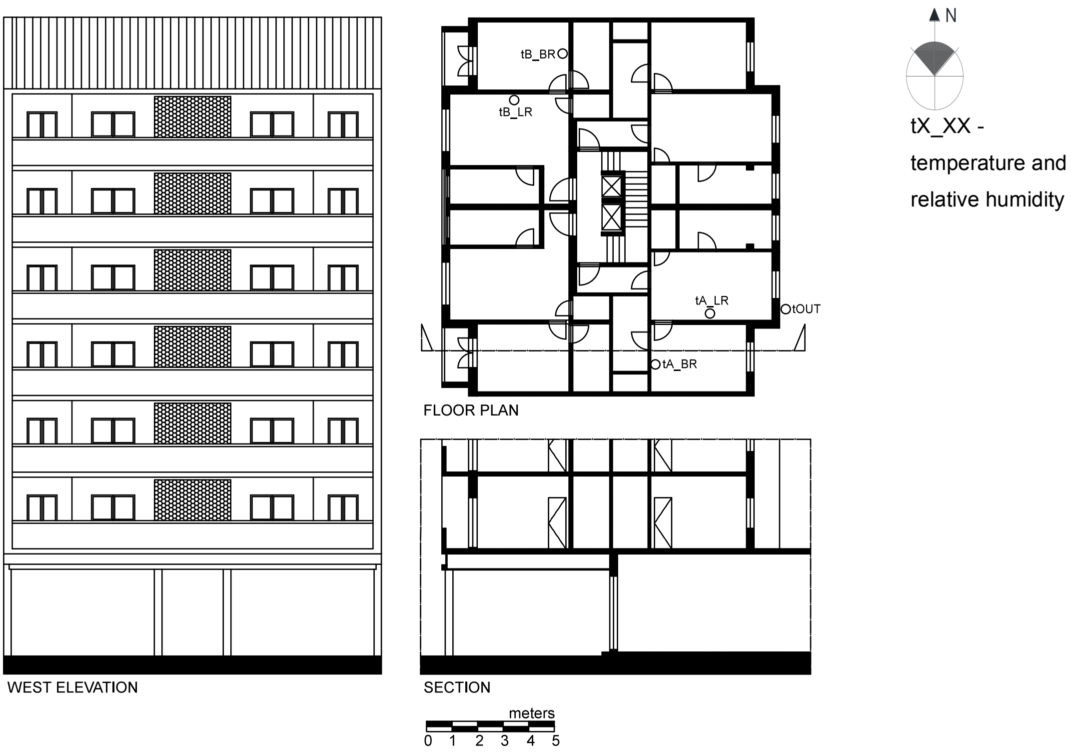


Figure 4.1 - Case study building: West Elevation; Section and Floor Plan with temperature sensor positioning

4.2.2 Materials and Methods

A six-stage methodology, which is bound to enable the construction of valid numerical models to predict indoor conditions, is considered and laid out in Figure 4.2.

In the first stage, preliminary data regarding climate, geometric and constructive characteristics (physical characteristics) and occupancy data are determined. This stage requires the acquisition and study of geometric field measurements and archive drawings, as well as observations of typical occupancy and window and shading devices operation.

The second stage relates to space monitoring with a focus on recording internal temperatures, in order to understand actual dwellings performance under occupant behavior.

The third stage of the methodology concerns the construction of a dynamical multi-zone thermal model. EnergyPlus (EP) was chosen to perform the analysis regarding dynamical thermal simulations, using Design Builder v4 as the graphical interface for input (DB, 2014). EP is widely considered as a credible and validated tool to evaluate free-running indoor environments, in dynamic regimes, using hourly and sub-hourly simulations (Crawley et al., 2008).

The model is then calibrated using the weather data recorded during the monitoring period.

The calibrated model is used to predict internal temperatures for both projected typical weather data and extreme conditions, while also being subjected to physical and behavioral variants regarding changes in order to assess its effect on internal temperatures.

In the final stage of the process – Comfort Assessment – predicted internal temperatures are compared with the appropriate thermal comfort standard to assess the extent of thermal comfort vulnerability.

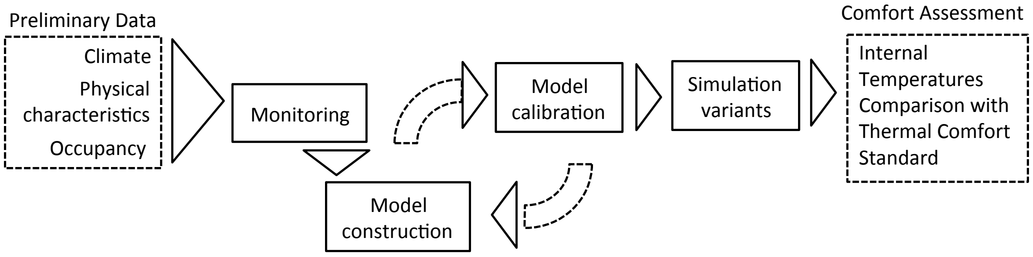


Figure 4.2 - Methodology for thermal comfort vulnerability assessment

4.2.2.1 *Preliminary Data*

Climate

For this study, two types of weather data are considered and described in this section.

The first is related with a real heat wave period (i.e. July 29th to August 15th 2003), collected from Gago Coutinho meteorological station (IPMA, 2013). Situated at approximately 1 km from the case-study building, the station location was absorbed by the city urban development and its data was also already used to study heat island effects (Alcoforado, 2006. Data was processed to fit EP format and in the case of missing data necessary for model simulation, interpolated typical weather data (IPMA, 2013) for the same period in the year was used.

The second type of data is related with climate change projections. In order to generate climate change scenarios weather data for Lisbon, a “morphing” methodology was used, using CCWorldWeatherGen weather file generator (Jentsch et al., 2013). This tool allows generating future Typical Meteorological Years (TMY) weather files in a compatible format with most building performance simulation programs. The “morphing” methodology was initially developed by Belcher et al.(2005) in order to combine “present day” data with hourly time steps and monthly projections of climate change into future hourly weather data. It adds the predicted absolute changes to the original weather data (a process designated as shift calculation), multiplies it by the predicted fractional change (stretch calculation) or combines the two approaches.

Using IPCC Third Assessment Report summary data of the HadCM3 experiment ensemble, hourly weather files considering A2 (medium-high) emission scenarios for two future time slices of 2041-2070 (2050) and 2071-2100 (2080) (Belcher et al., 2005) were generated by the TMY developed by INETI [42]. Despite the fact that the most recent Representative Concentration Pathways scenarios from IPCC (IPCC, 2014) are still not available within the tool, regarding mean temperature increase until 2100, strong similarities with RCP scenarios were found (Rogelj et al., 2012).

Physical Characteristics

Being an existing building, constructive components were assessed resorting to Lisbon Municipality Archives and the National Statistics Institute (INE). Data concerning thermal properties of materials was taken from indicative literature of reference values. Whenever possible, technical information from national sources was used. Both building and dwelling characteristics are presented in Table 4.1. Regarding construction materials, the only relevant modification to the original external envelope is the introduction of PVC windows frame and double-glazing.

Occupancy

Data used in simulations, related to occupancy profiles and natural ventilation habits through window opening strategies, were obtained from the occupants filling in a diary, during the monitoring period. The occupants could register window openings and shading schedule, which allowed for the identification of two differentiated profiles. Data was typified and is summarized in Table 4.2.

Table 4.1 - Building and dwelling characteristics.

Building general characteristics				Dwelling specific characteristics			
Component	Description	Thickness (mm)	U-Value (W/m^2°C)	Dwelling	Orientation	Glazed area(m^2)	Total exposed(m^2)
Exterior wall	Cement plaster Hollow brick masonry No insulation Gypsum render	240	1.7	A	East	3.8	24.4
Interior wall	Gypsum render Hollow brick masonry	150	2.6				
Floor and Pavement	100 mm Concrete slab No insulation* Wood flooring	200	3.1	B	West	4.4	54.8 *
Glazing and windows	PVC frame with double glazing		2.4				

Source for thermal properties material: (Santos and Matias, 2006; DOE, 2011)

*includes partially exposed slab

Table 4.2 - Occupancy, shading and ventilation profiles during the monitored period

Occupancy Profile	Young working couple (YC) (24y/23y)	Old retired couple (OC) (80y/73y)
	Living room Weekday: from 7pm to 0 pm Weekend: 10 am to 2 pm and 7pm to 0 pm Bedroom Weekdays: from 0 to 8 am Weekend: from 0 to 10 am	Living room Weekday and Weekend: from 12 am to 0 pm Bedroom Weekday and Weekend: from 9pm to 8 am
Shading	Weekdays: Internal blinds closed until 7pm Weekends: opened 9 am and closed around 8 pm	Internal blinds are closed around bed time – 10 pm.
Natural Ventilation (NVent)	Window opening schedule on Weekdays: From 8:00 am till 9 pm (30%) Weekends From 11:00 till 5 pm	Window opening schedule on Weekdays: From 14:00 till 16:00 Weekends From 9:00 till 16:00

4.2.2.2 Monitoring

The dwellings (A and B) were monitored during two months – October and November 2013, regarding temperature (°C) and relative humidity (%), in both bedrooms (A_BR and B_BR) and living rooms (A_LR and B_LR). Outdoor temperature was also collected (OUT). Five data-loggers TESTO 174H, meeting standard ISO 7726 requirements [44] were used as measuring instruments. These instruments have a temperature range of -20°C to 70°C and an accuracy of ±0.5°C and they were positioned according Figure 4.1, protected from solar radiation or close sources of internal gains.

4.2.2.3 Model construction

The model was constructed taking into consideration neighboring buildings that can cause potential shading (see Figure 4.3).

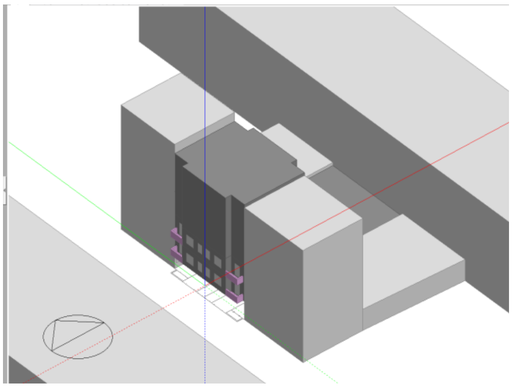


Figure 4.3 - Perspective of model integration in urban context

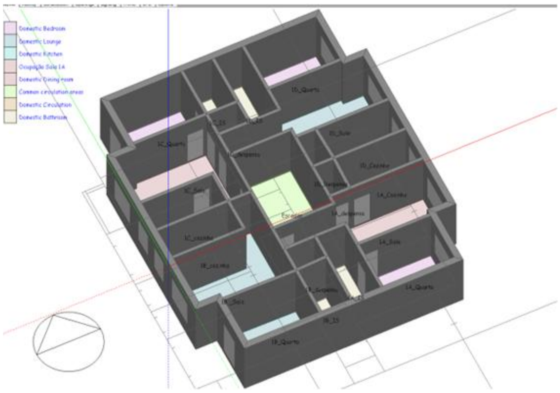


Figure 4.4 - Layout of multi-zone model (axonometric view of thermal zoning)

The assembly of the model considers 17 thermal zones (Figure 4.4), even if only 4 thermal zones (Bedrooms and Living Rooms) were to be analyzed in detail. This allows for gains verified in adjacent thermal zones to be taken into account in calculations. Internal gains were typified taking into consideration Table 4.3.

Table 4.3 – Typical internal gains (adapted from Canha da Piedade et al (2009))

Gains level	Lighting (W/m^2)	Equipment (W/m^2)
Low	5	5
Medium	15	10
High	25	20
Occupants	74.6 W/person	

4.2.2.4 Model Calibration

Despite EP being recognized as accurate and robust, the interface usage and incorrect accounting of variables can lead to an inaccurate analysis (Climaco, 2012). Discussion about uncertainty and error regarding building simulation is abundant and several perspectives can be found. Pertinently for this study, De Wilde and Tian (2012) alert for uncertainties inherent of the definition of the building itself, but also for the ones concerning occupant behavior and retrofit interventions, all of which can be represented by an unlimited number of combinations and parameters. Being so, the collection and use of real data in a calibration process can be a valuable tool to validate the simulation model. The calibration of the model was carried out through the improvement of several inputs in a way that the output results – in this case, internal temperatures – match the observed data. Using real weather data collected from the monitoring period a weather file was constructed to the specific purpose of calibrating the model. Occupancy was considered in the form of typified profiles (Table 4.2). Since technical characteristics of the physical elements were assessed with some detail, major modifications in these parameters were not expected. Thus, a sensitivity analysis to calibrate the model was performed, regarding air infiltration, natural ventilation and internal gains as main parameters. The procedure proposed by Liu and Liu (2011) using Root Mean Square Error (RMSE) was used, regarding the difference between measured and simulated temperatures. The value was calculated daily concerning the monitoring period. Following other studies (Climaco, 2012), results were considered acceptable, if the RMSE was below 1°C.

4.2.2.5 Simulation Variants

The simulation variants were performed for the two types of climate variation and change considered here – heat wave period and climate scenarios, resulting in 18 different combinations and 54 simulations, structured according to Figure 4.5. Regarding climate change simulations, occupied hours in the cooling season (June to September) were considered.

The objective of the first simulation (S01) is to obtain internal temperatures taking into consideration original characteristics, occupancy and ventilation strategies (NVent) as registered in 2013 during the monitoring period. The second simulation (S02) intends to analyze both dwellings while presenting the same occupancy and ventilation profiles. The worst case – longer occupancy time – is considered here. The next simulation (S03), uses the same approach as S02, but adopts what is designated here as an optimal ventilation strategy (OptVent). In practice, occupants will adjust ventilation strategies until a certain point when facing climate variability. This optimal strategy considers no physical constraints and windows opening when outdoor temperature is at least two degrees below indoor temperature (staying that way until this condition is valid), also allowing for night ventilation in bedrooms.

The last batch of simulations, designated as S04, intends to obtain internal temperatures to assess the effect of the insulation increase on dwellings. Buildings in Lisbon are thought to be responsible for 50.5% of primary energy consumption and 58% of associated greenhouse gas emissions (Lisboa E-Nova, 2008). Together with the installation of improved thermal performance windows and glazing solutions, increased insulation is a popular and government-incentivized measure for energy efficiency (DGEG; ADENE, 2008). The most common wall insulation types used in Portugal were assessed considering a market study from a national research institute (ITeCons, 2013). Different options regarding positioning of insulation (External/Internal), insulation thickness (it) and thermal transmittance coefficient

(UValue) were chosen, in compliance with reference values determined by the Portuguese thermal regulation for buildings (REH, 2013), and simulated for the two dwellings.

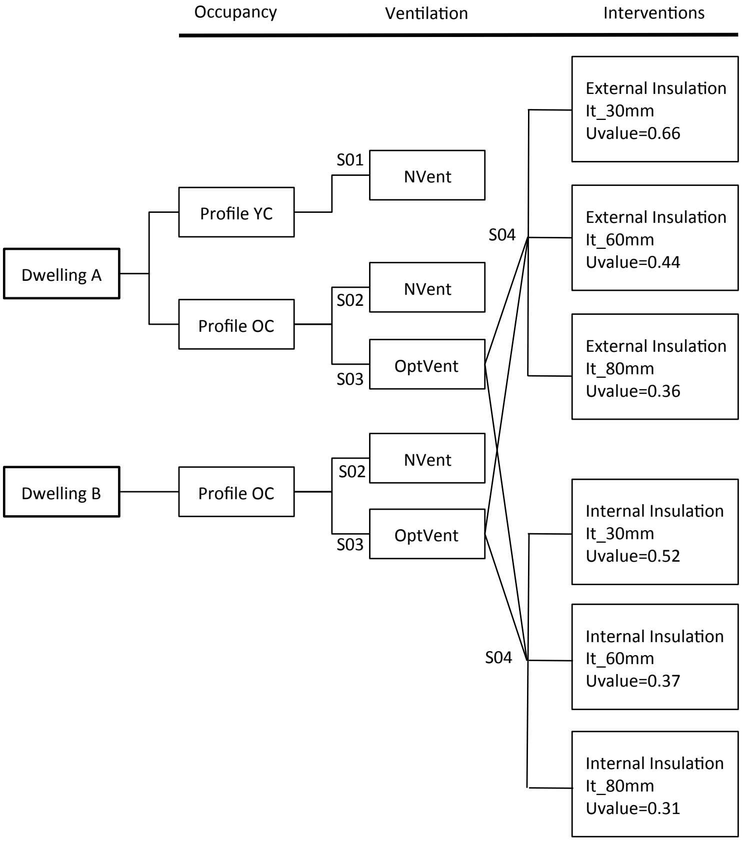


Figure 4.5 – Configuration of simulation variants

4.2.2.6 Models for Comfort assessment

Because it is rooted in human sensations, the concept of comfort is of difficult definition and depends on multiple factors (Nicol and McCartney, 2000). It can be defined as "the state of mind expressing satisfaction with the thermal environment" (ASHRAE 55, 2004). Two generally contrasting approaches can be distinguished regarding thermal comfort assessment. The analytical or static model (hereafter designated as STAT), mainly derived from thermal chamber studies (Fanger, 1970), is often criticized for considering individuals as only a recipient of the thermal stimulus (Kwok and Rajkovich, 2010), but has been the basis for the reference conditions for a significant number of thermal regulations in Europe, establishing fixed limits of comfort temperature, as in the case for Portugal, where a range of acceptable values for reference temperatures (18˚C to 25˚C) has been established (REH, 2013), mainly for energy demand calculation purpose. The adaptive model (hereafter designated as ADPT), developed by means of fieldwork studies (De Dear et al., 1997) considers the fact that people have a response to change and are willing to act in order to restore thermal comfort conditions. Additionally, it is based on the presupposition that there is a correlation between what occupants perceive as comfort temperature and the outdoor temperature, making it particularly suitable for assessing comfort in a changing climate context (Nicol and Stevenson, 2013; Lomas and Giridharan, 2012). Being so, ADPT was chosen as the primary model for assessing comfort in this study. While other options are available (e.g. (ASHRAE 55, 2004), the adaptive model defined in the European standard (CEN, 2007) offers advantages, namely regarding the temperature range applicability (Lomas and Giridharan, 2012). Additionally, this particular model uses data collected in several locations of Europe, including Portugal (Nicol and McCartney, 2000). Despite the fact that data is mainly from non-residential buildings, which can be pointed out as a potential limitation to the model, the use in residential contexts can also be found (Porrit et al., 2012).

This adaptive model allows for determination of the operative temperature of comfort T_{oc}, depending on exterior conditions, calculated through Eq.(1). Exterior conditions are considered in the form of the weighted running mean exterior temperature T_{rm}, which also accounts for temperatures recorded in previous days.

$$\boldsymbol{T_{oc}} = \boldsymbol{0{,}33.T_{rm}} + 18{,}8\ (^{\circ}\mathrm{C}) \qquad (1)$$

To the temperatures defined through this equation, it is suggested, in the standard, that the effect of the type of building typology should be considered. This is operationalized by the use of categories. Three categories are accounted for in this model: each category defines a determined interval of temperatures a user may find comfortable, depending on the type of the building and thereby defining a upper and lower threshold. Category I is the most demanding and used for indoor spaces with special requirements (like hospitals) and the range of temperatures considered here is narrower than the other two categories. Category II corresponds to the normal level of expectation for new buildings and renovations. The building in the case study is considered to be in category III, the one with the broader range of acceptable temperatures (±3°C) , applicable to existing and non-retrofitted buildings.

Figure 4.6 shows the upper and lower thresholds considered in both models. For the ADPT model, values were calculated using Eq(1).The graph highlights the significant range of temperatures that can be considered as operative temperatures within the range acceptable as comfortable, in particular in ADPT model, depending of the exterior conditions. For the STAT model, a lower threshold of 18°C and upper threshold of 25°C is considered, above which the room is in discomfort, independently of exterior conditions.

In order to operate EN15251 standard, T_{rm} is calculated for the three previous days. The resulting T_{oc} hourly values from simulations are then compared to the operative temperatures produced by Eq. (1). If the simulated temperature is higher than the one produced by the model, the zone is considered to be in discomfort for that whole hour. These calculations are performed for the living rooms and bedrooms of both dwellings, because these are the most occupied areas during the day.

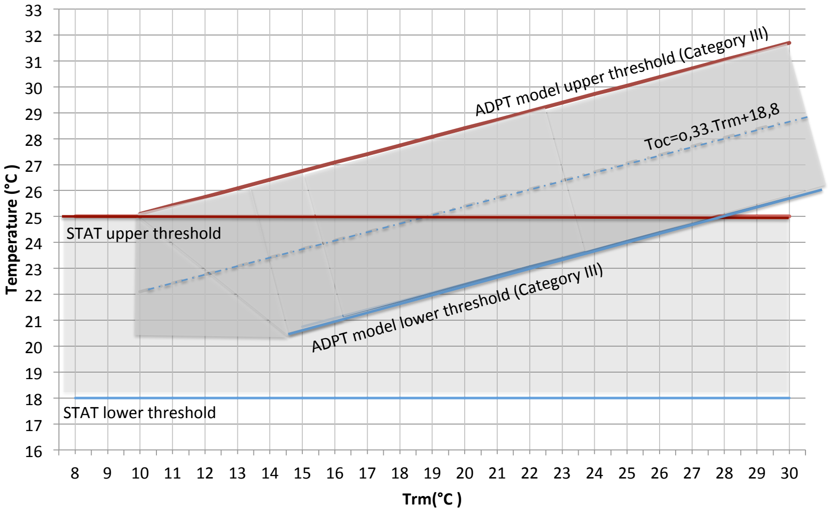


Figure 4.6 – Design values for STAT and ADPT models of comfort, as a function of outdoor temperature running mean. Source: adapted from CEN (2007) and REH (2013)

The two models present significant conceptual and practical differences in the way comfort is assessed. Regarding the study performed here, it is considered useful to compare the results obtained from simulations with STAT and ADPT models for comfort assessment.

If thermal comfort is assessed and the effect of insulation measures quantified, it is possible to consider the best option for implementation of insulation in terms of vulnerability of thermal comfort. This is performed by considering approximate costs and the effect of insulation measures in the form of decreasing or increasing of discomfort. Approximate costs per square meter of interventions were taken from CYPE database (CYPE, 2013) and total costs consider the implementation of insulation material (including the cost of labor) of the building envelope adjacent to dwelling.

4.3 Results

4.3.1 Climate

Heatwave period

In Figure 4.7, frequency of air temperature values for both Summer Design Week (SDW) – the week considered as the hottest in TMY - and the heat wave period (HW) is compared. While most of the temperatures in SDW are in the 14-18°C interval, in HW 28% of registered temperatures are in the highest interval considered here (>32 °C).

Climate Change

In Figure 4.8 it is possible to compare air temperatures frequency of values between the three typical years datasets used for simulation. Only the cooling season (from 1 st June to 30 th September) is considered here. There is a visible trend in data regarding increasing temperatures towards TMY 2080.

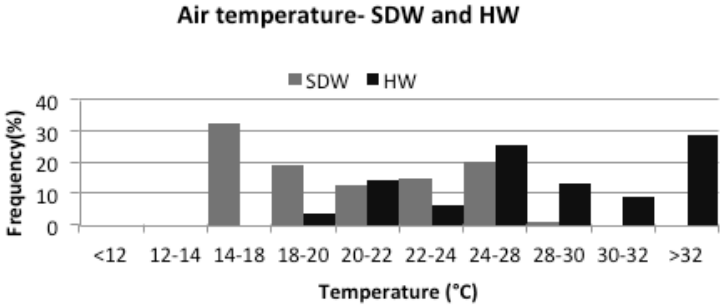


Figure 4.7 – Summer Design Week and Heatwave Period – Temperature frequency

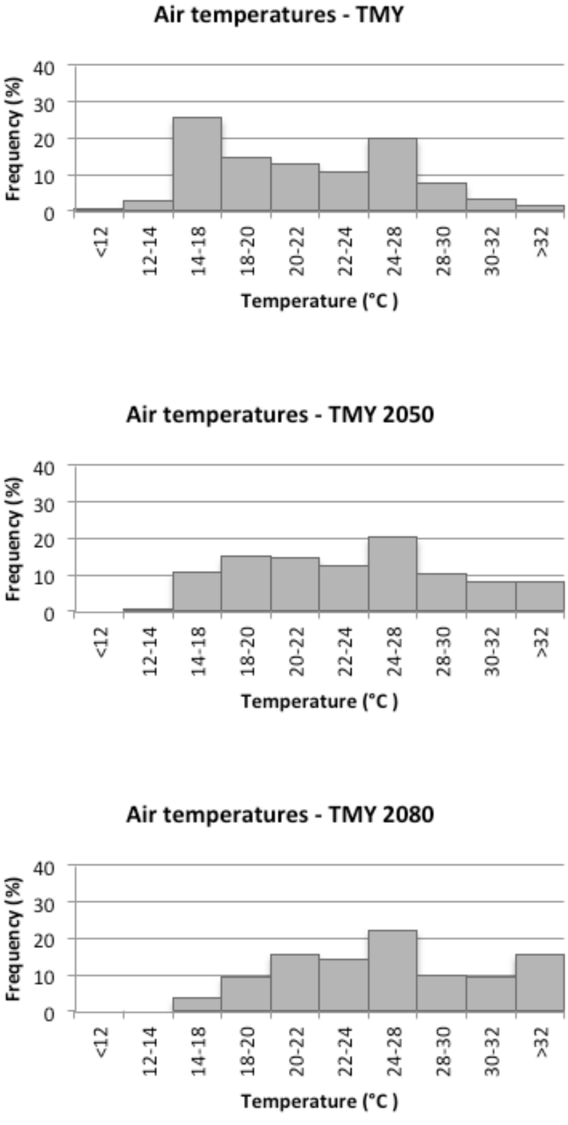


Figure 4.8 - TMY and Climate Change Scenarios - Temperature Frequency

4.3.2 Monitoring

Figure 4.9 plots the hourly temperature range recorded during the monitoring period. It is noticeable that the higher number of occurrences are in the 22-24°C range of temperatures on B_BR as well as in A_LR. During the monitoring period, most of the outdoor temperatures (37%) were between 18-20°C.

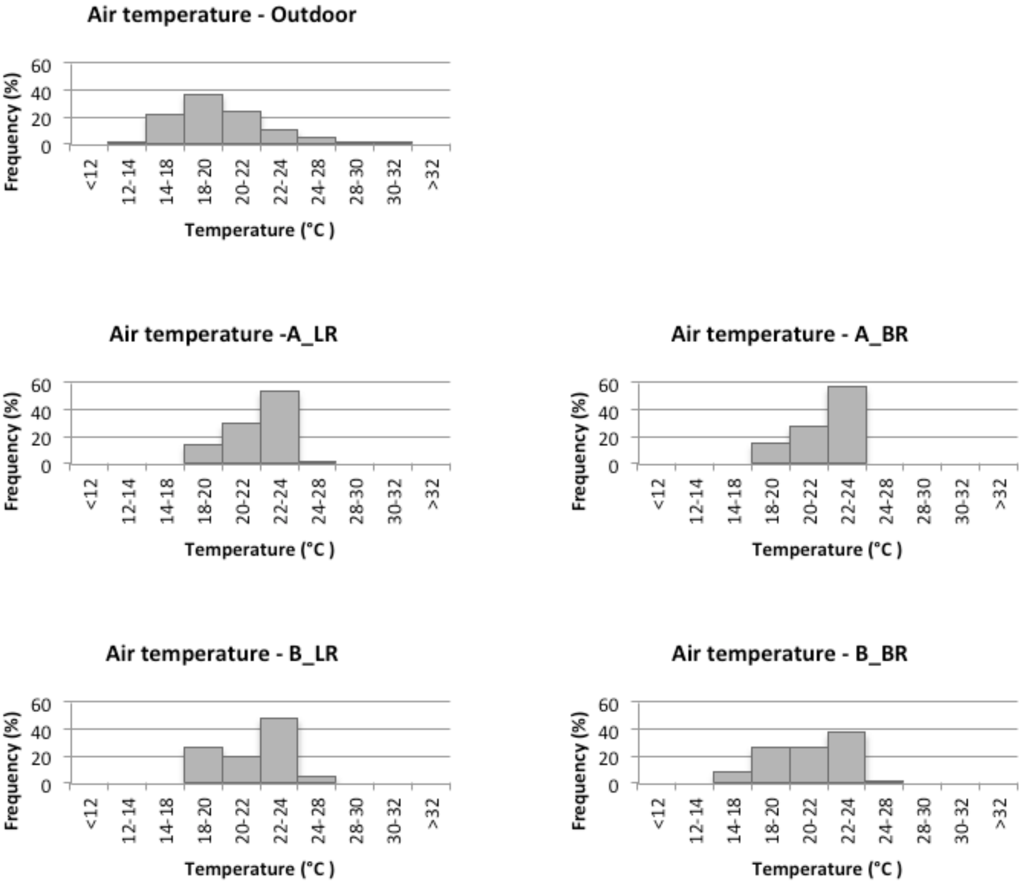


Figure 4.9 – Monitoring period – Temperature frequency

4.3.3 Calibration

The sensitivity analysis performed allowed to achieve considerably acceptable RMSE results. For A_LR, sensitivity analysis allowed for an RMSE average value of 0.44. For A_BR, the value was 0.38. Regarding dwelling B, the best result for B_LR was 0.61 and for B_BR, 0.85. Figure 4.10 illustrates the final results for B_LR. Resulting air infiltration rate was defined as 0.7 ac/h, which is consistent with the conventional values for residential buildings indicated in the national regulation, taking into consideration the exposure and class of windows (REH, 2013). Regarding natural ventilation, the maximum value was established at 5 ac/h, not allowing for cross ventilation (BRE, 2010).

4.3.4 Simulations variants

Figure 4.11 and Figure 4.12 show S01 simulation results. For HW, about 80% of occupied hours in discomfort in A_LR and B_LR zones are indicated. A_BR presents 47% less hours in discomfort than B_BR. For present TMY, no discomfort hours were calculated. However, for 2050 climate, both living rooms present results above 10% of occupied hours in discomfort for the cooling season. For 2080 climate, B_LR presents 23% more discomfort hours than A_LR while in both bedrooms, around 20% of the occupied time is calculated to be in discomfort. Figure 4.13 and Figure 4.14 show S02 and S03 simulations results. In the conditions considered for HW, A_LR presents significant less discomfort hours than B_LR, which has almost 80% of the occupied time in discomfort. Concerning bedrooms, the difference is also relevant, since results suggest only 5% discomfort hours for A_BR, which contrasts with 55% for B_BR. A decrease in the percentage of discomfort hours can be verified when OptVent profile is considered, achieving as much as a 63% decrease in percentage of discomfort hours in A_LR. In A_BR, the discomfort hours can be reduced to 0% and a decrease of 62% of hours in discomfort is verified in B_BR, which is considered to be significant. When climate change projections are considered, a gradual increase in the percentage of discomfort hours can be verified as projections approach the climate data for 2080. Concerning projections for 2050, it is worthy of note that the only zone with more than 10% of the occupied time calculated to be in discomfort is B_LR. However, when 2080 data is considered, both dwellings are predicted to present more than the double of discomfort hours than the ones predicted for 2050 climate. When OptVent is considered, a generalized decrease in discomfort hours is verified. However, it is worthy to note that when comparing the two ventilation profiles, in 2050, results for A_LR suggests only a 1% decrease in discomfort hours. The largest and more significant decrease can be verified in B_LR concerning 2080.

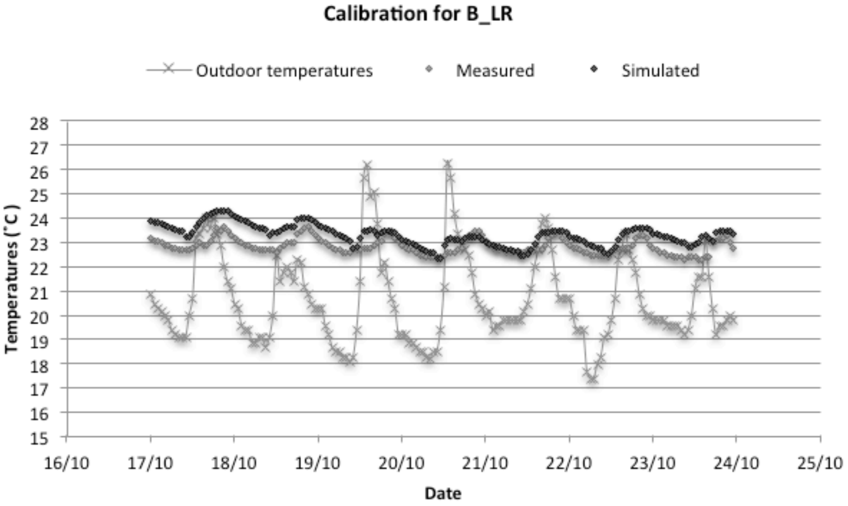


Figure 4.10 - Calibration results for zone B_LR

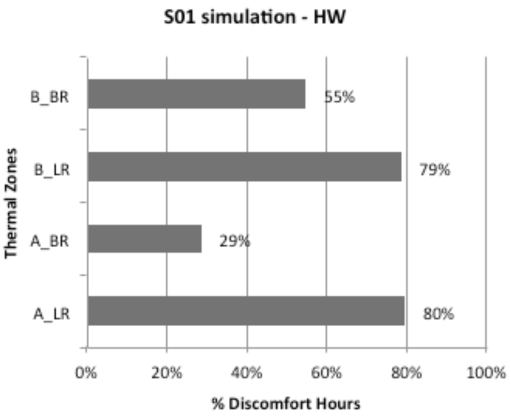


Figure 4.11- Percentage of Discomfort Hours for S01 simulation for Heatwave Period

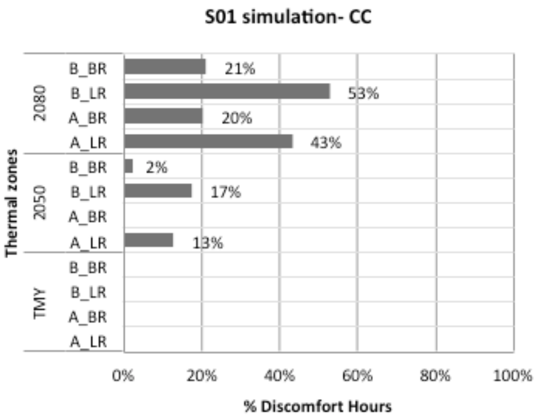


Figure 4.12 - Percentage of Discomfort Hours for S01 simulation for Climate Change

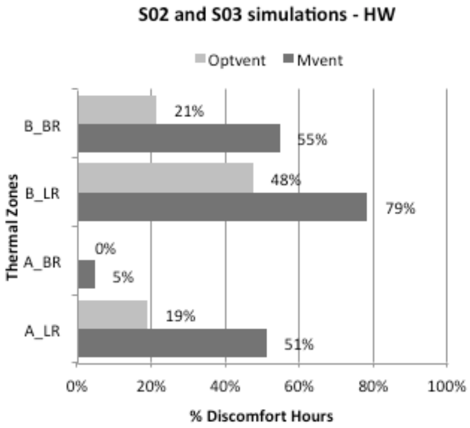


Figure 4.13 - Percentage of Discomfort Hours for S02 and S03 simulation for Heatwave period

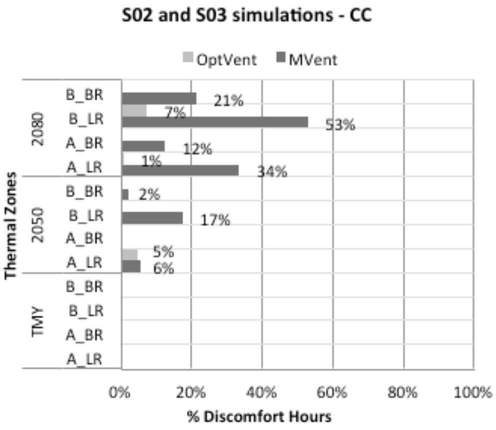


Figure 4.14 - Percentage of Discomfort Hours for S02 and S03 for Climate Change

Figure 4.15 presents results for discomfort hours comparison between the two models considered in subsection 4.2.7. For this comparison, OptVent profile was considered, since it presents the most optimistic results. It can be verified that when considering STAT model, with fixed thresholds independent of exterior conditions, discomfort is extremely significant for both the heatwave period and climate projections (2050 and 2080). Under these circumstances, every zone of the two dwellings presents more than half of the occupied time in discomfort. In comparison, with the exception for the heatwave period (and for zones A_LR, B_LR and B_BR), results indicate no significant discomfort when assessed with the ADPT model. For 2080 climate data, while in STAT model, results reveal all zones above 80% of the occupied time in discomfort, when the ADPT model is considered the higher value is 7% for B_LR.

Of note is the fact that zones in Dwelling B seems to present systematically smaller difference between the two models, since it is the dwelling which appears to be more vulnerable to changing conditions, independent of the model to assess comfort.

Figure 4.16 shows S04 simulation results. The most dramatic results appear to correspond to simulations concerning the heatwave period. In zone A_LR, results indicate a decrease from 19% to 0% in the percentage of discomfort hours with the implementation of insulation. In the case of Dwelling B, the most significance decrease is in zone B_BR (21%). Simulations regarding A_LR reveal a more light decrease in discomfort hours with the implementation of insulation, with better results being from external insulation. Concerning climate change projections, while Dwelling A does not present discomfort hours until 2080, B_LR results suggest a 1% discomfort hours in 2050 with an increase by 2% when internal insulation of 80 mm is considered. When 2080 data is considered, for A_LR, results suggest a decrease by 60% in discomfort hours for both external and internal insulation with 30 mm and an 80% decrease when the 60 and 80 mm insulation is considered. Results from simulations performed for zone B_LR and 2080 climate data, reveal that, while no effect of insulation on discomfort is verified for external insulation, results for the implementation of internal insulation suggest a 1% increase in discomfort hours.

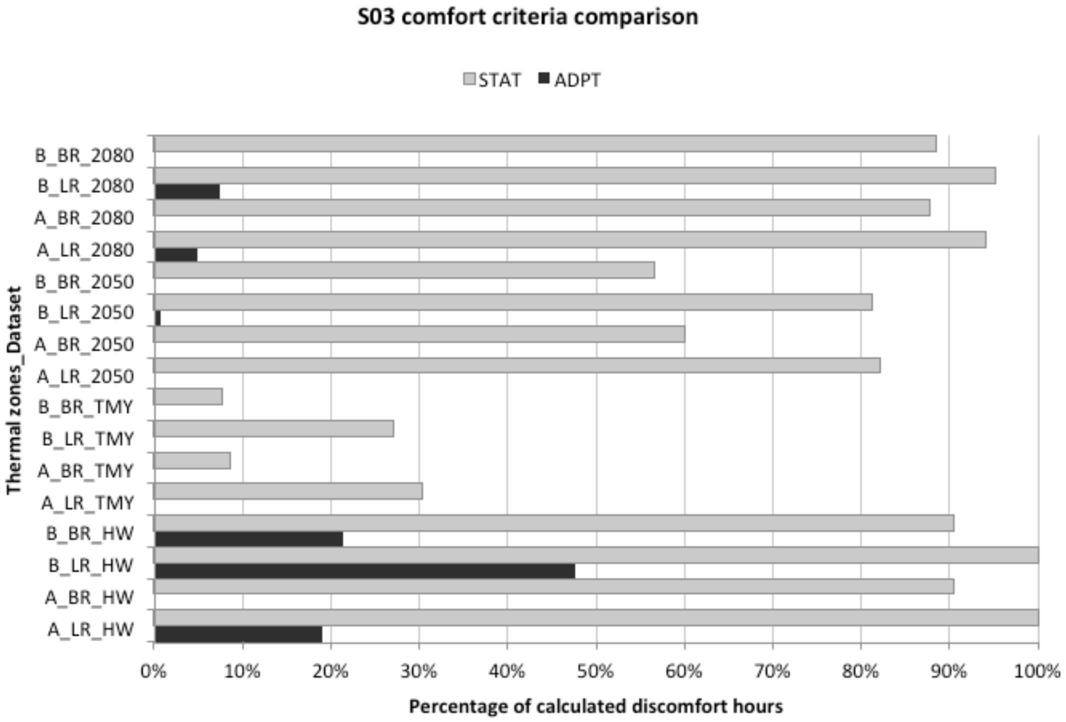
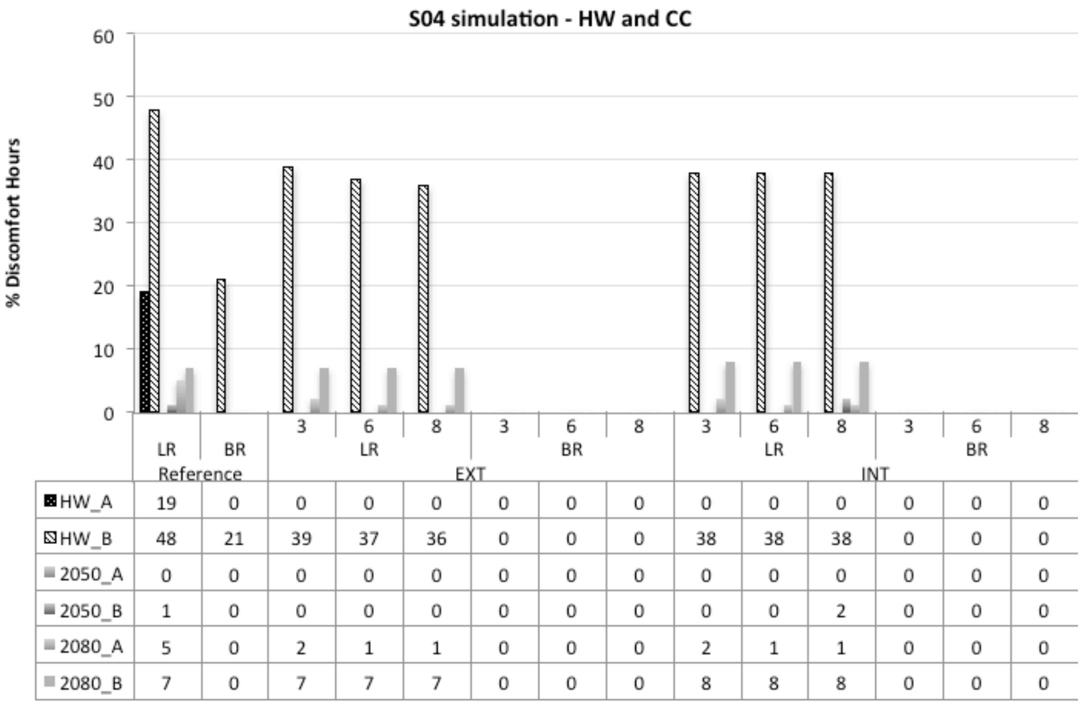


Figure 4.15 - Comfort criteria comparison



	Reference LR	Reference BR	EXT LR 3	EXT LR 6	EXT LR 8	EXT BR 3	EXT BR 6	EXT BR 8	INT LR 3	INT LR 6	INT LR 8	INT BR 3	INT BR 6	INT BR 8
■ HW_A	19	0	0	0	0	0	0	0	0	0	0	0	0	0
▨ HW_B	48	21	39	37	36	0	0	0	38	38	38	0	0	0
■ 2050_A	0	0	0	0	0	0	0	0	0	0	0	0	0	0
■ 2050_B	1	0	0	0	0	0	0	0	0	0	2	0	0	0
■ 2080_A	5	0	2	1	1	0	0	0	2	1	1	0	0	0
■ 2080_B	7	0	7	7	7	0	0	0	8	8	8	0	0	0

Figure 4.16 - Effect of insulation on percentage of discomfort hours – Heatwave period and climate change scenarios

In Table 4.4, the effect of insulation measures in terms of discomfort decrease for a heatwave period is compared with the costs for intervention. Results suggest that for A_LR, even the less costly measure corresponds to a total decrease in discomfort, whereas for A_BR, since no discomfort was initially determined, there is no influence of additional insulation measures..

Table 4.4 - Cost and effect on discomfort decrease in insulation measures on the thermal comfort in heatwave period

	Intervention Dwelling A	Total cost (€)	Discomfort Decrease (%)	Intervention Dwelling B	Total cost (€)	Discomfort Decrease (%)
Living Room	LR_EXT3	381,41	100%	LR_EXT3	403,24	18%
	LR_EXT6	404,1	100%	LR_EXT6	427,23	23%
	LR_EXT8	427,86	100%	LR_EXT8	452,35	25%
	LR_INT3	200,59	100%	LR_INT3	212,08	20%
	LR_INT6	208,73	100%	LR_INT6	220,68	20%
	LR_INT8	216,87	100%	LR_INT8	229,28	20%
Bedroom	BR_EXT3	373,7	0%	BR_EXT3	328,76	43%
	BR_EXT6	395,93	0%	BR_EXT6	348,31	43%
	BR_EXT8	419,21	0%	BR_EXT8	368,79	43%
	BR_INT3	196,54	0%	BR_INT3	172,9	43%
	BR_INT6	204,51	0%	BR_INT6	179,92	43%
	BR_INT8	212,49	0%	BR_INT8	186,93	43%

For B_LR, the most effective insulation measure is also the most costly, while for B_BR there is no difference between different options of insulations measures in terms of the effectiveness regarding discomfort decrease

4.4 Discussion

Changes in occupancy were found to have a significant impact on the sensitivity of dwellings. This parameter was responsible for a considerable difference between the two dwellings - up to 30% of discomfort hours. Some studies also found that occupancy and ventilation were significant in thermal performance in the case of a heatwave period, reporting differences of up to three times the overheating hours (Porrit et al., 2012). Other studies (e.g. Mavrogianni et al., 2012) did not consider variation in occupancy, but instead focused on the constructive characteristics of the building. Similarly to the present study, those also found distinctive results within dwelling types, depending on factors such as orientation and surrounding buildings. The performance of the two dwellings considered here also shows remarkable differences, when the same occupancy is verified. This is attributed to the inherent vulnerability of the physical characteristics of each dwelling, including different orientations and opaque surface and glazing area.

A key observation that emerged from the development of the methodology was that, in broad terms, insulations measures appear to add adaptive capacity to the system, both in extreme situations and gradual changes in typical conditions. However, it is worth noting that external insulation appears to be more effective than internal insulation in decreasing discomfort - a conclusion that is common to other studies (Mavrogianni et al., 2012). These findings can be explained by the lower thermal transmittance of an insulated wall, which when implemented from the internal side of the wall, allows for an easier accumulation of internal gains, as suggested also by Peacock et al. (2010). For Gupta and Gregg (2012), who obtained similar results regarding the positioning of insulation, its benefit is also directly related with the exposed thermal mass of external walls, the effect of which is reduced by internal insulation. There is also a significant distinction in the effect of insulation measures in the heatwave period and climate change scenarios. The effect under the climate scenarios appears to be limited, which has been argued to be caused by the “smoothness” of temperatures in TMY (Mavrogianni et al., 2012).

The present study only focused on insulation measures. Further research is needed in order to quantify the effect of other measures, such as increased fabric air-tightness, as well as the combination of measures, like improved glazing, window replacement options and additional shading devices. Additionally, the fact that only two dwellings were analyzed here with the purpose of illustrating the methodology, limits the applicability of results.

Comfort assessment using static upper temperatures thresholds, as considered in the Portuguese thermal codes, can be misleading in terms of discomfort. Furthermore as the climate warms and frequency of extreme events increases, interventions evaluated by analytical models may be ineffective in terms of cost, as also suggested by Lomas and Giridharan (2012).

A note should also be taken regarding climate data used in this study. Although real weather data was collected for a heatwave period, extreme events may present distinctive temperature profiles from the episode considered here, namely regarding relative humidity and wind, which also has a strong influence on thermal comfort. Furthermore, the use of morphed climate files, despite being easily available, requires some caution. While several limitations have been pointed out to the methodology, such as the validity of climate change projections used, or the assumed linearity of climate parameters, “morphing” has been used extensively in the UK (CIBSE, 2009). Jenkins et al. (2011) make a comprehensive review of studies using this methodology, while also discussing its limitations and associated uncertainties. In this context, a possible evolution of this work is the comparison between these results and the ones of downscaled climate data that reflects the probabilistic nature of global projections of climate change.

4.5 Conclusions

The present study aimed at developing a methodology to determine the impact of climate change and variability on thermal comfort, framing the problem in terms of relative vulnerability. The methodology also considered the possibility of variants both in occupancy and physical characteristics of dwellings.

An important finding of this study is that, while thermal comfort vulnerability can be found and quantified in relative terms, both optimal ventilation (which also considers night ventilation in bedrooms but disregards potential constraints such as safety or privacy) and insulation measures appear to lead to a decrease in internal temperatures. Consequently, it is possible to reduce vulnerability significantly, although not totally, in the occurrence of extreme events. Hence, an obvious implication is the consideration of insulation options, not only for potential energy-saving reasons, but also for the adaptive capacity it can provide. Therefore, it is important to consider this in addition to the impact of these retrofit options (and inherent costs) for winter thermal performance.

When applied to a building stock of a certain typology, the methodology developed here can be used to inform a statistical regression tool with the potential to determine the effect of individual characteristics and changes to dwellings in vulnerability of thermal comfort, through the development of markers for discomfort. A development of such a tool can be of interest to city planners and retrofit decision-making agents, as well as emergency response planners.

Acknowledgements

To the Foundation for Science and Technology, Portugal (Contract SFRH / BD / 70395/ 2010) for funding the research. To Prof. Dr. Mark Jentsch for overcoming problems with climate data and morphing methodology. To João Gouveia for constructive comments and valuable suggestions on an early version of the paper.

References

Aguiar, R., Oliveira, M. and Gonçalves, H. (2002) “Climate change impacts on the thermal performance of Portuguese buildings. Results of the SIAM study”, *Building Services Engineering Research and Technology*, vol. 23, pp. 223-231, Available: doi: 10.1191/0143624402bt045oa.

Alcoforado, M.J. (2006) “Climatic Information for urban planning”, in WMO (ed.) *Climate as a Resource*, Genéve.

ARSLVT (2012) *Alterações Climáticas e Saúde Humana - Gestão do Risco para a Saúde da População da Região de Lisboa e Vale do Tejo*, Lisboa: Administração Regional de Saude de Lisboa e Vale do Tejo.

ASHRAE 55 (2004) *Thermal environmental conditions for human occupancy. ANSI/ASHRAE Standard 55-2004*, AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS.

Barriopedro, D., Fischer, E., Luterbacher, J., Trigo, R.M. and Garcia-Herrera, R. (2011) “The hot summer of 2010: Redrawing the temperature record map of Europe”, *Science*, vol. 332 (6026), pp. 220-224.

Belcher, S.E., Hacker, J.N. and Powell, D.S. (2005) “Constructing design weather data for future climates”, *Building Services Engineering Research and Technology* , vol. 26, pp. 49-61.

Biesbroek, G.R., Swart, R.J., Carter, T.R., Cowan, C., Henrichs, T., Mela, H., Morecroft, M.D. and Rey, D. (2010) “Europe adapts to climate change: Comparing National Adaptation Strategies”, *Global Environmental Change*, vol. 20, no. 3, pp. 440-450.

BRE (2010) *The Government”s Standard Assessment Procedure for Energy Rating of Dwellings 2009 Edition*, Garston.

Canha da Piedade, A., Rodrigues, A.M. and Braga, A.M. (2009) *Térmica de Edificios*, Alfragide: Edições Orion.

CEN (2007) *Indoor Environmental input parameters for design and assessment of energy performance of buildings-addressing indoor air quality, thermal environment, lighting and acoustics. EN 15251:2007*, Comitée Européen Normalisation.

Chappels, H. and Shove, E. (2005) “Debating the future of comfort: environmental sustainability, energy consumption and the indoor environment”, *Building Research & Information*, vol. 33(1), pp. 32-40.

CIBSE (2005) *TM36 Climate change and the indoor environment: impacts and adaptation*, London: The Chartered Institution of Building Services Engineers.

CIBSE (2009) *Use of climate change scenarios for building simulation: the CIBSE future weather years e CIBSE TM48*, London: The Chartered Institution of Building Services Engineers.

Climaco, N. (2012) *Energy Efficient retrofit of Residential Buildings*, Lisboa: Universidade Técnica de Lisboa - Instituto Superior Técnico..

Coley, D., Kershaw, T. and Eames, M. (2012) “A comparison of structural and behavioural adaptations to future proofing buildings against higher temperatures”, *Building and Environment*, no. 55, pp. 159–166.

Crawley, D.B., Hand, J.W., Kummert, M. and Griffith, B.T. (2008) “Contrasting the capabilities of building energy performance simulation programs”, *Building and Environment*, no. 43(4), pp. 661-673.

CYPE (2013) *Gerador de preços para construção*, [Online], Available at: http://www.geradordeprecos.info (Acessed July 2013).

DB (2014) *Design Builder Software*, [Online], Available at: http://www.designbuilder.co.uk (Acessed 2014).

De Dear, R., Brager, G. and Cooper, D. (1997) *Developing an Adaptive Model of thermal comfort and Preference – Final Report*, ASHRAE RP-884.

de Wilde, P. and Tian, W. (2012) “Management of thermal performance risks in buildings subject to climate change “, *Building and Environment*, vol. 55, pp. 167-177, Available: doi:10.1016/j.buildenv.2012.01.018.

DGEG; ADENE (2008) *Portugal Eficiência 2015 - Plano Nacional de Acção para a Eficiência Energética*, Lisboa: Ministério da Economia e da Inovação.

DOE (2011) *Building Technologies Program – Energy Plus*, [Online], Available at: Http://apps1.eere.energy.gov/buildings/energyplus (Accessed June 2013).

EEA (2012) *Urban Adaptation to climate change in Europe – Challenges and Opportunities for cities together with supportive national and European policies – EEA report*, European Environment Agency.

Eurostat (2010) *EU Energy in Figures 2010 – Greenhouse Gas Emissions by Sector*, Luxembourg: Office for Official Publications of the European Communities.

Fanger, P. (1970) *Thermal comfort Analysis and applications in environmental engineering*, McGraw-Hill.

Fussel, H.-M. (2007) “Vulnerability: A generally applicable conceptual framework for climate change research “, *Global Environmental Change* , no. 17, pp. 155-167.

Gallopin, G.C. (2006) “Linkages between vulnerability, resilience and adaptive capacity”, *Global Environmental Change* , no. 16, pp. 293-303.

Gangolells, M. and Casals, M. (2012) “Resilience to increasing temperatures: residential building stock adaptation through codes and standards “, *Building Research & Information* , vol. 40, no. 6, pp. 645-664, Available: http://dx.doi.org/10.1080/09613218.2012.698069.

Gupta, R. and Gregg, M. (2012) “ Using UK climate change projections to adapt existing English homes for a warming climate”, *Building and Environment*, no. 55, pp. 20–42.

Hamilton, A., Mitchell, G. and Yli-Karjanmaa, S. (2002) “The BEQUEST toolkit: a decision support system for urban sustainability”, *Building Research & Information* , vol. 30, no. 2, pp. 109-115.

Hills , G. (2012) *Getting the measure of fuel poverty. Final Report of the fuel poverty review, CASE Report 72*, [Online], Available at: sticerd.lse.ac.uk/dps/case/cr/CASEreport72.pdf (Accessed March 2015).

INE (2011) *Censos 2011*, Instituto Nacional de Estatistica.

IPCC (2013) “Summary for Policymakers”, in Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (ed.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC (2014) “Summary for policymakers”, in Field, C.B., Barros, R., Dokken, D.J., Mach, K.J., Mastrandea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCraken, S., Mastrandea, P.R. and White, L.L. (ed.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPMA (2013) *Instituto Portugues do Mar e Atmosfera* , [Online], Available at :www.ipma.pt" (Accessed February 2013).

ITeCons - Instituto de Investigação e Desenvolvimento Tecnológico em Ciências da Comunicação (2013) *Estudo de Mercado e Inovação na Área das Tecnologias de Construção Sustentável*, Plataforma para a Construção Sustentável.

Jenkins, D.P., Patidar, S., Banfill, P.F. and Gibson, G.J. (2011) “Probabilistic climate projections with dynamic building simulation: Predicting overheating in dwellings”, *Energy and Buildings*, no. 43(7), pp. 1723–1731.

Jentsch, M.F., Bahaj, A.S. and James, P.A. (2008) “Climate change future proofing of buildings e generation and assessment of building simulation weather file”, *Energ Build* , no. 40.

Jentsch, M.F., James, P.A., Bourikas, L. and Bahaj, A.S. (2013) “Transforming existing weather data for worldwide locations to enable energy and building performance simulation under future climates”, *Renewable Energy*, no. 55, pp. 514–524, Available: doi:10.1016/j.renene.2012.12.049.

Kwok, A.G. and Rajkovich, N.B. (2010) “Addressing climate change in comfort standards”, *Building and Environment*, no. 45(1), pp. 18–22, Available: doi:10.1016/j.buildenv.2009.02.005.

Lisboa E-Nova (2008) *A Energia nas Cidades - Public CommunicationProf. José Delgado Domingos in Centro de Informação Europeia Jacques Delors*, [Online], Available at: www.lisboaenova.org (Accessed Janeiro 2013).

Liu, G. and Liu, M. (2011) “A rapid calibration procedure and case study for simplified simulation models of commonly used HVAC systems”, *Building and Environment*, vol. 46, no. 2, pp. 409-420, Available: doi:10.1016/j.buildenv.2010.08.002.

Lomas, K.J. and Giridharan, R. (2012) “Thermal comfort standards, measured internal temperatures and thermal resilience to climate change of free-running buildings: A case-study of hospital wards”, *Building and Environment*, no. 55, pp. 57-72, Available: doi:10.1177/0143624411432012.

Mavrogianni, A., Wilkinson, P., Davies, M., Biddulph, P. and Oikonomou, E. (2012) “Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings”, *Building and Environment*, no. 55, pp. 117–130, Available: doi:10.1016/j.buildenv.2011.12.003.

Miller, F., Osbahr, H., Boyd, E., Thomalla, F., Bharwani, S., Ziervogel, G., Walker, B., Birkmann, J., van der Leeuw, S., Rockstrom, J., HInkel, J., Downing, T., Folke, C. and Nelson, D. (2010) “Resilience and vulnerability: complementary or conflicting concepts?”, *Ecology and Society* , no. 15(3).

Nicol, F. and McCartney, K. (2000) *Smart Controls ad Thermal Comfort (SCATs) Project. Final Report.*, Joule III Project (Contract JO3-CT97-0066).

Nicol, F. and Stevenson, F. (2013) “Adaptive comfort in an unpredictable world”, *Building Research & Information*, no. 41(3), pp. 255–258, Available: doi:10.1080/09613218.2013.783528.

Peacock, A.D., Jenkins, D.P. and Kane, D. (2010) “Investigating the potential of overheating in UK dwellings as a consequence of extant climate change”, *Energy Policy*, no. 38, pp. 3277-3288, Available: doi:10.1016/j.enpol.2010.01.021.

Porrit, S.M., Cropper, P.C., Shao, L. and Goodier, C.I. (2012) “Ranking of interventions to reduce dwelling overheating during heat waves”, *Energy and Buildings*, no. 55, pp. 16–27, Available: doi:10.1016/j.enbuild.2012.01.043.

REH (2013) *Regulamento de Desempenho Energético dos Edifícios de Habitação. Decreto-Lei n.º 118/2013 de 20 de Agosto. Diário da República n.º159 – 1.ª série, pp 4988 a 5005*, Lisboa: Ministério da Economia e do Emprego.

Roaf, S., Crichton, D. and Nicol, F. (ed.) (2009) *Adapting Buildings and Cities for Climate Change*, Architectural Press.

Roetzel, A. and Tsangrassoulis, A. (2012) “Impact of climate change on comfort and energy performance in offices “, *Building and Environment* , vol. 57, pp. 349-361, Available: http://dx.doi.org/10.1016/j.buildenv.2012.06.002.

Rogelj, J., Meinshausen, M. and Knutti, R. (2012) “Global warming under old and new scenarios using IPCC climate sensitivity range estimates”, *Nature Climate Change*, no. 2, pp. 248–253, Available: DOI:10.1038/NCLIMATE1385.

Santos, C. and Matias, L. (2006) *Coeficientes de Transmissão Térmica de elementos da envolvente dos edifícios*, Lisboa: Laboratório Nacional de Engenharia Civil.

Santos, F.D. and Miranda, P. (ed.) (2006) *Alterações Climáticas em Portugal. Cenários, Impactos e Medidas de Adaptação" — Projecto SIAM II*, Lisboa: Gradiva.

Stern, N. (2007) *The Economics of Climate Change: The Stern Review*, Cambridge University Press.

Thomson, H. and Snell, C. (2013) “Quantifying the prevalence of fuel poverty across the European Union”, *Energy Policy*, vol. 52, January, pp. 563-572, Available: doi:10.1016/j.enpol.2012.10.009.

van Hooff, T., Blocken, B., Hensen, J.L.M. and Timmermans, H.J.P. (2015) “Reprint of: On the predicted effectiveness of climate adaptation measures for residential buildings “, *Building and Environment*, vol. 83, pp. 142-158, Available: http://dx.doi.org/10.1016/j.buildenv.2014.10.006.

Vandentorren, S., Bretin, P., Zeghnoun, A., Mandereau-Bruno, L., Croisier, A., Cochet, C., Ribéron, J., Siberan, I., Declercq, B. and Ledrans, M. (2006) “August 2003 heat wave in France: risk factors for death of elderly people living at home.”, *Eur J Public Health*, vol. 16, no. 6, December, pp. 583-91.

5 CHAPTER 5 - VULNERABILITY AND ADAPTATION MEASURES TO HIGH TEMPERATURES IN A SOUTHERN EUROPEAN CONTEXT - A BOTTOM UP APPROACH FROM LISBON RESIDENTIAL DWELLINGS

Paper III – Submitted to Energy and Buildings in July 2016

Vulnerability And Adaptation Measures To High Temperatures In A Southern European Context - A Bottom Up Approach From Lisbon Residential Dwellings

Ricardo Barbosa [1], Romeu Vicente [2], Rui Santos [1],

[1] CENSE - Center for Environmental and Sustainability Research, Departamento de Ciências e Engenharia do Ambiente, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Campus da Caparica, 2829-516 Caparica, Portugal

[2] RISCO - Research Centre of Risks and Sustainability in Construction, Departamento de Engenharia Civil, Universidade de Aveiro, Portugal

Abstract

Cities are in the center of the climate challenge. In regions where most of residential buildings still use natural ventilation for cooling, such as Southern Europe, the impact on thermal comfort can be significant with implications on health and energy. However, research of the topic in this region is limited and in order to manage high temperature related risks, information is required to identify the most vulnerable buildings and dwellings in the urban context.

With a focus on apartments and considering a base case dwelling derived from the main vulnerability factors found in literature, thermal comfort is assessed through an adaptive model for a heatwave period and two climate change scenarios for Lisbon, Portugal, using dynamical thermal simulation. The objective is two-fold: to assess relative vulnerability of different construction types found in the building stock and to evaluate effectiveness of adaptation measures in preventing discomfort regarding climate extremes and change.

Results from simulations indicate that N/S dwellings present, in average, 23% less discomfort hours than SW/NE orientation. Newer dwellings (1990 – 2006 and >2006) present higher vulnerability to projected climate change, but not to extreme events. For heatwaves periods, the most vulnerable are 1940-1960 dwellings, which present a difference of 13% in terms of discomfort hours from the dwellings built previous to 1940, which presented the best results regarding discomfort hours. In terms of decrease in discomfort and considering a cost-effect perspective, the best adaptation measure is low emissivity glazing followed by solar reflective coating for façades.

Implications of results and use of this approach to heat management and adaptation policy are discussed.

Key words: Vulnerability; Adaptation; Bottom up; Building Stock; Climate Change; Adaptation Measures, Dynamical thermal simulation

5.1 Introduction

The world is recognizing climate change, and in particular the exceptional increase in temperatures, as a key challenge for the 21st century. This change is projected to be reflected not only in mean temperatures, namely in the cooling season, but also in more frequent occurrence of extreme events, such heatwaves, which are likely to be also more severe than the ones registered so far. According to Intergovernmental Panel for Climate change (IPCC) the change in temperatures can range from 0.3°C to 4.8 °C until 2100 (IPCC, 2013). Heatwaves, which are expected to increase by a factor of 5 to 10 regarding its occurrence within the next 40 years (Barriopedro et al., 2011), have comprehensive implications for both human being and the environment, including water quality, energy consumption, air pollution and health issues (Zuo et al., 2015).

Research has shown that the increase in temperatures, whether due to slow changes or in the form of more severe extreme events, is also going to impact on buildings and urban infrastructure (Smith and Lawson, 2012; Institute for Sustainable Resources, 2010). An impact of interest for research, practice and policy is the possibility of increased overheating in existing buildings, which were not designed to deal with these future climate conditions (Roaf et al, 2009), resulting in higher periods of discomfort and possibly altering energy use patterns and increasing uptake of air conditioning devices (Peacock et al., 2010). These arguments are particularly important in regions where buildings remain essentially naturally ventilated, like Europe (Eurostat, 2010), because it is admitted that the increasing of installation of mechanical cooling devices would lead to a higher energy demand from the building sector. Besides obvious concerns regarding mitigation to climate change, and due to a weakened economy, this subject also has consequences in terms of summer fuel poverty (Hills , 2012).

This context triggered research to an increasing attention to adaptation to climate change in buildings. Studies show that buildings are vulnerable to these changes at different extent differing according to the geographical location, building type and function (Lomas and Giridharan, 2012), as well as constructive characteristics (Mavrogianni et al., 2012).

Vulnerability represents a well-researched and mature approach to understand a system's response to change, despite the variety of definitions and approaches found in literature (Fussel, 2007). The IPCC definition, as "the propensity or predisposition to be adversely affected" (IPCC, 2014) consider it to be a function of the magnitude and character of the climate variation and change, its exposure, sensitivity and adaptive capacity. While recognizing the generic nature of this definition, vulnerability here is approached from a biophysical perspective (Fussel, 2007) and the subject of vulnerability is considered to be thermal comfort itself. The cited definition presupposes exposure as related with "the presence of people (...) infrastructure or economic social or cultural assets in places that could be adversely affected" (IPCC, 2014). Furthermore, sensitivity is defined as "the degree to which a system (...) is affected (...) by climate variability or change” (IPCC, 2014) and adaptive capacity is considered to be “the ability of systems, (...) to adjust to potential damage (...) to respond to consequences” (IPCC, 2014). From this viewpoint, adaptive capacity is not a direct component of vulnerability, as generally interpreted (Gallopin, 2006). Instead, it is operationalized as a property of the system, capable of offsetting or reducing vulnerability, through the implementation of adaptation strategies.

Overheating is essentially a thermal comfort issue. The term is mainly used when a determined threshold regarding discomfort hours is surpassed. This fact is making thermal comfort and adaptation studies be conducted on a common ground (Chappells and Shove, 2007). Thermal comfort is a complex subject and is analysed in literature using different approaches from analytical to adaptive perspectives. Adaptive approach to comfort seems to begin to gain visibility in the field, mainly because of the recognition that behavioral adaptation as a response to outdoor temperatures is fundamental regarding adaptation to climate change buildings (Coley et al, 2012). As a matter of fact, people not only tend to adapt through behavior, but also by making incremental adaptive changes in their home. However, due to the intensity and extension of the projected changes, some authors argue for a more comprehensive and collective approach to adaptation (Williams et al., 2013).

Although is recognized that the vast majority of research studies regarding adaptation are concerned with office buildings (Zuo et al., 2015), there is significant peer-reviewed and “grey” literature concerning residential building highlighting the importance of studying the subject. The studies point out to building characteristics as being determinant in relation to vulnerability to climate change and variability. In the CIBSE study, four dwellings archetypes were simulated for three geographical locations - London, Manchester and Edinburgh. The results of the research suggest that the south of UK is more likely to face risk of overheating by mid-century. More importantly for the context of this study, using Medium-High Scenarios for 2020, 2050 and 2080, it concluded that overheating was verified in most conditions, in particular in lightweight constructions. The best indoor conditions were obtained for constructions with higher thermal mass. Other studies, such as Hacker (Hacker, 2008) and Kendrick et al. (Kendrick et al., 2012) corroborated these findings for UK. Mavrogianni et al. (2012), studied the effect of individual fabric attributes regarding indoor overheating. Their results suggest considerable variations between dwellings types in the existing building stock. UK is particularly prolific in research regarding the subject. An example of a study focusing in constructive characteristics of buildings in Netherlands found that there also significant differences between buildings constructed according national building codes and the less vulnerable ones built 40 years ago (van Hooff et al., 2014). On the other hand, studies originating from Australia suggest that more recent buildings – i.e. complying with national building codes are more capable of dealing with changes (BRANZ, 2007; Wang, Chen and Ren, 2010).

This research highlights the need for buildings to be adequately adapted to changing climate conditions. There mainly two approaches found in literature regarding adaptation – one is concerned with extreme events and the other is related with gradual climate change. However, it is also recognized that adaptation to extreme events serves as a “starting point” for vulnerability reduction to gradual climate change (Burton et al., 2004). In fact, there is evidence that supports that people are more motivated to act when faced with events perceived as immediate risks and that adaptation can go further when is rebranded with reduction of vulnerability (or resilience) to extreme weather (Porter et al, 2015).

There is no shortage of literature addressing adaptation to climate change from a technical perspective. CIBSE (2005) defines four principles guiding adaptation strategies at a building scale: switch off (reducing additional heat gains); absorb (thermal mass); blow away (a intelligent ventilation strategy) and finally, cool (active cooling). Although several authors acknowledge the need for air-conditioning as adaptation in extreme cases (Sanders and Phillipson, 2003; Brown and Walker, 2008), it is consensual that, for most cases, passive measures allow for occupants of buildings to maintain comfortable indoor conditions, without having the need for the increased energy consumption implied in active cooling (Roberts, 2008). In fact, regarding heat waves, the World Health Organization advises that a “climate adapted building and energy efficient design should be stressed over air-conditioning” (WHO, 2004).

An exemplary study of such approaches on the subject is Porrit et al. (2012), where several adaptation measures to heat waves are tested concerning typical terrace houses. Results suggest that measures such insulation, shading and ventilation have to be considered together for successful retrofits of buildings, taking in account both performance and cost. Gupta and Gregg (2012) agrees with the ranking of interventions proposed by the latter study, but their results concerning suburban houses suggest that even combined measures would not avoid overheating for 2080 scenarios. Some adaptation measures, such as internal insulation, could also increase the risk, as suggested by Mavrogianni et al. (2012). Van Hooff et al. (2014) also explored the effectiveness of six climate adaptation measures in residential buildings in Netherlands. It included an increase in thermal resistance and thermal capacity, as well as reflectivity measures and ventilation. Their results suggest that different measures should be considered depending on the age of the building and its constructive characteristics in the building stock. Findings from this type of research can be useful regarding public policy, namely regarding regulations and standards (Gupta and Gregg, 2012).

Buildings stocks are strongly marked by regionalisms, which arise from local availability of materials and traditional techniques. These traditional techniques were then influenced by the event of industrialization and globalization in newer buildings (Climaco, 2012). The combination between the specific characteristics of local climate, expected changes, and the unique composition of the building stock makes studies results significantly distinctive. Whereas most research regarding adaptation in residential buildings are focused in Northern Europe and Australia, Southern Europe have been receiving less attention in this subject. However, in addition to a recognized climate vulnerability (Santos and Miranda, 2006), this region building stock was already characterized as one of significant proportions, as well as stable and aging significantly (Eurostat, 2010), which translates into a research gap.

This paper contributes to the current body of knowledge by exploring relative vulnerability and adaptation of dwellings in apartment buildings in a Southern European context using Lisbon as a case study, regarding extreme and non-extreme conditions. In particular, the study intends to investigate differences between distinctive constructive characteristics throughout the building stock typified by building age and the effect of adaptation measures. The objective is not to define the building stock with accuracy, but to illustrate the application of a comfort assessment methodology to an adaptation context in order to support policy. Being so, the following specific objectives can be identified:

I. Define a base case dwelling typology for the building stock in order to study influence of different constructive characteristics present in the building stock, as an input for dynamic thermal simulation;
II. Apply an appropriate methodology to assess comfort in a changing climate;
III. Evaluate different measures used to prevent overheating regarding extreme events and its effect on climate change adaptation

5.2 Methodology

5.2.1 Targeted dwellings

With a registered increase in average temperature of 0,5˚C per decade, Southern Europe is more vulnerable to climate change than Northern Europe (Santos and Miranda, 2006). As exemplary of dense Mediterranean cities with a significant heat island effect (Alcoforado, 2006), Lisbon has mild winters and hot and dry summers with high levels of solar radiation. The hottest month is August, with an average temperature of 23.5˚C. In terms of climate extremes, the highest registered absolute temperature was 42˚C, during the 2003 heatwave (IPMA, 2013). In the last decade, in at least half the years, a heatwave was recorded, occasionally more than once a year, associated with significant damages in terms of loss of human lives and disruption in well-being (ARSLVT, 2012).

The region of Lisbon is the most populous in Portugal (INE, 2012) and an important socio-economic center for the country. The majority of the buildings in the city are predominantly residential. Lisbon Municipality is home for an estimated 53191 buildings containing almost three hundred thousand dwellings (INE, 2012), 70% of which are built previous to the first thermal regulations in 1990 (INE, 2012), which raise concerns regarding both adequate thermal performance and energy efficiency. Figure 5.1 shows the percentage of existing dwellings in relation to building age at the time of last extensive survey realized in Portugal. 21% of dwellings originate from the 70´s decade, the majority of them being apartments. According to city statistics, the most predominant typology is the two-bedroom dwelling (INE, 2011).

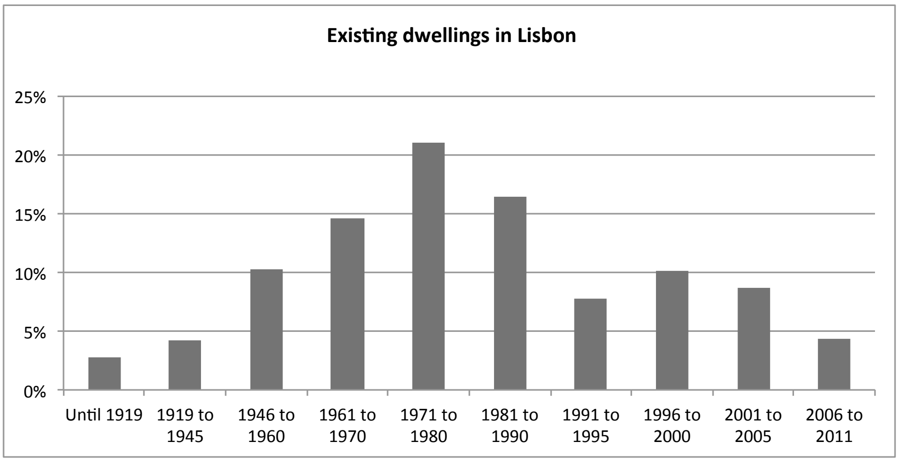


Figure 5.1 - Percentage of dwellings regarding building age . Source: INE (2012)

5.2.2 Building model and settings

In order to analyze the vulnerability of the dwellings different constructive characteristics and the effect of adaptation measures, a bottom-up approach based in building physics (Kavigic et al., 2010) is used, in addition to a methodology for comfort assessment in a changing climate (Barbosa et al., 2015), which uses dynamical thermal simulation. In order to be used in this study, the methodology is adapted to be consisted of three main phases 1) preliminary data collection; 2) model construction and 3)comfort assessment.

The objective is to obtain an image of relative vulnerability concerning the different construction techniques found in the building stock and therefore no representation of a specific existing building is attempted. Other authors have used similar perspectives in different building contexts when studying adaptation and overheating in the face of climate change (e.g. Porrit et al., 2012; Gupta and Gregg, 2012).

Preliminary Data collection

In order to be possible to build a consistent model for dynamical thermal simulation, it is necessary to obtain preliminary data to inform model construction.

Building characteristics

For the purpose of dynamical thermal simulation model construction, an approach based in a Synthetical Average Building Methodology was used in this study. This approach consists of the creation of a "virtual building which for each relevant parameter includes the most commonly used material" (Monteiro et al., 2015). It is the composite of the features within the building stock. Here, additionally to statistical data, model construction also use empirical data drawn for existing studies and municipality archives.

Following Sousa et al. (Monteiro et al., 2015), this methodological approach include several steps:

Parameter definition.

In this step, the necessary parameters for the model are identified.

The main factors influencing vulnerability to high temperatures in buildings were already identified as: 1) location; 2) form; 3) occupancy and behavior and 4) Construction characteristics (Barbosa et al., 2016).

Categorization

Parameter definition is necessary to define the ones acting as base criteria for the several categories. Since the focus of the study is to investigate differences in relation to construction characteristics, building age was used for categorization. Building age was already used as a representation of the building characteristics (e.g. Mavrogianni et al., 2012)).

The aggregation proposed by the Portugal´s National Laboratory of Civil Engineering (LNEC, 2005) and the National Statistical Institute (INE, 2012), although useful, were not designed to study thermal performance. The implementation of building codes and thermal regulations has the potential to significantly influence performance of buildings in the stock, namely by introducing mandatory requirements (Climaco, 2012). Taking as reference the two existing aggregations, building age categorization is modified to five base categories to take into account significant changes in building construction techniques and materials, in particular the ones driven by thermal and building codes implementation influencing significantly the performance of buildings in the stock. Of particular interest is the agreed date for the generalized use of concrete in building structure (1940) and the one concerning the first regulations regarding concrete and construction (1960) (LNEC, 2005). Of relevance are also the introduction of the first thermal regulation In Portugal in 1990 - (Decree-Law 40/90 from the 6th February) and the transposition of the European Directive 2002/91/CE in 2006 (Decree-Law 80/2006, from 4th April).

Characterization.

The essential characteristics for each base typology are defined in this step. The approach taken here is the adoption of a base case layout (where location, form and occupancy and behavior are “averaged” values –Table 5.1) from which modifications in relation to the building characteristics are introduced depending of the age category.

Because of the dominant typology in the city, a 70´s dwelling layout was chosen to serve as basis. Following the analysis of a sample of 200 plans and projects of buildings in municipality archive, Climaco (2012) defined several generic models for the city of Lisbon. This study draws on a 70´s two-bedroom generic model used in that study, consistent with a typical building floor also indicated in other relevant study (Bragança et al., 2007). Figure 5.2 shows the base layout.

Besides relative position of the rooms and size, the generic model also considers “average” building block characteristics, such as building height and street width. Dwelling is considered to be situated in a linear block of building with two exposed façades (85% of block types) (Climaco, 2012). Table 5.3 details the most significant parameters considered here.

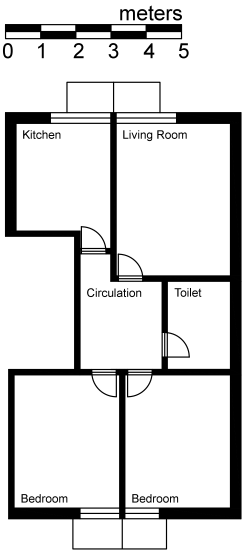


Figure 5.2 - Layout of base case dwelling used in this study

Table 5.1 - Location and form parameters for the base case dwelling (source: Climaco, 2012; Bragança et al. 2007)

Location and form

Building block	Average street width	27,9	**Dwelling**	Depth	11.1
	Number of floors	8		Number of exposed façades	2
	Building Height	19		Gross Area (sqm)	73
	Dominant orientations	N/S and SW/NE		Useful Area(sqm)	59

The dwelling is considered to be situated in a middle-level floor of the residential building, corresponding to the majority of situations. Regarding internal gains, occupancy and behavior and assuming it to be the worst-case scenario in terms of vulnerability (White-Newsome et al., 2011), the study adopts data obtained from another study, which is consistent with an older couple staying at home most of the day (Barbosa et al., 2015). Window opening behavior is considered to be optimal i.e. windows are open when outdoor temperature is at least two degrees below indoor temperature (staying this way until this condition is no longer valid) and considered no physical constraints (e.g. privacy or security).

Finally, construction characteristics are drawn for information provided by statistical data and construction materials technical data for Portugal. When data is not available, calculated values from DOE (2011) are used (Table 5.2).

Table 5.2 - Age categorization and constructive characteristics (sources: Santos and Matias , 2006; DOE, 2011; INE, 2011)

	Building constructive characteristics						
Age	**Walls (exterior and interior) and Slabs**				**Windows**		
	Description	Thickness (mm)	Thermal Capacity (KJ/m^2-C)	U-value (W/m^2 –C)	Description	U-value (W/m^2 –C)	Glazing to floor ratio
<1940	Stone Masonry	500	168	2.9	Single glazing Wood frame	4.3	7.2
	Wooden frame with masonry infill	250		2.4			
	Wood floor and beams	200		2.2 1.9			
1940 to 1960	Stone/Brick Masonry	300	150	2.9	Single Glazing Wood frame	4.3	7.2
	Gypsum plaster Hollow Brick 110 mm	150		2			
	Wood floor Concrete slab	200		3.5			
1960 to 1990	Cement plaster Hollow brick Masonry 150 mm Gypsum render	240	132	1.7	Single glazing Aluminum frame	3.8	15
	Gypsum render Hollow and brick masonry	150		2			
	Wood floor Concrete slab	200		2			
1990 to 2006	Cement Plaster Hollow brick 110+110 mm Gypsum render	300	122	1.1	Double glazing Aluminum frame	3.2	15
	Gypsum render Hollow brick masonry	150		2			
	Concrete slab With XPS Insulation (40 mm)	200		0.85			
>2006	Cement Plaster Hollow brick masonry 15+11 with XPS insulation (40 mm) Gypsum plaster	300	46	0.54	Double glazing Plastic frame	2.7	15
	Gypsum render Hollow brick masonry	150		2			
	Concrete slab With XPS insulation	200		0.85			

Climate Data

Two types of data are considered in this study. The first is related with a real heat wave period (i.e. July 29th to August 15th 2003). The data was collected from recordings made by Gago Coutinho meteorological station (IPMA, 2013). Data collected from the meteorological station was processed and in the case of missing data necessary for model simulation, interpolated typical weather data from IPMA (2013) for the same period in the year was assessed.

The second type of data concerns climate change projections. Two scenarios originating from the 5 th Assessment Report from IPCC (IPCC, 2014) - Representative Concentration Pathways (RCP) - were considered here. RCP 4.5 corresponds to a socio-economic evolution in which the increase in greenhouse gas emissions is controlled and therefore corresponds to the least burdensome scenario. From the other hand, RCP 8.5 represents a significant increase in emissions during the 21st century (Meinshausen et al., 2011).

In order to generate the two climate change scenarios for Lisbon, a “weather generator” using historical data from 1971-2000 (IPMA, 2013) and Coupled Model Intercomparison Project Phase 5 (CMIP5) (CMIP5, 2012) information was prepared through analysis of anomalies found through the difference between historical and CMIP5 data. The same methodology was used to inform Building Energy Certification Scheme in Portugal regarding climate change data and more information can be found in Aguiar (2013).

Besides air temperature, climate data considers solar radiation, relative humidity and wind, even if no anomaly is calculated for wind.

When compared to other methodologies for generating climate change files, such as “morphing”, the one considered here has three major advantages: 1) it considers non-linearity of climate parameters; 2) uses the most recent RCP scenarios and 3) allows for the consideration of uncertainty by comparison between the two scenarios for the same time frames (2030, 2050 and 2080). Both extreme weather and climate data were processed to fit dynamical thermal simulation software format. Figure 5.3 shows the frequency in air temperatures for both extreme weather and climate change projections considered in this study.

Adaptation Measures

The study focuses on passive measures that could be structurally implemented in existing buildings skins in order to reduce overheating. A range of adaptation measures is identified throughout the literature in several studies (e.g. Gupta and Gregg, 2012; Porrit et al., 2012; van Hooff et al, 2014). In this study, five single measures and three aggregated packages of measures are considered for dynamical thermal simulation (Table 5.3).

The minimum required thermal resistance have been increasing dramatically throughout Europe, mainly to reduce energy for heating (BPIE, 2011).

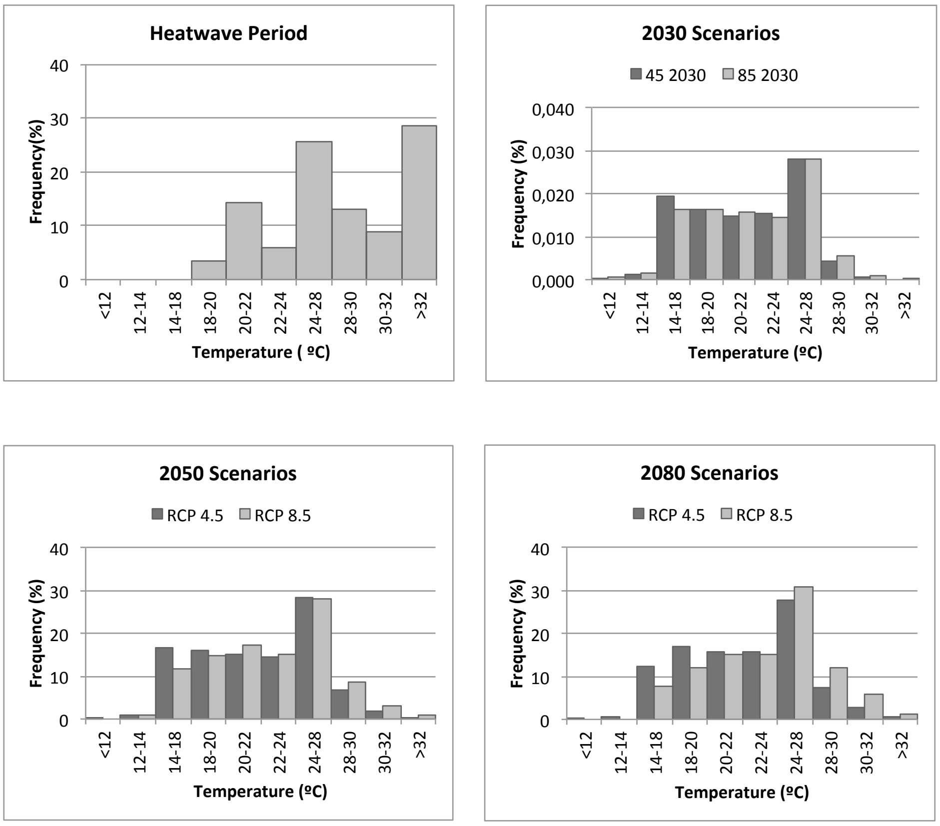


Figure 5.3 - Air temperature Frequency of Weather and Climate Data considered in this study

Better insulation – i.e. the reduction of thermal transmittance of the building envelope – can be achieved on both opaque and glazed elements taking into consideration that glazing is usually the least insulating part of the envelope. In Portugal, thermal regulations establish reference values for walls and windows, which differ according to climate zone (REH, 2013). Additional insulation interventions in walls were selected in order to comply with references values. Interventions are therefore differentiated, depending of the wall considered in the age category. Despite the potential as a protective measure, there is strong evidence that internal insulation can aggravate overheating (e.g. Mavrogianni et al., 2012)). Being so, for the purpose of this study, only external insulation was considered. Additionally, adding insulation to already high insulated dwellings does not make sense and therefore >2006 dwellings are not considered eligible to these measures.

Solar control is analyzed through simulations concerning three single measures. Low emissivity glazing can be used to restrict solar radiation from windows (Porrit et al., 2012). The effect of blocking solar radiation through windows is further modelled through the implementation of external shutters, which remain activated throughout the day. The last single measure concerns short-wave reflectivity, which is the fraction of radiation that is reflected (van Hooff et al., 2014). Several studies (e.g. Cheng et al., 2005; van Hooff et al., 2014) have already suggested this measure as a significantly successful form of lowering exterior surface temperature and consequently, the heat flux from exterior surface to indoor environment Additionally, in hotter regions of Portugal, it is common to paint external surfaces white in order to increase solar reflectance.

Table 5.3 - Adaptation measures . (Source for reference values:REH, 2013; Porrit et al., 2012; van Hooff et al., 2014)

Designation	Type of Measure	Description	Reference value
Measure 1 (M1)	Wall insulation	Implementation of external insulation	0.4 W/m2.°C)
Measure (M2)	Glazing insulation	Windows replacement	2.8 W/m2.°C)
Measure 3 (M3)	Low emissivity glazing	Glazing replacement	Solar transmittance =0.6
Measure 4 (M4)	Window shading	Implementation of shutters in existing windows	
Measure 5 (M5)	Reflectivity	Solar reflective coating (high albedo) added to external walls	solar absorptance value=0.3
Package 1 (P1)	Wall and glazing insulation	Combination of Measure 1 and Measure 2	
Package 2 (P2)	Solar control	Combination of Measure 3, Measure 4 and Measure 5	
Package 3 (P3)		All single measures combined	

Model construction

EnergyPlus (EP) was chosen to perform the analysis regarding dynamical thermal simulations, using Design Builder v4 as the graphical interface for input (DB, 2014). EP is widely considered as a credible and validated tool to evaluate free-running indoor environments, in dynamic regimes, using hourly and sub-hourly simulations (Crawley et al., 2006).

The model was constructed taking into consideration location and form parameters detailed in Table 5.1.Being so, neighboring buildings causing potential shading are also modelled. Additionally, the assembly of the model considers 41 thermal zones in total, allowing for gains verified in adjacent dwellings to be taken into account in thermal calculations. Two thermal zones (bedroom and Living room) were analyzed in detail for the five age categories and the two dominant orientations, as schematized in Figure 4. Adaptation measures were then applied and simulated for each category and orientation. A total of 560 simulations were performed.

Comfort assessment

In order to assess comfort, an adaptive model is used. Recognizing that occupants of buildings are not only a mere recipient of the thermal stimulus (Kwok and Rajkovich, 2010), the use of such model is consistent with a socio-technical perspective of comfort (Hinton, 2010). The adaptive model acknowledges the central role of buildings as well as the significance of occupant's interactions with technical systems in order to achieve comfort. In fact, the model is conceptually based on the assumption that people have a response to change and are willing to act in order to restore comfort conditions. In addition, it is particular suitable for assessing comfort in a changing climate due to the presupposition of a correlation between comfort temperature and outdoor temperature (Nicol and Stevenson, 2013; Lomas and Giridharan, 2012).

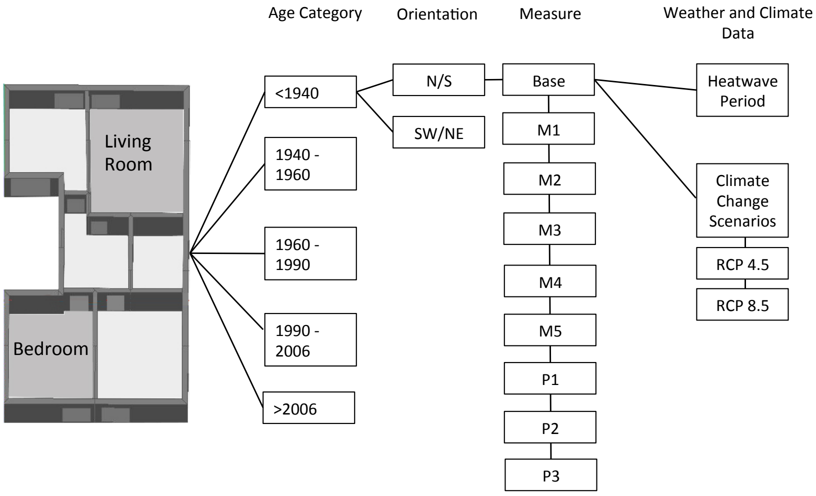


Figure 5.4 - Configuration of performed simulations

The adaptive model was developed after field studies (De Dear et al, 1997) in clear opposition to analytical models, mainly derived from thermal chamber studies (Fanger, 1970). The European standard EN15251 (CEN , 2007) is considered to be adequate to this study, mainly because of the temperature range applicability (Lomas and Giridharan, 2012) and the fact that also uses data collected in Portugal (Nicol and McCartney, 2000).

This adaptive model allows for determination of the operative temperature of comfort *Toc*, depending on exterior conditions, calculated through Eq. (1). Exterior conditions are considered in the form of the weighted running mean exterior temperature *Trm*, accounting for temperatures recorded in previous days.

$$\boldsymbol{T_{oc}} = \boldsymbol{0{,}33.Trm} + 18{,}8\ (^{\circ}\mathrm{C}) \qquad (1)$$

The effect of type of building is considered in the standard through the application of categories. The category defines the interval a determined user may find comfortable. Categories range from I (the most demanding, used for hospitals for example) to Category III, which is applied to existing and non-retrofitted buildings. This last category presents the broader range of acceptable temperatures (±3 °C). Figure 5.5 graphically demonstrates the range of temperatures considered in the model in relation to outdoor temperatures.

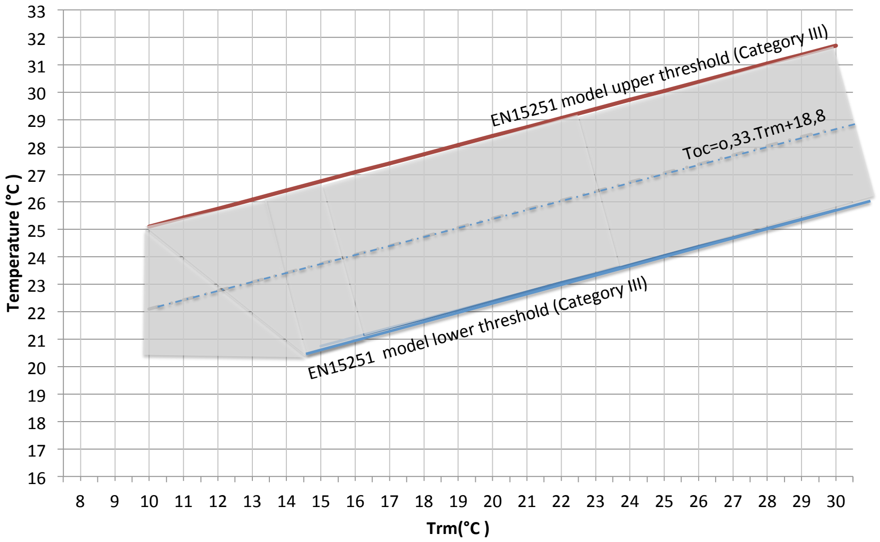


Figure 5.5 - Design values for EN15251, as a function of outdoor temperature running mean. Source: adapted from CEN (2007)

In order to operate EN15251 standard, T_{rm} is calculated for the three previous days (CEN , 2007). The resulting *Toc* hourly values from simulations are then compared to the operative temperatures produced by Eq. (1). If the simulated temperature is higher than the one produced by the model, the zone is considered to be in discomfort for that whole hour. The most occupied rooms in dwellings are the Living Room and Bedroom and comfort is accessed for these rooms.

Additionally, after thermal comfort assessment and from the quantification of the effect of adaptation measures, it is possible to identify the best measure to reduce vulnerability of thermal comfort. This is performed from a cost-effect perspective, where approximate costs per square meter of implementation are considered from CYPE database (CYPE, 2013).

5.3 Results

Vulnerability of thermal comfort

Concerning heatwaves, dwellings with SW/NE orientation are the ones with higher discomfort hours. Results from simulations indicate that N/S dwellings present, in average, 23% less discomfort hours than SW/NE. Every simulated zone present values higher than 50% of occupied hours in discomfort. Living Rooms are the most vulnerable zones, achieving values of 80% of occupancy in discomfort (1990-2006 dwelling). In comparison, the higher value for bedrooms is for 1940-1960 dwelling (65%). Figure 5.6 shows results for heatwaves simulations. For the extreme conditions simulated here, and considering both simulated zones, the higher mean is for 1940-1960 dwellings with 64,6% of percentage of discomfort hours. The lowest mean is for dwellings constructed previously to 1940 (57,52%).

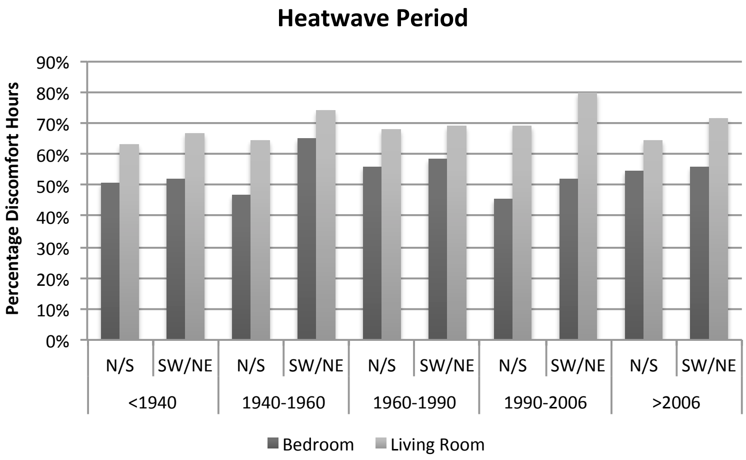


Figure 5.6 - Results for percentage of discomfort hours by age category and orientation in relation to heatwave period

In relation to climate change, relative vulnerability to comfort in the apartment is inferred from the distribution of total discomfort hours in the two rooms, for the two RCP scenarios. Results indicate that buildings constructed after 2006 present the higher number of discomfort hours in relation to occupied time. Additionally, simulations concerning dwellings with SW/NE orientation present higher values consistently, throughout the scenarios.

Figure 5.7 shows variation of values regarding the two rooms in two RCP scenarios for 2030, 2050 and 2080 timeframes. For 2030, the results indicate mean values below 5% of percentage of discomfort hours, except for >2006 dwellings (9,73%). Results are more significant in relation to SW orientation, whereas NS present values very close to zero. This relation is maintained in 2050 scenarios simulations. However, values are significant higher. In particular, for SW orientation, values are in average 44% higher than for 2030 simulations. Simulations for 2080 timeframe indicate considerable percentage of time in discomfort for all type of dwellings except <1940 and 1960-1990, which still maintains value closer to zero and below 5% of discomfort hours, respectively. However, all values are significantly higher than in 2050 (67% in average).

Another aspect that is drawn from the graphs and should be highlighted here concerns the maximum values. Results expressed in the graphs by outliers point out the significant increase in not only in mean values, but also suggesting that in 2050, for example and regarding 1940-1960 dwellings, percentage of discomfort can be as high as 15% and 31,15% in the case of dwellings built after 2006, despite means being relatively low. 2080 scenarios are even more dramatic regarding maximum values, indicating, for >2006 dwellings, a maximum of 40% of discomfort hours in occupied time indoors.

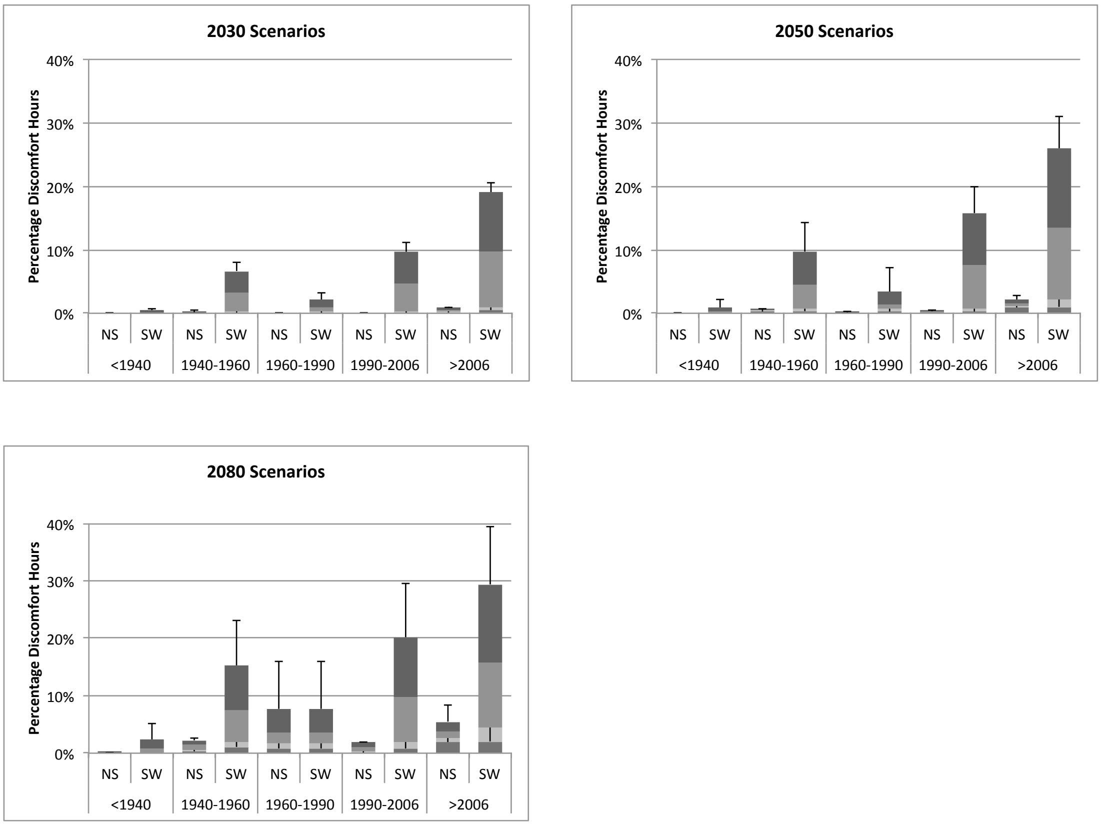


Figure 5.7 - Results regarding variation of values of percentage of discomfort hours for 2030, 2050 and 2080 climate scenarios

Effect of adaptation measures

Figure 5.8 shows simulations results in terms of reduction of percentage of discomfort hours for the heatwave period, in relation to the cost of the measure. It is noticeable that simulation results for determined measures indicate negative results for reduction of discomfort hours, which suggest an increase in overheating time. The most significant negative values correspond to the increase in insulation in walls for 1960-1990 dwellings (19% increase) and >1940 (14% increase) both for SW/NE orientation. Results suggest that combined measures (P1, P2 and P3) are the most effective, achieving values of 100% in decrease in discomfort. However, the best cost-effect ratio is obtained by the implementation low emissivity glazing (M3) in dwellings built prior to 1940 (Euro10/decreased discomfort hour). In fact, this measure is consistently the one with the best ratio throughout the measures simulated here (with a mean of Euro37/decreased discomfort hour), followed by improvement of reflectivity of façade (M5) and combined reflectivity measures (P2), in this last case, in particular taking into consideration results regarding 1990-2006 dwellings.

Concerning the effect of measures on indoor temperatures simulated with climate projections, the most significant decrease in discomfort is verified in simulations concerning M5 and P2. M3 presents a significant mean value for decrease in percentage of discomfort hours of 52%, which is lower than M5 (73%) and P2 (64%). Table 5.4 presents the mean decrease in discomfort hours per measure and age category, as well as standard deviations for the means.

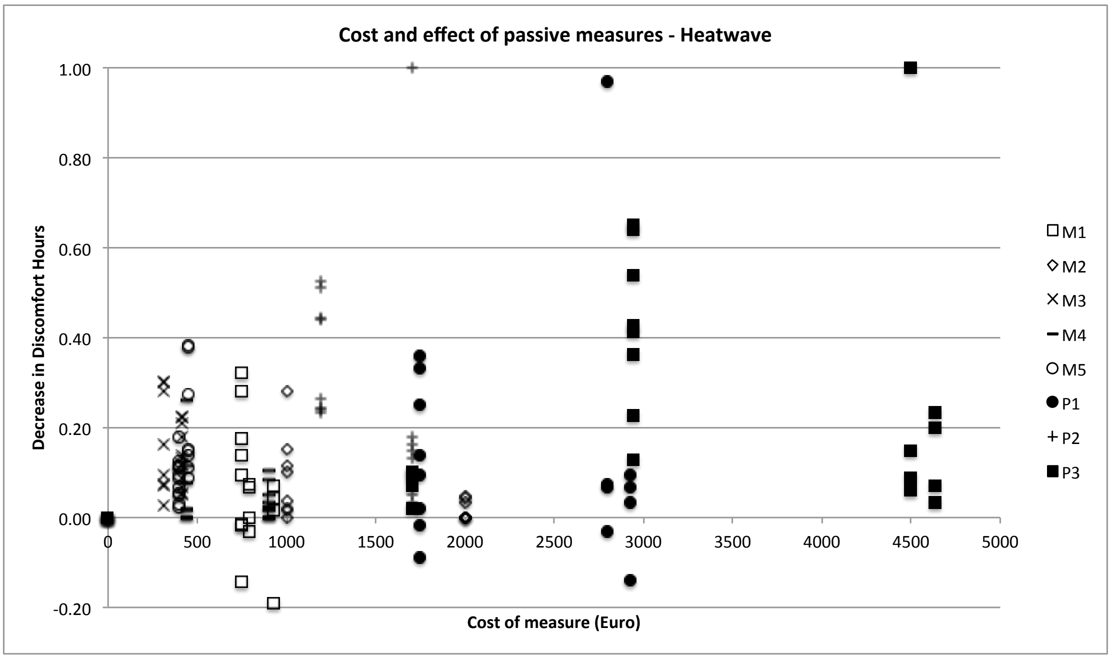


Figure 5.8 - Relation between decrease in discomfort hours effect and cost of adaptation measure for heatwave period

In terms of combined measures, mean values for P2 is 45% higher than P1 and only 3% higher than P3. It is noticeable that the higher decrease in discomfort regarding adaptation measures is resulting from 2080 simulations.

Results also allow analyzing the specific contribution of each measure in relation to building age. The most significant decrease in <1940 and 1940-1960 dwellings is given by the simulations with p1, p2 and p3. M5 is the most effective regarding 1960-1990 dwellings (75%). Dwellings simulated with constructive characteristics related with 1990-2006 indicate negative values for M1, M2, M4 and P1. The best result for this type of dwellings is given by M5 (in average 80,6% decrease). This measure is also effective in >2006 dwellings (94%), alongside M3 (85,9%).

5.4 Discussion

Results suggest that newer buildings (>2006) are the most vulnerable to the increase in mean temperatures. However, when sudden change such as an extreme event is considered, dwellings with building characteristics consistent with 1990-2006 period are the ones presenting the highest percentage of discomfort hours. In opposition, older buildings (<1940), with less insulated skins (but significant thermal capacity) and lowest glazing-to-floor ratio, are the ones presenting the best results both regarding climate change projections and heatwaves. However, 1940-1960 is the most vulnerable type of dwellings in the analysis, when the heatwave period is considered.

Table 5.4 - Mean decrease in discomfort hours by measure and age category regarding climate change scenarios

	M1		M2		M3		M4		M5		P1		P2		P3	
	Mean	StD	Mean	StD	Mean	StD	Mean	StD	Mean	StD	Mean	StD	Mean	StD	Mean	StD
2030	18	40	9	21	42	47	18	39	59	49	24	43	55	46	53	46
<1940	25	46	8	17	8	17	25	46	25	46	25	46	25	46	25	46
40-60	57	47	5	10	6	10	70	44	72	45	66	44	73	45	71	44
60-90	13	38	30	37	50	53	2	9	50	53	36	44	49	52	49	52
90-06	-8	11	-1	1	50	53	-1	1	50	53	-8	11	43	48	39	45
>2006	0	0	0	0	97	4	-5	10	100	0	0	0	84	15	84	15
2050	12	38	12	25	55	43	18	37	75	37	26	47	65	36	62	37
<1940	15	31	3	7	2	6	25	46	25	46	21	40	25	46	25	46
40-60	55	34	16	9	16	9	67	30	82	19	74	23	86	20	86	16
60-90	0	24	44	39	88	35	7	18	88	35	46	42	75	33	78	34
90-06	-11	49	-4	12	85	27	-4	12	93	14	-14	51	71	30	57	33
>2006	0	0	0	0	83	16	-6	8	89	14	0	0	66	15	66	15
2080	27	41	13	20	58	41	22	39	84	33	39	43	72	33	69	33
<1940	45	49	13	20	14	20	49	52	50	53	49	53	50	53	50	53
40-60	67	33	14	5	15	5	68	14	90	12	79	23	94	8	89	14
60-90	14	41	39	20	87	35	0	2	88	35	56	37	80	34	81	34
90-06	9	25	-2	13	96	3	-2	13	99	1	9	25	78	17	67	22
>2006	0	0	0	0	78	7	-4	4	93	2	0	0	57	12	57	12
Mean	19	40	11	22	52	44	19	38	73	41	29	44	64	39	62	39

These results, in particular newer building presenting higher vulnerability, are consistent with other studies such as van Hooff et al. (2014). Their study also found that buildings constructed in 2012 presented higher number of discomfort hours than the ones constructed in 1970. This effect is suggested to be caused by the reduction of heat transport through the building skin, which is amplified by solar gains from glazing. Larger glazing-to-floor ratios are, therefore, also a potential issue. Newer buildings, which usually verify these two conditions – being highly insulated and presenting larger windows – by gaining and retaining heat for longer periods are potentially more vulnerable (van Hooff et al., 2014). Other contexts, however, present different perspectives. Studies originating from Australia, where adoption of mechanical cooling is high - suggest that more recent buildings – i.e. complying with national building codes are more capable of dealing with gradual changes, but not so well with extreme events (BRANZ, 2007; Wang et al., 2010). This report highlights the significance of mechanical cooling in Australian context, at the same time that considers that existing buildings can be adapted, even if adaptive measures functions as resources to reduce cooling energy consumption.

In the study presented here, adaptive measures are focused on the reduction of discomfort hours. The purpose is to contribute to enhancing adaptive capacity in the system consisted of buildings, occupants and climate. In terms of adaptation measures, results from this study suggest that the best measure regarding extreme events, also bring significant decrease in the case of change in mean temperatures. Considering a cost-effect perspective the three best adaption measures are 1) low emissivity glazing 2) low reflectivity coating in façades and 3) combined reflectivity measures. Other studies (e.g. (van Hooff et al., 2014; Porrit et al., 2012; Gupta and Gregg, 2012) also tested this type of measure and results suggest that the effect of decrease depends on the type of building and the thermal transmittance of the building skin. While not being structural to the building, these types of measures have the advantage of being easily applied without the need of compromising habitability. However, for Gupta and Gregg (2012), measures increasing the albedo in surfaces can result, in the future, in an increase in heating energy, because they lead to a loss in solar gain through the building skin in the winter. Implementation of such measures is not, therefore, free from limitations.

External insulation is also capable of acting as a protective measure, in particular in older dwellings such as the ones simulated here with the characteristics of <1940. Results also suggest that in determined dwellings such as the 1990-2006, additional insulation can increase discomfort hours, which can indicate the measure is not suitable to every type of dwelling existing in the building stock and caution in the use of the measure is necessary. Results also suggest that bringing buildings to thermal reference values stated in building codes and regulations with a focus on heating energy reduction can make dwellings more vulnerable and in need of significant interventions in the future, as also argued by Mulville and Stravoravdis (2016). Research such as this suggest that there is a need for a tool to assess an optimal level of insulation because when appropriate, the measure can potentially have the dual benefit of protecting indoor space of increased outdoor temperatures and improve energy efficiency of the dwelling.

Results also suggest that is possible, in particular when combined measures are considered, to reduce discomfort hours by 100%, although not being the most cost-effective solution. This is interesting in the sense that opposes to the perspective taken in other studies suggesting that passive adaptive measures could not be enough to mitigate high temperatures, in particular in 2080 (Gupta and Gregg, 2012). However, it can be verified here, in the majority of simulations and similarly to Mavrogianni et al. (2012), the effect of adaptation measures when data from climate projections is considered, seems to be limited. This can be caused by the spread of mean temperatures common in a typical meteorological year such as the ones considered here for the scenarios.

Understanding the most effective adaptation measure in relation to a determined building stock constructive characteristics can assist in the design and implementation of adaptation and high temperature response plans by promoting the best fitting measures and its correct implementation to protect residential building, while mitigating the use of cooling devices. A possible direction - in addition to the development of consideration of future vulnerability in building codes – is the promotion of incentives driving generalized implementation in construction industry.

Additionally, even if additional measures, such as an efficient mechanical cooling system, may be admitted as necessary in the future, future proofing buildings with passive measures, can assist in the gradual transformation of infrastructure in (nearly) zero buildings. Future work can also explore additional climate change adaptation measures such as the effect of evaporative cooling and green and water roofs.

The study embraced uncertainty in projections by considering the mean values and distribution of values in the two RCP scenarios. Although this is considered to be a step forward in relation to more deterministic approaches, such as "morphing", modelling can be enhanced by following the trend in climate change impact assessments that tries to define overheating risk in terms of probabilities. For that purpose, a probabilistic approach in terms of projections would be needed and it is not yet available for the urban context considered here.

The study assumed one type of occupancy and one ventilation profile. Additionally, no changes in air infiltration were calculated for different age categories. Further work is needed to understand the effect of mean air infiltration in relation to different constructive characteristics, which have the potential to exacerbate differences already found in this study. In the same direction it can also be useful to explore the effect of different occupancies and ventilation habits. A subsequent analysis can also investigate the difference between occupant exposure to high temperatures during the night time and during the day.

The approach taken here also does not allow drawing specific conclusions regarding each and every dwelling in the urban context of Lisbon. The study assumed a simplified average "typical" dwelling, with the purpose of study and assess the differences between constructive characteristics. Other studies such as Mavrogianni et al. (2012) indicate that dwelling form and location are also determinant for vulnerability to high temperatures and further studies should also investigate the subject regarding southern housing. Other type of buildings, which have specific characteristics and needs can also be studied in this context (e.g. hospitals, schools).

5.5 Conclusion

The study comprises a modelling analysis of five types of construction materials assemblies. The study has taken a Synthetical Average Building methodology to define a "typical" dwelling in terms of layout and form. The study also adapted a methodology to assess comfort in a changing climate to investigate dwelling vulnerability and the effect of seven type of adaptation measures regarding extreme events and climate change projections scenarios.

The following conclusions can be derived:

There is a significant difference between the two dominant orientations. N/S dwellings present in average more than 20% less discomfort hours than SW/NE dwellings for the two most occupied rooms.

The percentage of discomfort hours for buildings constructed >1990 seem to be higher than for older buildings. However, for the heatwave period, the most vulnerable type of dwellings is the one with constructive characteristics consistent with 1940-1960 (13% higher than <1940 dwellings)

Thermal transmittance, thermal capacity and glazing to floor ratio seem to be determinant in terms of vulnerability of thermal comfort regarding extreme events and climate change projections.

Adaptation measures can be used to alleviate discomfort in terms of extreme events, and the most cost-effective are related with increasing reflectivity of surfaces and avoiding solar radiation through glazing.

Promoting external insulation up to reference values can potentiate a negative effect, by increasing vulnerability to high temperatures and should, therefore, be implemented with caution.

Acknowledgements

To the Foundation for Science and Technology, Portugal (Contract SFRH/BD/ 70395/ 2010) for funding the research. CENSE is financed through the Strategic Project Pest-OE/AMB/UI4085/2013 from the Foundation for Science and Technology, Portugal. To Ricardo Aguiar for the assistance in providing climate change projections.

References

Aguiar, R. (2013) *Climatologia e Anos Meteorológicos de Referência para o Sistema Nacional de Certificação de Edifícios (versão 2013) - Relatório para ADENE - Agência de Energia*, Laboratório Nacional de Energia e Geologia, I.P.

Aguiar, R., Oliveira, M. and Gonçalves, H. (2002) “Climate change impacts on the thermal performance of Portuguese buildings. Results of the SIAM study”, *Building Services Engineering Research and Technology*, vol. 23, pp. 223-231, Available: doi: 10.1191/0143624402bt045oa.

Alcoforado, M.J. (2006) “Climatic Information for urban planning”, in WMO (ed.) *Climate as a Resource*, Genéve.

ARCC (2011) *Adaptation and Resilience in a Changing Climate* , [Online], Available at: http://www.ukcip-arcc.org.uk (Accessed December 2014).

ARSLVT (2012) *Alterações Climáticas e Saúde Humana - Gestão do Risco para a Saúde da População da Região de Lisboa e Vale do Tejo*, Lisboa: Administração Regional de Saude de Lisboa e Vale do Tejo.

ARUP and BDA (2005) *UK Housing and Climate Change - Heavyweight vs. lightweight construction*, [Online], Available at: http://web.mit.edu/cron/project/concrete-sustainability-hub/Literature%20Review/Building%20Energy/Industry%20Claims/Climate_Change_BDA_report.pdf (Accessed December 2014).

Barbosa, R., Vicente, R. and Santos, R. (2016) “Comfort and buildings: climate change vulnerability and strategies “, *International Journal of Climate Change Strategies and Management*, vol.8, issue 5, pp. 670-688.

Barbosa, R., Vicente, R. and Santos, R. (2015) “Climate change and thermal comfort in Southern Europe housing: A case study from Lisbon “, *Building and Environment* , vol. 92, pp. 440-451, Available: http://dx.doi.org/10.1016/j.buildenv.2015.05.019.

Barriopedro, D., Fischer, E., Luterbacher, J., Trigo, R.M. and Garcia-Herrera, R. (2011) “The hot summer of 2010: Redrawing the temperature record map of Europe”, *Science*, vol. 332 (6026), pp. 220-224.

Belcher, S.E., Hacker, J.N. and Powell, D.S. (2005) “Constructing design weather data for future climates”, *Building Services Engineering Research and Technology* , vol. 26, pp. 49-61.

Borrell, C., Dell´Olmo, M., Guez-Sanz, M., Garcia-Olalla, P., Cayla, J., Benach, J. and Muntaner, C. (2006) “Socioeconomic position and excess mortality during the heat wave of 2003”, *European Journal of Epidemiology*, vol. 21, pp. 633-640.

Bouchama, A., Dehbi, M., Mohamed, G., Matthies, F., Shoukri, M. and Menne, B. (2007) “Prognostic factors in heat wave related deaths: a meta-analysis “, *Archives of Internal Medicine* , vol. 167, pp. 2170-2176.

BPIE (2011) *Europe’s buildings under the microscope: a country-by-country review of the energy performance of buildings.*, [Online], Available at: http://bpie.eu/uploads/lib/document/attachment/20/HR_EU_B_under_microscope_study.pdf (Accessed November 2015).

Bragança, L., Almeida, M. and Mateus, R. (2007) “State of the Art :Portugal”, in Andeweg, M.T., Brunoro, S. and Verhoef, L.G. *Cost C16, improving the quality of existing urban building envelopes. State of the art*, IOS Press.

BRANZ (2007) *An Assessment of the Need to Adapt Buildings for the Unavoidable Consequences of Climate Change*, Canberra: BRANZ for AGO. Dept of the Environment and Water Resources.

Brown, S. and Walker, G. (2008) “Understanding heat wave vulnerability in nursing and residential homes “, *Building Research & Information* , vol. 36, no. 4, pp. 363-372, Available: DOI: 10.1080/09613210802076427.

Burton, I., Malone, E. and Huq, S. (2004) *Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures*, Cambridge University Press.

CEN (2007) *EN 15251:2007: Indoor Environmental input parameters for design and assessment of energy performance of buildings-addressing indoor air quality, thermal environment, lighting and acoustics.*, Comité Européen de Normalisation.

Chappells, H. and Shove, E. (2007) “Debating the future of comfort: environmental sustainability, energy consumption and the indoor environment “, *Building Research and Information*, vol. 33, no. 1, pp. 32-40.

Cheng, V., Ng, E. and Givoni, B. (2005) “Effect of envelope colour and thermal mass on indoor temperatures in hot humid climate. “, *Sol.Energy*, vol. 78, pp. 528-534.

Climaco, N. (2012) *Energy Efficient retrofit of Residential Buildings*, Lisboa: Universidade Técnica de Lisboa - Instituto Superior Técnico..

CMIP5 (2012) *Coupled Model Intercomparison Project Phase 5* , [Online], Available at: http://cmip-pcmdi.llnl.gov/cmip5/index.html (Accessed November 2015).

Coley, D. and Kershaw, T. (2010) “Changes in internal temperatures within the built environment as a response to a changing climate “, *Building and Environment* , vol. 45, pp. 89-93, Available: 0.1016/j.buildenv.2009.05.009.

Coley, D., Kershaw, T. and Eames, M. (2012) “A comparison of structural and behavioural adaptations to future proofing buildings against higher temperatures”, *Building and Environment*, no. 55, pp. 159–166.

Crawley, D.B., Hand, J.W., Kummert, M. and Griffith, B.T. (2008) "Contrasting the capabilities of building energy performance simulation programs", *Building and Environment*, no. 43(4), pp. 661-673.

CYPE *Gerador de preços para construção*, [Online], Available at: http://www.geradordeprecos.info (Accessed July 2013).

DB (2014) *Design Builder Software*, [Online], Available at: http://www.designbuilder.co.uk [Accessed 2014].

De Dear, R., Brager, G. and Cooper, D. (1997) *Developing an Adaptive Model of thermal comfort and Preference – Final Report*, ASHRAE RP-884.

de Wilde, P. and Tian, W. (2012) "Management of thermal performance risks in buildings subject to climate change ", *Building and Environment*, vol. 55, pp. 167-177, Available: doi:10.1016/j.buildenv.2012.01.018.

Diaz, J., Garcia, R., Velázquez de Castro, F., Hernández, E., López, C. and Otero, A. (2002) "Effects of extremely hot days on people older than 65 years in Seville (Spain) from 1986 to 1997.", *International Journal of Biometeorology* , vol. 46, pp. 145-149.

DOE (2011) *Building Technologies Program – Energy Plus*, [Online], Available at: http://apps1.eere.energy.gov/buildings/energyplus (Accessed June 2013).

Eurostat (2010) *EU Energy in Figures 2010 – Greenhouse Gas Emissions by Sector*, Luxembourg: Office for Official Publications of the European Communities.

Fanger, P. (1970) *Thermal comfort Analysis and applications in environmental engineering*, McGraw-Hill.

Fouillet, A., Rey, G., Laurent, F., Pavillon, G., Bellec, S., Guihenneuc-Jouyaux, C., Clavel, J., Jougla, E. and Hemon, D. (2006) "Excess mortality related to the August 2003 heat wave in France. ", *International Archives of Occupational and Environmental Health* , vol. 80, pp. 16-24.

Fussel, H.-M. (2007) "Vulnerability: A generally applicable conceptual framework for climate change research ", *Global Environmental Change* , no. 17, pp. 155-167.

Gallopin, G.C. (2006) "Linkages between vulnerability, resilience and adaptive capacity", *Global Environmental Change* , no. 16, pp. 293-303.

Greenburg, J.H., Bromberg, J., Reed, C., Gustafson, T. and Beauchamp, R. (1983) "The epidemiology of heat-related deaths, Texas – 1950, 1970 – 79, and 1980 ", *American Journal of Public Health*, vol. 70, no. 7, pp. 805-807.

Gupta, R. and Gregg, M. (2012) "Preventing the overheating of English suburban homes in a warming climate", *Building Research and Information*, vol. 41, no. 3, pp. 281-300.

Gupta, R. and Gregg, M. (2012) " Using UK climate change projections to adapt existing English homes for a warming climate", *Building and Environment*, no. 55, pp. 20–42.

Hacker, J.N. (2008) *Climate change in London: implications for passive and active cooling of dwellings*, London UK: ARUP.

Hacker, J., Capon, R. and Mylona, A. (2009) *Use of Climate Change Scenarios for Building Simulation: the CIBSE Future Weather Years*, London: Chartered Institution of Building Services Engineers.

Hajat, S., Kovats, R.S. and Lachowycz, K. (2007) "Heat-related and cold-related deaths in England and Wales: who is at risk? ", *Occupational and Environmental Medicine* , vol. 64, pp. 93-100.

Haldi, F. and Robinson, D. (2008) "On the behaviour and adaptation of office occupants ", *Building and Environment*, vol. 43, pp. 2163-2177, Available: doi:10.1016/j.buildenv.2008.01.003.

Harlan, S.L., Brazel, A.J., Prashad, L., Stefanov, W.L. and Larsen, L. (2006) "Neighborhood microclimates and vulnerability to heat stress", *Social Science & Medicine* , vol. 63, pp. 2847-2863.

Hills , G. (2012) *Getting the measure of fuel poverty. Final Report of the fuel poverty review, CASE Report 72*, [Online], Available at www.sticerd.lse.ac.uk/dps/case/cr/CASEreport72.pdf" (Accessed March 2015]).

Hinton, E. (2010) "Review of the literature relating to comfort practices and socio-technical systems", *Environment, Politics and Development Working Paper Series*.

Holmes, M.J. and Hacker, J.N. (2007) "Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century ", *Energy and Buildings*, no. 39, pp. 802-814, Available: doi:10.1016/j.enbuild.2007.02.009.

INE (2011) *Estatisticas da Construção e Habitação 2010*, Lisbon: Instituto Nacional de Estatistica.

INE (2012) *Anuário Estatístico da Região de Lisboa 2011*, Lisbon: Instituto Nacional de Estatistica.

INE (2012) *Censos 2011 Resultados Definitivos - Portugal*, Lisbon: Instituto Nacional de Estatistica.

Institute for Sustainable Resources (2010) *Impacts and Adaptation Response of Infrastructure and Communities to Heatwaves: the South Australian Experience of 2009*, Institute for Sustainable Resources, QUT, Brisbane in collaboration with Monash University and University of Southern Queensland, with contributions from Access Macquirie Ltd and the Royal Melbourne Institute of Technology for NCCARF.

IPCC (2013) "Summary for Policymakers", in Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (ed.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC (2014) "Summary for policymakers", in Field, C.B., Barros, R., Dokken, D.J., Mach, K.J., Mastrandea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCraken, S., Mastrandea, P.R. and White, L.L. (ed.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPMA (2013) *Instituto Portugues do Mar e Atmosfera* , [Online], Available at: www.ipma.pt (Accessed February 2013).

Jentsch, M.F., James, P.A., Bourikas, L. and Bahaj, A.S. (2013) "Transforming existing weather data for worldwide locations to enable energy and building performance simulation under future climates", *Renewable Energy*, no. 55, pp. 514–524, Available: doi:10.1016/j.renene.2012.12.049.

Kavigic, M., Mavrogianni, A., Mumovic, D., Summerfield, A., Stevanovic, Z. and Djurovic-Petrovic, M. (2010) "A review of bottom-up building stock models for energy consumption in the residential sector", *Building and Environment*, vol. 45, no. 7, July, pp. 1683–1697, Available: doi:10.1016/j.buildenv.2010.01.021.

Kempton, W., Feuermann, D. and McGarity, A.E. (1992) "I always turn it on super": user decisions about when and how to operate room air conditioners", *Energy and Buildings*, vol. 18, pp. 177-191.

Kendrick, C., Ogden, R., Wang, X. and Baiche, B. (2012) "Thermal mass in new build UK housing: A comparison of structural systems in a future weather scenario", *Energy and Buildings*, vol. 48, pp. 40-49, Available: doi:10.1016/j.enbuild.2012.01.009.

Kwok, A.G. and Rajkovich, N.B. (2010) "Addressing climate change in comfort standards", *Building and Environment*, no. 45(1), pp. 18–22, Available: doi:10.1016/j.buildenv.2009.02.005.

LNEC (2005) *Evolução das tipologias construtivas em Portugal*, Abril, [Online], Available at: http://www-ext.lnec.pt/LNEC/DE/NESDE/divulgacao/evol_tipol.html (Accessed November 2015).

Lomas, K.J. and Giridharan, R. (2012) "Thermal comfort standards, measured internal temperatures and thermal resilience to climate change of free-running buildings: A case-study of hospital wards", *Building and Environment*, no. 55, pp. 57-72, Available: doi:10.1177/0143624411432012.

Lomas, K.J. and Ji, Y. (2009) "Resilience of naturally ventilated buildings to climate change: advanced natural ventilation and hospital wards.", *Energy Build*, vol. 41, no. (6), pp. 629-653.

Mavrogianni, A., Wilkinson, P., Davies, M., Biddulph, P. and Oikonomou, E. (2012) "Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings", *Building and Environment*, no. 55, pp. 117–130, Available: doi:10.1016/j.buildenv.2011.12.003.

Meinshausen, M., Kainuma, M., Kainuma, M.T., Lamarque, J.-F., Matsumoto, K., Montzka, S.A., Raper, S.A., Riahi, K., Thomson, A., Velders, G.J.M. and van Vuuren, D.P.P. (2011) "The RCP greenhouse gas concentrations and their extensions from 1765 to 2300", *Climatic Change*, vol. 109, no. 213, November, Available: 10.1007/s10584-011-0156-z.

Michelozzi, P., De´Donato, F., Accetta, G., Forastiere, F., D´Ovidio, M. and Perucci, C. (2004) "Impact of heat waves on mortality – Rome, Italy, June – August 2003", *Morbidity and Mortality Weekly Report,* , vol. 53, no. 17, pp. 369-371.

Monteiro, C.S., Cerezo, C., Pina, A. and Ferrão, P. (n.d) "A method for the generation of multi-detail building archetype definitions: Application to the city of Lisbon", CISBAT 2015 - International Conference on Future Buildings and Districts, Lausanne Switzerland.

Mulville, M. and Stravoravdis, S. (2016) "The impact of regulations on overheating risk in dwellings", *Building Research and Information*, March, Available: The impact of regulations on overheating risk in dwellings.

NHBC (2012) *OVerheating in new homes - a review of the evidence*, HS BRE Press on behalf of the NHBC Foundation.

Nicol, F.J., Hacker, J., Spires, B. and Davies, H. (2009) "Suggestion for new approach to overheating diagnostics ", *Building Research & Information* , no. 37:4, pp. 348-357, Available: DOI: 10.1080/09613210902904981.

Nicol, F. and McCartney, K. (2000) *Smart Controls ad Thermal Comfort (SCATs) Project. Final Report.*, Joule III Project (Contract JO3-CT97-0066).

Nicol, F. and Stevenson, F. (2013) "Adaptive comfort in an unpredictable world", *Building Research & Information*, no. 41(3), pp. 255–258, Available: doi:10.1080/09613218.2013.783528.

Nicol, F. and Stevenson, F. (2013) "Adaptive comfort in an unpredictable world", *Building Research & Information*, no. 41(3), pp. 255–258, Available: doi:10.1080/09613218.2013.783528.

O´Neill, M.S., Zanobetti, A. and Schwartz, J. (2005) "Disparities by race in heat-related mortality in four US cities: the role of air-conditioning prevalence. ", *Journal of Urban Health*, vol. 82, no. 2, pp. 191-197.

OIkonomou, E., Davies, M., Mavrogianni, A., Biddulph, P., Wilkinson, P. and Kolokotroni, M. (2012) "Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London", *Building and Environment*, vol. 57, pp. 223–238, Available: doi:10.1016/j.buildenv.2012.04.002.

Orme, M. and Palmer, J. (2003) *Control of overheating in future housing, Design guidance for low energy strategies*, Hertfordshire, UK: Faber Maunsell Ltd.

Peacock, A.D., Jenkins, D.P. and Kane, D. (2010) "Investigating the potential of overheating in UK dwellings as a consequence of extant climate change ", *Energy Policy*, no. 38, pp. 3277-3288, Available: doi:10.1016/j.enpol.2010.01.021.

Porrit, S.M., Cropper, P.C., Shao, L. and Goodier, C.I. (2012) “Ranking of interventions to reduce dwelling overheating during heat waves”, *Energy and Buildings*, no. 55, pp. 16–27, Available: doi:10.1016/j.enbuild.2012.01.043.

Porter, J.J., Demeritt, D. and Dessai, S. (2015) “The right stuff? informing adaptation to climate change in British Local Government”, *Global Environmental Change*, vol. 35, November, pp. 411-422, Available: doi:10.1016/j.gloenvcha.2015.10.004.

REH (2013) *Regulamento de Desempenho Energético dos Edifícios de Habitação. Decreto-Lei n.º 118/2013 de 20 de Agosto. Diário da República n.º159 – 1.ª série, pp 4988 a 5005*, Lisboa: Ministério da Economia e do Emprego.

Roaf, S., Crichton, D. and Nicol, F. (ed.) (2009) *Adapting Buildings and Cities for Climate Change*, Architectural Press.

Roberts, S. (2008) “Effects of climate change on the built environment “, *Energy Policy*, no. 36, pp. 4552–4557.

Rogelj, J., Meinshausen, M. and Knutti, R. (2012) “Global warming under old and new scenarios using IPCC climate sensitivity range estimates”, *Nature Climate Change*, no. 2, pp. 248–253, Available: DOI:10.1038/NCLIMATE1385.

Sanders, C.H. and Phillipson, M.C. (2003) “UK adaptation strategy and technical measures: the impacts of climate change on buildings”, *Building Research and Information*, vol. 31, no. 3-4, pp. 210-221.

Santos, C. and Matias, L. (2006) *Coeficientes de Transmissão Térmica de elementos da envolvente dos edifícios*, Lisboa: Laboratório Nacional de Engenharia Civil.

Santos, F.D. and Miranda, P. (ed.) (2006) *Alterações Climáticas em Portugal. Cenários, Impactos e Medidas de Adaptação" — Projecto SIAM II*, Lisboa: Gradiva.

Semenza, J.C., Rubin, C.H., Falter, K.H., Selanikio, J.D., Flanders, W.D., Howe, H.L. and Wilhem, H.L. (1996) “Heat-related deaths during the July 1995 heat wave in Chicago “, *New England Journal of Medicine* , vol. 335, no. 2, pp. 84-90.

Smith, C. and Lawson, N. (2012) “Identifying extreme event climate thresholds for greater Manchester, UK: examining the past to prepare for the future”, *Meteorol. Appl. 19 (1), 26e35.*, vol. 19, no. 1, March, pp. 26-35, Available: DOI: 10.1002/met.252.

Taylor, A.J. and McGwin, G. (2000) “Temperature-related deaths in Alabama “, *Southern Medical Journal*, vol. 93, no. 8, pp. 787-792.

TRCCG (2008) *Your home in a Changing Climate - Retrofitting Existing Homes for Climate Change Impacts*, London: Greater London Authority.

van Hooff, T., Blocken, B., Hensen, J.L.M. and Timmermans, H.J.P. (2014) “On the predicted effectiveness of climate adaptation measures for residential buildings* “, *Building and Environment*, vol. 82, pp. 300-316, Available: http://dx.doi.org/10.1016/j.buildenv.2014.10.006.

Wang, X., Chen , D. and Ren, Z. (2010) “ . Assessment of climate change impact on residential building heating and cooling energy requirement in Australia “, *Building and Environment*, vol. 45, pp. 1663-82.

White-Newsome, J.L., Sanchéz, B.N., Parker, E., Dvonch, T., Zhang, Z. and O´Neill, O. (2011) “Assessing heat-adaptive behaviors among older, urban-dwelling adults”, *Maturitas*, vol. 70, no. 1, pp. 85–91, Available: doi:10.1016/j.maturitas.2011.06.015.

WHO (2004) *Health and Global Environmental Change: Heat Waves: Risks and Responses*, World Health Organisation.

Williams, K., Gupta, R., Hopkins, D., Gregg, M., Payne, C., Joynt, J. and Bates-Brkljac, N. (2013) “Retrofitting England’s suburbs to adapt to climate change”, *Building Research & Information*, no. 41(5), pp. 517-531, Available: doi:10.1080/09613218.2013.808893.

Zuo, J., Pullen, S., Palmer, J., Bennets, H., Chileshe, N. and Ma, T. (2015) “Impacts of heat waves and corresponding measures: a review”, *Journal of Cleaner Production*, vol. 1, no. 12, Available: http://dx.doi.org/10.1016/j.jclepro.2014.12.078.

6 CHAPTER 6 - EXPLORING VULNERABILITY FACTORS AND INDIVIDUAL ADAPTIVE PRACTICES TO HIGH TEMPERATURES IN BUILDINGS: INSIGHTS FROM A CASE STUDY IN LISBON

Paper IV

Exploring Vulnerability Factors and Individual Adaptive Practices to High Temperatures in Buildings: Insights from a Case Study in Lisbon

Ricardo Barbosa [1], Alice Ramos [2], Rui Santos [1], Romeu Vicente [3]

[1] CENSE - Center for Environmental and Sustainability Research, Departamento de Ciências e Engenharia do Ambiente, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Campus da Caparica, 2829-516 Caparica, Portugal

[2] ICS - Instituto de Ciências Sociais, Universidade de Lisboa, Portugal

[3] RISCO - Research Centre of Risks and Sustainability in Construction, Departamento de Engenharia Civil, Universidade de Aveiro, Portugal

Abstract

The world has been experiencing a significant increase in daily average temperatures in the last decades and climate change scenarios are projecting high probability of more frequent extreme events, such as heat waves.

Despite the growing consensus about the fundamental role of individual adaptive capacity to face climate change, research focusing on this scale is still scarce, particularly in vulnerable regions such as Southern Europe. This paper aims to investigate the individual adaptive practices implemented by residential building occupants in a Southern European context when dealing with the occurrence of high temperatures.

Using a vulnerability framework and considering a socio-technical approach to comfort, the research employed factor analysis in order to conceptually aggregate actions into four types of individual adaptive practices – (Indirect and Direct) Personal Practices and (Passive and Active) Environmental Practices- used by occupants of dwellings. Significant differences regarding the adoption of practices in relation to vulnerability factors were then assessed using variance analysis. Data was collected by means of a questionnaire, which was disseminated in the metropolitan region of Lisbon, Portugal.

Results suggest that the sex of occupants is relevant when it comes to the adoption of personal and passive environmental practices. Other personal and socio-demographic factors such as age, were found to be significant in relation to personal practices, but not to environmental ones.

One key issue arising from the findings is that contextual factors, in particular the ones associated with the building's physical characteristics and occupancy are relevant features not only for environmental practices but also for practices of personal nature.

The study leads to a discussion regarding the way these results can be useful in formulating adaptation policies and building design.

Keywords: Vulnerability; Climate Change; Adaptive Practices; Thermal Comfort; Buildings

6.1 Introduction

As the world experiences changes in climate, progressive increase in temperatures is recognized as an important global challenge. According to the Intergovernmental Panel for Climate Change (IPCC), an increase in the global mean surface temperature is expected to range from 0.3˚C to 4.8˚C until 2100, in relation to a 1986-2005 baseline (IPCC, 2013). Furthermore, results from modelling studies point out to a 5 to 10 factor of increased probability in the occurrence of heatwaves, with a significant incidence in Europe (Barriopedro et al., 2011). European countries have already been registering frequent and intense heatwaves with consequences in terms of loss of human lives (EEA, 2012). During the 2003 heatwave, still seen as a reference due to its intensity, duration and geographical extension (IPMA, 2013), countries like France, England and Portugal registered an increased number of deaths related to abnormal high temperatures inside dwellings (Vandentorren et al., 2006).

This context is particularly important in areas already considered to be more vulnerable, such as Southern Europe (Santos and Miranda, 2006), where occupants of dwellings will have to deal with climate conditions for which buildings were not designed for, potentially compromising their role as “climate moderators” (Roaf et al., 2009). This topic is significant both from the thermal comfort and energy use perspective. Although it is admitted that the larger portion of the European residential building stock remains naturally ventilated (Eurostat, 2010), the response to this change in climate and frequency of extreme temperatures has already been appointed as one of the enhancing factors for an increased use of air-conditioning in dwellings, which leverages energy demand in buildings.

As a result, the problem is the focus of different research fields. Research regarding mortality associated with heat stress is generally treated within epidemiological studies, using past data to identify the most vulnerable population or the conditions in which the capacity to adapt is reduced (Brown and Walker, 2008). In the field of thermal comfort and energy, the majority of the research done so far is focused on understanding the relation between the buildings” physical characteristics, location and vulnerability of indoor conditions (De Dear et al., 1997), as well as the measures that can be applied to improve thermal performance in the face of change (CIBSE, 2005; Mavrogianni et al., 2012). Both fields highlight and recognize the importance of the role of buildings in determining adequate and comfortable indoor conditions when facing climate change.

Despite the recognized potential and cost-effectiveness of “behavioral” adaptation (Coley et al., 2012), attention given to dwellings occupants” behavior when adapting to high temperatures inside buildings in Europe, is limited. Technical studies, which have a clear focus in Northern Europe, usually consider occupancy, use of available controls and typified window-opening profiles as a way to take the interaction with the building into consideration (e.g. Porrit et al., 2012). However, the type of actions occupants take to achieve comfort are not limited to interaction with the building. These actions are extremely dynamic, can hardly be expressed using fixed parameters (De Dear, 2006) and are influenced by an interaction between individuals and the systems of power, infrastructures, technologies, society and culture (Guy, 2006; Maller and Strengers, 2011).

Some studies suggest that, in order to determine how vulnerability is generated (and moderated), one has to look beyond epidemiological studies and technical assessments. This perspective argues for the influence of personal, social and contextual factors in regulating vulnerability (Brown and Walker, 2008; Maller and Strengers, 2011), and for an existing (and not yet explored) relationship between these factors and the actions performed by occupants (Maller and Strengers, 2011). Understanding such relationship, as well as a clearer characterization of actions to deal with high temperatures, in particular in a vulnerable context such as Southern Europe, can provide useful insights for both adaptation and health policy, namely regarding the design of buildings and its relation with effective and sustainable strategies to adapt. Furthermore, policies focusing on improving existing adaptive capacity are more likely to be effective if they are built over what people are already doing (Wamsler and Brink, 2015).

Therefore, the approach taken in this study aims at contributing to: 1) a better understanding of the way occupants engage and use their capacity to counteract high temperatures inside their buildings, through the implementation of actions; 2) explore the potential relationship between vulnerability-underlying factors and actions, as well as possible implications for policy. A case study was developed in the metropolitan region of Lisbon, Portugal, to illustrate and discuss the application of the proposed approach.

6.2 Individual adaptive practices to achieve comfort as a response to vulnerability

The context presented in the previous section stresses the need to approach the behavior of occupants of a dwelling and the composition of factors influencing vulnerability to climate change and extreme events through a systemic lens. These two subjects are the focus of the present section.

6.2.1 Occupant Behavior for Thermal Comfort – from actions to practices

Comfort is being increasingly recognized as a complex and interdisciplinary subject, distancing itself from the engineered and simplified perspective that thermal regulations often assume (Haldi and Robinson, 2008; Kempton et al., 1992). A special issue of Building Research and Information is worthy of note, as it approached the subject by presenting studies dedicated to understanding how the expectations of thermal comfort are created

(Shove et al., 2008), the influence of thermal comfort standards in shaping the built environment and the way people live inside a building (Healy, 2008). This perspective acknowledges that, to some extent, the question “How do people behave?” is as important as “Why do they behave the way they do?”.

While the most common approaches seem to offer partial views on human behavior towards the achievement of thermal comfort conditions (e.g. technically driven studies focusing on window operation), the Schweiker and Skukuya (2009) study takes on a conciliatory perspective on the subject and argues about the existence of two types of drivers for behavior – “external” and “internal”. In this context, an example of an external driver would be the exterior temperature, whereas internal drivers would include individual preferences, cultural habits and attitudes.

While human agency is admitted to be limited by social and cultural contexts, such as social norms, political, economic or demographic factors (Hinton, 2010), Stern argues that drivers can also be limited or influenced by infrastructural and situational constraints (Stern, 2000), a statement corroborated by the contributions from technical studies, which recognize the importance of a material agency (Hinton, 2010). Following this rationale, a significantly growing body of research is considering both socio-cultural and socio-technical perspectives regarding the way comfort is created, operationalized and assessed. In particular, in the socio-technical approach, the concept of comfort is understood as being associated and co-evolving with technical systems (Shove, 2003; Guy, 2006), as well as being a social and historical construct (Chappels and Shove, 2005; Shove, 2003), highly dependent on the context (Hitchings, 2009). Behavior towards comfort is recognized as resulting from the interplay of several elements – a “seamless web” (Hinton, 2010), which form socio-technical assemblages, where agency is attributed not only to humans, but also to things (such as buildings and artifacts available to humans).

If to understand comfort we must understand “what people do, as a matter of course” as Shove suggests (Shove, 2006), one needs to look further into the response of occupants to high temperatures. Behavior is operationalized through the implementation of actions. The response in terms of occupants” reactions, in the case of high temperatures in particular, was already defined in three generalized but distinctive levels in thermal comfort literature: 1) unconscious physiological changes (e.g. shivering, sweating); 2) behavioral changes; and 3) use of controls available in the building (Roaf et al., 2009). While all levels are dependent on particular and subjective parameters of comfort of the individual, the last two levels are of interest, because they imply undertaking a voluntary action, in opposition to the (involuntary) bodily response to thermal conditions considered in the first level.

Behavioral change, as it is understood in this study and drawing broadly from other studies (Heerwagen and Diamond, 1992; Haldi and Robinson, 2008), ranges from changes made directly to the person’s body (i.e. adjustments in clothing, intake of fluids or showering) to changes affecting it indirectly, such as avoiding turning heat sources on, using fans, moving to cooler areas or even abandoning the building (Coley et al., 2012; Nicol and Roaf, 2007).

The use of controls of the building - in particular regarding operation of windows and blinds (Nicol and Stevenson, 2013; De Dear et al., 1997) - is extensively treated in building and comfort-related literature as important for both comfortable indoor conditions and tolerance to high temperatures. Operation of windows and blinds have been strongly associated with changes in both outdoor and indoor temperature (Andersen et al., 2009) and with specific characteristics of the building, such as orientation of windows (Nicol and Humphreys, 2004). Mechanical cooling can also be considered in this level as an "active" control in opposition to "passive" controls, which generally do not require energy to be operated, such as windows and blinds.

Despite the relatively wide range of possible actions taken by occupants, Ropke claims that "in continual flow of activities (or actions) it is possible to identify clusters or blocks of activities where coordination and interdependence make it meaningful for practitioners to conceive them as entities" (Ropke, 2009). This idea would also constitute the foundations for practice theory. Conceptually, practice theory is tightly connected with Bordieu´s work (Bourdieu, 1990). Early works on practice theory include Giddens (1984), where it is argued that practices are the reproduction of the social structure of society. In the same direction, Schatzki (1996) claims that, when individuals participate in a social practice, such as cooking, they participate in the same practice even when they do not know each other, meaning that they perform the same "actions and expressions", like cleaning vegetables and cooking rice.

Practices have already been defined as "co-ordinated entities that are temporarily unfolded and constitute spatially dispersed nexuses of doings and sayings" (Schatzki, 1996).

For Geels (2004), practices are produced and changed in socio-technical regimes, which similarly to a theatrical stage, is the setting where action unfolds. In this view, socio-technical systems support different regimes and hence, different practices. Therefore, practices are important in order to understand regimes and vice versa. In a close subject to this study, Maller and Strengers make the case for a practice approach to vulnerability to heat. Rather than analysing individual behavior, it argues that practice theory enables the study of how multiple actors behave "across time and space" (Maller and Strengers, 2011). Furthermore, as representations of socio-technical regimes, practices are seen as conceptually connected with components of complex systems implicated in the creation of vulnerability, which can also be seen as part of the construction of the practice (Maller and Strengers, 2011).

Considering this context, in relation to establishing comfortable conditions, and following Ropke (2009), practices are clusters of actions undertaken by occupants of dwellings while adapting to high temperatures. These clusters are designated here by individual adaptive practices and are considered to be related to the socio-technical assemblage supporting (and acting on) a determined regime.

6.2.2 Factors influencing vulnerability

Despite the wide range of definitions and perspectives found in literature, resulting from the various fields in which the concept is addressed (Miller et al., 2010), vulnerability represents a well-researched and mature approach to understand a system's response to change. The approach taken in this study considers vulnerability to be inherent to the system and it is explored by the change in climate and frequency and severity of extreme events (O´Brien et al., 2004). Vulnerability, following the IPCC definition, is "the propensity or predisposition to be adversely affected" (IPCC, 2014). This view considers vulnerability to be a function of the magnitude and character of the climate variation and change, its exposure, sensitivity and adaptive capacity. Adaptive capacity, in particular, can be defined as "the ability of systems, (…) to adjust to potential damage." (IPCC, 2014).

Considering that the subject of vulnerability is comfort itself, and if a socio-technical perspective is taken, the factors regulating the predisposition to be adversely affected will be dependent on the networked interplay present in socio-technical assemblages. Being so, to distinguish the factors influencing vulnerability in these systems, an interdisciplinary view is necessary. Therefore, factors considered here range from individual and social characteristics identified in epidemiological and sociological literature, such as age and income (e.g Diaz et al. (2002)) to building characteristics, mostly treated in technically driven studies (e.g. Hacker et al. (2009)). Three factors were extracted from literature: socio-demographic factors; personal factors (which include individual preferences in relation to comfort in high temperatures) and contextual factors (which, following another study (Maller and Strengers, 2011), also include building characteristics). Table 1 lists the factors and parameters, as well as the major sources of evidence.

6.3 Methodology

The study was produced by means of a survey using a questionnaire with the objective of collecting data regarding variables related with socio-demographic, personal and contextual factors of vulnerability, as identified in Table 6.1. Data regarding the actions performed by the occupants of dwellings in order to adapt to high temperatures was also collected. Besides a descriptive analysis of the data, several statistical techniques were used to explore the relationship between the variables. This section describes the materials and methods employed.

6.3.1 The study area

The portuguese metropolitan region of Lisbon (AML) was the focus for dissemination for the questionnaire. Lisbon climate is characterized as Mediterranean, with mild winters and hot and dry summers with high levels of solar radiation. According to the monthly climate data for Lisbon, the hottest month is August, with an average temperature of 23.5˚C. In terms of climate extremes, the highest registered absolute temperature was 42˚C, during the 2003 heatwave (IPMA, 2013). It is exemplary of South European cities with a significant heat island effect associated with high density (Alcoforado, 2006). During the last decade, heatwaves episodes have been recorded in, at least, half the years, occasionally more than once a year (ARSLVT, 2012).

Table 6.1 - Vulnerability factors and sources of evidence

Factors	Parameters	Variables	Major sources of evidence
Socio Demographic	Age		(Diaz et al., 2002) (Fouillet et al., 2006)
	Sex		(Diaz et al., 2002) (Hajat, Kovats and Lachowycz, 2007) (Taylor and McGwin, 2000)
	Socio-economic status	Disposable income	(Harlan et al., 2006) (Borrell et al., 2006)
	Size of household	Number of people living in dwelling	(Semenza et al., 1996)
Personal	Individual preferences	Level of discomfort	(Nicol and McCartney, 2000) (Nicol and Stevenson, 2013) (Nicol et al., 2009)
	Health Status	Pre-existence of cardio-vascular, pulmonary or mental illness	(Bouchama et al., 2007)
	Occupancy	Time spent indoors(h)	(Porrit et al., 2012) (Gupta and Gregg, 2012)
		Time of occupancy (0-24h)	(Porrit et al., 2012) (Gupta and Gregg, 2012)
		Occupied room	(Orme and Palmer, 2003) (Peacock, Jenkins and Kane, 2010)
		Internal gains of occupied room (W/m2.year)	(Orme and Palmer, 2003) (Holmes and Hacker, 2007)
Contextual	Dwelling Age		(Orme and Palmer, 2003) (Sanders and Phillipson, 2003) (Hacker, Capon and Mylona, 2009)
	Type of dwelling		(Porrit et al., 2012)
	Size of dwelling		(Coley, Kershaw and Eames, 2012) (Porrit et al., 2012) (Mavrogianni et al., 2012) (Gupta and Gregg, 2012)
	Orientation		(Coley and Kershaw, 2010) (Porrit et al., 2012)
	Building floor		(Orme and Palmer, 2003) (CIBSE, 2005) (Mavrogianni et al., 2012) (Olkonomou et al., 2012)
	Building fabric (U value)		(CIBSE, 2005) (Hacker, 2008) (Kendrick et al., 2012) (ARUP and BDA, 2005) (Coley and Kershaw, 2010)

6.3.2 Sample

Sample population was selected from the target universe of 2.013.170 people living in AML (INE, 2011). The selection focused on people living in housing units within the metropolitan region who were approached through a form constructed using an online survey service – Survey Monkey (Survey Monkey Inc., 2014) - and disseminated via electronic mail. For the purpose of this study, “people living in housing units” is defined as permanent residents occupying dwellings all year round.

In addition to personal networks, the online questionnaire was disseminated through mailing lists from Emergency Services (Protecção Civil) of Lisbon and Amadora Municipalities as well as from the city's energy agency – Lisboa E-Nova. The use of organizations and communities of users is critical in order to help establish a sample frame and overcome sampling concerns in relation to Internet-based surveys, as argued by Wright (2005). The advantages and challenges of this type of methodology of data collection are widely discussed in research literature (Wright, 2005; Riva et al., 2003). Besides being cost-effective and open for a wider participation (Rhodes et al., 2003), the methodology can reduce errors and provide more usable information than other data collection methodologies, with regard to behavioral data.

The responses to the questionnaire which presented basic information omissions or more than half of invalid question responses were excluded and not considered, resulting in 352 valid questionnaires, out of 569 responses. Thus, the sample cannot be considered to be representative of the entire population of the metropolitan area. However, considering the exploratory nature of this work and following other studies (e.g. Rodham and Bell (2002)), a purposive sample such as the one presented here, is considered adequate for the analysis.

6.3.3 Questionnaire

The questionnaire was initially pre-tested in December 2013 to a selected group of 10 people in order to assess readability and identify potential misinterpretations regarding questions that might lead to biased answers. Minor adjustments were made to the final version and the online questionnaire was launched on January 14, 2014, and closed on September 9, 2014.

The questionnaire itself consists of 26 questions (mainly in the form of closed questions) divided into 4 sections: (I) Occupant characterization, (II) Dwelling occupancy profile (III) Dwelling characterization (IV) Thermal environment and strategies. Table 6.2 provides an overview of its contents.

Table 6.2 - Questionnaire contents

Questionnaire Section	Objective	Data collected
Occupant characterization	Individual and household characterization	Age
		Sex
		Level of income
		Type and size of household
		Health status
Dwelling occupancy profile	Characterization of occupancy throughout the year	Schedule of occupancy
		Most occupied room
Building and Dwelling characterization	Basic ascertaining of technical characteristics of dwelling and building	Dwelling age
		Type of windows and glazing
		Size of dwelling
		Orientation
		Type of dwelling
		Building floor
Thermal environment and strategies	Personal characterization of thermal environment	Level of discomfort (scale 1 to 5)
		Actions adopted in case of high temperatures

6.3.4 Data analysis

After the collection period, data was imported from the online service and resulting variables were recoded for consistency and readability (e.g. an index for occupancy was computed). New variables were added to include aggregated information from open questions. Data was analysed with Statistical Package for the Social Sciences (SPSS) v. 21 software (IBM Corp, Released 2013) using the following methodological steps:

1. A **descriptive analysis** was first performed mainly based on absolute frequencies in order to characterize both respondents and actions;

2. Secondly, **Exploratory Factorial Analysis** was used, taking as an essential assumption the rationale laid out in section 6.2.1. The application of this technique is particular useful when trying to reduce the variables available to a relatively small number of dimensions – denominated latent variables or constructs (Reis, 1990). For the extraction of dimensions, Principal Component Analysis (PCA) method with varimax rotation was used. Only dimensions presenting eigenvalues higher than 1 were considered for further analysis.

To test the adequacy of the method to the data (sampling adequacy), a Kaiser-Meyer-Olkin (KMO) test was performed and values between 0.6 and 0.7 were considered reasonable. Below those values, adequacy is weak and less than 0.5 is considered unacceptable (Reis, 1990). An internal consistency test using Cronbach Alpha was also performed, assuming that in exploratory analysis values close to 0.5 can be accepted. (Johnson and Wichern, 2007).

3. The variables computed from the results of PCA were then submitted to a **one-way analysis of variance (ANOVA**), with the purpose of assessing the statistical significance of differences in adaptive practices in relation to vulnerability factors (see Table 1). All variables were scored in the direction of frequency of use, meaning that higher scores indicate more frequent practices. Probability values below 0.05 were considered statistically significant (Bewick et al., 2004). When significant differences were found, subsequent post-hoc comparisons using the Schefee test were performed.

6.4 Results

Respondents and characterization of cooling actions

Results indicate that most of the respondents belong to the 30-40 age group (42.6%), divided almost equally between men and women (50.6% female respondents), have a higher education degree and live with a partner. A significant part of the sample (46.7%) also indicated living with a larger household composition, namely children. The majority of the respondents indicated an income ranging from 21.000 Euros to 31.000 Euros/year, working outside the home and living in an apartment. Most of the respondents (43.1%) reported living in a building dated from 1990 to 2007.

Regarding cooling actions, the one most frequently reported was changing clothes and drinking liquids, opening the windows at times of the day when temperature is lower, as well as closing blinds and windows.

Figure 6.1 shows results regarding frequency of respondents' actions

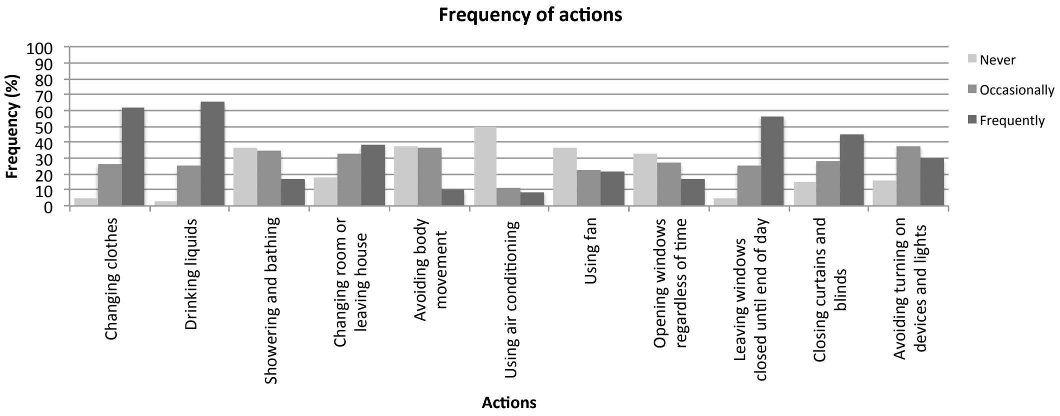


Figure 6.1 - Percentage of Frequency regarding respondents" cooling actions

Individual Adaptive Practices

The PCA performed on the actions" variables identified four components or dimensions that are responsible for 57% of the variance. The value resulting for the KMO test indicates that the data is adequate for the analysis. Alpha values are classified as acceptable, which allows for the assumption that there is an internal consistency that reflects valid latent variables or constructs (Table 6.3).

The way variables are grouped leads to the attribution of a specific meaning to each of the constructs and allow for a bi-dimensional structure of four components - Passive and Active Environmental practices and Direct and Indirect Personal practices - which differ according to scope and the way the practice is implemented. Environmental Practices relate with the level of response concerning the use of available controls in the building and are further specified as Passive (PE) and Active (AE), to distinguish between practices where the use of energy is implied. In that context and according to results of PCA, the action regarding the use of air conditioning is distinctive enough to be isolated as one single practice.

Personal practices are closely related with behavioral change and further detailing distinguishes between the way they affect body temperature – Directly (DP) or Indirectly (IP).

Differences in vulnerability factors in relation to adaptive practices

Tables 6.4, 6.5 and 6.6 show the descriptive (mean and standard deviation) of the variables in the groups of factors, in which significant differences were found and relates them with the ANOVA variance analysis results.

In terms of socio-demographic factors, the analysis of variance using age as an independent variable shows significant differences between groups in relation to the use of IP practices.

Post hoc comparisons test revealed that the mean for >50 group is significantly different from the mean for 30-50 group.

Table 6.3 - Principal Component Analysis (varimax rotation) and classification of practices

Actions	**Component**				**Practices**	**Level of response**
	1	2	3	4		
Closing curtains and blinds	**.838**	.062	.110	.052	Passive Environmental (PE)	Use of building controls (Passive)
Opening windows regardless of time	**.832**	.024	-.093	.259		
Leaving windows closed until end of day	**.612**	.140	-.068	-.238		
Avoiding body movement	.055	**.721**	.062	-.043	Indirect Personal (IP)	Behavioral change
Changing room or leaving house	.174	**.677**	.170	-.104		
Using fan	-.078	**.606**	-.102	.437		
Avoiding turning on devices and lights	.341	**.460**	.250	-.361		
Changing clothes	.078	.001	**.747**	-.153	Direct Personal (DP)	
Showering and bathing	-.089	.328	**.618**	.168		
Drinking liquids	-.049	.024	**.580**	.326		
Using air-conditioning	.110	-.051	.187	**.756**	Active Environmental (AE)	Use of building controls (Active)
Variance explained (%) (before rotation)	21.43	15.0	11.32	9.20		
KMO	0.639					

No other differences between groups were considered statistically significant. Results regarding sex as the independent variable indicate that there is a significant difference between men and women concerning PE practices, DP practices and IP practices. Means are consistently higher for female group respondents.

Table 6.4 - Descriptive and variance analysis for Socio Demographic factors

		PE			**AE**			**IP**			**DP**		
Socio Demographic Factors		mean	sd	Variance	mean	sd	Variance	mean	sd	Variance	mean	sd	Variance
Age	<30	2.27	.30		1.27	.60		2.06	.49		2.39	.41	
	30-50	2.31	.43		1.42	.69		**1.94**	**.57**	F(2,320)=3.68,p<0.5.	2.38	.48	
	>50	2.40	.41		1.65	.89		**2.17**	**.50**		2.39	.46	
Sex	M	**2.26**	**.42**	F(1,381)=9.38,p<0.01	1.38	.70		**1.88**	**.54**	F(1,355)=18.34, p< 0.001	**2.30**	**.48**	F(1,366)=10.28,p<0.01
	F	**2.38**	**.41**		1.45	.72		**2.13**	**.55**		**2.46**	**.46**	

When variables concerning personal factors were analysed, it was found that the reported level of discomfort with high temperatures indicates a significant difference between the groups regarding IP practices and AE practices. Post hoc tests showed that for IP practices, the mean for level 1 of discomfort is significantly different from levels 3 and 4. For AE practices, the same test indicated that level 1 was significantly different from 4. Additionally, an effect of occupancy on PE and IP practices was also found. Post hoc comparisons indicated that regarding PE practices, the mean for degree 1 of occupancy is significantly different from degree 4. For IP practice, the mean for degree 1 was found to be significantly different from 2.

Table 6.5 - Descriptive and variance analysis for Personal factors

		PE			**AE**			**IP**			**DP**		
Personal factors		mean	sd	Variance	mean	sd	Variance	mean	sd	Variance	mean	sd	Variance
Level of discomfort	0	2.34	.49		1.22	.44		1.85	.70		2.36	.50	
	1	2.28	.42		**1.15**	**.44**		**1.82**	**.70**		2.29	.53	
	2	2.30	.41		1.47	.74	F(4,257)=2.79,p< 0.05	1.95	.50	F(4,348)=4.57,p<0.01	2.38	.43	
	3	2.36	.39		1.40	.69		**2.12**	**.55**		2.43	.43	
	4	2.34	.46		**1.63**	**.84**		**2.17**	**.57**		2.41	.54	
Occupancy	1	**3.0**	**.00**		2.00	.		**2.91**	**.14**		2.88	.19	
	2	2.32	.39		1.44	.73		**1.87**	**.56**		2.47	.41	
	3	2.35	.39	(5,359)=2.63,p<0.05	1.42	.71		2.01	.55	F(5,353)=3.26,p<0.01	2.34	.51	
	4	**2.28**	**.40**		1.40	.67		2.05	.50		2.35	.47	
	5	2.26	.55		1.27	.59		2.17	.63		2.36	.39	
	6	2.32	.53		1.45	.82		1.87	.63		2.50	.42	

When it comes to variables relating to contextual factors, a significant effect of type of dwelling was found on DP and IP practices. In both analysis, means are higher for Apartments group (For DP and for IP).To further detail regarding this result, the location of the apartment in the building was analysed. The variable was disaggregated into 3 groups – situated on the ground floor, on an intermediate floor and on the last floor of the building. The variance analysis indicates differences between groups concerning AE practice. Differences were statistically significant between means for ground floor group and last floor.

Size of dwelling was found to present differences regarding the adoption of AE practice only among the groups indicating 2 rooms and 5 rooms.

The number of exposed walls (coded from 1 to 4) was also found to have an effect, in particular regarding the use of PE practices and in what concerns dwellings with 2 exposed walls and 3 exposed walls.

As proxies for assessing building construction materials, variables regarding the type of glazing existing in the dwelling and the age of the building was analysed. Type of glazing results indicates a noteworthy difference between groups concerning IP, DP and AE practices. For IP and DP, means are higher for single glazing group of respondents. For AE practices, the mean for single glazing is lower than the one for double glazing.

Dwelling age indicated important differences regarding IP practices. The mean regarding 1960-1990 is found to be significantly different from 1990-2007.

6.5 Discussion

The results presented above suggest that the socio-demographic factors are relevant in analysing the differences in individual adaptive practices. Regarding sex, results are consistent with findings in Khare et al. (2015), which argue that this prevalence is due to a greater vulnerability in women, a statement strongly refuted by other sources (Michelozzi et al., 2004). Differences in vulnerability and adaptive capacity, regarding male and female are also discussed in a vast array of literature such as Patt et al. (2009), as being the result of cultural norms and specific roles in society, work and domestic life, which may call for a sex-differentiated perspective regarding adaptation.

Table 6.6 - Descriptive and variance analysis for Contextual factors

		PE			**AE**			**IP**			**DP**		
Contextual factors		mean	sd	Variance	mean	sd	Variance	mean	sd	Variance	mean	sd	Variance
Type of Dwelling	Apartment	2.33	.42		1.41	.70		**2.04**	**.57**	F(1,358)=2.7,p<0.001	**2.42**	**.47**	F(1,357)=1.22,p<0.05
	House	2.20	.39		1.47	.72		**1.88**	**.44**		**2.18**	**.45**	
Building Floor	Floor	2.39	.51		**1.12**	**.48**	F(2,220)=3.59,p<0.01	2.04	.62		2.32	.50	
	Intermediate	2.32	.40		1.37	.69		1.99	.54		2.40	.46	
	Last	2.33	.42		**1.59**	**.75**		2.14	.58		2.49	.45	
Size of dwelling	1	2.25	.37		1.07	.267	F(8,257)=3.8,p<0.001	1.81	.44		2.31	.47	
	2	2.30	.38		**1.16**	**.51**		1.92	.58		2.45	.45	
	3	2.36	.41		1.31	.62		2.02	.57		2.38	.45	
	4	2.29	.43		1.49	.75		2.01	.53		2.41	.48	
	5	2.27	.37		**1.85**	**.89**		2.02	.52		2.34	.43	
	>5	2.28	.50		1.18	.40		2.08	.56		2.20	.48	
Exposed Walls	1	2.30	.44	F(3,358)=3.02,p<0.05	1.27	.66		1.96	.54		2.42	.48	
	2	**2.36**	**.36**		1.42	.69		2.05	.54		2.40	.45	
	3	**2.19**	**.46**		1.56	.79		1.98	.57		2.35	.48	
	4	2.35	.46		1.33	.57		1.96	.59		2.29	.51	
Glazing	single	2.36	.42		**1.18**	**.52**	F(1,223)=11.96,p<0.01	**2.16**	**.54**	F(1,297)=9.99, p<0.01	**2.48**	.49	F(1,306)=5.81,p<0.05
	double	2.3	.43		**1.53**	**.74**		**1.95**	**.55**		**2.34**	.45	
Dwelling Age	After 2007	2.34	.44		1.54	.68		1.87	.49	F(4,348)=3.96,p<0.01	2.36	.49	
	1990 - 2007	2.27	.42		1.48	.73		**1.94**	**.53**		2.33	.45	
	1960- 1990	2.35	.40		1.36	.72		**2.14**	**.57**		2.43	.48	
	1940- 1960	2.41	.40		1.27	.63		2.06	.60		2.43	.48	
	Before 1940	2.36	.42		1.11	.33		2.28	.50		2.60	.38	

Results also indicate age as being relevant for the analysis of indirect personal practices. Age is a well-known and established factor for vulnerability (Michelozzi et al., 2004), but there is limited knowledge regarding its influence on the adoption of adaptive practices. Some studies approach behavior from an age perspective, but working as a starting point and not as an explanatory variable. One clear example is White-Newsome et al. (2011), whose results concerning urban older adults suggest practices, identified here as indirect personal, as associated with environmental and structural factors.

Results regarding personal factors, such as the level of discomfort, also reveal a significant difference concerning indirect personal practices, which can be an indication of a relationship between vulnerability and practices. The level of discomfort considered here is self-reported and therefore closely related with the individual's perception of the risk, which some authors argue, besides being undervalued, is not being considered properly in policy formulation regarding heat protection (Wolf et al., 2010).

Contextual factors, and in particular, variables relating to dwelling physical characteristics, also seem to be relevant regarding the adoption of practices. In this study, results suggest expressive differences in relation to contextual factors regarding practices connected with changes to the indoor environment. This argument points in the same direction as other studies highlighting the influence of dwelling characteristics and the surrounding settings in adoption of certain practices (White-Newsome et al., 2011). In this context, the differences found in personal practices in relation to contextual factors are noteworthy, suggesting that physical characteristics of dwellings are important not only for the practices that involve building controls, such as windows, but also for practices focused on the personal level.

Another finding which is worth highlighting is the fact that there is no indication of socio-demographic or personal factors presenting significant differences in the use of active environmental practices (i.e. use of air conditioning), which suggests that, again, contextual factors and in particular, the design of the built environment, are at the core of inductors of this practice. This is also the approach taken by Chappels and Shove (2005), while discussing the importance of such practices in the construction of the current understanding of the concept of comfort, as well as in the evolution of the built environment.

Although it is sometimes dubbed as “protective measure”, air conditioning has, however, been in the center of a heated discussion about sustainability of measures regarding adaptation (Maller and Strengers, 2011). Taking into consideration the arguments stated above about older people and vulnerable populations, this last point is particularly important in the sense that it suggests that there is unleashed potential in the design of the built environment to promote adequate adaptive practices even at the personal level, as already been broadly indicated in other studies (Strengers and Maller, 2011).

If the systemic perspective of Maller and Strengers (2011) is considered, results suggest that practices are, in fact, conceptually connected with the very components implicated in the creation of vulnerability. Accordingly, Hinton (2010) argues that multi level interventions are needed in order to drive change in socio-technical regimes, which means that, in order to change to a more sustainable course, policies have to be directed at the different parts of the assemblage.

Policies designed to deal with high temperatures are normally based on early warnings and public information policies, which have already been suggested as not being effective in reducing vulnerability to heat (Wolf et al., 2010). Understanding the most significant vulnerability factors, such as age, sex or the characteristics of physical environment in relation to the adoption of practices, can assist in the design and implementation of adaptation policies and high temperature response plans by supporting the diversity of existing practices (in opposition to the administration of mass communication campaigns) (Strengers and Maller, 2011). It can also benefit integration of adaptation policies for improved effectiveness. A possible direction is the development of regulations and building codes aiming at promoting practices which seek to be more sustainable or effective, as broadly argued also in other studies (Maller and Strengers, 2011; Shove et al., 2008). However, these instruments alone have been insufficient in order to drive the necessary behavior change (UK Government, 2005). A complementary possible direction is the implementation of incentives. The knowledge acquired from research relating factors and practices can be used to inform a comprehensive behavior change model like the one suggested in the UK strategy for sustainable development (UK Government, 2005). In particular, the context of the study presented here can be of interest regarding the implementation of economic incentives schemes (such as tax systems or grants) for the purpose of preparing the building stock for climate change impacts, as proposed in LCCP (2009) study.

Regardless of the potential of the developed research, limitations are recognized. The study was designed to capture the maximum diversity in terms of responses concerning actions, which, due to limited available resources, was achieved through online survey tools. Being so, the study assumes that participants" response is close to their actual behavior. However, some unintentional bias should be considered possible in responses, namely regarding actions. Subsequent analyses with smaller samples, preferably including monitoring campaigns and logs of occupant behavior, can be used to validate and detail further the influence of factors on adoption of practices. Furthermore, the approach can be extended by including other regions and climates – for example, other countries in Southern Europe or Northern Europe - which can be useful for comparing notable differences already suggested by empirical research.

6.6 Conclusions

With the objective of exploring the relationship between factors regulating vulnerability and the actions undertaken by dwellings occupants, an approach was developed using a southern European city – Lisbon, Portugal - as a case study.

In the first phase of the analysis, and assuming a socio-technical framework for comfort, clusters of actions were theorized as practices. Four types of practices are proposed – Passive Environmental; Active Environmental; Indirect Personal and Direct Personal. It was then possible, using analysis of variance, to infer statistically significant differences between the various factors in relation to the adoption of practices.

Socio-demographic and personal factors are suggested to be significant in respect to the adoption of practices. Age and sex, in particular, seem relevant in relation to the practices adopted.

Additionally, a relation between practices and the level of discomfort is indicated as relevant, point out to an association with vulnerability itself. In this context, a statistical analysis considering results of a vulnerability assessment of Lisbon building stock and the practices inferred here can potentially provide interesting results.

Results also point to significant differences in contextual factors such as building characteristics and its occupancy. It is suggested that different building characteristics, for example, can be significant regarding practices related with a personal as well as an environmental control of indoor conditions. Further research can help to validate these results and identify which building (and dwelling) characteristics are more important in the promotion of adequate and sustainable practices.

Despite some limitations and the need for further research, this kind of insight is considered potentially useful to provide constructive information for the design and implementation of adaptation policies and building design. Collection and analysis of data originating from other urban settings and climates could also provide valuable comparative analysis and support the design of more effective and tailored policies adjusted to different socio-economic-cultural-climate contexts.

Acknowledgements

To the Foundation for Science and Technology, Portugal (Contract SFRH/BD/ 70395/ 2010) for funding the research.

CENSE is financed through the Strategic Project Pest-OE/AMB/UI4085/2013 from the Foundation for Science and Technology, Portugal.

The authors would also like to thank Protecção Civil of Amadora and E-Nova Lisboa for the help in the questionnaire dissemination.

References

Abrahamse, W. and Steg, L. (2009) "How do socio-demographic and psychological factors relate to households" direct and indirect energy use and savings? ", *Journal of Economic Psychology* , vol. 30, pp. 711-720.

Akturk , D., Gun, S. and Kumuk, T. (2007) "Multiple correspondence analysis technique used in analyzing the categorical data in social sciences ", *Journal of Applied Sciences* , vol. 7, no. 4, pp. 585-588.

Alcoforado, M.J. (2006) "Climatic Information for urban planning", in WMO (ed.) *Climate as a Resource*, Genéve.

Andersen, R.V., Toftum, J., Andersen, K.K. and Olesen, B. (2009) "Survey of occupant behaviour and control of indoor environment in Danish dwellings", *Energy and Buildings*, vol. 41, no. 1, pp. 11-16, Available: doi:10.1016/j.enbuild.2008.07.004.

Andersen, R.V., Toftum, J., Andersen, K.K. and Olesen, B.W. (2009) "Survey of occupant behaviour and control of indoor environment in Danish dwellings ", *Energy and Buildings*, vol. 41, pp. 11-16, Available: doi:10.1016/j.enbuild.2008.07.004.

ARCC (2011) *Adaptation and Resilience in a Changing Climate* , [Online], Available at: http://www.ukcip-arcc.org.uk/ (Accessed December 2014).

ARSLVT (2012) *Alterações Climáticas e Saúde Humana - Gestão do Risco para a Saúde da População da Região de Lisboa e Vale do Tejo*, Lisboa: Administração Regional de Saude de Lisboa e Vale do Tejo.

ARUP (2008) *Your home in a Changing Climate - Retrofitting Existing Homes for Climate Change Impacts*, London: Greater London Authority.

ARUP and BDA (2005) *UK Housing and Climate Change - Heavyweight vs. lightweight construction*, [Online], Available at http://web.mit.edu/cron/project/concrete-sustainability-hub/Literature%20Review/Building%20Energy/Industry%20Claims/Climate_Change_BDA_report.pdf (Accessed December 2014).

Barriopedro, D., Fischer, E., Luterbacher, J., Trigo, R.M. and Garcia-Herrera, R. (2011) "The hot summer of 2010: Redrawing the temperature record map of Europe", *Science*, vol. 332 (6026), pp. 220-224.

Bewick, V., Cheek, L. and Ball, J. (2004) "Statistics review 9: One way analysis of variance", *Critical care*, vol. 8, no. 2, April, pp. 130-138, Available: DOI 10.1186/cc2836.

Borrell, C., Dell´Olmo, M., Guez-Sanz, M., Garcia-Olalla, P., Cayla, J., Benach, J. and Muntaner, C. (2006) "Socioeconomic position and excess mortality during the heat wave of 2003", *European Journal of Epidemiology*, vol. 21, pp. 633-640.

Bouchama, A., Dehbi, M., Mohamed, G., Matthies, F., Shoukri, M. and Menne, B. (2007) “Prognostic factors in heat wave related deaths: a meta-analysis “, *Archives of Internal Medicine* , vol. 167, pp. 2170-2176.

Bourdieu, P. (1990) “Structures, habitus, practices”, in Elliot, A. (ed.) *Contemporary Social Theory*, Blackwell Publishers.

Brown, S. and Walker, G. (2008) “Understanding heat wave vulnerability in nursing and residential homes “, *Building Research & Information* , vol. 36, no. 4, pp. 363-372, Available: DOI: 10.1080/09613210802076427.

Bryman, A. and Cramer, D. (2001) *Quantitative Data Analysis with SPSS release 10 for Windows*, Routledge.

Chappels, H. and Shove, E. (2005) “Debating the future of comfort: environmental sustainability, energy consumption and the indoor environment”, *Building Research & Information*, vol. 33(1), pp. 32-40.

CIBSE (2005) *TM36 Climate change and the indoor environment: impacts and adaptation*, London: The Chartered Institution of Building Services Engineers.

CIBSE (2006) *CIBSE Guide A, 7th edn - Thermal comfort: annotated definitions of main thermal parameters*, London: Chartered Institution of Building Services Engineers.

Coley, D. and Kershaw, T. (2010) “Changes in internal temperatures within the built environment as a response to a changing climate “, *Building and Environment* , vol. 45, pp. 89-93, Available: 0.1016/j.buildenv.2009.05.009.

Coley, D., Kershaw, T. and Eames, M. (2012) “A comparison of structural and behavioural adaptations to future proofing buildings against higher temperatures”, *Building and Environment*, no. 55, pp. 159–166.

Costa, P.S., Santos, N.C., Cunha, P., Cotter, J. and Sousa, N. (2013) “The Use of Multiple Correspondence Analysis to Explore Associations between Categories of Qualitative Variables in Healthy Ageing”, *Journal of Aging Research*, p. 12, Available: http://dx.doi.org/10.1155/2013/302163.

Cronbach, L. (1990) *Essentials of psychological testing*, New York: Harper Collins Publishers.

De Dear, R. (2006) “Adapting buildings to a changing climate: but what about the occupants?,”, *Building Research & Information*, no. 34:1, pp. 78-81, Available: DOI: 10.1080/09613210500336594.

De Dear, R. (2006) “Adapting buildings to a changing climate: but what about the occupants?, “, *Building Research & Information,* no. 34:1, pp. 78-81, Available: DOI: 10.1080/09613210500336594.

De Dear, R., Brager, G. and Cooper, D. (1997) *Developing an Adaptive Model of thermal comfort and Preference – Final Report*, ASHRAE RP-884.

Diaz, J., Garcia, R., Velázquez de Castro, F., Hernández, E., López, C. and Otero, A. (2002) “Effects of extremely hot days on people older than 65 years in Seville (Spain) from 1986 to 1997.”, *International Journal of Biometeorology* , vol. 46, pp. 145-149.

Dubrul, C. (1897) *IEA Annex VIII: Inhabitants” behaviour with respect to ventilation*, Conventry: Air Infiltration and Ventilation Centre, EEA.

EEA (2012) *Urban Adaptation to climate change in Europe – Challenges and Opportunities for cities together with supportive national and European policies – EEA report*, European Environment Agency.

Eurostat (2010) *EU Energy in Figures 2010 – Greenhouse Gas Emissions by Sector*, Luxembourg: Office for Official Publications of the European Communities.

Fabi, V., Andersen, R.V., Corganti, S.P., Olesen, B.W. and Filippi, M. (2011) “DESCRIPTION OF OCCUPANT BEHAVIOUR IN BUILDING ENERGY SIMULATION: STATE-OF-ART AND CONCEPTS FOR IMPROVEMENTS “, Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November. , Sydney.

Fanger, P. (1970) *Thermal comfort Analysis and applications in environmental engineering*, McGraw-Hill.

Fouillet, A., Rey, G., Laurent, F., Pavillon, G., Bellec, S., Guihenneuc-Jouyaux, C., Clavel, J., Jougla, E. and Hemon, D. (2006) “Excess mortality related to the August 2003 heat wave in France. “, *International Archives of Occupational and Environmental Health* , vol. 80, pp. 16-24.

Geels, F.W. (2004) “From sectoral systems of innovation to socio-technical systems - Insights about dynamics and change from sociology and institutional theory “, *Research Policy* , vol. 33, pp. 897-920.

Giddens, A. (1984) *The Constitution of Society*, Cambridge: Polity.

Gram-Hanssen, K. (2010) “Residential heat comfort practices: understanding users “, *Building Research and Information* , vol. 38, pp. 175-186.

Greenacre, M.J. (1984) *Theory and applications of correspondence analysis*, London: Academic Press.

Gupta, R. and Gregg, M. (2012) “ Using UK climate change projections to adapt existing English homes for a warming climate”, *Building and Environment*, no. 55, pp. 20–42.

Guy, S. (2006) “Designing urban knowledge: competing perspectives on energy and buildings “, *Environment and Planning C-Government and Policy* , vol. 24, pp. 645-659.

Hacker, J.N. (2008) *Climate change in London: implications for passive and active cooling of dwellings*, London UK: ARUP.

Hacker, J., Capon, R. and Mylona, A. (2009) *Use of Climate Change Scenarios for Building Simulation: the CIBSE Future Weather Years*, London: Chartered Institution of Building Services Engineers.

Hajat, S., Kovats, R.S. and Lachowycz, K. (2007) “Heat-related and cold-related deaths in England and Wales: who is at risk? “, *Occupational and Environmental Medicine* , vol. 64, pp. 93-100.

Haldi, F. and Robinson, D. (2008) “On the behaviour and adaptation of office occupants”, *Building and Environment*, vol. 43, no. 12, pp. 2163–2177, Available: doi:10.1016/j.buildenv.2008.01.003.

Harlan, S.L., Brazel, A.J., Prashad, L., Stefanov, W.L. and Larsen, L. (2006) “Neighborhood microclimates and vulnerability to heat stress”, *Social Science & Medicine* , vol. 63, pp. 2847-2863.

Healy, S. (2008) “Air-conditioning and the “homogenization” of people and the built environments. “, *Building Research & Information* , vol. 36, no. 4, pp. 312-322.

Heerwagen, J. and Diamond, R. (1992) *Adaptations and Coping: Occupant Response to Discomfort in Energy Efficient Building*, American Council for an Energy Efficient Economy.

Hinton, E. (2010) *Review of the literature relating to comfort practices and socio-technical systems - Environment, Politics and Development Working Paper Series*, [Online], Available at: http://www.kcl.ac.uk/schools/sspp/geography/research/epd/working.html" (Accessed 2014).

Hitchings, R. (2009) “Studying thermal comfort in context”, *Building Research and Information*, vol. 37, pp. 89-94.

Holmes, M.J. and Hacker, J.N. (2007) “Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century “, *Energy and Buildings*, no. 39, pp. 802-814, Available: doi:10.1016/j.enbuild.2007.02.009.

Hwang, H. and Takane, Y. (2002) “Generalized constrained multiple correspondence analysis”, *Psychometrika* , vol. 67, pp. 211-224.

IBM Corp (Released 2013) *IBM SPSS Statistics for Macintosh, Version 21*, Armonk: IBM Corp.

INE (2011) *Censos 2011*, Instituto Nacional de Estatistica.

IPCC (2013) “Summary for Policymakers”, in Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (ed.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC (2014) “Summary for policymakers”, in Field, C.B., Barros, R., Dokken, D.J., Mach, K.J., Mastrandea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCraken, S., Mastrandea, P.R. and White, L.L. (ed.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPMA (2013) *Instituto Portugues do Mar e Atmosfera* , [Online], Available at: www.ipma.pt (Accessed February 2013).

Jackson, T. (2005) *Motivating sustainable consumption: a review of evidence on consumer behaviour and behavioural change*, Guildford: University of Surrey.

Johnson, R.A. and Wichern, D.W. (2007) *Applied Multivariate Correspondence Analysis*, 6th edition, Upper Saddle River, NJ: Prentice-Hall.

Kaiser, H.F. (1960) “The application of electronic computers to factor analysis “, *Educational and Psychological Measurement*, vol. 20, pp. 141-151.

Kempton, W., Feuermann, D. and McGarity, A.E. (1992) “I always turn it on super”: user decisions about when and how to operate room air conditioners”, *Energy and Buildings*, vol. 18, pp. 177-191.

Kendrick, C., Ogden, R., Wang, X. and Baiche, B. (2012) “Thermal mass in new build UK housing: A comparison of structural systems in a future weather scenario”, *Energy and Buildings*, vol. 48, pp. 40-49, Available: doi:10.1016/j.enbuild.2012.01.009.

Khare, S., Hajat, S., Kovats, S., Lefevre, C., de Bruin, W., Dessai, S. and Bone, A. (2015) “Heat protection behaviour in the UK: results of an online survey after the 2013 heatwave”, *BMC Public Health*, vol. 15, no. 878, Available: doi:10.1186/s12889-015-2181-8.

Kovats, R. and Hajat, S. (2008) “Heat Stress and Public Health: A Critical Review”, *Annual Review of Public Health*, no. 29, pp. 41-55.

LCCP - London Climate Change Partnership (2009) *Economic Incentive Schemes for Retrofitting London”s Existing Homes for Climate Change Impacts*, London: Greater London Authority.

Lomas, K.J. and Ji, Y. (2009) “Resilience of naturally ventilated buildings to climate change: advanced natural ventilation and hospital wards.”, *Energy Build*, vol. 41, no. (6), pp. 629-653.

Maller, C.J. and Strengers, Y. (2011) “Housing, heat stress and health in a changing climate: promoting the adaptive capacity of vulnerable households, a suggested way forward”, *Health Promotion International* , vol. 26, no. 4.

Maller, C.J. and Strengers, Y. (2011) “Housing, heat stress and health in a changing climate: promoting the adaptive capacity of vulnerable households, a suggested way forward “, *Health Promotion International*, vol. 26, no. 4, Available: doi:10.1093/heapro/dar003.

Mavrogianni, A., Wilkinson, P., Davies, M., Biddulph, P. and Oikonomou, E. (2012) “Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings”, *Building and Environment*, no. 55, pp. 117–130, Available: doi:10.1016/j.buildenv.2011.12.003.

Michelozzi, P., De´Donato, F., Accetta, G., Forastiere, F., D´Ovidio, M. and Perucci, C. (2004) “Impact of heat waves on mortality – Rome, Italy, June – August 2003”, *Morbidity and Mortality Weekly Report,* , vol. 53, no. 17, pp. 369-371.

Miller, F., Osbahr, H., Boyd, E., Thomalla, F., Bharwani, S., Ziervogel, G., Walker, B., Birkmann, J., van der Leeuw, S., Rockstrom, J., HInkel, J., Downing, T., Folke, C. and

Nelson, D. (2010) “Resilience and vulnerability: complementary or conflicting concepts?”, *Ecology and Society* , no. 15(3).

NHBC (2012) *Overheating in new homes - a review of the evidence*, HS BRE Press on behalf of the NHBC Foundation.

Nicol, F.J., Hacker, J., Spires, B. and Davies, H. (2009) “Suggestion for new approach to overheating diagnostics “, *Building Research & Information* , no. 37:4, pp. 348-357, Available: DOI: 10.1080/09613210902904981.

NIcol, J. and Humphreys, M. (2004) “A stochastic approach to thermal comfort-occupant behavior and energy use in buildings.”, *ASHRAE Transactions* , vol. 110, no. 2, p. 554.

Nicol, F. and McCartney, K. (2000) *Smart Controls ad Thermal Comfort (SCATs) Project. Final Report.*, Joule III Project (Contract JO3-CT97-0066).

Nicol, F. and Roaf, S. (2007) “Progress on passive cooling: adaptive thermal comfort and passive architecture”, in Santamouris, M. (ed.) *Advances in Passive Cooling* , London: Earthscan.

Nicol, F. and Stevenson, F. (2013) “Adaptive comfort in an unpredictable world”, *Building Research & Information*, no. 41(3), pp. 255–258, Available: doi:10.1080/09613218.2013.783528.

O´Brien, K., Eriksen, S., Schjolden, A. and Nygaard, L. (2004) “What’s in a Word? Conflicting Interpretations of Vulnerability in Climate Change Research.”.

OIkonomou, E., Davies, M., Mavrogianni, A., Biddulph, P., Wilkinson, P. and Kolokotroni, M. (2012) “Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London”, *Building and Environment*, vol. 57, pp. 223–238, Available: doi:10.1016/j.buildenv.2012.04.002.

Orme, M. and Palmer, J. (2003) *Control of overheating in future housing, Design guidance for low energy strategies*, Hertfordshire, UK: Faber Maunsell Ltd.

Patt, A., Dazé, A. and Suarez, P. (2009) “Gender and climate change vulnerability: what´s the problem, what´s the solution?”, in Ruth, M. and Ibarrarán, M.E. (ed.) *Distributional Impacts of Climate Change and Disasters: Concepts and Cases*, Edward Elgar Publishing.

Peacock, A.D., Jenkins, D.P. and Kane, D. (2010) “Investigating the potential of overheating in UK dwellings as a consequence of extant climate change “, *Energy Policy*, no. 38, pp. 3277-3288, Available: doi:10.1016/j.enpol.2010.01.021.

Porrit, S.M., Cropper, P.C., Shao, L. and Goodier, C.I. (2012) “Ranking of interventions to reduce dwelling overheating during heat waves”, *Energy and Buildings*, no. 55, pp. 16–27, Available: doi:10.1016/j.enbuild.2012.01.043.

Reis, E. (1990) *Análise factorial das componenetes principais: um método de reduzir sem perder informação*, Lisboa: Giesta - ISCTE.

Rhodes, S.D., Bowie, D.A. and Hergenrather, K.C. (2003) “Collecting behavioural data using the world wide web: considerations for researchers”, *Journal of Epidemiology & Community Health*, vol. 57, pp. 68-73, Available: doi:10.1136/jech.57.1.68.

Riva, G., Teruzzi, T. and Anolli, L. (2003) “The Use of the Internet in Psychological Research: Comparison of Online and Offline Questionnaires”, *CYBERPSYCHOLOGY & BEHAVIOR*, vol. 6, no. 1.

Roaf, S., Crichton, D. and Nicol, F. (ed.) (2009) *Adapting Buildings and Cities for Climate Change*, Architectural Press.

Roberts, S. (2008) “Altering existing buildings in the UK”, *Energy Policy*, no. 36(12), pp. 4482–4486, Available: doi:10.1016/j.enpol.2008.09.023.

Rodham, K. and Bell, J. (2002) *Journal of Nursing Management*, vol. 10, pp. 5-11.

Ropke, I. (2009) “Theories of practice - New inspiration for ecological economic studies on consumption “, *Ecological Economics*, vol. 68, pp. 2490-2497.

Sanders, C.H. and Phillipson, M.C. (2003) “UK adaptation strategy and technical measures: the impacts of climate change on buildings”, *Building Research and Information*, vol. 31, no. 3-4, pp. 210-221.

Santos, F.D. and Miranda, P. (ed.) (2006) *Alterações Climáticas em Portugal. Cenários, Impactos e Medidas de Adaptação" — Projecto SIAM II*, Lisboa: Gradiva.

Schatzki, T. (1996) *Social practices: A Wittgensteinian approach to human activity and the social*, Cambridge University Press.

Semenza, J.C., Rubin, C.H., Falter, K.H., Selanikio, J.D., Flanders, W.D., Howe, H.L. and Wilhem, H.L. (1996) “Heat-related deaths during the July 1995 heat wave in Chicago “, *New England Journal of Medicine* , vol. 335, no. 2, pp. 84-90.

Shove, E. (2003) *Comfort, Cleanliness and Convenience: The social organisation of normality*, Oxford: Berg.

Shove, E. (2003) “Converging conventions of comfort, cleanliness and convenience “, *Journal of Consumer Policy* , vol. 26, pp. 395-418.

Shove, E. (2006) “Efficiency and consumption: technology and practice”, in Jackson , T. (ed.) *The Earthscan Reader in Sustainable Consumption* , London: Earthscan.

Shove, E., Chappells, H., Lutzenhiser, L. and Hackett, B. (2008) “Comfort in a lower carbon society “, *Building Research & Information* , vol. 36, no. 4, pp. 307-311.

Shove, E. and Walker, G. (2010) “Governing transitions in the sustainability of everyday life “, *Research Policy* , vol. 39, pp. 471-476.

Shweiker, M. and Shukuya, M. (2009) “Comparison of theoretical and statistical models of air-conditioning-usage behavior in a residential setting under Japanese climatic conditions “, *Building and Environment*, vol. 44, pp. 2137-2149.

Spaargaren, G. (2005) “Comfort, cleanliness plus convenience: The social organization of normality “, *Sociology-the Journal of the British Sociological Association* , vol. 39, pp. 177-179.

Stern, P.C. (2000) “Psychology and the science of human-environment interactions “, *American Psychologist* , vol. 55, pp. 523-530.

Stern, N. (2007) *The Economics of Climate Change: The Stern Review*, Cambridge University Press.

Strengers, Y. (2010) “Air-conditioning Australian house- holds: a trial of Dynamic Peak Pricing. “, *Energy Policy*, vol. 38, pp. 7312-7322.

Strengers, Y. and Maller, C. (2011) “Integrating health, housing and energy policies: social practices of cooling”, *Building Research and Information*, vol. 39, no. 2, pp. 154-168, Available: http://dx.doi.org/10.1080/09613218.2011.562720.

Survey Monkey Inc. (2014) *Survey Monkey*, [Online], Available: HYPERLINK "www.surveymonkey.com" www.surveymonkey.com [December 2013].

Tabachnick, B. and Fidell, S. (1996) *Using multivariate statistics*, Harper Collins College Publishers.

Taylor, A.J. and McGwin, G. (2000) “Temperature-related deaths in Alabama “, *Southern Medical Journal*, vol. 93, no. 8, pp. 787-792.

Thompson, B. (2004) *Exploratory and confirmatory factor analysis: Understanding concepts and applications*, Washington: American Psychological Association.

UK Government, HM (2005) *The UK Government Sustainable Development Strategy*, London: The Stationery Office UK Government.

Vandentorren, S., Bretin, P., Zeghnoun, A., Mandereau-Bruno, L., Croisier, A., Cochet, C., Ribéron, J., Siberan, I., Declercq, B. and Ledrans, M. (2006) “August 2003 heat wave in France: risk factors for death of elderly people living at home.”, *Eur J Public Health*, vol. 16, no. 6, December, pp. 583-91.

Wamsler, C. and Brink, E. (2015) “The role of individual adaptive practices for sustainable adaptation”, *International Journal of Disaster Resilience in the Built Environment*, vol. 6, no. 1, pp. 6-29.

White-Newsome, J.L., Sanchéz, B.N., Parker, E., Dvonch, T., Zhang, Z. and O´Neill, O. (2011) “Assessing heat-adaptive behaviors among older, urban-dwelling adults”, *Maturitas*, vol. 70, no. 1, pp. 85–91, Available: doi:10.1016/j.maturitas.2011.06.015.

Wolf, J., Adger, W.N., Lorenzoni, I., Abrahamson, V. and Raine, R. (2010) “Social capital, individual responses to heat waves and climate change adaptation: An empirical study of two UK cities”, *Global Environmental Change*, vol. 20, no. 1, pp. 44-52, Available: doi:10.1016/j.gloenvcha.2009.09.004.

Worfolk, J.B. (2000) “Heat waves: their impact on the health of elders. “, *Geriatric Nursing* , vol. 21, no. 2, pp. 70-77.

Wright, K.W. (2005) “Researching Internet-Based Populations: Advantages and Disadvantages of Online Survey Research, Online Questionnaire Authoring Software Packages, and Web Survey Services”, *Journal of Computer-Mediated Communication*, vol. 10, no. 3, Available: DOI: 10.1111/j.1083-6101.2005.tb00259.x.

Yun, G.Y. and Steemers, K. (2008) “Time-dependent occupant behaviour models of window control in summer “, *Building and Environment*, vol. 43, pp. 1471-1482, Available: doi:10.1016/j.buildenv.2007.08.001.

Zhang, Y. and Barret, P. (2012) “Factors influencing the occupants” window opening behaviour in a naturally ventilated office building “, *Building and Environment* , vol. 50, pp. 125-134, Available: doi:10.1016/j.buildenv.2011.10.018.

7 CHAPTER 7 - DISCUSSION

“We become what we behold. We shape our tools, and thereafter our tools shape us.”
Marshall McLuhan

DISCUSSION

Buildings are at the center of the climate challenge for the next century. Residential buildings, which represent the majority of the built environment, are also the ones responsible for the greatest share of energy consumption. However, as certainty regarding the changes in climate grows, there is the need to ensure that thermal conditions inside existing residential buildings remain comfortable, while still considering energy efficiency demands.

With the purpose of providing recommendations to policy and retrofit interventions, the study draws on an integrated vulnerability framework, which considers socio-technical dynamics, focusing on both behavioral and infrastructural aspects. Therefore, this chapter presents an integrated discussion of the results from the empirical work undertaken to address the five research questions identified:

1. What are the main relevant factors influencing vulnerability and adaptive capacity in Lisbon buildings in relation to thermal comfort?
2. What is the effect of different occupancies and behavior in vulnerability assessment of residential building of Lisbon?
3. What is the effect of technological passive adaptations on residential buildings in Lisbon?
4. What – and how significant – are the differences regarding practices of comfort in relation to factors influencing vulnerability?
5. How can the study of occupant behavior, infrastructures and the relation between the two improve retrofit interventions and adaptation policy in southern European housing?

As to explore the issues brought up by the research questions, the discussion chapter is organized in the following way: the first section answers questions 1, 2, 3 and 4. It discusses what the main findings of the empirical work are and their interactions while also reflecting on the use of a socio-technical view of comfort in the two interpretations of vulnerability. The next section discusses implications for policy and therefore answers question 5. It uses results from empirical work to discuss challenges and opportunities regarding the use of an integrated framework of vulnerability and the need to conciliate adaptation policies with other sectors.

7.1 Integrating two interpretations of vulnerability

There is no lack of conceptualizations and approaches to vulnerability to climate change (Adger, 2006). It is a rich and productive field and a number of disciplines, ranging from economics to engineering, use the term “vulnerability” and explores attempts to act on it. It can however, be argued that all these different approaches are summarized in two distinct interpretations of vulnerability – outcome and contextual vulnerability (O´Brien et al., 2007). The two interpretations correspond to different fields of knowledge and would individually help reduce the impact of high temperatures, but there is the need for a more comprehensive approach where interaction between components of a system can be better understood, as argued by Cutter (2005) and McEntire et al. (2010).

Framing the problem of thermal comfort as a socio-technical issue is fundamental in this matter. A socio-technical perspective on comfort stresses the importance of interdependency and distribution of agency between human and non-human actors, where the interaction of the different components are determinant for the performance of the system, as detailed in section 2.1.5.

Given this context, to consider just one interpretation of vulnerability would significantly reduce the comprehension of the problem and the adaptation options with potential to alleviate the issue of thermal discomfort in the face of climate change and extreme events.

If on the one hand, only the outcome in terms of thermal performance of the dwelling was to be analyzed, then the vulnerability assessed (and possible measures to adapt) would have to be considered under the uncertainty that surrounds climate change projections and scenarios, which can hinder decision-making due to the costs inherent to “hard” adaptations. In addition, this type of analyses considers necessarily closed systems and a narrow spectrum of parameters, which restricts wider considerations of distributed agency and context where the thermal performance is achieved. In that perspective, Brooks (2003) argues that this particular interpretation “leads to the danger that adaptation is reduced to building local capacity to make sectorial and technological changes, rather than addressing the fundamental causes of vulnerability (…)”. However, analysis under this interpretation of vulnerability has the benefit of providing a basis to establish intervention priorities at the city scale and, in addition, several authors recognize the role of objective and quantitatively measured research in claiming attention for adaptation from decision-makers in the policy realm and in providing a solid basis for discussing adaptation goals (Funfgeld and McEvoy, 2011).

On the other hand, in the scope of an interpretation that sees vulnerability as a starting point – as contextual vulnerability does – it is considered that although it could be triggered by a specific phenomenon, vulnerability is part of a broader process where factors relating to personal, social, cultural and others are included (O´Brien et al., 2007). While starting to assume that vulnerability is inherent to the system, it also sees adaptation as a process where continuous feedbacks between context and responses have to be accounted for. Being so, modifying contextual conditions can provide answers in relation to responses to (climate) *stimuli*. Given the approach to thermal comfort adopted in this study, if it is assumed that the “relational array of people and things in their domestic environment” are related with the socio-demographic factors, then some studies may be suggesting that different socio-technical assemblages support different types of practices. (Hinton, 2010)

This is particularly important in the context of the topic of sustainable consumption and technological lock-ins (Shove, 2003) because this view assumes that it is clear that appliances and infrastructures have agency and mediate comfort practices. Therefore, material infrastructures can influence thermal expectations and the adoption of unsustainable practices, such as the use of air conditioning as a “one size fits all” solution (Strengers and Maller, 2011).

Such an approach can, consequently, bring significant contributions in providing the basis for discussing the suitability and effectiveness of adaptation measures in a local context (including the ones potentially suggested by outcome interpretations of vulnerability), as well as in integrating adaptation with other policy sectors, such as poverty and social justice.

Nonetheless, despite the relevance of the approach, the apparent permeability of the analyzed system in contextual vulnerability as well as its subjective and qualitative nature prevents decision-makers from considering it in a systematic form (Funfgeld and McEvoy, 2011).

In the case for this study, a socio-technical view was acknowledged by both interpretations, creating a common background in order to integrate results. In the case of outcome vulnerability, the use of an adaptive model for comfort assessment, as well as considering different occupancies and window schedules, is argued to be coherent with the STS approach connecting “comfort temperature to the context in which subjects find themselves” (Roaf et al., 2009). For contextual vulnerability, this view is considered by assuming the potential influence of material agency (i.e. the building, available controls and appliances) as contextual and focusing on adaptive practices as a social construct, instead of individual actions, as a response to high temperatures.

In this study, the outcome vulnerability approach allowed to understand the extent of the problem in the city of Lisbon, Portugal, and also the constructive and non-constructive characteristics, which enable moderation capacity for high temperatures, either for a gradual increase in temperature and for a heatwave episode. While physical characteristics of the buildings were determinant in establishing vulnerability, results suggest that window opening schedule and occupancy (i.e. occupant behavior) presented significant differences in terms of discomfort hours. This result is consistent with other studies, namely in Northern Europe (Porrit et al., 2012), and highlights the importance of considering diverse interactions with the building. It also stresses the differences in vulnerability in two physically similar dwellings (as the ones used to develop the methodology in Chapter 4) where occupant behavior is totally distinct depending on the context. The characteristics of people occupying the two monitored dwellings varied considerably, namely regarding age of occupants and professional occupation (and consequently work schedules). In fact, data from the performed statistical analysis from more than 300 respondents (reported in Chapter 6) suggests that it is possible to find significant differences regarding the adoption of individual practices depending on socio-demographic, personal and contextual factors. In particular, results point out in the direction that socio-demographic factors such as sex and age can be relevant for understanding practices. Differences in adaptive practices regarding sex, namely the prevalence of adoption of certain practices by women, are discussed as being the result of cultural norms and roles in society, work and domestic life in Patt et al. (2009). This can help to understand results arising from the statistical analysis reported in this study, which suggest that women takes charge more often of the task of ventilating the dwelling. Age, on the other hand, is seen as one of the most prominent vulnerability factors (Michelozzi et al., 2004). The significant differences regarding age found in this study suggest relations with other studies indicating that isolation, age-associated health conditions and limitations in mobility can influence the adaptive practices adopted by occupants (White-Newsome et al., 2011), namely by choosing practices that involve less movement to adapt. Consequently, even if the analysis of a certain building stock (such as the one reported in Chapter 5) indicates that relative vulnerability of a determined type of building to extreme events is considerably low, it still could be worth to implement adaptation measures to the building envelope if the occupants are less prone to actively use passive building controls, as suggested by results in Chapter 6.

In the case of Lisbon, the most vulnerable buildings to the gradual increase in temperatures are not the same as for the case of extreme events. In this study, dwellings situated in buildings previous to 1990 present significant discomfort hours in both situations. However, while newer buildings (>2006) are the most vulnerable to climate change, the dwellings situated in the 1940-1960 tier are the ones performing the worst in the case of extreme events. These results are consistent with other studies such as van Hooff et al. (2014), namely regarding the high vulnerability of the most recent buildings. While the research presented in Chapter 5 highlights the importance of thermal capacity of exterior walls - usually found in buildings with stone walls – for adaptation, it equally draws attention to the vulnerability of highly insulated and high glazing-to-floor ratios that characterize the most recent buildings. Interestingly, results of the variance analysis in this study indicate that the level of discomfort reported by occupants can be also relevant in terms of adoption of practices, which may suggest a relation between outcome vulnerability and practices. In this context, regarding the data collected by the online survey, there is a significant difference concerning the adoption of active practices (associated with air conditioning devices) in the most recent buildings (> 2006), which strengthens claims of practice theorists in relation to the importance of material agency and the need to debate the significance of regulations, such as buildings thermal codes in shaping the adaptive capacity of occupants to moderate high temperatures (Strengers and Maller, 2011).

This argument stresses the need to find adaptations that are suitable for comfort in a “low carbon society” (Shove et al., 2008). By far, the most used adaptation in naturally ventilated buildings is ventilation. The importance of ventilation could also be verified in the analysed dwellings in Chapter 4 when optimal ventilation was considered. The consideration of optimal ventilation signified a decrease in terms of discomfort hours, lowering them to as much as 63%. However, it is not always possible that occupants can maintain optimal ventilation. Varied reasons including privacy can constraint such a strategy, which can help explain why the adoption of passive environmental practices was reported as being more frequently adopted by people spending less time at home in the statistical analysis reported in this study.

Other studies such as Coley et al (2012) also worked on the potential of behavioral adaptation. However, two points separate those studies from the approach taken here. The first regards the model used for comfort assessment. Although it was found that behavioral adaptations could lead to significant reduction of discomfort, the model in their study considered only a fixed range of temperatures to determine if the indoor environment presented temperatures outside of comfort zone. The type of analytical model used for Coley et al. (2012) and others in assessing comfort can be misleading in terms of effectiveness and inclusively incur in unnecessary costs, as also suggested by Lomas and Girdharan (2012). Using an adaptive approach and when costs are considered in relation to the effectiveness of the measure, the best adaptation measures considering the predominant construction types in Lisbon building stock are 1) low emissivity glazing 2) low reflectivity coating in façades and 3) combined reflectivity measures. Importantly, it additionally shows that the measures that have the most significant effect in terms of decrease in discomfort hours during heatwave periods, also present benefits when simulated in a climate change context. Passive adaptation measures applied to buildings were also tested in other contexts by different studies (e.g. van Hooff et al., 2014; Porrit et al., 2012; Gupta and Gregg, 2012) and results also suggest decrease in discomfort depending significantly on the type of building and the original thermal transmittance of the building skin. Results of the study presented here additionally indicate that it is possible, in particular when combined measures in buildings envelope are considered, to reduce discomfort hours by 100% by using passive adaptation measures alone, despite not being the most cost-effective solution.

Within the adaptation measures considered here, insulation deserves special attention. Increasing insulation is a popular measure for the improvement of energy efficiency performance in buildings, but it is found here to also be capable of acting as an adaptation measure – as also argued by other studies (e.g. Porrit et al., 2012; Mavrogianni et al., 2012). Nevertheless, results from both Chapter 2 and Chapter 5, indicate that in certain situations, for instance when it is applied internally or associated with a determined set of constructive characteristics (e.g. 1990-2006), additional insulation can actually increase discomfort hours for the climate and weather conditions considered in this study. The discussion about increased vulnerability derived from insulation, and in particular from interventions in building envelopes in order to achieve reference values demanded by regulations which have a focus on heating energy efficiency, finds echo in Mulville and Stravoravdis (2016) study. Their research is relevant for the context of Southern European housing, because when optimally implemented, insulation can bring the dual benefit of moderating high outdoor temperatures and improving energy efficiency of the dwellings, as pointed out in the study of Porrit et al. (2012). In this context, interesting insights from a contextual vulnerability approach taken by Judson and Maller (2014) and Vlasola and Gram-Hanssen (2014) regarding the relation of occupants practices and energy renovations contribute to a better understanding that the implementation of such measures in buildings may have only a limited impact if daily practices are not comprehended and material agency is not considered. Therefore, although out of scope of this study, the results reported in Chapter 4 and 5 regarding measures applied to buildings envelope, should be taken in consideration with the diversity of practices also acknowledged by this study, the vulnerability context associated and the potential feedback effects in terms of responses.

7.2 Policy towards climate adapted housing

How can this discussion and the results from the study inform adaptation policy?

Adaptation policy is contextualized in section 2.1.4. According to the typology presented in that section, five main types of policy measures can be distinguished – Regulatory, Financial, Technological, Institutional Capacity Building and Behavioral (Funfgeld and McEvoy, 2011) – all of which can be implemented through several policy instruments. Regarding the instruments, the nomenclature proposed by Mees et al (2014) is adopted here.

Keskitalo (2010) makes the case for three different stages of adaptation policy: the first is dedicated to the necessary establishment of institutional mechanisms for directing and implementing adaption, the second concerns the formulation or modification of policies to adapt or to take adaptation into consideration and the final one regards the integration of adaptation measures at the project level. This context stresses the fact that there is the need for multi-level intervention in adaptation policy governance. There are conceptual similarities between this and the Multi-Level Perspective (MLP) of Geels (2004) addressed in section 2.1.4, which structure the change needed in socio-technical systems in order to achieve transitions in three different levels. In this view, the emphasis on different strategies and measures will help define the type of transition, alongside with a complex combination of timing and nature of the interaction between levels, as discussed by Geels and Schot (2005)[4]. Furthermore, the proponents of the MLP model argue that in order to drive changes, all three levels should be addressed through policy, making the case for comprehensive and integrated measures and instruments.

The stage of adaptation policy is also dependent on how the policy system is organized, which by its turn, has consequences in terms of type of governance and policy approaches. In a context where impacts are clear and transmitted adequately and governments are committed to adaptation needs, adaptation measures are likely to be developed in an explicit form and be present in the cited above levels, which according to the author can later be formulated in the form of regulation and legislation with the power to bind citizens and institutions. Exemplary of such approaches are the UK and countries such as Finland and Norway. However, one should also recognize contexts where adaptation is less explicit and

---

[4] Transitions have been a proficous subject on STS literature. For more on transitions, please refer to Geels work (Geels and Schot, 2007), but also Pelling (2011) an adaptation perspective on transitions.

existing in an informal manner. In such contexts, the focus can be the response to a determined hazard in the form of emergency management and where a more structured approach can stem from local authorities. Examples of such approaches are France, Italy, Spain and also Portugal (Keskitalo, 2010).

Whatever the policy system, the local scale plays a significant role in this kind of policy. This is emphasized in the report published by the European Union (Institute et al., 2011), where a comprehensive analysis of the instruments used in several European cities is conducted, and also in the study from Mees et al (2014) where the type of governance within the local scale is further distinguished, depending on the intervention of private actors. These studies highlight that the most used measures and instruments are regulatory (concerning legal or regulatory instruments, such as standards and technical requirements), financial (comprising economic instruments, such as subsidies and taxes) and behavioral (including communicative instruments, such as information campaigns). These measures are implemented independently or by mainstreaming adaptation into existing policies – such as urban planning (Smit and Wandel, 2006) and directed to both stakeholders responsible for building construction (architects, engineers, promoters and builders) and dwellings occupants.

Behavioral measures, which include policy instruments such as awareness campaigns for buildings occupants with the aim to inform about adequate behavior in the case of a period with high temperatures, is the most common measure used in Europe (EEA, 2014). In Portugal, adaptation policy is considered to be developed only at the earliest phase with the existence of National Strategy for Adaptation to Climate Change (Carvalho et al., 2013), despite the existence of a contingency plan for high temperatures (ARSLVT, 2012) and several valuable initiatives concerning information development such as SIAM (Santos and Miranda, 2006) and CLIMADAPT (CLIMADAPT, 2016). These initiatives highlight the recognized need to formulate and develop policy measures that can be effective at the project level (Carvalho et al., 2013)

The selection of policy instruments is complex and dependent on criteria such as effectiveness and legitimacy (Mees et al, 2014), and a deeper analysis of the issue is beyond the scope of this thesis. While the study presented here is limited in sample size and in the number of buildings analyzed, it is argued that it is possible and useful to discuss policy implications to southern European contexts from the insights reported here.

Structurally, the matter of the model of comfort used in regulatory measures, such as building codes and thermal regulations, stands out. Comfort has been understood so far as a mere analytical technological and standardised tool and some authors have argued that this view has prevailed in the design of buildings and indoor environments and consequently structured the way occupants "think, practice and experience comfort" (Jaffari and Matthews, 2009), as well as shaping "the adaptive capacity of households" (Strengers and Maller, 2011). This line of thinking is coherent with the narrative of material influence in the conceptualization of thermal expectations argued by the socio-technical perspective. Therefore, the introduction of adaptive thinking in understanding comfort in policy instruments such as thermal codes can prioritize infrastructures that facilitate adaptive practices as also discussed by other authors (e.g. (Maller and Strengers, 2011; Shove et al., 2008), while still maintaining a focus on reducing energy consumption (Mulville and Stravoravdis, 2016). In this context, an interesting perspective related with regulatory measure was already presented in terms of Sustainable Comfort Standards (Nicol and Humphreys, 2002). Additionally, the study results stress the need for regulatory instruments to integrate climate projections and uncertainty, which could provide additional adaptive capacity to buildings when designed or subjected to intervention. This subject is being integrated in several countries (such as Portugal, see Aguiar (2013)), and has been discussed extensively by numerous authors (e.g. ABCB, 2010; Gangolells and Casals, 2012).

Results from this study point out the cost-effectiveness of some passive adaptation interventions – as well as combined measures – that can dramatically offset high indoor temperatures, when taking into consideration occupant behavior and the specific construction types existing in the southern European context. In the field of policy, results can be used to develop economic incentives schemes (such as grants or subsidies) to promote the most cost-effective retrofit interventions for a given construction type. With the same purpose, the London Climate Change Partnership conducted a study arguing for this type of approach in relation to green roofs (LCCP, 2009). The use of economic instruments in adaptation has been argued to have untapped potential, partially because of the challenges in funding adaptation (Agrawala et al., 2008). Another way to promote adequate and cost-effective retrofit measures is through market mechanisms. Market mechanisms using target systems or tradable units, such as the ones used for mitigation, are an emerging concept in adaptation research (Butzengeiher-Geyer et al, 2011) and are argued to have economic and social benefits, while potentially involving both local governments and business interested in pursuing assigned targets

As stated, behavioral measures, namely in the form of informational instruments are one of the most used instruments throughout Europe. Results from this study have the power to inform and become significantly useful in formulating behavioral measures and policy instruments. In particular, public information campaigns can benefit from the knowledge of local individual adaptive practices, by taking into account diverging and competing cooling practices adopted by dwellings occupants (Strengers and Maller, 2011) and that can undermine the efforts of such a measure. This is likely one of the reasons for the low effectiveness of such campaigns in reducing vulnerability to heat (Wolf et al., 2010). Supporting the existing practices, in opposition to conducting generalized mass communication campaigns, can also favor the integration of adaptation and health policies regarding heat. It can additionally help to identify practices that need to be changed and to encourage new forms of adapting through new technologies, as also suggested by White-Newsome et al., 2011) or new artifacts such as portable personal fans (Strengers and Maller, 2011).

As already adressed previously, while most measures are implemented in isolation, the need for policy mixes follows the same direction as the approach stated by the EU White Paper: “employing a combination of policy instruments to ensure effective delivery of adaptation” (Keskitalo, 2010).

There are two possible forms to combine policy instruments for adaptation: either by mainstreaming adaptation in sectors such as energy, transport, urban planning and agriculture or, following the line of other climate policy sectors, by considering a policy mix where several instruments aim to a common objective (Mees et al., 2014). In this context, integrating the knowledge of practices and contextual vulnerability factors into adaptation retrofit interventions can help connect adaptation policy measures with social policies and sustainable development goals (O´Brien et al., 2007). This, for example, can prevent potential “lock in” situations of implementing “hard” adaptations and could also be significant in the context of summer fuel poverty already identified in some countries (Hills, 2012).

The use of policy mix has been advocated as necessary because using several instruments can be useful in order to compensate for the weaknesses of each one (Taylor et al., 2012). In that context, the need to complement adaptation with mitigation of climate change is a pressing issue in adaptation in cities (Hamin and Gurran, 2009). In that sense, results from the integrated approach, such as the one presented here, can inform, from a more holistic perspective, the transition for a more adapted and sustainable building stock. Mixed instruments can include tax instruments regarding the appropriate use of air conditioning devices - considering both vulnerability of indoor environments in dwellings, but also of their occupants – and performance standards which take in consideration optimal levels of insulation in both retrofit interventions and new buildings, in order to promote energy efficiency and moderate outdoor temperatures.

References

ABCB (2010) *An Investigation of Possible Building Code of Australia (BCA) Adaptation Measures for Climate Change*, Canberra: Australian Building Codes Board.

Adger, W.N. (2006) “Vulnerability”, *Global Environmental Change*, vol. 16, pp. 268-281.

Agrawala, S., Fankhauser, S., Hanrahan, D., Pope, G., Skees, J., Stephens, C. and Yasmine, S. (2008) “Economic and Policy Instruments to Promote Adaptation”, in *Economic Aspects of Adaptation to Climate Change: Costs, Benefits and Policy Instruments*, OECD Publishing.

Aguiar, R. (2013) *Climatologia e Anos Meteorológicos de Referência para o Sistema Nacional de Certificação de Edifícios (versão 2013)* - Relatório para ADENE - Agência de Energia, Laboratório Nacional de Energia e Geologia, I.P.

ARSLVT (2012) *Alterações Climáticas e Saúde Humana - Gestão do Risco para a Saúde da População da Região de Lisboa e Vale do Tejo*, Lisboa: Administração Regional de Saude de Lisboa e Vale do Tejo.

Brooks, N. (2003) *Vulnerability, Risk and Adaptation: A Conceptual Framework* , Tyndall Centre for Climate Change Research.

Butzengeiger-Geyger, S., Michaelowa, A., Kohler, M., Stadelmann, M., (2011) *Market Mechanisms for adaptation to climate change – lessons from mitigation and a pathway to implementation,* Center for Comparative and International Studies, University of Zurich

Carvalho, A., Schmidt, L., Santos, F.D. and Delicado, A. (2013) “Climate change research and policy in Portugal”, *WIREs Clim Change*, Available: doi: 10.1002/wcc.258.

CLIMADAPT (2016) Estrategias Municipas de Adaptação às Alterações Climáticas. [Online],Available: http://climadapt-local.pt/

Coley, D., Kershaw, T. and Eames, M. (2012) “A comparison of structural and behavioural adaptations to future proofing buildings against higher temperatures”, *Building and Environment,* vol. 55, pp. 159-166, Available: doi:10.1016/j.buildenv.2011.12.011.

Cutter, S.L. (2005) “Are we asking the right questions?”, in Perry, R.W. and Quarantelli, E.L. (ed.) *What is a disaster?New answers to Old Questions*, Philadelphia : Xlibris.

EEA (2014) *National adaptation policy processes in European countries*, Copenhagen: Environmental European Agency.

Funfgeld, H. and McEvoy, D. (2011) *Framing Climate Change Adaptation in Policy and Practice*, Victorian Centre for Climate Change Adaptation Research.

Gangolells, M. and Casals, M. (2012) “Resilience to increasing temperatures: residential building stock adaptation through codes and standards”, *Building Research & Information*, vol. 40, no. 6, pp. 645-664, Available: http://dx.doi.org/10.1080/09613218.2012.698069.

Geels, F.W. (2004) “From sectoral systems of innovation to socio-technical systems - Insights about dynamics and change from sociology and institutional theory “, *Research Policy*, vol. 33, pp. 897-920.

Gupta, R. and Gregg, M. (2012) “ Using UK climate change projections to adapt existing English homes for a warming climate”, *Building and Environment*, no. 55, pp. 20–42.

Hamin, E. and Gurran, N. (2009) “Urban form and climate change: Balancing adaptation and mitigation in the U.S. and Australia”, *Habitat International*, pp. 238-245.

Hills, G. (2012) *Getting the measure of fuel poverty.* Final Report of the fuel poverty review.

Hinton, E. (2010) *Review of the literature relating to comfort practices and socio-technical systems,* [Online], Available: http://www.kcl.ac.uk/schools/sspp/geography/research/epd/working.html

Institute, E., Group, A., Sustainability, I.-L.G.f. and (REC), E.R.E.C.f.C.a.E.E. (2011) *Policy Instruments for Adaptation to Climate Change in Big European Cities and Metropolitan Areas, European Union*, Committee of the Regions (link is external) (CoR).

Jaffari, S.D. and Matthews, B. (2009) “From occupying to inhabiting - a change in conceptualising comfort”, in *Beyond Kyoto: Addressing the challenges of climate change. Science meets industry, policy and public*, , IOP Publishing.

Judson, E. and Maller, C. (2014) “Housing renovations and energy efficiency: insights from homeowners” practices”, *Building research and Information*, vol. 42, no. 4, pp. 501-511, Available: http://dx.doi.org/10.1080/09613218.2014.894808.

Keskitalo, E.C. (ed.) (2010) *Developing Adaptation Policy and Practice in Europe: Multi-level Governance of Climate Change*, Springer Netherlands.

Lomas, K.J. and Giridharan, R. (2012) “Thermal comfort standards, measured internal temperatures and thermal resilience to climate change of free-running buildings: A case study of hospital wards”, *Building and Environment,* no. 55, pp. 57-72, Available: doi:10.1177/0143624411432012.

Mavrogianni, A., Wilkinson, P., Davies, M., Biddulph, P. and Oikonomou, E. (2012) “Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings”, *Building and Environment*, no. 55, pp. 117–130, Available: doi:10.1016/j.buildenv.2011.12.003.

McEntire, D., Crocker, C. and Peters, E. (2010) “Addressing vulnerability through an integrated approach”, *International Journal of Disaster Resilience in the Built Environment* , vol. 1, no. 1, pp. 50-64.

Mees, H.L.P., Djik, D., van Soest, D., Driessen, P.P.J., van Rijswick, M.F.H.M.W. and Runhaar, H. (2014) “A method for the deliberate and deliberative selection of policy instrument mixes for climate change adaptation”, *Ecology and Society*, vol. 19, no. 2, p. 58, Available: http://dx.doi.org/10.5751/ES-06639-190258.

Michelozzi, P., De´Donato, F., Accetta, G., Forastiere, F., D´Ovidio, M. and Perucci, C. (2004) “Impact of heat waves on mortality – Rome, Italy, June – August 2003”, *Morbidity and Mortality Weekly Report* , vol. 53, no. 17, pp. 369-371.

Mulville, M. and Stravoravdis, S. (2016) “The impact of regulations on overheating risk in dwellings”, *Building Research and Information*, March, Available: The impact of regulations on overheating risk in dwellings.

Nicol, J.F. and Humphreys, M.A. (2002) “Adaptive thermal comfort and sustainable thermal standards for buildings”, *Energy and Buildings*, vol. 34, no. 6, pp. 563-572.

O´Brien, K., Eriksen, S., Nygaard, L. and Schjolden, A. (2007) “Why different interpretations of vulnerability matter in climate change discourses “, *Climate Policy*, vol. 7, pp. 73-88.

Patt, A., Dazé, A. and Suarez, P. (2009) “Gender and climate change vulnerability: what´s the problem, what´s the solution?”, in Ruth, M. and Ibarrarán, M.E. (ed.) *Distributional Impacts of Climate Change and Disasters: Concepts and Cases*, Edward Elgar Publishing.

Porrit, S.M., Cropper, P.C., Shao, L. and Goodier, C.I. (2012) “Ranking of interventions to reduce dwelling overheating during heat waves”, *Energy and Buildings*, no. 55, pp. 16–27, Available: doi:10.1016/j.enbuild.2012.01.043.

Roaf, S., Crichton, D. and Nicol, F. (ed.) (2009) *Adapting Buildings and Cities for Climate Change*, Architectural Press.

Santos, F.D. and Miranda, P. (ed.) (2006) *Alterações Climáticas em Portugal. Cenários, Impactos e Medidas de Adaptação" — Projecto SIAM II*, Lisboa: Gradiva.

Shove, E. (2003) “Converging conventions of comfort, cleanliness and convenience “, *Journal of Consumer Policy* , vol. 26, pp. 395-418.

Shove, E., Chappells, H., Lutzenhiser, L. and Hackett, B. (2008) “Comfort in a lower carbon society “, *Building Research & Information* , vol. 36, no. 4, pp. 307-311.

Smit, B. and Wandel, J. (2006) “Adaptation, adaptive capacity and vulnerability”, *Global Environmental Change*, vol. 16, pp. 282-292.

Strengers, Y. and Maller, C. (2011) “Integrating health, housing and energy policies: social practices of cooling”, *Building Research and Information*, vol. 39, no. 2, pp. 154-168, Available: http://dx.doi.org/10.1080/09613218.2011.562720.

Taylor, C., Pollard, S., Rocks, S. and Angus, A. (2012) “Selecting policy instruments for better environmental regulation: a critique and future research agenda.”, *Environmental Policy and Governance* , vol. 22, no. 4, Available: http://dx.doi.org/10.1002/eet.1584.

van Hooff, T., Blocken, B., Hensen, J.L.M. and Timmermans, H.J.P. (2014) “On the predicted effectiveness of climate adaptation measures for residential buildings* “, *Building and Environment*, vol. 82, pp. 300-316, Available: http://dx.doi.org/10.1016/j.buildenv.2014.10.006.

Vlasova, L. and Gram-Hanssen, K. (2014) “Incorporating inhabitants” everyday practices into domestic retrofits”, *Building Reseach and Information*, vol. 42, no. 4, pp. 512-524.

White-Newsome, J.L., Sanchéz, B.N., Parker, E., Dvonch, T., Zhang, Z. and O´Neill, O. (2011) “Assessing heat-adaptive behaviors among older, urban-dwelling adults”, *Maturitas*, vol. 70, no. 1, pp. 85–91, Available: doi:10.1016/j.maturitas.2011.06.015.

Wolf, J., Adger, W.N., Lorenzoni, I., Abrahamson, V. and Raine, R. (2010) “Social capital, individual responses to heat waves and climate change adaptation: An empirical study of two UK cities”, *Global Environmental Change*, vol. 20, no. 1, pp. 44-52, Available: doi:10.1016/j.gloenvcha.2009.09.004.

8 Chapter 8 – Conclusion

CONCLUSIONS

The objective of this study was to provide in-depth knowledge on how an integrated view of vulnerability would help renovate the understanding of social and technical aspects of vulnerability and adaptation to high temperatures. The problem of provision of thermal comfort in a changing climate was conceptualized as a socio-technical issue that was used as a background for the two interpretations of vulnerability under analysis – outcome and contextual vulnerability.

The study was divided in independent chapters where distinctive methodologies were used in order to provide insights for the case study of Lisbon, Portugal.

Results from the methodology developed based on thermal simulations related with the city of Lisbon indicate that buildings constructed under the new thermal regulations present a higher relative vulnerability to the gradual increase in temperatures projected by climate models but not to the occurrence of extreme events. For the assessment of vulnerability, the type of construction techniques used was determinant, but results indicate that non-constructive characteristics, such as orientation and occupancy, are also relevant at the dwelling scale. Although significant, is not clear if adaptation through behavior is sufficient to deal with high vulnerability in terms of discomfort hours, in particular regarding extreme events. However, a variance analysis allowed improved knowledge regarding the personal and environmental dimensions of adaptive practices implemented by occupants, as well as their relation with occupants" context. Results suggest statistically significant variance of socio-demographic, personal and contextual factors in relation to adoption of practices.

In terms of discomfort reduction, the most cost-effective adaptation measure is low emissivity glazing followed by solar reflective coating for façades. Additionally, increasing insulation, a popular measure for energy retrofitting existing buildings, was found to possibly influence vulnerability in a negative form, under some circumstances.

By integrating results around a common problem, was possible to suggest complementary insights of the two approaches to vulnerability. On one hand, results regarding simulated thermal comfort assessment can be complemented with knowledge regarding context and responses for a more holistic view on vulnerability and to help with suitability of measures to be implemented in buildings. On the other hand, a view on the diversity of practices and the significant differences assessed can benefit from information regarding quantitative assessment of vulnerability, in the sense that can shed light into the relation between vulnerability and unsustainable practices such as the ones related with the use of air conditioning. Integrated results can therefore also be useful to better understand feedback responses of retrofit interventions and agency of material infrastructures.

Importantly, results suggest that there are significant relations that can be drawn from both interpretations that can be integrated in a common approach to policy. The most significant concern the model of comfort used in technical requirements instruments, such as building regulations and performance standards.

The thesis contributes to socio-technical literature by framing policy implication of such an approach. Furthermore, it also contributes to vulnerability literature by integrating two distinctive interpretations, through the use of a common background of systemic nature.

8.1 Possible future research developments

The approach taken here does not allow drawing specific conclusions regarding each and every dwelling in the urban context of Lisbon. In that context and in order to support and validate the methodology for vulnerability assessment, extensive monitoring campaigns in several types of dwellings during normal summer conditions can provide additional clarifications regarding both performance and comfort practices. Regarding practices, subsequent analyses with smaller samples, preferably including monitoring campaigns and logs of occupant behavior, can be used to validate and further detail the influence of factors on the adoption of practices. A social practices approach, focusing on exploring materiality, embodied habits and practical understanding in cooling practices in a Southern Europe context can complement this study and also be useful for improving knowledge in the relation of infrastructures and regulations and the influence on adaptive capacity.

Not all types of structural adaptation measures were approached in this study. An interesting research venue can be the application of the methodology applied here in new technologies such as phase change materials (PCM). Results regarding the implementation of additional insulation in dwellings suggest that there is a need for a tool to assess an optimal level of insulation because when appropriate, the measure can potentially have the dual benefit of protecting indoor space from increased outdoor temperatures and improving energy efficiency of the dwelling.

The study used two types of downscaled methodologies in order to generate climate files for dynamical simulation. The study embraced uncertainty in projections by considering the mean values and distribution of values in the two RCP scenarios. Although this is considered to be a step forward in relation to more deterministic approaches, such as “morphing”, modelling can be enhanced by following the trend in climate change impact assessments that tries to define overheating risk in terms of probabilities. For that purpose, a probabilistic approach in terms of projections would be imperative and it is not yet available for the urban context considered here. A possible evolution of this work is also the comparison between the two climate projection models used here. The methodology and the integrated approach to vulnerability can also be adapted to other types of buildings or contexts, which have specific characteristics and needs (e.g. hospitals, schools).

9 Appendices

9.1 Appendix 1 - Diary Sheet used for Monitoring Period

Investigação Doutoramento

FACULDADE DE
CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE NOVA DE LISBOA

Registo comportamento de ocupantes

Habitação______			**Sexo:** ☐ M ☐ F		**Idade:______**	
Data	Hora de entrada	Hora de saida	Abertura janela	Fecho janela	Abertura estore	Fecho estore

9.2 Appendix 2– Comfort Practices and Vulnerability Survey

ESTRATÉGIAS ADAPTATIVAS PARA O CONFORTO TÉRMICO NAS HABITAÇÕES

Integrado no âmbito de uma investigação em desenvolvimento na Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa, este questionário visa analisar a forma como os ocupantes dos edifícios se adaptam às temperaturas exteriores no interior das habitações, com um foco significativo na ocorrência de ondas de calor que assolam as cidades no Verão. O preenchimento das respostas que compõem este questionário deverá demorar menos de 10 minutos.

O questionário é confidencial e os dados recolhidos destinam-se somente à investigação em curso na Universidade Nova de Lisboa – Faculdade de Ciências e Tecnologia no âmbito do Programa Doutoral em Alterações Climáticas e Politicas de Desenvolvimento Sustentável e não serão utilizadas para qualquer outro fim.

Agradecemos muito a sua disponibilidade para participar e queremos que se sinta à vontade para partilhar qualquer opinião que julgue importante, nomeadamente sugerindo aspectos que não estejam aqui contemplados e que julgue relevantes. No fim do questionário haverá um espaço para estes comentários.

Questionário

Grupo I: Caracterização do inquirido e aglomerado familiar

1.Em que faixa etária se encontra?

○ 20-30 ○ 30-40 ○ 40-50 ○ 50-60 ○ 60-70 ○ >70

2.Qual é o seu sexo?

☐M ☐F

3. Quando se verificam temperaturas elevadas, o nível de incómodo que causam no seu dia-a-dia é:

☐ Muito alto
☐ Alto
☐ Médio
☐ Baixo

4. Tem alguma condição de saúde (ex: diabetes, condição cardíaca ou respiratória) que o(a) faça sentir-se mal com o calor?

☐ Sim. Qual(is)____ ☐Não

5.Com quem vive? (escolher uma ou várias opções)

Sozinho (a)	
Marido/Esposa/companheiro(a)	
Filho(s)	
Outros	

6. Quantas pessoas no total residem na sua habitação? _____

7.Qual o grau de ensino mais elevado que possui?

Inferior ao ensino básico (9º ano)	
Ensino básico	
Ensino secundário	
Ensino Superior	

8. Qual é o nível de rendimento anual líquido do seu agregado familiar?

☐ Até 5000€ ☐ De 5 000€ até 10 500€ ☐ De 10 500€ até 15 500€

☐ De 15 500€ até 21 000€ ☐ De 21 000 € até 31 000€ ☐ Superior a 31 000 €

9.Sobre a sua ocupação (indique todas as opções que achar pertinente):

☐ Trabalho fora de casa.

☐ Trabalho em casa.

☐ Sou estudante.

☐ Estou desempregado.

☐ Sou reformado.

Grupo II: Perfil de Ocupação da Habitação

10. Indique os períodos do dia em que normalmente se encontra em casa, no Verão.

	Manhã	Tarde	Noite
De 2º a 6º feira			
Dia de descanso/Fim de semana			

11. Indique o período do dia em que normalmente se encontra em casa, no Inverno.

	Manhã	Tarde	Noite
De 2º a 6º feira			
Dia de descanso/Fim de semana			

Grupo III: Caracterização da habitação

12. Em que tipo de habitação vive?

☐ Moradia

☐ Apartamento RC

☐ Apartamento Andar Intermédio

☐ Apartamento Ultimo andar

13. Quantas assoalhadas tem a sua habitação?

______

14.Quantas frentes expostas têm a sua habitação?

☐1 ☐2 ☐3 ☐ 4

15. Indique a orientação predominante das frentes da sua habitação.

☐ Norte/Sul ☐Este/Oeste ☐ Não sei

16. Indique a época de construção do edifício onde vive.

☐ Anterior a 1940 ☐Entre 1940 e 1960 ☐ Entre 1960 e 1990 ☐ Entre 1990 e 2007☐ Posterior a 2007

17. Indique o tipo de janelas que possui na sua habitação.

Caixilharias	☐ Madeira ☐ Alumínio/Aço ☐ PVC
Vidro	☐ Vidro simples ☐ Vidro Duplo

18.Num dia de maior calor, conseguir temperaturas confortáveis em sua casa é:

☐ Extremamente fácil

☐ Fácil

☐ Um pouco difícil

☐ Difícil

☐ Muito difícil

19. Num dia de maior frio, conseguir temperaturas confortáveis em sua casa é?

☐ Extremamente fácil

☐ Fácil

☐ Um pouco difícil

☐ Difícil

☐ Muito difícil

Grupo IV: Ambiente térmico e estratégias adaptativas

20. Possui algum equipamento de climatização que permita controlar a temperatura interior da sua habitação?

☐Ventoinha
☐Ar condicionado ou bomba de calor
☐Aquecedores portáteis
☐Aquecimento central

20.1 Se indicou possuir ar condicionado ou bomba de calor, quando utiliza mais o aparelho?

Estação do ano	Frequentemente	Ocasionalmente	Nunca
Dezembro a Fevereiro	☐	☐	☐
Março a Maio	☐	☐	☐
Junho a Agosto	☐	☐	☐
Setembro a Novembro	☐	☐	☐

21.Nos dias em que a temperatura está mais alta, como classificaria a sensação térmica na sua habitação, se não tomar nenhuma medida para a arrefecer?

☐ Muito quente
☐ Quente
☐ Ligeiramente quente
☐ Nem frio nem quente
☐ Ligeiramente frio
☐ Frio
☐ Muito Frio

22. Nos dias mais quentes, quais as medidas que utiliza para se refrescar quando está em casa? Indique a frequência com que adota as medidas enunciadas.

Medidas	Frequentemente	Ocasionalmente	Nunca
Mudo de roupa quando chego a casa.	☐	☐	☐
Procuro beber líquidos frescos.	☐	☐	☐
Tomo duches frios.	☐	☐	☐
Recolho-me para divisões mais frescas da casa.	☐	☐	☐
Procuro repousar e não me mexer muito.	☐	☐	☐
Mudo as atividades mais intensas fisicamente para alturas menos quentes do dia.	☐	☐	☐
Outra. Especifique qual______________________________	☐	☐	☐

23.Nos dias mais quentes, quais as medidas que utiliza para tornar o espaço da sua habitação mais fresco? Indique a frequência com que adota as medidas enunciadas

Medidas	Frequentemente	Ocasionalmente	Nunca
Utilizo o ar condicionado	☐	☐	☐
Utilizo a(s) ventoinha(s)	☐	☐	☐
Abro as janelas para ventilar os espaços, a qualquer hora do dia.	☐	☐	☐
Abro as janelas para ventilar os espaços, apenas quando começa a anoitecer.	☐	☐	☐
Fecho todas as janelas para não deixar entrar o calor.	☐	☐	☐
Evito ligar aparelhos e iluminação que gere calor (fogão, iluminação incandescente, etc)	☐	☐	☐
Outra. Especifique qual__________________________	☐	☐	☐

24.Quais as razões que o levam a adotar as medidas escolhidas na questão anterior (indique todas as razões que são relevantes na sua decisão)

☐ São as medidas mais custo-eficazes
☐ São as medidas mais eficazes
☐ São as medidas que têm menor custo
☐ São medidas que são mais ecológicas
☐ São medidas indicadas por amigos/sítios da internet/campanhas de informação
☐ São as medidas mais fáceis e que consigo realizar sem a ajuda de terceiros
☐ São medidas que estou habituado a tomar
☐ Não tenho outra alternativa

25.Como classificaria a sensação térmica na sua habitação, nos dias mais quentes, após tomar as medidas que indicou na questão 23?

☐ Muito quente
☐ Quente
☐ Ligeiramente quente
☐ Nem frio nem quente
☐ Ligeiramente frio
☐ Frio
☐ Muito Frio

26.No caso de saber que os dias seguintes são dias quentes, prepara a sua habitação?

☐ Sim, deixo os estores fechados e as janelas abertas
☐ Sim, tento que a casa arrefeça ao promover correntes de ar

☐ Sim, tenho o cuidado de fechar as janelas e os estores
☐ Sim, programo o ar condicionado para ligar a determinada hora
☐ Sim, Outra____
☐ Não. Não posso deixar as janelas abertas por uma questão de segurança
☐ Não. Não tenho como preparar a minha habitação para dias mais quentes.
☐ Não. Outra____-

Agradecemos a sua participação neste estudo. Caso deseje receber mais informações sobre este trabalho ou sobre o resultado do estudo realizado neste inquérito, indique por favor o seu endereço eletrónico na caixa abaixo.

Existe alguma questão que ache importante nesta temática e que não esteja abordada no questionário? Gostaria de partilhar a sua opinião sobre este assunto? Use por favor a caixa em baixo.

Conhece alguém que possa recomendar para responder a este inquérito? Indique por favor na caixa abaixo a(s) morada(s) de endereço eletrónico

Investigação financiada por:

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA