



UNIVERSIDADE DE LISBOA
INSTITUTO SUPERIOR TÉCNICO

**Integrated Evaluation of Comfort, Well-being and Energy Efficiency:
Methodology applied to 10 case studies in Portugal**

Mariana Rego Neto

Supervisor: Doctor Carlos Augusto Santos Silva

Co-Supervisor: Doctor Armando Teófilo dos Santos Pinto

**Thesis approved in public session to obtain the PhD Degree in
Sustainable Energy Systems**

Jury final classification: Pass with Distinction

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Abstract

Managing energy resources requires intervention in energy supply and demand, with a focus on sustainability, energy efficiency and renewable sources. It is necessary to adopt construction solutions that provide comfort and well-being with the minimum use of resources. The assessment of comfort and well-being in housing has several dimensions and although there are assessment methods, there is no national practice for the integrated assessment of multiple aspects, centred on the occupants, considering energy efficiency.

This study seeks to develop and test an integrated method for assessing comfort and well-being in their multiple aspects and their relationship with the energy efficiency of buildings. The aim of this method is to carry out post-occupancy evaluations, identifying the comfort and well-being parameters to be improved in a dwelling, taking into account feedback from occupants, and proposing improvement measures that contribute to increased satisfaction and comfort. This method was applied to ten case studies in Portugal and is based on surveys, indoor environment measurements and a collection of energy consumption and housing characteristics.

This study showed that the relationship between energy efficiency, building characteristics, comfort and well-being is undeniable, but subjective, as people's perceptions are affected by their experiences, emotional state and other subjective factors. Comfort and well-being parameters to be improved were identified, and recommendations were formulated to improve the houses indoor environment. Of these recommendations, it was found that some have an impact on more than one parameter and on energy consumption and others do not affect energy consumption but contribute to overall comfort. After implementing the measures to improve thermal comfort, simulation models showed that the indoor temperature generally increases in winter and decreases in summer, reducing the need for air conditioning to keep the houses within the comfort range.

Keywords:

Comfort, Well-Being, Energy Efficiency, Post-occupancy evaluation, Residential buildings

Resumo

A gestão dos recursos energéticos requer intervenção na oferta e procura de energia, com foco na sustentabilidade, eficiência energética e fontes renováveis. É necessário adotar soluções construtivas que proporcionem conforto e bem-estar com o uso mínimo de recursos. A avaliação do conforto e bem-estar das habitações tem diversas dimensões e apesar de existirem métodos de avaliação, não existe uma prática nacional para a avaliação integrada das múltiplas vertentes, centrada nos ocupantes, considerando a eficiência energética.

Este estudo procura desenvolver e testar um método integrado para avaliar o conforto e o bem-estar nas suas múltiplas vertentes e a sua relação com a eficiência energética dos edifícios. Com este método pretende-se realizar avaliações pós-ocupação, identificando os parâmetros de conforto e bem-estar a melhorar numa habitação, considerando o feedback dos ocupantes, e propondo medidas de melhoria que contribuam para o aumento da satisfação e conforto. Este método foi aplicado a dez casos de estudo em Portugal e suporta-se em questionários, medições do ambiente interior e no levantamento do consumo energético e das características da habitação.

Com este estudo verificou-se que a relação entre eficiência energética, características dos edifícios, conforto e bem-estar é inegável, mas subjetiva, pois as perceções das pessoas são afetadas pelas suas experiências, estado emocional e outros fatores subjetivos. Foram identificados parâmetros de conforto e bem-estar a melhorar, tendo sido formuladas recomendações para melhorar o ambiente interior das habitações. Destas recomendações, verificou-se que algumas têm impacto em mais do que um parâmetro e no consumo de energia e outras não afetam o consumo energético, mas contribuem para o conforto geral. Após a aplicação das medidas de melhoria de conforto térmico, verificou-se através de modelos de simulação que a temperatura interior geralmente aumenta no inverno e diminui no verão, reduzindo a necessidade de climatização das habitações para estarem na gama de conforto.

Palavras-Chave:

Conforto, Bem-estar, Eficiência energética, Avaliação pós-ocupação, Edifícios residenciais

Index

Index of tables	xv
Index of figures	xvii
List of acronyms and symbols	xxi
1. Introduction	1
1.1. Motivation	1
1.2. Objectives	2
1.3. Document organisation	3
2. State of the art	5
2.1. Comfort and well-being	5
2.1.1. General aspects	5
2.1.2. Architecture and constructive aspects	9
2.1.3. Interior environment characteristics	12
2.1.4. Personal aspects	13
2.1.5. Thermal	14
2.1.6. Acoustic	16
2.1.7. Indoor air quality	17
2.1.8. Lighting	18
2.2. Buildings energy performance	19
2.3. Legislation and regulation	23
2.3.1. Context	23
2.3.2. Comfort requirements	25
2.4. Evaluation methods	26
2.4.1. Comfort and well-being assessment methods	26
2.4.2. Buildings energy performance assessment methods	33
2.5. Summary	35
3. Methodology	37
3.1. Parameters and methods selection	37
3.2. Method implementation	39
4. Case studies	47
5. Right-now survey	55
5.1. Measured indoor environment data	55
5.2. Analysis of air temperature measurement intervals	58
5.3. Measured indoor temperature and people's perception	63
5.4. Other survey topics	71

5.5.	Conclusions of right-now survey	79
6.	Extensive survey.....	81
6.1.	Measured indoor environment data.....	81
6.2.	Satisfaction.....	82
6.3.	Thermal environment.....	84
6.4.	Ventilation.....	86
6.5.	Indoor air quality.....	88
6.6.	Lighting.....	89
6.7.	Acoustics.....	91
6.8.	Other parameters and features.....	92
6.9.	Conclusions of extensive survey.....	96
7.	Comfort and well-being improvement: parameters and measures	99
7.1.	Comfort and well-being parameters to be improved.....	99
7.2.	Proposed measures	101
7.3.	Conclusions of parameters and measures	116
8.	Case studies simulation models.....	117
8.1.	Simulation models	117
8.2.	Models' calibration	122
8.3.	Improvement measures	126
8.4.	Conclusions of simulation models	156
9.	Conclusions and future work.....	159
9.1.	Conclusions.....	159
9.2.	Future work.....	160
	References	163
	APPENDIX	175
	APPENDIX A – Summary of the literature review	177
	APPENDIX B – Extensive survey (summer).....	195
	APPENDIX C – Extensive survey (winter)	213
	APPENDIX D – Right-now survey (winter).....	225
	APPENDIX E – Right-now survey (summer).....	235
	APPENDIX F – Systematize information from each case study (feedback and measurements)....	245

Index of tables

Table 2.1 - Surveys/questionnaires consulted for the preparation of the study's survey	29
Table 3.1 - Points used from existing surveys to draw up the survey for the present study	38
Table 3.2 - Range, accuracy and resolution of the sensors and equipment used in the study	42
Table 3.3 - Main characteristics of the extensive and the right-now survey	44
Table 4.1 - General characteristics of the case studies people	47
Table 4.2 - General characteristics of the case studies	48
Table 4.3 - Envelope characteristics of the case studies.....	48
Table 4.4 - Energy systems of the case studies	49
Table 5.1 - Indoor and outdoor measured mean air temperatures during the right-now survey	56
Table 5.2. - Measured minimum and maximum indoor and outdoor air temperatures during the right-now survey	57
Table 5.3 - Indoor and outdoor measured mean relative humidity during the right-now survey.....	57
Table 5.4 - Measured minimum and maximum indoor and outdoor relative humidity during the right-now survey	57
Table 5.5 - Measured minimum, maximum, and mean living room CO ₂ concentration during the right-now survey	58
Table 5.6 - Comfort and discomfort ranges for the case studies	66
Table 5.7 - Typical behaviour regarding the use of windows, blinds and HVAC during the day occupants filled the right-now survey	74
Table 5.8 - Typical behaviour regarding the use of windows, blinds and HVAC at the moment occupants filled the right-now survey	74
Table 6.1 - Indoor measured mean air temperatures during one year, including during the extensive survey	82
Table 6.2 - Main reasons for not opening windows as much as occupants would like for each case study by season (winter and summer).....	87
Table 6.3 - Level of discomfort that dark stains and/or mould on the ceiling and/or walls cause the occupant in specific rooms of the house in winter	87
Table 6.4 - Positive and negative points of the houses according to the occupants	95
Table 7.1 - Summary of the satisfaction and importance that the occupants attached to comfort and well-being parameters	99
Table 7.2 - Classification of the priority of the comfort and well-being parameters	101
Table 7.3 - Systematisation of the parameters to be improved, problems identified and proposed improvement measures for each case study	112
Table 8.1 - Simulation models envelope characteristics of the case studies	121
Table 8.2 - Model calibration criteria.....	122
Table 8.3 - Real and simulation monthly energy consumption of each case study (kWh)	123
Table 8.4 - Energy model calibration of each case study	124
Table 8.5 - Real and simulation living room monthly temperature of each case study (°C)	124
Table 8.6 - Temperature model calibration of each case study	124
Table A.1 - Variables and parameters of comfort and well-being of the consulted literature studies	179
Table A.2 - Parameters and methods of evaluating the energy performance of the consulted literature studies.....	192
Table F.1 - Case study 1 summary: comfort and well-being parameters	247
Table F.2 - Case study 1 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)	247

Table F.3 - Case study 2 summary: comfort and well-being parameters	248
Table F.4 - Case study 2 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)	248
Table F.5 - Case study 3 summary: comfort and well-being parameters	249
Table F.6 - Case study 3 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)	249
Table F.7 - Case study 4 summary: comfort and well-being parameters	250
Table F.8 - Case study 4 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)	251
Table F.9 - Case study 5 summary: comfort and well-being parameters	251
Table F.10 - Case study 5 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)	252
Table F.11 - Case study 6 summary: comfort and well-being parameters	252
Table F.12 - Case study 6 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)	253
Table F.13 - Case study 7 summary: comfort and well-being parameters	253
Table F.14 - Case study 7 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)	254
Table F.15 - Case study 8 summary: comfort and well-being parameters	254
Table F.16 - Case study 8 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)	255
Table F.17 - Case study 9 summary: comfort and well-being parameters	255
Table F.18 - Case study 9 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)	256
Table F.19 - Case study 10 summary: comfort and well-being parameters	256
Table F.20 - Case study 10 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)	257

Index of figures

Figure 2.1 - Post-occupancy evaluation scheme	27
Figure 3.1 - Diagram of the application of the methodology for collecting indoor environment data and occupant feedback	41
Figure 3.2 - Hobo UX100-003	42
Figure 3.3 - Hobo U10-003	42
Figure 3.4 - Hobo MX2301A	42
Figure 3.5 - Rotronic	42
Figure 3.6 - PEL	42
Figure 3.7 - Simplified diagram that reflects the method to classify the priority of the comfort and well-being parameters	45
Figure 4.1 - Representation of case study 1	49
Figure 4.2 - Representation of case study 2	50
Figure 4.3 - Representation of case study 3	50
Figure 4.4 - Representation of case study 4	51
Figure 4.5 - Representation of case study 5	51
Figure 4.6 - Representation of case study 6	51
Figure 4.7 - Representation of case study 7	52
Figure 4.8 - Representation of case study 8	52
Figure 4.9 - Representation of case study 9	53
Figure 4.10 - Representation of case study 10	53
Figure 5.1 - Graphical representations of air temperature measurements intervals for each case studies (1-5) by compartment (living room and main bedroom) and by season (winter and summer).....	59
Figure 5.2 - Graphical representations of air temperature measurements intervals for each case studies (6-10) by compartment (living room and main bedroom) and by season (winter and summer).....	61
Figure 5.3 - Graphical representations of air temperature measurements and sensation for each case studies (1-5) by compartment (living room and main bedroom) and by season (winter and summer). 67	
Figure 5.4 - Graphical representations of air temperature measurements and sensation for each case studies (6-10) by compartment (living room and main bedroom) and by season (winter and summer)69	
Figure 5.5 - Graphical representations of the use of windows, blinds and HVAC during the day for each case studies by compartment (living room and main bedroom) and by season (winter and summer).. 72	
Figure 5.6 - Graphical representations of the use of windows, blinds and HVAC at the moment of filling the survey for each case studies by compartment (living room and main bedroom) and by season (winter and summer).....	73
Figure 5.7 - Graphical representations of weather and thermal sensation perceptions for each case studies (1-5) by compartment (living room and main bedroom) and by season (winter and summer).....	75
Figure 5.8 - Graphical representations of weather and thermal sensation perceptions for each case studies (6-10) by compartment (living room and main bedroom) and by season (winter and summer).....	77
Figure 6.1 - Graphical representations of satisfaction for each case studies (1-5) by season (winter and summer).....	83
Figure 6.2 - Graphical representations of satisfaction for each case studies (6-10) by season (winter and summer).....	83
Figure 6.3 - Graphical representations of satisfaction for each case studies (1-10).....	84
Figure 6.4 - Graphical representations of the indoors thermal sensation and preference and type of clothing that occupant usually wears indoors for each case study (1-5) by season (winter and summer)	85

Figure 6.5 - Graphical representations of the indoors thermal sensation and preference and type of clothing that occupant usually wears indoors for each case study (6-10) by season (winter and summer)	85
Figure 6.6 - Graphical representations of the frequency of use of air conditioning equipment for each case study by season (winter and summer)	86
Figure 6.7 - Graphical representations of the frequency of open windows and opens up as much as would like for each case study by season (winter and summer)	86
Figure 6.8 - Graphical representations of the odour intensity for each case study by season (winter and summer).....	88
Figure 6.9 - Graphical representations of the odour type and frequency for each case study by season (winter and summer)	89
Figure 6.10 - Graphical representations of the natural lighting and use of artificial lighting for each case study (1-5) by season (winter and summer)	89
Figure 6.11 - Graphical representations of the natural lighting and use of artificial lighting for each case study (6-10) by season (winter and summer)	90
Figure 6.12 - Graphical representations of the use of shading for each case study by season (winter and summer).....	91
Figure 6.13 - Graphical representations of the level of disturbance regarding the perceived noise inside the home caused by different factors for each case study (1-5) by season (winter and summer)	91
Figure 6.14 - Graphical representations of the level of disturbance regarding the perceived noise inside the home caused by different factors for each case study (6-10) by season (winter and summer)	92
Figure 6.15 - Graphical representations of view importance for each case study	92
Figure 6.16 - Graphical representations of biophilia importance for each case study	93
Figure 6.17 - Graphical representations of system type preference for each case study	93
Figure 6.18 - Graphical representations of the importance of three aspects for each case study	94
Figure 6.19 - Graphical representations of the importance of comfort and well-being parameters for each case study	94
Figure 6.20 - Graphical representations of improvement measures priority for each case study.....	95
Figure 7.1 - Diagram that reflects the method to classify the priority of the comfort and well-being parameters	100
Figure 8.1 - 3D model of case study 1	117
Figure 8.2 - 3D model of case study 2	118
Figure 8.3 - 3D model of case study 3	118
Figure 8.4 - 3D model of case study 4	118
Figure 8.5 - 3D model of case study 5	119
Figure 8.6 - 3D model of case study 6	119
Figure 8.7 - 3D model of case study 7	119
Figure 8.8 - 3D model of case study 8	120
Figure 8.9 - 3D model of case study 9	120
Figure 8.10 - 3D model of case study 10.....	120
Figure 8.11 - Hourly temperature model calibration of each case study	125
Figure 8.12 - Living room temperature after improvement measures in case study 1 for real and nominal scenarios with and without using HVAC	129
Figure 8.13 - Living room discomfort hours after improvement measures in case study 1 for real and nominal scenarios with and without using HVAC	130
Figure 8.14 - Living room temperature after improvement measures in case study 2 for real and nominal scenarios with and without using HVAC	132

Figure 8.15 - Living room discomfort hours after improvement measures in case study 2 for real and nominal scenarios with and without using HVAC	133
Figure 8.16 - Living room temperature after improvement measures in case study 3 for real and nominal scenarios with and without using HVAC	135
Figure 8.17 - Living room discomfort hours after improvement measures in case study 3 for real and nominal scenarios with and without using HVAC	136
Figure 8.18 - Living room temperature after improvement measures in case study 4 for real and nominal scenarios with and without using HVAC	138
Figure 8.19 - Living room discomfort hours after improvement measures in case study 4 for real and nominal scenarios with and without using HVAC	139
Figure 8.20 - Living room temperature after improvement measures in case study 5 for real and nominal scenarios with and without using HVAC	140
Figure 8.21 - Living room discomfort hours after improvement measures in case study 5 for real and nominal scenarios with and without using HVAC	141
Figure 8.22 - Living room temperature after improvement measures in case study 6 for real and nominal scenarios with and without using HVAC	143
Figure 8.23 - Living room discomfort hours after improvement measures in case study 6 for real and nominal scenarios with and without using HVAC	144
Figure 8.24 - Living room temperature after improvement measures in case study 7 for real and nominal scenarios with and without using HVAC	146
Figure 8.25 - Living room discomfort hours after improvement measures in case study 7 for real and nominal scenarios with and without using HVAC	147
Figure 8.26 - Living room temperature after improvement measures in case study 8 for real and nominal scenarios with and without using HVAC	149
Figure 8.27 - Living room discomfort hours after improvement measures in case study 8 for real and nominal scenarios with and without using HVAC	150
Figure 8.28 - Living room temperature after improvement measures in case study 9 for real and nominal scenarios with and without using HVAC	152
Figure 8.29 - Living room discomfort hours after improvement measures in case study 9 for real and nominal scenarios with and without using HVAC	153
Figure 8.30 - Living room temperature after improvement measures in case study 10 for real and nominal scenarios with and without using HVAC	155
Figure 8.31 - Living room discomfort hours after improvement measures in case study 10 for real and nominal scenarios with and without using HVAC	156

List of acronyms and symbols

Acronyms

AC	Air conditioning
BIM	Building Information Modelling
BPE	Building Performance Evaluation
BUS	Building Use Studies
CBE	Center for the Built Environment
COPE	Cost-effective Open-Plan Environments
CV(RMSE)	Coefficient of variance of the root mean squared error
EU	European Union
EPBD	Energy Performance of Buildings Directive
FCT	Portuguese Foundation for Science and Technology
HOPE	Health Optimization Protocol for Energy-efficient buildings
HVAC	Heating, ventilation and air conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
IST	Instituto Superior Técnico
LNEC	Laboratório Nacional de Engenharia Civil
LR	Living room
MBE	Mean Bias Error
nZEB	Nearly zero energy buildings
PEL	Power Energy Logger
PhD	Doctor of Philosophy
PMV	Predicted Mean Vote
POE	Post-occupancy evaluation
PROBE	Post-Occupancy Review of Building Engineering
RCCTE	Regulation of the Thermal Behaviour Characteristics of Buildings
RH	Relative Humidity
RMSE	Root Mean Square Error
RSECE	Regulation of Energy and Air Conditioning Systems of Buildings
WWR	Window-to-Wall Ratio

Symbols - Alphanumeric

B	Bedroom
CO ₂	Carbon dioxide
T	Temperature

Symbols – Greek Letter

Δ	Difference
$^{\circ}$	Degrees

1. Introduction

1.1. Motivation

The buildings sector accounts for around 30% of total primary energy consumption in Portugal [1]. In this context, the National Energy and Climate Plan 2030 called for a 35% reduction in primary energy consumption by 2030 [2]. Looking at the European Union, buildings are responsible for 40% of this consumption and 36% of total greenhouse gas emissions. Buildings, therefore, have immense potential in the fight against climate change through efficiency gains, reducing consumption and emissions, and increasing safety standards and occupant comfort [3].

Energy consumption is a global economic and environmental concern since most energy comes from non-renewable sources [2]. At a time when sustainable alternatives are needed to cope with the impact of climate change, it will be an obligation for all buildings to increase the energy performance of buildings so that they become nearly zero energy buildings (nZEB) through the implementation of energy efficiency measures and local renewable energy generation while maintaining comfort and well-being indices [4].

In general, the constructive quality of buildings has improved in recent years due to increasing requirements for occupant comfort and energy performance. Occupants' needs have also increased regarding hygiene, food preparation and preservation, thermal comfort (heating and cooling), and electrical equipment to support tasks or just for entertainment. Despite the improvement in building quality, the increase in comfort needs and the lack of awareness of responsible energy use often leads to greater energy consumption with repercussions in terms of increased gas emissions, in the case of fossil fuels use, which contributes to global warming [5].

Despite improvements in buildings quality, contemporary architecture with large glazed areas and low thermal inertia has, in some cases, been overriding the appropriate bioclimatic design and construction of buildings, providing low adaptive capacity for occupants (e.g. absence of external shading, movable window leaves), leading to the use of energy-consuming mechanical or electrical systems to achieve comfort levels or providing less satisfaction [6] [7]. In this way, a low adaptive capacity of buildings and occupants is reflected in low energy efficiency, low levels of comfort and well-being, satisfaction and low productivity, particularly in office and service buildings [7].

Bearing all this in mind, it must not be overlooked that it is imperative to create conditions in buildings for greater comfort and well-being for occupants while also considering energy consumption to avoid contributing to the worsening of climate change. Investing in more efficient equipment, using better construction techniques and materials, and monitoring the behaviour of occupants and buildings all contribute to this increase in the energy efficiency of buildings and the comfort and satisfaction of occupants.

To understand these issues, it is necessary to introduce some concepts. Comfort results from the interaction of the environment (physical conditions), physiological conditions, the occupants' perception of psychological, social and cultural conditions/rights, architecture, clothing, eating habits and climate [8]. Well-being consists of the positive psychological experiences that occur in life and reflect an individual's good psychological functioning [9]. It relates to the concepts of happiness, positive experiences or ideas, satisfaction with life, pleasure and prosperity [10] [11]. The comfort and well-being of the interior environment of buildings is a relevant issue, given the implications for occupants' health (physical and mental) and productivity [12], as well as buildings' construction and operating costs.

To assess comfort and well-being, aspects of thermal comfort, acoustics, air quality, lighting and spatial-functional aspects are usually involved [13] [14] [15] [16][17] [18].

According to the literature, comfort, well-being, preferences and behaviour of occupants can be known through post-occupancy evaluation [12][19][20][21] combined with sensor measurements [15][22][23], control devices, mobile devices and *wearable devices* [24]. The assessment of comfort and well-being has several dimensions, and there is no consensus on an integrated assessment. This assessment is more complex when the interactions between the physical parameters of the building and the type of use of the occupants are considered [20][25][26][27]. The perception of comfort and well-being depends on each occupant, and this assessment is subjective [28]. This scientific development area, namely empirical/experimental, is not yet sufficiently developed, so the option could have been a rhetorical one of validating certain methods.

Having understood the above concepts, it is also necessary to realise that currently, the energy certificate for buildings in Portugal provides an assessment of energy performance and the identification of improvement measures for the energy class. Although, does not include an integrated assessment of comfort and well-being multiple aspects, centred on the occupants considering energy efficiency. When certifying the sustainability of buildings [29], the assessment is generally focused on the performance of the building, with the comfort conditions, behaviour and feedback of the occupants taking a second stage [30][31][32]. On the other hand, certification centred on well-being, health, productivity, and indoor environmental quality considers the building's characteristics, takes measurements and carries out post-occupancy evaluations [29][33], not considering or putting in second place the energy performance of buildings. Directive (EU) 2018/844 requires analysing energy and comfort [34]. Although the revision of the Energy Performance of Buildings Directive (EPBD) in 2010 introduced Portuguese legislation in 2013 [35][36][37], the concept of passive building and hybrid building also specify requirements for air quality and lighting [38], other aspects relevant to comfort and well-being are missing and require a multidisciplinary approach that takes the occupant into account when choosing energy efficiency improvement measures.

That being said, the relationship between the energy efficiency of buildings and the comfort and well-being of occupants in all aspects of the studies analysed in this research area needs further study, given the complexity of the interactions between the different physical parameters of the building, the type of use of the buildings and the individuals [27] [20]. From the literature, no tools were found to assess and study a specific house with specific people, making it possible to formulate recommendations for the post-occupancy assessment of the comfort, well-being and energy efficiency of existing residential buildings. In this sense, it was identified the need and opportunity to develop a holistic method centred on the occupants that would make it possible to assess and relate comfort and well-being in the different aspects and the energy efficiency of housing. This method will also make it possible to realise which comfort and well-being parameters should be improved according to feedback from occupants and the impact that certain improvement measures can have on the indoor environment.

1.2.Objectives

This research aims to develop and test a comprehensive method for evaluating comfort and well-being in its multiple aspects (thermal, indoor air quality, lighting, acoustics, other housing characteristics, furnishings, finishes and materials and personal aspects) and its relationship with the energy efficiency of buildings. It is also intended that this method will reveal what comfort and well-being parameters should be improved according to the feedback from occupants and the impact that certain improvement measures can have on the indoor environment.

The main research question of this doctoral thesis centres on how to evaluate the comfort and well-being of occupants, integrating aspects and characteristics of the energy efficiency of buildings (construction aspects, energy systems, usage profiles, and others). When answering this central question, it will be possible to identify the relationship between the energy efficiency characteristics of buildings and comfort and well-being. It will also be possible to formulate recommendations for post-occupancy evaluation and improve residential buildings' indoor environment, making them more sustainable and comfortable for the occupants.

This work makes a contribution to the area of comfort and well-being in residential buildings, as it considers occupant feedback as a starting point for improving the indoor environment and explores improvement measures that not only increase the comfort experienced by occupants but also increase energy efficiency. This integrated assessment of comfort, well-being, energy efficiency, and their relationship is innovative and essential for decarbonising the building stock.

To conduct this study, a comprehensive, in-depth, state of the art review is needed to understand each comfort and well-being parameter, characterise the most relevant parameters, the factors that can affect the perception of occupants, and the methods for assessing comfort, well-being and energy performance. Then, it is necessary to implement the methodology outlined for this study, considering the literature review. This is followed by a definition of the methodology to be applied to obtain the desired results and, in the end, an assessment of the impact of each improvement measure on the indoor environment.

To support the development and testing of the occupant-centred method, the object of study are existing air-conditioned and passive residential buildings. This study sought to ensure that the case studies were diverse in terms of the profile of the occupants, the use of the dwelling and the characteristics of the building since homogeneity, generalisation and the relationships of specific characteristics of the occupants and/or the dwelling is not the main focus. In the literature review, these relationships and correlations are addressed to determine which personal and physical factors of the indoor environment affect comfort and well-being, only to serve as a basis for developing the method and selecting the factors that interest this study. This study doesn't pretend to be a statistical validation but rather aims to ensure that the developed method responds to each case's needs and specific characteristics, requiring different inputs. Thus, 10 case studies were selected to apply this method.

1.3.Document organisation

This research is organised into nine chapters. Chapter 1 describes the motivation and objectives of this study. Chapter 2 describes the state of the art of the comfort and well-being and the energy efficiency of buildings. Legislation and evaluation methods are also covered. Chapter 3 defines the methodology applied in this study, namely the parameters and methods selection and then the method implementation. Chapter 4 presents the case studies. Chapter 5 and Chapter 6 presents the results and discussion obtained in the right-now survey and extensive survey, respectively. Chapter 7 presents the comfort and well-being parameter identified to be improved and the suggestions of improvement measures to improve the indoor environment. Chapter 8 presents the case studies simulation models. In the last chapter, Chapter 9, the main conclusions of this study and future work are presented.

2. State of the art

This chapter aims to better understand the variables affecting occupant comfort, well-being and building energy performance. Thus, a review of the literature on these subjects was carried out. The review used search engines and databases such as Google Scholar, ScienceDirect, and Scopus. The literature selection was mainly of recent journal articles, conferences, theses, books and standards. It was tried to ensure they were no older than 2015, although some are. To search the literature, the following keywords were used to identify those related to the scope of this thesis: occupant comfort, occupant well-being, building, residential building, houses, indoor environmental quality, thermal comfort, visual comfort, air quality, acoustic quality, energy efficiency, adaptive behaviour, survey, questionnaires, post-occupancy evaluation, energy consumption, and building energy.

This study is about comfort and well-being in houses. However, the literature review presents more studies on office buildings and other commercial and service buildings. Thus, these studies are also included to help explain and understand some of people's sensations and perceptions that may be transferable to their homes. This literature review will detail the groups of comfort and well-being factors to be evaluated in this study.

Chapter 2.1 discusses comfort and well-being in general by explaining the concepts and the most important factors. The subchapters address the different aspects of comfort and well-being by listing the occupants' preferences and behaviours to achieve comfort. Chapter 2.2 deals with the factors that influence the energy performance of buildings and measures to improve energy efficiency. Chapter 2.3 discusses the Portuguese legislation regarding buildings' comfort and energy performance and approaches some international legislation about these subjects. Chapters 2.4 address the methods of evaluating the comfort, well-being and energy performance of buildings. Finally, Chapter 2.5 presents a summary of the state of the art.

2.1.Comfort and well-being

2.1.1. General aspects

Occupants spend much of their time in indoor buildings. These indoor environments influence their comfort, productivity, health and well-being [12] [39] [40] [41]. It is crucial to identify the most relevant parameters and understand the interactions and trade-offs among indoor environmental quality factors to promote positive effects on the indoor environment. The concepts of comfort, well-being, and quality of life have become relevant in different contexts, namely in the building sector [42]. Commonly, comfort and well-being are used interchangeably and are presented as concepts related to the quality of life [42]. This led several authors and disciplines to study these concepts. Although several theories have been developed concerning each concept specifically, the distinction between these concepts remains unclear.

- **Comfort**

Current research and standards have mainly focused on establishing acceptable ranges of indoor environmental conditions to provide thermal comfort, air quality, light, acoustics, productivity and others. Also, these studies and standards pretend to reduce negative effects such as discomfort or adverse health effects. Acceptable indoor climates in buildings are essential to the success of a building, not only in making it comfortable but also in deciding its energy consumption and ensuring its sustainability [43]. Comfort perception can be influenced by climate and weather conditions and building-related factors like design, disposition and control in systems, and individual characteristics of the occupants [27] [40].

Comfort definition can differ depending on the global approach or the study discipline (Indoor Environmental Quality (IEQ), healthcare, ergonomics, others) [18]. According to Fabbri [8], it results from the interaction between the environment (physical conditions), physiological conditions, the occupants' perception of psychological, social and cultural conditions/rights, architecture, clothing, eating habits and climate. It is typically studied from the perspective of the physical environment and the physiology of the occupant, from the side of thermal comfort, acoustic quality, air quality and visual quality [18].

According to Alhorr et al. [12], comfort is defined by an absence of unpleasant sensations, thus positively affecting well-being and is highly subjective. Occupant comfort depends on personal variables such as individual metabolism, clothing preference, activity patterns and the localized conditions of different zones inside an office. In an office environment, there are different types of comfort. It includes physical comfort (air quality, climate, noise), functional comfort (disturbances, interruptions, distance from work, resources) and psychological comfort (privacy, territoriality).

Defining and achieving comfort is very complex because it responds to the physical state created by the combined effect of the environment's physical characteristics. Identifying each physical factor's comfort zone and reaching the comfort zone of the overall physical state is necessary. Adds the complexity of the occupants' response to the overall physical state [12]. The literature shows that comfort is a broad, deep phenomenon of subjective nature and contextual dynamism [18].

- **Well-being**

Psychological well-being reflects characteristics related to positive or optimal psychological functioning and is associated with different positive processes, not only at the behavioural and cognitive level but also at the neuroendocrine level [44]. Well-being consists of the positive psychological experiences that occur in life and reflects an individual's good psychological functioning [9]. It relates to concepts of happiness, positive experiences or ideas, life satisfaction, pleasure, and prosperity [10] [11]. Other dimensions constitute psychological well-being, such as self-acceptance, life purpose, dominance over the environment, positive relationships, personal growth, and autonomy [44]. It is often simplistically synonymous with wellness, happiness and quality of life or related to comfort and health [45]. Well-being is broader than comfort and refers to a neutral and durable but basic, relaxed or pleasant state [46].

According to the World Health Organisation [47], "health and well-being" include social, psychological and physical factors. The World Health Organisation defines health as "a state of complete physical, mental and social well-being". Social well-being is determined by the individual's relationship strength and how they function within their community. Health and well-being are affected by a combination of genetics, behaviour, lifestyle, and environmental factors that impact persons differently, depending on individual characteristics (age, gender, pre-existing health conditions, and others). Socio-economic factors also impact because lifestyles are determined by choice and heavily influenced by income, education and social connectedness. Generally, well-being consists of physical, mental and social factors, and overall satisfaction promotes health [27]. Health, well-being and productivity are interrelated, but the relationships are not always overlapping and/or symbiotic. For example, it is difficult to be productive if someone is sick. Still, it is possible to be productive without being in better health. Also, it is possible to be healthy without a sense of well-being [48].

Sick building syndrome occurs when building occupants develop disease symptoms or become infected with chronic diseases from the building frequented for living or working. This syndrome includes a group of symptoms related to the eyes, nose and throat, dry skin, headache and lethargy that are temporally related to working in particular buildings. The workers are symptomatic, and the building or its services are the cause. According to Burge, there are many sceptics regarding the diagnosis of this

syndrome, and the "sickest" buildings often have air temperature, humidity, and lighting levels that meet current standards. Visiting the workplace and implementing a questionnaire makes it possible to better understand the severity level of this syndrome in each case [49].

In the field of the built environment, the values and beliefs have changed over the years about how spatial and environmental qualities can influence well-being, underlining the need for greater clarity about the role, significance, contribution and interrelationships of many factors and dimensions (satisfaction, aesthetics, ergonomics, performance, affect, and others) [45].

- **Evaluating comfort and well-being**

To evaluate comfort and well-being, besides personal aspects that condition this evaluation, there are different aspects and variables of comfort and well-being that must be taken into account, namely thermal comfort (air speed, humidity and temperature), acoustics (unwanted sound control, vibrations and reverberations), air quality (smells, outside air and ventilation), lighting (view, illuminance and reflections) [18] [41] [50] and space-functional aspects (interior design, size of compartments, among others) [13] [14] [17]. The factors related to the architecture and construction of buildings must also be considered since they influence the comfort and well-being felt indoors and the occupants' ability to adapt [50]. The buildings should be able to react and adapt to weather, occupancy and function requirements [27].

A study about the impact of homeworking during the 2020 pandemic time on physical and mental well-being concluded that health and well-being were affected, namely poor sleep, increased fatigue, increased alcohol consumption in some countries, reduced exercise frequency, isolation, work-life balance and others. The study recommends ensuring a safe and ergonomic home office set-up with the necessary tools, providing mental health support and information for healthy habits, and others [51].

According to Alhorr et al. [12], the comfort factors also affect the satisfaction and productivity of the occupants of an office building and can be distributed in four main aspects: personal, social, organizational and environmental factors. His study also identifies eight physical factors that affect occupant satisfaction and productivity in an office environment and have significant interactions and crossover between them: indoor air quality and ventilation, thermal comfort, lighting and daylighting, noise and acoustics, office layout, biophilia and views, look and feel, and location and amenities. It is complex to understand, measure and achieve occupant productivity in an office environment and occupant comfort because it directly relates to the physical factors of the indoor environment. The study of Ornstein [52] included five groups of questions: Interviewee characteristics (socioeconomic conditions, education levels, work-home distance, other); Neighbourhood (network of services, commerce, public transportation and other urban infrastructure elements available in the vicinity); Building (automation; fire safety; burglary safety; handicapped access; appearance; leisure and living area in the building and parking performance); Floor (floor-type, distribution of spaces and furniture); Observations and comments.

From the literature, the studied parameters (thermal comfort, acoustics, lighting, personal aspects, office layout, cleanliness, and/or others) are not always addressed in all, i.e., some only study one or two parameters and others end up addressing more. There are two main approaches to evaluating comfort: some assess a single comfort factor and others a multiple comfort factor. Single-factor analyses has as main objective to investigate the variables that affect a specific aspect of comfort. These variables include building construction features, occupant characteristics, IEQ, and outdoor climate. Another objective of this analysis is the characterization of acceptable and preferred indoor environmental ranges for the occupants. The multi-factor approach simultaneously evaluates more than one aspect of occupant comfort and satisfaction. This multi-factor approach can have three approaches: an independent

approach in which two or more of the aspects of occupant comfort are evaluated separately and the purpose of these studies is to assess the impact of different factors on comfort (as in the one-factor approach); a ranking-based approach, which evaluates the importance of each comfort aspect to overall comfort and ranks the different comfort aspects to be shown, which should be given priority in an attempt to optimize building occupant comfort; an interrelation approach, which is intended to assess the impact that perceived thermal, visual and acoustic comfort levels may have on each other (or other comfort and well-being factors) [40]. The selection of the studied parameters depends on the study's objectives. It also appears that the way the different parameters are grouped into groups of factors may vary according to the objective and methodology of the study.

People have the natural tendency to adapt and change their environment's conditions. If a change leads to discomfort, people react in a way that makes them comfortable again [26] [27] [43]. Occupants can adapt to the environment through physical actions (changing clothes, others), behaviour (changing of habits), and physiological adaptation (eye accommodation, others). The occupants' interaction with the building, service system and appliances allow them to achieve the desired indoor comfort level [53]. Giving them the ability to control the indoor environment of buildings has a beneficial effect on perceived comfort [50].

Taking into account the existing concerns with planet sustainability certification schemes such as LEED, BREEAM, WELL, and CASBEE that consider the design, operation and maintenance environmental impacts are increasingly used [54] [45]. These certifications apply to different types of buildings and can even broaden the spectrum and certify communities. The parameters and requirements of these evaluations may differ according to the type of building, but the basic parameters remain the same. This type of certification is used in several phases, i.e. building design, operation and renovation. This building sustainability certification considers parameters of comfort (thermal, indoor air quality, acoustic, lighting, views), well-being (health, security, fitness, mind, nutrition), resource management (energy, water, materials, waste, ecology and land use in a life cycle approach) and others such as transport, location, innovation [55][56][57][58]. This approach has a larger scope than the current Portuguese legislation. Comfort, well-being, productivity, satisfaction, preferences and behaviour of the occupants can be assessed through post-occupancy evaluation [19][20][21][59] combined with sensor measurements [12][15][22][23]. Building Information Modelling (BIM), cloud computing, remote access technology, extensive data analysis and sophisticated sensors and simulation tools can also be methods to assess productivity and indoor environmental quality [12].

In summary, the literature review shows that comfort and well-being are interconnected, broad and deep phenomena of a subjective nature. Also, they had contextual dynamism since they were influenced by multiple factors. Two or more people in the same space can have different perceptions and feelings about various parameters of comfort and well-being. However, comfort can be a concept more related to the possibility of measuring the conditions of the interior environment (temperature, humidity, noise, illuminance, and others). Well-being is more qualitative and involves analysing factors that cannot be measured, such as view, biophilia, safety, furniture, and others.

This study will mention comfort and well-being when it pretends to refer to concepts of comfort, well-being, satisfaction and perception of occupants about the indoor environment. Although this study focuses on comfort and well-being in residential buildings, the literature review presents studies on office buildings and other commercial and service buildings because there are more and more comprehensive studies that can also help to explain and understand some of the sensations and perceptions of occupants in homes. For this multiple comfort factors study, it was considered that the groups of factors to be studied would be personal aspects, thermal comfort, acoustics, indoor air quality, lighting, functional space and architecture and construction aspects. The following subchapters have a

more detailed literature review regarding the parameters of comfort and well-being intended to be studied.

2.1.2. Architecture and constructive aspects

Buildings are often not built and designed centred on the occupants and environmental impacts. An opportunity exists to develop and construct buildings with more comfortable and healthy indoor environments connected to the natural environment [45]. The buildings should be able to react and adapt to weather, occupancy and function requirements. These adaptation processes could be at the building design and construction level with passive and active design, at the management of indoor environmental controls and/or at the occupant level [27].

- **Personal control**

Personal control refers to the occupant's possibility of adjusting the automated control and using blinds, lighting, opening/closing a window or using a fan [27]. In some cases, evidence suggests that building occupants are often dissatisfied with automation technologies, which can include energy-intensive behaviours (window open in winter, cover motion sensors that control lighting, cover inefficiently using a space heater, others). Designers often ignore or don't understand that providing greater control to building occupants increases their acceptance and preference for a broader range of indoor conditions. Thus, it is essential to understand the ideal between building automation and manual systems to provide and improve occupant comfort, usability, perception of control, and energy efficiency [60]. In nearly zero-energy houses, the controllability of the indoor climate is a relevant evaluation parameter in satisfaction [61]. It is also important to mention that detailed information provision (initial instructions and written manuals) is critical and should not be neglected. For instance, the perception of poor levels of control, dry air in winter, and noise or odour problems can sometimes be eliminated if specialised information is given to occupants [61].

- **Natural Light**

Buildings should be designed to provide light levels that enable occupants to maintain health and well-being, avoiding problems such as a deficit of vitamin D, a non-well-balanced circadian rhythm, depression, seasonal affective disorder and others [62]. Home design should provide good daylight through building form, orientation and space planning [63]. When planning a space, the use and layout of the space where daylight will be most useful or desirable, the views, comfort and privacy should be considered [47]. The shape and location of these glazed openings, the type of shading devices and any external obstructions can influence the occupants' feelings of satisfaction and well-being and, consequently, their visual performance [64]. Of course, these design guidelines can be applied in non-residential buildings. Buildings that do not allow sunlight can cause disease, directly or indirectly. However, it is not always possible to satisfy the need for sunlight exposure everywhere in a building. Therefore, it is suggested that solariums, balconies, atriums, and terraces be incorporated so that the occupants can access sunlight [62]. However, it is not just the light matters but also the view. Central courtyards, atriums, communal sky gardens, and roof gardens with real trees and plants may be solutions in congested urban environments. Where real natural features can't be introduced, art and mimicking shapes and forms found in nature can be a solution [48].

- **Windows**

Windows provide daylighting, views, solar gain, and heat losses; some types can arrange natural ventilation. However, inappropriate glazing design can impact privacy, furniture layouts, solar gain and heat loss. Ideally, buildings should receive low-level sun in winter and block the high-level sun in summer. Large windows facing south or west will have high heat gains except if exist external shading

or solar control glazing, and large windows on north-facing elevations will contribute to additional heat loss. Also, natural ventilation through open windows can provide a pleasant breeze and help cool buildings [47]. High windows, protected from direct radiation, benefit the light distribution in work environments, such as greater uniformity through the greater range and less possibility of glare because they are above the visual field of the worker [65]. In buildings, glazed windows play a fundamental role by allowing the capture of natural light and visual contact with the outside environment [64]. The decrease of the size of windows to increase thermal comfort should factor in the potentially damaging impact on occupants' emotional subjective wellbeing and psychological health. Preserving and/or improving natural light conditions in houses should be a concern of built environment planning to improve occupant's emotional subjective wellbeing [66]. The conscious and programmed use of daylight in interior spaces has become essential for improving energy efficiency by minimising energy consumption for lighting, heating, and cooling [64].

Hee Ko et al. suggest that people close to windows are more forgiving of small thermal comfort deviations and feel cooler and more comfortable in a space with windows. That could be explained because the window helped them to shift their focus from their thermal discomfort to the much richer sensory stimuli seen through the window and/or understand that the external environment is sunny and warm, so this might be associated with an expectation of the indoor temperature being warmer as well. Also, it could be a compensation effect of indoor environmental factors. For instance, having a window can compensate for the possible negative impact of an unpleasant thermal environment [23]. However, tables that are too close to windows will most likely cause problems such as glare for the occupants [65]. In general, having a window enhances psychological well-being and provides a visual connection to the outdoor (especially with nature), is positively related to occupants' productivity [23] [27] [48] [62] [65].

- **Noise**

The building envelope (opaque and glazed) thus influences the acoustic and thermal behaviour of buildings. It also ensures and controls lighting and ventilation conditions [67]. Besides the thermal and light comfort, a building structure and envelope should be designed to minimize the disruption from external noise [12]. The sound insulation of the building façade, roof and windows protects the indoor environment from unwanted outdoor noise [27]. Also, the building envelope can reduce solar heat gains through building façade orientation and the type of glazing shading system. Buildings should have appropriate insulation levels and high-performance windows, considering the role of thermal mass [39].

- **Green structural elements**

Green façades, walls and roofs are considered nature-based solutions that look up the occupants' perception of indoor and outdoor space, improving comfort and well-being. According to Cirrincione et al. [68], their study results show that in relation to standard roofs, green roofs reduce energy demand for heating and cooling and improve indoor thermal comfort conditions for the top floor (reduction of average PMV values). In this way, green roofs act as a reliever of the increasingly higher outdoor temperatures resulting from climate change. According to climate classification and building typology, these thermo-hygrometric benefits can be more or less effective. These benefits allow green roofs to limit and reduce the size of technical plants, causing a positive impact on the outdoor urban environment by reducing CO₂ emissions, mitigating the urban heat islands effect, air purification and aesthetic aspects. However, Cirrincione et al. [68] indicate that previous studies have demonstrated that green roofs are often not a cost-effective solution at the single-building level.

- **Design for climate**

When designing a building, it is required to consider the climate in which the building will be built. For example, the relative humidity difference between the building's indoor environment and the outside

buildings requires specific architecture due to the consequent variation in temperature. This will define the use or not of natural ventilation, the type of inertia of the building, the size of the openings, solar protection, and others. In a region, the distribution of the buildings also impacts people's comfort. For example, buildings that shade each other, street dimensions, the use of fountains (leading to humidification of outdoor spaces), and the chosen materials (which can reflect a lot of radiation and/or store a lot of heat), among others [69]. The growth of housing density and the increase in building heights lead to an overall decrease in direct and indirect natural light access to indoor residential spaces. This trend may lead to potentially harmful effects on emotional subjective wellbeing [66]. The design parameters used to create urban areas (settlement texture, building form and envelope, and landscape planning) impact the indoor climate and, consequently, the buildings' energy performance [70].

Buildings should be orientated with openings and outdoor spaces away from pollution, and filtration could be considered. Internal accumulation of pollutants should be avoided and should be used in the construction of building materials, fittings and finishes with a low impact on air quality [47]. Offices that rely on opening windows for ventilation may have problems related to noise and pollution from outdoor (traffic), which can drive to air conditioning or ventilate the space mechanically [48].

Moisture, mould and condensation on walls in indoor environments can appear for many reasons. Still, the low quality of the construction, the design, and occupant behaviour are the main causes of the high humidity levels in indoor environments [71]. However, low air humidity can affect human health, particularly respiration, eyes and skin irritation, infections, allergy symptoms, and overall comfort [72].

- **Green buildings and nZEBs**

The World Green Building Council indicates that a green building reduces or eliminates negative impacts and can positively impact climate and the natural environment in its design, construction or operation [73]. Green building features include efficient use of resources, use of renewable energy, measures to reduce pollution and waste, enabling re-use and recycling, good indoor environmental air quality, and use of non-toxic, ethical and sustainable materials. Green buildings also should consider the environment and occupants quality of life in design, construction and operation, and use a design that enables adaptation to a changing environment [46] [73].

Occupants are more forgiving and arranged to work in a greater range of temperatures in green buildings [48]. According to Zitars et al. [46], the potential link between wellbeing, productivity and green office buildings generally needs further examination while previous research has established it. Also, the fulfilment of security and shelter, social contact regulation, symbolic identification, task instrumentality, pleasure, growth and sustainability may change significantly between individual buildings due to differences in features. Green buildings (low carbon and resource efficient) do not necessarily mean healthier and more productive for occupants than the “normal” buildings. There are some good features for people and the planet and some tensions. In more extreme climates, it can be necessary to use other options than exclusively passive design [48].

A nZEB houses study in Belgium [74] shows that summer thermal discomfort is frequent in these buildings despite their temperate climate. In living rooms, the long-term appraisal of thermal conditions is related to the frequency of extreme temperatures and the occupants' thermal perception in bedrooms is more affected by smaller temperature deviations. The study findings emphasize the need for better integration, even in temperate climates, of environmental controls operated by the occupants to mitigate overheating risks. On the other hand, a Netherlands study [61] indicates that end users living in highly energy-efficient houses are quite satisfied and have high comfort levels. However, the study also highlights the problems of overheating in summer and the provision of good air quality (particularly air humidity) and temperature control in winter is required. Also, energy costs associated with a dwelling

might be important to encourage potential residents to choose a nearly zero-energy home, alongside other factors such as size, location, neighbourhood and purchase price. Still, user satisfaction and comfort satisfaction depend on the properties of specific projects, and positive or negative appreciation cannot be generalised.

There has been an increasing concern about raising comfort and making buildings more energy-sustainable in design, operation, and maintenance. Environmental rating tools such as LEED, BREEAM, WELL, and CASBEE have contributed to the sustainability agenda in a central role [54]. According to Schiavon and Altomonte, occupants of LEED-rated buildings have equal satisfaction with the building/workspace and other parameters of the indoor environment than users of non-LEED certified buildings independently of office type, spatial layout, distance from the window, building size, gender, age, type of work, and weekly working hours. LEED buildings' occupant satisfaction with the workspace is higher for users of open spaces with limited or no partitions or group work areas. It may be more effective in providing occupant satisfaction in open spaces instead of enclosed offices [54]. According to the results of the Sant'Anna et al. study [75], the green label may influence employees, but customers do not distinguish between green and conventional buildings.

2.1.3. Interior environment characteristics

The configured interior of an office profoundly impacts concentration, collaboration, confidentiality, creativity, productivity, health and well-being [48]. Spatio-functional in this context includes the interior layout (workstation density, task-based spaces, breakout spaces and social features, and active design), the views and biophilia, and look and feel (colours, shapes and textures).

There is a significant focus on open-plan and cellular offices in office environments. The literature indicates the importance of layout to achieve productivity in an office environment. In general, mixed-mode offices with the characteristics of open plan and cellular office plan are recommended, depending on the requirements of the office. To determine the office layout's suitability and degree of influence, an analysis of the layout type should consider the complement of the organization's work strategies and processes and the occupants' response to a survey [12]. National culture can indirectly affect the layout and the organizational culture [12].

Workstation density, workspace configuration, breakout and social space to people congregate and relax affect well-being and productivity. These factors influence noise, concentration, collaboration, confidentiality and creativity [48]. The workplace should provide comfort and privacy for its occupants and be designed to accommodate an organization's core operations flexibly. A distraction-free work environment can be provided by using different proximity types and partition measures [12].

The association and satisfaction with interior space are influenced by including nature around building occupants. Thus, office design should include biophilic design features since a greater connection with nature results in higher productivity in an office environment [12] [23]. Biophilia features in an office can be views of nature and greenery when looking outside a building or biophilia features inside the building (plants, water features, and others) [12]. Developers and urban planners are more aware of biophilic design, green spaces and nature since they positively impact occupants' mental health [48]. According to Rasheed [76], indoor plants influence human behaviour and psychology (reduce stress, improve mood and cognitive function) and some had also potential to improve air quality by filtering pollutants (VOCs, PM and CO₂). However, the benefits of biophilia vary based on occupant preferences and the implementation should consider the environmental context and the specific needs of the occupants.

Views, especially nature, positively impact well-being and closely connect with daylight. A work pause that permits not looking at computer screens or written documents and looking at more extended distance views allows the eyes to adjust and refocus. This reduces fatigue, headaches, and eye strain effects in the long term [48].

Evidence shows that the design of an office impacts the health, well-being and productivity of occupants [48]. The aesthetic environment of an office is made up of colour schemes, spatial features and textures. The sense of comfort and well-being regarding these parameters depends on the building's occupants' social norms and personal preferences [12]. Parameters like the type of space, building design, and working conditions impact the occupants' overall satisfaction with the building's indoor environment [27]. Smooth curves and contours are preferred because sharp objects instinctively create a sensation of danger. The angular design and pointed forms can subconsciously aid alertness and concentration in certain task-based spaces [48].

Certain materials, particularly their colour, also affect how light is experienced [48]. According to Barbosa, occupants of office buildings prefer furnishing materials with lower reflectances near openings to avoid glare. Work tables with light materials (pastel shades, ivory, not white) also stimulate work and the feeling of greater luminosity. The use of light colours on the floor, walls and ceiling (not necessarily white) makes the environment brighter due to higher reflectances and contributes to a reduction in energy consumption for artificial lighting. It is also essential to use colours, leaving absolute neutrality [65].

Vision may have a relevant influence on how occupants perceive other senses, such as thermal responses. Visual and thermal comfort are influenced by diverse factors that may differ when simultaneous inputs from other sensory systems (auditory, visual, tactile) [23]. Literature suggests a clear interaction between office layout, acoustic properties and noise distraction in an indoor environment [12] [48]. These aspects described in this chapter can be evaluated using a survey [12].

2.1.4. Personal aspects

The buildings, namely office ones, impact their occupants' health, well-being, and productivity. Many factors related and unrelated to the indoor environment can impact comfort and well-being. Personal characteristics of the occupants, building-related factors such as the type of building and control over the indoor environment and the outdoor climate can influence the perception of comfort [50].

The overall comfort perception can be affected by the individual characteristics of the occupants, such as gender, age, type of work and others [27]. According to Pastore and Andersen's study [77], gender, the climate of occupant origin and duration of residence in the country impact comfort. Different occupant groups (gender, weight) require different comfort zones, and this should be taken into count when designing/operating spaces [78].

According to Frontczak and Wargocki [50], there are inconsistencies of personal factors that influence comfort. In most cases, factors such as age, body build, fitness, health, self-estimated environmental sensitivity, menstruation cycle, addictions like smoking and coffee, job stress and hours worked per week do not influence the indoor environment evaluation. In most cases, country of origin, education level, type of job, work psychosocial atmosphere and time pressure affect the indoor environment assessment. According to the authors, gender, job satisfaction, and relationships with superiors and colleagues can or can't influence the evaluation of indoor environment comfort.

Surroundings and community contexts can affect individual perceptions and behaviour [48]. Convenient office location and amenities (healthcare, childcare, recreational space, sports and entertainment facilities) could help to improve office productivity, the well-being of occupants [12] and satisfaction

[48]. According to Altomonte et al. [45], other aspects such as biophilia, safety and security, physical activity, ecology, food, inclusive design and others can impact occupant's well-being.

2.1.5. Thermal

Of the comfort and well-being variables listed in 2.1.1, thermal comfort is one of those with the most developed studies. Thermal comfort is vital for the built environment as it affects occupant satisfaction, health, productivity [79] and workplace satisfaction [48]. When a sensation of cold or heat exists, there is a loss of work capacity and/or health problems [69]. The decision to act or not on the thermal conditions of the physical environment influences the individuals' perception of this environment and, consequently, their feeling of thermal comfort [80]. Satisfaction with the indoor environment occurs through appropriate adaptation and can be a physiological, psychological or behavioural adjustment [81]. The thermal comfort sensation allows maximum work capacity when heat exchanges occur between the human body and the surrounding environment effortlessly (thermoregulation) [69].

According to Raimundo and Oliveira [82], the level of thermal comfort relates to the energy demand, the economic cost, the type of use of the building, the opaque thermal insulation elements, the climate intensity, the type of control of the climatization system and the energy price evolution rate. Regardless of the building's type of use, the intensity and severity of the climate cause a significant increase in energy demand for heating. The energy need for cooling also increases, although more moderate.

Fanger's [83] and Macpherson's [84] study mark early fundamental studies in thermal comfort. The literature review underlines two major thermal comfort approaches: Fanger's rational approach and De Dear's adaptive approach [79] [80]. The Predicted Mean Vote (PMV) model treats thermal comfort as a physical-physiological phenomenon. The human thermal sensation results from the heat transfer between a human body and its surroundings. Fanger developed this model, which later became the basis of ISO 7730 [85] and ASHRAE 55 [79] [86]. Fanger's studies aim to estimate a temperature range considered comfortable for most occupants of spaces and would be universally and uniformly applied to all types of buildings, regardless of their geographic location and cultural context. These studies present gaps as they do not integrate factors that potentially influence comfort, such as the spatio-temporal context and the psychosocial component of the occupants [80] and require concrete input variables [79].

The adaptive approach is the natural tendency of people to change conditions in naturally-conditioned building environments. This approach is based on the findings of thermal comfort surveys conducted by studies. Field surveys focus on data collection about the thermal environment and the occupant's simultaneous thermal response in real situations. The researcher's interventions should be minimum [43]. There are mainly two adaptive model standards: the ASHRAE 55 [86] adaptive model by de Dear and Brager and the EN 15251 [87] adaptive model by Nicol and Humphreys [79]. Both models do not adapt or re-learn since they are based on a fixed set of data collected from either laboratory (PMV) or field (adaptive) measurements. Thus, model properties and coefficients cannot accurately describe the individual occupants' comfort characteristics in a particular environment [79].

Nicol and Humphreys [88] identified three variables that have an influence on thermal comfort perception: climate (with the corresponding culture and thermal attitudes), nature of a building (and its services), and time (the rate at which the changes occur, and the occupants adapt). Kim et al. [79] identified that the factors that can influence individuals' thermal comfort are time (hour, day, season), thermal conditioning systems and settings (active/passive systems, heating/cooling setpoints, occupant control), building type (home/office), culture (socio-economic status, clothes), health, mood, demographic characteristics (sex, age) and thermal history (environments that usually is exposed). The human aspect, namely perception, acceptance, and preference, is important to thermal comfort. A

thermal state can trigger a diverse range of human responses because it depends on occupants' age, gender, metabolic rate, clothing, activity and regional weather [12]. However, there is ample evidence to define a temperature range favourable for office occupants to perform most tasks efficiently [12]. The Rijal, Humphreys and Nicol study [89] suggests that the comfort temperature changes according to the season.

Literature indicates that male occupants are more likely to express thermal discomfort caused by warm sensations than female ones. In addition, females declared discomfort more frequently to feeling 'cold'. Overweight occupants are more likely to register warm 'discomfort' than normal or underweight occupants and those the cold 'discomfort' [78]. Also, subjective assessment, skin temperature and heart rate variability analysis suggest that females prefer neutral or slightly warmer conditions. In contrast, males prefer neutral or slightly cooler conditions. Compared to males, females are more sensitive to temperature and less sensitive to humidity [90]. Other study indicate that comfort temperatures are very similar for women and men [89]. These conclusions may not always be applicable in all cases since comfort is subjective and depends on person to person, as mentioned above (age, culture, experiences, and others). During summer, a nursing study home in Spain [91] shows that under the same conditions, the staff and other people who work there felt that the environment was warmer and they were less tolerant than older people (residents). In another way, older people were less sensitive to thermal changes, and their comfort zone was wider than that of the adults who worked there.

The conditions and factors that define thermal state are mean radiant temperature, relative humidity, and air temperature, measured using sensors. Air velocity is also a thermal comfort parameter [12] [27] [48]. Barros and Schiffer [69] identified that the main climate variables of thermal comfort are temperature, humidity and incident solar radiation. A way to simplify the study is to consider air temperature as the only parameter to model the thermal preference of the occupants. However, from the literature review, other factors influence thermal comfort, and this assumption is very limiting when analysing the results of a study [16]. According to ASHRAE [86], six primary factors must be addressed when defining conditions for thermal comfort: two occupant characteristics factors, metabolic rate and clothing insulation, and four thermal environment factors, air temperature, radiant temperature, air speed, and humidity.

The main contributors to the thermal indoor environment are the heating, ventilation and air conditioning (HVAC) systems [92] [27]. They were controlled and standardized based on "maximum loads" and/or thermal comfort metrics or legislation. However, field studies demonstrated that the "feeling of comfort" was very personal and could not be characterized objectively due to individuals' physiological and psychological differences [93]. Thermal comfort standards and references are essential for designing HVAC and ventilation systems for an indoor environment. However, regional climatic factors and occupant behaviour patterns must be considered when determining the thermal comfort range for a given building in a given geographical condition [12].

Literature reveals that people who use air conditioning (AC) more frequently are more likely to express 'warm' discomfort than those who use less, and vice versa for those who use AC less regularly [78]. Plus, a study demonstrates a better thermal comfort quality, with lower costs, through control of the HVAC system with Predicted Mean Vote (PMV) setpoints instead of the traditional control with air temperature [82]. According to Dear and Brager [81], occupants in naturally ventilated buildings appear tolerant of a much wider range of temperatures than in centralized HVAC buildings. According to the Zhang et al. study [92], the occupants of centralized air-conditioning systems and split-type air-conditioner buildings reported the same thermal sensations, and their neutral temperatures and thermal sensitivities were not significantly different. Also, perceived control and thermal expectation contribute to understanding human thermal comfort, and it is recommended to study them quantitatively. It is

important to note that the occupants' age and body mass index from the centralized air-conditioning buildings were significantly larger than those from the split-type air-conditioning buildings. According to the authors, this did not impact the findings.

Different solutions involving individual preference feedback are recommended to achieve indoor environments, and occupants' preference feedback is essential for these strategies [93]. The building should allow occupants to adjust indoor environmental conditions since discomfort increases if control is not provided or if existing controls are not effective, appropriate, or usable [43] [94]. A study investigating thermal comfort in homes, specifically in the bedroom and living room, concluded that people make clothing adjustments to adapt to the bedroom temperature [89]. The inside condition temperature in the office room and the impossibility of adjusting the temperature and air velocity of the air-conditioning system contribute to the dissatisfaction of the building's occupants [95]. In occupational settings, the increased building temperature and extreme weather events are particularly relevant to workers' productivity and performance for the worse [27]. Personal control over thermal comfort can have productivity improvements. However, this is readily achieved in a cellular office where individuals can operate a window or an HVAC, but it can be more problematic in an open-plan office [48].

Thermal comfort is one of the most studied comfort variables. Finding single-factor studies is more frequent and less frequent with other factors, such as lighting or ventilation. Combining objective and subjective data will help understand the occupants' thermal comfort. Objective data is provided by physical measurements with a sensor or other and subjective data collection, such as surveys, interviews and others [12] [40] [79] [92] [94].

2.1.6. Acoustic

Acoustic comfort is frequently understood as a situation where the noise level is acceptable to the occupants [27]. Building acoustics ensure satisfaction to the occupants since they can communicate, do some activities, sleep and relax in houses, work in offices without disturbance and enhance health and well-being [96]. The perception of sound is complex because it depends on the sound intensity and its temporal and spectral features, the person's activity, state of mind, expectations and other factors [27]. Unwanted noise in buildings can be a nuisance but, in the worst case, can cause long-term health issues [47] [48].

Building acoustics is about noise control and related to the building design and construction [96]. To achieve comfort and well-being related to the acoustic environment, the first thing to do is to understand the purpose and the use of the built space, i.e. if the space is for a performance, for studying, for working and/or others [45]. The acoustic strategy depends on the internal and external noise levels, the building structure and envelope, the type of room layout and others [12] [45]. Noise distractions are related to interior layout [48]. The street design influences outdoor sound propagation (vehicles, people) [96].

There is a relationship between the sound levels of an indoor environment and its occupants' productivity. Noise can provide unwanted distractions, which can affect productivity. However, certain soundscapes, more natural than urban sound, can be restorative [48]. To analyse the acoustic comfort can be used a survey and monitoring of indoor and outdoor sound levels [12] [67] [97] [98]. Standards are available to indicate the requirements in this area. Other standards and organisations describe methods to evaluate sound insulation and the buildings acoustic quality [67] [99]. Background noise, privacy, interference and vibration can be evaluated to understand noise and acoustic satisfaction [48].

According to Paris-Newton et al. study [98], in old properties, upgrading the windows causes more consequences for sound insulation than for energy savings and the health and well-being of the occupants changed significantly.

2.1.7. Indoor air quality

Acceptable indoor air quality (IAQ) is a relevant aspect of a comfortable and healthy home. Despite advances in mechanical and hybrid ventilation systems, natural ventilation constitutes a challenge: optimising natural ventilation to reach IAQ while minimising thermal discomfort and energy consumption [100]. Indoor air quality can be extremely poor, severely affecting building occupants' health. The two main issues associated with indoor air quality are the accumulation of internal pollutants and the entrance of external pollutants into the building [47]. Typically, the internal pollutants come from combustion sources (tobacco, fireplaces, cooking appliances), cleaning supplies, paints, insecticides and other building materials. The external sources come from outdoor air pollution by opening windows/doors, ventilation systems, and cracks in structures. Outdoor climate and weather conditions simultaneously with occupant behaviour can also affect IAQ [101].

The IAQ may have four areas: air quality (which focuses on relative humidity, air temperature, pollutants, contaminants, and air movement), ventilation (depends on the typology of the building, outside climate, architectural features, activity in the building, and others), effect on human health (Sick Building Syndrome and Building Related Illness) and occupant perception and productivity [12]. Ventilation rate, indoor pollutant levels, and outdoor air monitoring can be measured, and an occupant survey helps understand occupants' perceptions of indoor air quality [12]. According to the World Green Building Council [48], pollutants, CO₂, aroma, ventilation rate or fresh air, and moisture content are the factors that can be evaluated or measured.

The literature identifies that productivity loss due to bad air quality and the perceived air quality signifies the importance of occupants' perception of healthy indoor air for better work performance [12]. IAQ benefits health and productivity in the office context and can be indicated by low CO₂ and pollutant concentrations and high ventilation rates [48]. The level of CO₂ is influenced by the occupancy levels, activity and behaviours (window opening) [102]. Typically, the highest CO₂ values in a building are in winter because the windows are opened less often. However, if all the windows are closed for a year, it will be in the summer that the values of CO₂ levels will be highest due to the less wind and stack effect. Elevated CO₂ levels can contribute to temporary cognitive impairment and poor sleeping quality [102].

Poor ventilation, in addition to contributing to the increase in CO₂ and pollutants in buildings, also contributes to condensation and growth of mould. High humidity levels in indoor environments [71] can affect human health and comfort but low air humidity can also affect particularly in respiration, eyes and skin irritation, infections, allergy symptoms, and overall comfort [72]. Increasing the ventilation through the use of mechanical or natural ventilation can rectify the situation. As mentioned before, some indoor plants can improve air quality by filtering pollutants (VOCs, PM and CO₂) [76].

IAQ can be controlled naturally through operable windows and wall openings and artificially by mechanical systems [27]. Rasheed et al. [103] identify that some studies said mixed-mode buildings have been reported to provide better environmental comfort and occupant satisfaction than naturally ventilated buildings. However, the findings of Rasheed et al. [103] showed that occupants of the naturally ventilated office building were slightly more satisfied and comfortable than those in the mixed-mode office. Furthermore, the study indicates that well-designed, naturally ventilated office spaces can provide more comfort than mixed-mode office spaces. In another way, Mucha et al. study [72] reveals that people might choose to change natural ventilation systems to mechanical ones for some reasons, namely the efficiency of controlling air flow rates and consistent airflow, the control of airflow and temperature and the possibility to incorporate filtration technologies to remove air pollutants.

There are principles and standards which establish requirements and methods for evaluating indoor air quality. However, there are sensors that measure certain types of pollutants and the application of surveys makes it possible to know the occupants' perception of indoor air [12] [77] [104].

2.1.8. Lighting

Lighting is essential to the indoor environment's quality and supports many tasks. It contributes to the occupants' well-being, productivity, satisfaction [47] [105], health [48] [62], provides aesthetic pleasure [45] and can influence occupants' safety [106]. Light interferes with the mood of the building's occupants and can contribute to the development of different activities as well as to physical and mental relaxation or stimulation [62][65]. Natural lighting conditions of houses significantly impact people's perceptions of happiness and sadness [66]. A designed lighting system must provide adequate illumination to guarantee safety, occupant movement, and visual comfort and facilitate visual performance and colour perception [27]. Designers should evaluate and balance the heat gain and loss, glare control, visual quality, and variations in daylight availability in different climates and seasons when they design a lighting system for maximum daylight (and views) [48].

Lighting can be artificial or natural, where the latter is desired by building occupants [64][48]. This preference is more accentuated if considering the view/landscape [65]. People enjoy the use of natural light in work and school environments. It has benefits such as reduced stress, increased productivity levels, the feeling of visual comfort [47] [64], satisfaction and health [48]. To point out that daylight is a zero-carbon source and good daylighting of indoor environments means less energy consumption for electric lighting during daylight hours [47] [48]. According to Altomonte et al. [45], the easiest way to achieve adequate circadian stimulation inside buildings is through naturally daylighted spaces. Another study also pointed out that daylighting interacts directly with thermal comfort in the office [12].

The light control allows comfort and minimises energy use and adaptability. The use of shading in the form of blinds or curtains in homes is recommended on any window or skylight to avoid glare from sunlight and privacy and to block unnecessary daylight. In the domestic environment, the colour of electric lighting is essential. People prefer warmer light unless it is recommended cooler sources for cooking or make-up, for example [47].

Nowadays, there are different standards and measurement methods to control lighting in the indoor environment. Daylighting and lighting design in a building should be strategically designed to achieve lighting levels that are comfortable for the indoor environment and for occupants' functions' performance. Note that different activities require different lighting levels [12]. For this motive, it is often necessary to resort to artificial lighting [65]. To reduce the use of artificial lighting and achieve energy savings, it is necessary to have a good lighting system to harvest the maximum amount of available sunlight [12] [62]. Individual lighting control enhances user satisfaction [105].

A study in Sweden [107] concluded that lights left on in unoccupied rooms in people's homes can serve a purpose for the residents. It can be for avoiding visual or aesthetic discomfort, eliminating dark spaces visible from other rooms, making the home inviting and visitors feel welcome, benefitting people outside and providing safety knowing that people are inside. This study also identifies nine capabilities of home lighting. Some are 'to enable vision', 'to offer a visual aesthetic experience', 'to send a message' and others.

The factors contributing to maintaining healthy indoor lighting levels are the luminance level, the daylight and artificial light ratio and the glare index [12] [27]. Although the human eye responds more often to luminance, illuminance is commonly used for lighting performance evaluation because it is cheaper and easier to measure [105]. These factors can be measured using sensors, through mathematical

calculations (glare index), and/or using a survey to collect occupants' responses about indoor lighting comfort and well-being [12] [64] [106].

Indicators such as spectrum, discomfort glare, flicker, and personal control are useful and often considered in lighting quality assessments and can identify poor lighting conditions and uncover visual performance issues with associated health problems [105]. Control of shadows, luminance, colour contrast and glare prevention are necessary to consider when providing an environment with clear visibility and psychological comfort [106].

2.2.Buildings energy performance

While global expectations of comfort are increasing, various new technologies may or may not be able to meet this demand. While the building envelope, equipment and systems become more efficient, the impact of occupants on building energy consumption increases. Meanwhile, telecommuting, co-working and home-sharing trends mean different occupancy than standard occupancy schedules. The convergence of these trends has required a fresh look at how occupants are incorporated into building design and operating practice throughout the building's life cycle.

The relationships between energy, comfort and well-being are complex and involve many variables. One of the relationships between well-being and energy use in buildings is related to the standard of living and quality of life. Several energy-consuming activities improve comfort and well-being and bring convenience to the occupants: the possibility of adequate room temperature, cooling products, heating water, lighting, and others. However, it is known that it is possible to have energy savings while maintaining a quality of life and well-being [18].

Energy consumption is the total energy used for specific work during certain periods. It can be reduced by improving energy efficiency [27]. Energy consumption happens when people interact with such technologies when seeking comfort and well-being. Habits and control actions are behaviour types that may or may not consume energy and are, to some extent and among other factors, influenced by a person's attitudes and emotions. These attitudes and behaviours toward energy vary from person to person. Consequently, energy consumption needs to be understood from a behavioural perspective relative to the pursuit of comfort and well-being [18].

Chapter 2.1 presents the comfort parameter that the literature suggests as the preferences of the occupants, their behaviour and solutions that lead them to a state of comfort, well-being and satisfaction with the interior environment. Also, energy savings were mentioned (green roofs, passive solutions, and others). As mentioned, all the comfort parameters must be controlled to ensure occupants' health and productivity. However, thermal comfort control remains dominant in achieving comfort and energy consumption, as the other parameters have less impact [108].

Understanding the occupants' behaviour is essential for achieving high-performance buildings and low energy use since the behaviour influences energy consumption significantly during the operational phase of the building [109][110]. Occupant densification has been considered a contributor to energy consumption, not a strategy to increase building performance. In building energy usage prediction, occupant behaviour is a factor of uncertainty, causing inaccuracies in building energy consumption analyses [53].

Occupants' socio-demographic backgrounds and occupancy profiles can significantly influence energy use. Note that the occupancy profiles vary considerably for each household since they have different ages, numbers of occupants, and lifestyles [111]. Low-income levels negatively influence consumers' overall energy efficiency, and they are at risk of energy poverty. Consumers with high income levels are more likely to invest in energy-efficiency technologies. Age and education are the more determining

factors. The level of education is important for energy-conscious behaviour: better-educated occupants know better the environmental problems and have more knowledge about how to engage in energy-conscious behaviours [27]. According to Šujanová et al. [27], there are critical factors for behavioural adaptation regarding energy saving and indoor environment: knowledge about how to use or which technology, motive for change and opportunity of available resources (time, money, others). Energy-consuming technologies enable occupants to achieve desired levels of comfort and well-being, but using these technologies often involves energy consumption. Controlling habits and actions are behaviours influenced by a person's attitudes and emotions [26].

Since occupants' behaviour directly influences their comfort, they should be advised on the importance of adopting eco-sustainable practices when using electrical systems and equipment. Additionally, they should be informed about the benefits of renewable energy and how improving the energy efficiency of energy-consuming equipment contributes to reducing overall energy consumption [5]. The change in occupants' behaviour can promote building energy efficiency and the use of less energy when exposed to feedback. However, occupant behaviour is difficult to quantify because the human decision-making process is complex and multifactorial, and numerous and varied factors influence behaviour [20].

There are alternatives besides studying and understanding the occupants' behaviour to improve the energy efficiency of buildings. Replace or introduce more efficient technology and use passive or active design strategies improves building efficiency. Passive building design refers to the ability to benefit from local climate and conditions, such as the passive use of solar radiation and natural ventilation, while using no energy. Active technology solutions refer to energy use but with solutions that consume energy savings from heat pumps and automated control of the indoor environment. Maximizing passive characteristics (cooling, heating and natural light) leads to increased energy availability, emission-conscious designs, become energy and cost-efficient buildings and increased building resilience, i.e., in the event of an interruption in energy supply, buildings remain habitable, passively providing shelter [70] [27].

Energy efficiency and comfort can have similar priorities in the design and operation of buildings, namely the building envelope [39]. For example, improving the external walls' U-value can reduce heating energy use during winter [111]. The heat needed to keep a building thermally comfortable depends on the thermal insulation. Insulation prevents heat loss and gain between the inside and outside of a building. Thermal insulation should preferably be installed from the outside, given the advantages over installing it from the inside [63]. A poorly insulated building means higher heating costs in the winter because it consumes more energy, and there is an increased risk of condensation and cooling costs in the summer [5]. However, according to Moeller and Bauer [112], it is more difficult for occupants to quickly regulate their indoor environment in highly insulated buildings. This occurs because this type of building tends to produce thermal monotony and increase building inertia. Also, highly insulated buildings can lead the occupants to increase open windows to regulate temperatures and to reduce their clothing or establish other psychological or habitual adaptations to achieve comfort. In this way, energy efficiency improvements can be accompanied by undesirable adaptive behaviours, leading to energy performance gaps.

A building should be constructed considering the location's climatic conditions. Solar heat gains can be reduced through building façade orientation and glazing shading, proper insulation levels, high-performance windows, and considering the role of thermal mass [5]. In general, the materials and the architectural and construction characteristics of buildings have a decisive influence on indoor comfort conditions. For comfort performance, it is important to evaluate the occupants and their relationship to the interior systems and architecture and then evaluate the mechanical system of the building. The

reduction should address the highest priority and most cost-effective strategies for energy and then study renewable energy sources [39].

Factors that also affect the buildings' energy performance are the overall climate conditions, settlement and building geometry, thermal properties of the building envelope, energy systems efficiency, and occupant profiles [70]. Contemporary architecture with large, glazed areas and low thermal inertia sometimes overlaps with the proper bioclimatic design and construction of buildings. This provides a low adaptive capacity to the occupants, leading to the use of energy-consuming mechanical or electrical systems and less satisfaction [6] [7]. Considering the characteristics of the building that are pretended to become more energy efficient, it is possible to adopt measures for lower energy consumption, maintaining or even improving the occupants' comfort, well-being and satisfaction. Considering building operation and design, if it were possible to increase summer set-points and reduce excess cooling, energy would be saved, and occupant comfort and health would be improved. Suppose efficient and successful ways can be found to allow a broader range of building temperatures. In that case, the potential for energy savings is enormous [39].

In Portugal, the effective capture of solar energy is a primary factor, as it is considered to have a moderate climate. However, there is a significant difference between summer and winter. The indoor comfort offered to occupants and the consequent energy consumption and costs depend on the ability of a building to capture and retain solar radiation in winter and dissipate heat in summer. In winter, there is a greater need for energy. In summer, the smallest possible surface area is exposed to solar radiation. In such a climate area, the solar exposure of the surfaces to the east and west should be reduced because these are orientations that are irradiated mainly during the summer, and it is difficult to control the entry of radiation since it is made almost perpendicular to the windows. It is advisable to reduce the walls and windows facing north and increase those facing south, given the influence of winter. To the north, it is advisable to have rooms that don't need few openings to the outside because, in this orientation, great thermal losses originate through the glass during the cold season [5]. Again, it is essential to make the right choices regarding the materials, the type of construction, and the distribution of the rooms in the building itself.

Maximising daylight can provide a relevant decrease in energy used when considering factors such as heat gain and loss, glare control, and variations in daylight during seasons. Yet, electric lighting is required for some spaces and times of the day. So, the choice for LED is the better option since this technology has efficiencies exceeding traditional technology. This will help to reduce energy use if energy demand doesn't increase [48]. However, the light spectrum of LED is poor compared to other technologies, which may lead to a lower visual comfort level. To reduce the usage of artificial lighting, it is crucial to have a good lighting system to harvest the maximum amount of available sunlight. The literature recommends reviewing traditional and vernacular architecture to develop simple, effective lighting design strategies [12]. The use of window protection systems enables control of the entry of sunlight in summer and the penetration of sunlight in winter. Window protection systems could be shingles, canopies, awnings, venetian blinds, climbing plants and/or shrubs if they have deciduous foliage to allow solar radiation to enter in winter, and others [5]. When designing a lighting enhancement in a given space, it should be considered that materials and colours affect the sensation of light in an indoor environment. Light-optimising finishes that are less absorptive could result in lighting energy savings [48].

Outdoor air renews indoor oxygen and dilutes pollutants. However, increasing ventilation rates provides a challenge if it does not lead to increased energy use. Whether for naturally ventilating, providing air conditioning, or a mixed-mode system is complex and relates closely to thermal comfort. In appropriate climates, a mixed-mode system allows the optimal balance between occupants and energy use [48].

However, natural ventilation should be a priority whenever possible [5]. Note that opening windows for ventilation in an office building can cause problems related to outdoor noise and pollution. This can drive air conditioning use or mechanically ventilate the space [48].

Green roofs reduce energy demand for heating and cooling, improve indoor thermal comfort for the top floor, and positively impact the outdoor urban environment by reducing CO₂ emissions, mitigating the urban heat islands effect and air purification. However, Cirrincione et al. point out that previous studies have verified that green roofs are often not a cost-effective solution at the single-building level [68].

Wireless sensor technology enables sophisticated monitoring and logging of temperature, humidity and lighting. Digital technology is likely to become more incorporated into building structures, equipment, and even our clothing and person through wearable technology. However, despite these advances, one of the simplest innovations is not technology but encouraging occupants to dress suited to the climate [48].

In general, a low adaptive capacity of buildings and occupants is reflected in low energy efficiency levels, low satisfaction levels, comfort, well-being, and low productivity, particularly in office and service buildings [7]. The future buildings should be able to react and adapt themselves to immediate requirements such as weather, occupancy and function. For a balance between comfort and efficiency, it is essential to establish synergies between building design, building climate control, and occupant needs [27]. The prediction gap between the building's design and operation phases concerning energy consumption and comfort settings was more significant for low-energy buildings with more passive design features. As mentioned in this state of the art, occupants interact proactively with the indoor environment to achieve comfort, driving the prediction gaps [110].

It is pointed out that introducing energy conservation measures without considering the occupants' satisfaction can often be counter-productive since they will try to adapt their environment to obtain satisfying comfort conditions [20]. Also, optimal management of buildings' energy-consuming systems is crucial to minimize energy consumption while satisfying the occupants. Since building systems' operations depend on occupants' presence, the dynamic occupancy information is essential to reflect this dynamism and the random occupant behaviour. Therefore, occupancy-centred control strategies are required to enhance the buildings' energy management, remembering the importance of localized and customizable comfort controls to improve the occupants' satisfaction and productivity, as verified in Chapter 2.1 [113].

Attention must be paid to simplifying the problem of reducing energy demand, as decoupling energy consumption from economic growth is challenging [27]. It is important to emphasize that some building energy efficiency policies that focus on efficiency improvement can lead to a "rebound effect", especially for economies with quick social and economic development [53] [114] [115]. In this study, the rebound effect is the phenomenon of increased energy usage following the adoption of energy-efficient products [114] and/or cost falls [116]. Efficiency improvement pretends to reduce energy needs, but looking at global energy consumption, what is happening contradicts this [115]. Even though cost-reducing energy efficiency might improve comfort and well-being, the possibility of a rebound effect means that energy consumption will not reduce significantly in the long term [116]. According to Rajabi [115], the rebound studies make clear that considering only efficiency improvement is not enough to mitigate energy consumption and should be followed by proper policies. When implementing an energy-efficiency policy targeting consumers, policymakers should consider the consumer response to this measure and its consequences [114].

Lastly, default occupant behaviour assumptions happen in building energy regulation and can cause the wrong choice of the building envelope, technologies, system design and operation. Understanding the

real occupancy patterns and behaviours would contribute to a proper choice close to real occupant behaviour and less with the current choices (deviated from real occupant behaviour) in building energy policies [53]. According to Hu et al. [53], misunderstanding the stochastic, diversity and interdisciplinary occupant behaviour is problematic in building energy policies' development, implementation, monitoring and evaluation.

2.3. Legislation and regulation

2.3.1. Context

In Portugal, the concern with legislating both the energy efficiency of buildings and the comfort they can and should provide to the occupants has been a concern over the last years. The evolution of legislation and the requirements being demanded have occurred progressively. Gradually, they have become more exigent and included more building types and construction phases (project and/or small/extensive renovation). This evolution process follows European and world trends.

The Regulation of the Thermal Behaviour Characteristics of Buildings (Regulamento das Características de Comportamento Térmico dos Edifícios (RCCTE)) [117], approved in 1990 by Decree-Law No. 40/90, was the first legal instrument that imposed in Portugal requirements on the design of new buildings and major renovations to ensure the satisfaction of the conditions of thermal comfort in buildings without excessive energy needs in winter and summer. It was also aimed to ensure the minimisation of negative effects on the durability of building materials and indoor air quality.

In 2006, a new wave of regulations was introduced regarding the design of buildings. This regulation followed the Energy Performance of Buildings Directive (EPBD) recast in 2002 (Directive 2002/91/EC), which was developed from the need to reduce CO₂ emissions associated with the energy consumption of buildings in the EU and has been the main instrument for promoting energy efficiency in this area. First, it introduced the second version of the RCCTE (DL 80/2006) [118], which had a greater rigour in terms of consumption and demand on the thermal quality of the building envelope and imposed mandatory air renewal rates for air quality control. Then, a new decree-law (No. 79/2006) called Regulation of Energy and Air Conditioning Systems of Buildings (RSECE) [119] established the conditions for the design of new air conditioning systems (thermal comfort, renovation, treatment and indoor air quality), energy efficiency through the appropriate choice of equipment, the terms of design, installation and establishment of the maintenance conditions of air conditioning systems and the monitoring conditions. Finally, the Decree-Law 78/2006 approved the National System of Energy Certification and Indoor Air Quality in Buildings and partially transposed Directive No. 2002/91/EC on the energy performance of buildings into national law.

With this revision of the legislation, it became mandatory to implement an energy certification system to certify the energy performance in buildings, inform the citizens about the thermal quality of buildings, and identify the applicable corrective or energy performance improvement measures. It also identifies the main types of technical building systems, being subject to minimum energy efficiency standards, air conditioning, domestic hot water preparation, lighting, renewable energy use and energy management systems. Natural ventilation is now privileged to the detriment of mechanical ventilation equipment, and the maintenance of the minimum values of new airflow per space and the protection thresholds for concentrations of indoor air pollutants have also become relevant. This direction of the legislation was intended to safeguard the levels of health protection and well-being of the occupants of the buildings.

In 2010, there was a new recast of the EPDB (Directive 2010/31/EU), which induced new changes in 2013. The new regulation introduced the differentiation in the assessment of residential and commercial and service buildings, the concept of passive building and hybrid building, and also specifying

requirements for air quality and lighting. The imposition of a built stock progressively composed of buildings with almost zero energy needs (nZEB) meant that national legislation established those new buildings designed and built from January 2021 onwards had to comply with this condition of being nZEB. nZEBs are buildings that, without compromising the thermal comfort of their occupants and the quality of indoor air, have reduced energy needs, which are mostly met using energy from renewable sources on-site, thus leading to buildings with high energy performance.

In 2018, Directive (EU) 2018/844 amends Directive 2010/31/EU on the energy performance of buildings (EPBD) and Directive 2012/27/EU on energy efficiency. This revision aimed to increase the energy performance of buildings through measures in the building envelope, technical elements and systems and the passive elements that are part of passive techniques that aim to reduce energy needs for heating/cooling, lighting and ventilation. These measures allow for an improvement in thermal and visual comfort. Nature-based solutions such as green roofs and walls are also measures indicated in the Directive [90] [91].

Decree-Law No. 101-D/2020 [120] transposed Directive 2018/844 and updated the methodology for calculating energy performance, the criteria for energy certification of buildings and the obligations of the intervening entities. This decree-law is complemented by other ordinances and orders published in 2021, namely, Order No. 6476-H/2021 [121] approving the Manual of the Energy Certification System for Buildings (SCE Manual)[122], which brings the calculation methodologies used by experts closer to the normative references defined in the EPBD. The SCE Manual [122] establishes the calculation methodology to assess the energy performance of buildings covered by the building energy certification (SCE) system. This assessment has different methods depending on the type of building, i.e. residential or commercial and services. The evaluation of the energy performance of buildings results in the determination of an energy class as a function of the ratio of primary energy consumption for regulated uses, considering the contribution of renewable energy sources between the planned and reference buildings. To this end, energy needs are determined by considering reference conditions to ensure indoor air quality, thermal comfort, and the health of spaces. In other countries, other standards and directives are used to assess the energy performance of buildings and determine energy needs.

As mentioned before, Portugal followed in the footsteps of other countries regarding energy efficiency in buildings and the comfort they provide for occupants. Many European and American standards discuss these issues and set recommended comfort values. In 1977, the International Energy Agency (IEA) recognised the importance of energy use in buildings by establishing an Energy in Buildings and Communities (EBC) Implementing Agreement whose aim is to investigate the energy efficiency of buildings and disseminate it internationally. The tasks are carried out through a series of ‘Annexes’ to the EBC Implementing Agreement [123]. Annex 66 was important in formalising experimental research methods, modelling and model validation, and occupant simulation [124]. However, there was a need to answer questions about thermal comfort, occupant behaviour and the minimal penetration of advanced occupant modelling in practice. Annex 79 explores these issues, providing new insight into occupant behaviour related to comfort, building interactions, and the impact on energy performance. This Annex is ongoing from 2018 to 2023 [60].

Other organisations and associations focus more on a particular comfort concept and/or parameter. For example, ASHRAE is an international association of HVAC (Heating, Ventilation and Air Conditioning) engineers with members from several countries that aims to publish standards and technical guidelines and offer educational information, courses, seminars, professional guidance and publications related to the HVAC sector. ASHRAE standards are developed so professionals in this sector can access up-to-date procedures when testing, installing and designing equipment.

ISO is an independent, non-governmental international organization that, through its members, develops International Standards that support innovation and provide solutions to global challenges. It should be mentioned that the ISO Standards served as a reference for the SCE Manual, both for developing calculation methods and defining requirements. Several standards of comfort and indoor environment are in practice. ISO 17772-1 [125] specifies requirements and how to establish parameters for building system design and energy performance calculations for the thermal environment, indoor air quality, lighting and acoustics. This ISO also specifies how to establish parameters for building system design and energy performance calculations. Other standards indicate how to calculate energy performance in buildings. European standards define lighting requirements for indoor spaces, such as EN 12464-1 [126] and EN 12193 [127]. EN 15251 [87] specifies the indoor environmental parameters that impact the energy performance of buildings and the methods for long-term evaluation of the indoor environment obtained from calculations or measurements. Other standards had guidelines about sound insulation and absorption measurement and simulation procedures, such as ISO 10140 [128], ISO 717 [129], ISO 3382 and ISO 12354 series [130]. According to the type of building, some recommended values can be found in the Guidelines for indoor air quality for selected air pollutants. EN 16798-3 [131] provides performance requirements for non-residential buildings. ASHRAE 62.1 [132] and 62.2 [133] and CR 1752 [134] describe general ventilation requirements for acceptable indoor air quality.

Nowadays, other building certification systems are sought by the industry that go beyond energy performance. These systems evaluate the level of sustainability of a building in its environmental, social and economic dimensions and in an integrated manner to promote and encourage sustainable building practices. These certificates have differences, but they generally favour sustainability, comfort, and well-being. The BREEAM, LEED, and WEL certification systems are the most relevant nowadays since they explore several concepts and parameters such as thermal comfort, energy efficiency, resource management, transportation, and others. These certification systems are widely spread worldwide, and it is possible to find certified buildings in Portugal. There are other certifications, such as CASBEE, GREENGUARD, LiderA, and many others. This type of certification focused on the sustainability of buildings can be a way to know and compare the buildings' quality, sustainability, and comfort as long as it is accredited and evaluated from the initial project phase to the final one, passing through the intermediate processes. The fact that these certification schemes introduce new credits and concepts allows the availability of other practical guidelines for all those who wish to promote well-being in their projects [45].

From the above mentioned, it is clear that several standards, guides and organizations explore comfort and well-being. They indicate reference values and measures to improve the comfort and well-being of people in buildings. These and other standards can be consulted to learn more about comfort parameters, how they can be assessed and monitored, and the acceptable values for comfort, well-being and safety. There has been an evolution and introduction of concepts such as comfort in the revisions of directives and standards related to the energy efficiency of buildings. Although there is a greater concern with ensuring the comfort of building occupants, other relevant aspects are omitted and require a multidisciplinary approach. When choosing measures to improve energy efficiency, the impact of each measure on occupant comfort is also not explicit.

2.3.2. Comfort requirements

Currently, some standards and directives establish requirements, i.e., recommended and/or limit values for some comfort parameters. Since this study takes place in Portugal, and the buildings being studied are residential, below are some requirements that impact the indicators of comfort, energy performance, and indoor air quality that the Portuguese legislation indicates. However, it is important to emphasise

that there are other ranges of comfort and requirements that can be considered that are present in other standards, legislation, studies and articles.

According to the SCE Manual [122], energy balances in residential buildings are determined under nominal conditions, considering an indoor temperature of 18°C in the heating and 25°C in the cooling seasons. For relative humidity values inside residential buildings, no Portuguese legislation has been found. However, Decree-Law no. 243/86 [135] states that for commercial, office and service establishments the relative humidity should be between 50% and 70%.

Ordinance 138-G/2021 [136] determines the requirements related to indoor air quality and is aimed at commercial and service buildings in operation. The protection threshold for CO₂ is 1250 ppmv. Residential buildings must guarantee an hourly air renewal rate of 0.5, in accordance with Ordinance 138-I/2021 [137]. This Ordinance and the SCE Manual indicate various installed power density values for different spaces. There are other requirements regarding the indoor environment of residential buildings that can be consulted in Portuguese and international legislation and standards.

2.4.Evaluation methods

2.4.1. Comfort and well-being assessment methods

As previously mentioned, evaluating comfort and well-being includes several physical parameters: thermal comfort, indoor air quality, lighting, noise, spatial and functional characteristics, personal aspects and building characteristics (construction type, systems, among others). The interactions between the physical parameters of the building and the occupants' type of use make this assessment even more complex.

Measuring the physical comfort and well-being parameters described above is complicated by the range of components. Some are easier, like air temperature and humidity, but others are not. Practice guides and national and international standards provide minimum and maximum acceptable levels or best practices. Also, environmental rating tools (LEED, BREAM, and others) assign credits relating to the indoor environment. However, taking care of best practices and having gone through a rating process during construction or fit-out may not necessarily help to measure the elements of indoor environment quality. It is essential to identify the physical environment measures that can be carried out by occupants (or indeed owners/managers) and which require experts with specialist equipment [48]. In this way, comfort, well-being, productivity, preferences and behaviour of the occupants can be known through post-occupancy evaluation [19][20][21][59][138] combined with sensor measurements [12][15][22][23][139], control devices, mobile devices and wearable devices [24].

Post-occupancy evaluation (POE) evaluates buildings after being constructed and occupied [103] [71]. This evaluation aims to understand how the building functions, whether it meets the occupants' needs, whether it is satisfactory from the occupant's perspective and whether the comfort goals are achieved [12] [47]. It is a general approach to obtain feedback about a building's performance in use, including energy performance, indoor environment quality, occupants' satisfaction, productivity, and others [138]. POE also allows the discovery of solutions to detected problems, highlights what should be repeated and avoided, and disseminates design guidelines to improve future projects [71]. In summary, there are POE for direct and indirect purposes. The direct purpose can be to evaluate design, occupants, energy performance, IEQ, and/or facility. The indirect purpose can identify issues, inform future projects, improve the POE method, impact standards/criteria, evaluate technology and/or validate models [138].

This evaluation uses three sources for data collection: occupant feedback through questionnaires and interviews (subjective evaluation), billing and measurement collection (objective and indirect

evaluation), and measurement of indoor environmental conditions [12] [140] [139]. It may also include energy and water performance assessments and indoor environmental quality [59]. According to Peixian Li et al. [138], there are subjective methods (occupant surveys, interviews and walkthroughs) and physical measurements (IEQ in-situ measurements of thermal condition, lighting, IAQ and acoustics, energy and water assessed via meters, bills and/or others).

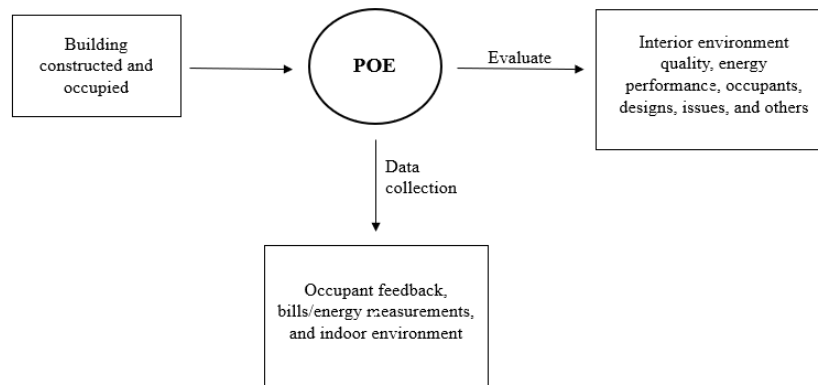


Figure 2.1 - Post-occupancy evaluation scheme

Nowadays, there are many systematic methodologies of POE, namely Post-Occupancy Review of Building Engineering (PROBE), Center for the Built Environment (CBE), Building Performance Evaluation (BPE) toolkit, Cost-effective Open-Plan Environments (COPE), Health Optimization Protocol for Energy-efficient buildings (HOPE) and many others that Peixian Li presents and compares [138].

Interviews and surveys provide an understanding of participants' experiences and explanations to pair with quantitative data [141]. This assessment provides building managers and owners information to identify specific problems, improve them, and provide feedback and knowledge on planning, design, construction, and operation of future facilities for designers/architects to improve future buildings [59] [142]. Besides applying surveys, observations of all building features contribute to evaluating comfort (including heater types, room orientation, presence of curtains/blinds, and others) [141].

2.4.1.1. Surveys, questionnaires and interviews

Survey refers to the complete data collection process, which can include the questions and the process of data collecting, aggregating and analysing the responses. Is a broader term that describes content, method and analysis [143]. A survey can involve different methods, such as interviews, observations and questionnaires and is used to remotely obtain information by sending a questionnaire to multiple people [12]. Interviews and questionnaires are methods of gathering information by asking occupants questions [12] [20] [40]. Interviews can include structured or semi-structured interviews and focus group meetings with occupants and sometimes with experts [138]. Interviews are used in a detailed study where the sample volume is very low, while surveys collect information remotely from multiple participants, in this case, indoor building occupants. These evaluation methods can be done using "paper" or online. Sometimes, surveys cannot be administered in all cases since they require occupants' involvement and some of their time. It is crucial to have a well-planned communication approach and to use an optimized survey regarding duration and content [86].

Surveys are widely used to assess occupants' comfort and satisfaction perception with their environment in domestic and non-domestic buildings [94] [144]. Such surveys have become popular for the associations between a building's physical and organisational characteristics and the occupants' self-

reported experiences [144]. According to Roa et al. [59], there are two main types of surveys: general and comprehensive assessments and ‘right-now’ surveys (momentary assessments).

Depending on the type of study, long-term or right-now evaluations can be applied [22] [138]. Point-in-time or right-now surveys should be required during the representative time of the building’s occupancy. This type of survey can correlate thermal comfort with environmental factors such as metabolic rate, clothing, air temperature, humidity and others [86].

It may also be relevant to conduct the survey during the two periods of the year when the environmental conditions are more disparate to ascertain the level of satisfaction with the indoor environment during the two seasons (summer and winter) [16] [77] [78] [86] [92]. Other authors apply surveys on weekdays during working hours. Each subject receives a maximum of three surveys per day, at least 2 h apart, for about two months [59]. Other experiences occur over a month [23] or even 4 years with five different survey periods and occupants responding to a questionnaire six times a day in the living rooms and twice in the bedroom [89]. The first thermal satisfaction survey (long-term) in a new building may be performed approximately six months after occupancy [86].

Data collection through surveys can be based on a repeated application of the same survey on a schedule/calendar basis, based on a time interval, or manual triggers. These survey-distributing methods lack a feedback mechanism, resulting in responses that do not add new information to the measurement set. Suppose environmental conditions are oversampled, or the research objectives don't verify the previous study's outcomes. Subjects are unnecessarily disturbed, leading to survey fatigue and unbalanced or incomplete datasets [59]. The challenges and shortcomings of the currently used methods cause a need for more advanced and robust survey tools. They should have features such as the ability to store and retrieve complete responses from occupants and specific environmental conditions when the survey was taken and completed. The ability to distribute the questionnaires to occupants under specific environmental conditions or the full range of environmental conditions defined by the investigator should also be a feature. These two design features require continuous real-time indoor environmental quality measurements, a survey distribution and implementation tracking system, target conditions, and recording when surveys are sent and completed. To design this tool, the authors used Python to import the survey data from a platform that supports a download [59].

In practice, achieving the environmental characteristics desired by the researcher can be challenging because respondents may not answer the survey immediately upon request or within the range of environmental conditions desired and/or if researchers have no control over the environment to which respondents are exposed during studies there is a likelihood of surveying in average rather than more extreme conditions [59].

It is necessary to have adequate data (quantity and quality) for a reliable behavioural model to predict the future reaction of occupants. The building occupants must regularly respond to a survey to collect feedback to access the data. This could lead to an uncomfortable feeling, and to address this issue, there are three major solutions [93]:

- Increase the period of applying the survey (occupants do not feel dissatisfied with answering questions in a short period);
- Collect feedback during different seasons and climates (long-term data collection is not a synonym for data quality and consequently valuable data for developing advanced controls);
- Simplify the model and ignore less significant parameters.

The surveys can be used to study the impact of an intervention in a building (design change, renovation or new workplace) [142][145]. The first survey is implemented when occupants are in the old or pre-renovated building/space. Another survey can be implemented six months after moving into the new

building/space [142]. Surveys can also be applied to understand if environmental rating tools such as LEED, BREEAM, WELL, and CASBEE contribute to greater workplace satisfaction and comfort [54]. The surveys can be useful in measuring how effectively a building promotes and protects its occupants' health and comfort needs. These surveys also provide feedback, and having an interest in the comfort and well-being of the occupants can positively impact the mood of the occupants [146].

Interviews and surveys can include personal questions since they can affect the comfort and well-being of the occupants. Typically, the questions are age, gender [12] [59] [78] [92], nationality [50], type of work performed in the study room/building, the number of weekly working hours [77], and socioeconomic conditions, among other parameters [52]. This data can be requested at the beginning or end of the survey. However, answering at the end may help avoid conditional answers [75].

Other questions should be present in the survey to allow the comfort and well-being parameters evaluation addressed in Chapter 2.1 and the factors that had influence. It can also include questions about support activities with which the household heads had been involved, comfort experiences, energy use, trade-offs, effects of discomfort and energy inefficiency, household characteristics, and fundamental changes in the household [141]. It can also be asked about the activity level in the last 15-20 min, the clothing set, and the use of fans and windows [59]. Sometimes, it may be possible to include open-ended questions in the survey to allow participants to add their comments [77]. In other studies, the adaptive behaviour of the occupants is observed, namely the opening of windows and the use of HVAC [50] [78].

Different surveys that evaluate satisfaction, comfort and well-being are available, which can be applied to residential buildings and/or commercial and service buildings. Several building standards and surveys/questionnaires focus on energy consumption and occupant comfort [12]. These surveys developed by organizations and/or presented in norms, scientific articles and articles that evaluate comfort and well-being are presented in Table 2.1.

Table 2.1 - Surveys/questionnaires consulted for the preparation of the study's survey

	REF	Application
Standards		
ASHRAE 55-2017	[86]	• Developed in the USA. • Thermal comfort evaluation • Point-in-time survey and thermal satisfaction survey • Point-in-time surveys are used to evaluate the thermal sensations of occupants at a single point in time. Satisfaction surveys evaluate the thermal comfort response of the building occupants in a certain period • Use physical measurements along with survey instruments
EN 15251	[87]	• Provides examples of questions occupants can be asked about temperature and indoor air quality
Organizations		
CBE Survey	[14] [54] [142] [147] [148]	• Developed in the Center for the Built Environment (CBE) at the University of California, Berkeley, in 2000 • Occupant responses were collected online and recorded in a secure Microsoft SQL Server 2000 database • Comprised a core survey and an optional survey module • Core questions: occupant satisfaction with the office layout, office furnishings, thermal comfort, indoor air quality, lighting, acoustics, and building cleanliness and maintenance • Optional modules: wayfinding, safety and security, operable windows, shading systems, floor diffusers, washrooms, and others • Survey: 7-point scale to gauge satisfaction with the survey areas with a neutral midpoint • Core survey: 5-12 minutes to complete • Customized modules adding the core survey: 20 minutes • Use physical measurements along with a survey (air temperature, radiant temperature, air speed and humidity) • WELL certification uses this survey in buildings with 10 or more occupants. The survey allows occupants to provide feedback and help develop the WELL Building Standard

Table 2.1 - Surveys/questionnaires consulted for the preparation of the study's survey (cont.)

	REF	• Application
Building Use Studies (BUS) Methodology	[144][148]	• A BUS Methodology Partner guides the survey process and advises on the key decisions • The method was developed in the 1980s in the Office Environment Survey (OES). OES was modified for use in the Post-occupancy Review of Buildings and their Engineering (PROBE) • Internet or paper-based surveys • Questionnaire: 5-15 minutes to complete • Up to 45 quantitative and qualitative questions: thermal comfort and ventilation, lighting and noise, personal control, space, design and image. • Commercial building occupants are asked about productivity and how they travel to the building • Domestic building occupants are asked about their lifestyle and environmental issues • Survey: 7-point Likert scale
World Green Building Council	[48]	• This is a survey proposal. Organisations should select the questions to suit their objectives • Proposal design survey developed in World Green Building Council • List of possible organisation survey questions, divided into the following groups: general information, building/company general, the role of sustainability, building fabric and systems, office design/layout, location and amenities, the workplace and me, employer: employee engagement, post refurbishment/post-move section • List of possible tenants survey questions, divided into the following groups: indoor air quality, thermal comfort, lighting, biophilia, design including active design, amenities and location, and post-occupancy evaluation • Responses anonymized • Scale responses: 1 is a very negative response (strongly disagree/definitely not/very unsatisfactory), 3 is a neutral or a no opinion, and 5 is a very positive (strongly agree/definitely/very satisfactory) • Open-ended questions to respondents provide other information not covered in the survey (at the end of the survey or in each section) • Survey duration no more than 15 minutes

Today, web-based tools like SurveyMonkey™, Qualtrics™, and Google Forms™ have reduced the technological barriers to creating, distributing, and analysing digital surveys [59]. SurveyMonkey and Qualtrics are one of the oldest online survey tools available. These two tools aren't considered direct competitors because they have two different target markets. SurveyMonkey [149] is the top choice for small to medium-sized businesses and communities because they see it as an easy tool. Qualtrics [150] focuses on developing advanced tools for enterprise markets willing to invest time training users to gather data using a premium product. SurveyMonkey permits the export of data in different formats such as PDF, XLS, CSV, PPT for summary data (results by questions) and SPSS for response data (how each respondent answered). Qualtrics have other file formats to export data. CSV, TSV, Excel, XML, SPSS, Google Drive and others. Both tools have free and paid plans.

Regarding the number of responses needed when implementing a survey, according to ASHRAE 55 [86], surveys should be requested from the entire or a representative sample of the occupancy. If more than 45 occupants are asked, the response rate should exceed 35% and if the number of requested occupants is between 20 and 45, at least 15 must respond. For fewer than 20 requested occupants, 80% must respond [86].

The questions asked in the survey should respond with the possibility for the occupants to select the best that suits them, and the use of a scale is applicable. From Table 2.1, it can be seen that these scales are applied in different standards and organizations.

Some literature suggests the use of ratings using a 5 or 7-point Likert scale, with 1 being "very dissatisfied" and 5/7 being "very satisfied" [77] [23] [103] [95]. For productivity, a 5-point discrete scale can be used [59]. A 4-point scale can be used for satisfaction evaluation as 1) dissatisfied, 2) slightly satisfied, 3) satisfied, and 4) very satisfied. The need to integrate an intermediate or neutral point is alerted [52]. Other literature suggests a Pleasure-Arousal-Dominance questionnaire rating the emotional

states of the occupants using a non-verbal pictorial technique. The rating of the parameters ranges from 1 to 9, where for the pleasure parameter, grade 1 means unpleasant and grade 9 is very pleasant. For the arousal parameter grade, 1 means sleepy, and 9 is very excited. For the dominance parameter, grade 1 means very dominant, and grade 9 means not dominant [109]. The Sant'Anna et al. study [75], used a 6-points Likert-type scale and Visual Analogue Scale that used 6 points as well.

The European Standard EN 15251 [87] indicates that the direct subjective evaluation of the occupants, that is, questionnaires, can be used to evaluate the indoor environment [87]. However, the standard doesn't explain how to combine different environmental parameters into one indicator to classify the overall indoor environmental conditions.

Regarding thermal comfort, responses may include thermal sensation, thermal comfort and thermal acceptability [23] [78] [92]. Thermal sensation refers to the feeling of heat and cold, and thermal comfort and thermal acceptability reflect how people evaluate the thermal environment [92]. For thermal comfort, there are several rating scales. ISO 10551 uses an extended 9-point scale for rating thermal sensation: "very cold" (-4), "cold" (-3), "cool" (-2), "slightly cool" (-1), "neutral" (0), "slightly warm" (1), "warm" (2), "hot" (3), and "very hot" (4) [151]. ASHRAE and EN 15251 use a 7-point scale: cold, cool, slightly cool, neutral, slightly warm, warm, and hot [86] [87]. For rating thermal comfort, a 4-point scale can be used with the grades of "comfortable" (1), "slightly uncomfortable" (2), "uncomfortable" (3), and "very uncomfortable" (4). Other studies use only comfortable and uncomfortable [78]. In some studies, occupants are asked to rate their thermal preference, selecting whether they prefer to be cooler, warmer, or unchanged [59] [78] [91].

The thermal acceptability rating contains the acceptable grades of "just acceptable" and "clearly acceptable" and the unacceptable grades of "just unacceptable" and "clearly unacceptable" [87] [92]. Other authors used a 7-point scale from clearly not acceptable (3) to just unacceptable (0.1) and from just acceptable (+0.1) to clearly acceptable (+3), whereby the subjects were required to distinguish between acceptable and unacceptable [59]. ASHRAE uses a continuous or seven-point scale ending with the choices "very unacceptable" and "very acceptable" [86]. Other studies use only acceptable and unacceptable [78] [91].

The standard EN 15251 [87] proposes a subjective scale of 6 points to evaluate the perceived odour intensity by the building occupants: "no odour", "weak odour", "moderate odour", "strong odour", "very strong odour", and "overpowering odour" [87]. The Positive and Negative Affect Schedule (PANAS) is a scale that describes feelings and emotions with 20 items (10 positive and 10 negative affect), such as interested, enthusiastic, attentive, and others. When using the PANAS, participants measure their feelings and respond via a questionnaire. A 5-point Likert scale is then used for scoring (1- Very Slightly or Not at All, 2- A Little, 3- Moderately, 4- Quite a Bit, 5- Extremely). Additional versions of the PANAS scale have been created: PANAS-C (for children), PANAS-SF (more concise), I-PANAS-SF (international version) and PANAS-X (more refined version) [152].

There are many questionnaires, surveys and interviews besides the ones presented, which are described and available in standards, studies and organisations. These have a huge variety in the type of questions, the scales used, the frequency of implementation, the parameters studied and other aspects. In Appendix A, there is a Table that summarizes consulted literature studies: variables and parameters of comfort and well-being, methods of measuring and obtaining data, and the main conclusions. In general, it can be seen that the application of a survey/questionnaire is the most used method to obtain feedback from occupants. However, how it is implemented, size, type of questions, evaluation scale and periodicity in which it is implemented varies significantly according to the kind of study.

2.4.1.2. Devices and sensors

Devices and sensors are used to measure indoor environmental conditions. In some cases, they are already integrated into buildings, as they are becoming more intelligent and adaptable, using wireless data collection devices, making it easier to monitor, collect and analyse the collected data [12]. In other cases, sensors are used and placed in the spaces to be studied. These sensors are programmed, and all the recorded data is exported at the end of the experimental campaign. Wearable devices or body-worn devices can also be used. However, the use acceptance of these devices is highly context-dependent [153].

Measuring the indoor environmental conditions of the building can be done with many types of sensors. Usually, is used temperature sensors and/or humidity and temperature sensors [16] [59] [78] [89] [145] and sensors that detect different indoor gases [12] [77] [104][138]. Sensors for lighting (illuminance, luminance, others) and acoustics (sound level meter, reverberation test) can also be used [138]. Other studies also collect different temperatures, such as radiant zone slab and zone dry-bulb, as measured through the thermostat and outdoor air [59]. Collecting the internal and external temperatures can assess the difference between inside and outside temperatures. Temperature data can also determine time spent in thermally comfortable conditions inside the building (comfort zone) [141]. The external temperature can be obtained using data from a meteorological station near the study [78] [89] or using proper sensors.

The period of measurements was typically every 5 minutes [12] [77] [140]. ASHRAE 55 [86] indicates that measurement intervals for air temperature, mean radiant temperature, and humidity shall be 5 minutes or less, and for air speed shall be 3 minutes or less. This standard also mentioned the measuring instrumentation's requirements (range and accuracy) [86]. It is also important to say that the sensors/loggers should be sited away from heat sources and direct sunlight [74] [154]. In the case of office buildings, studies suggest that the measurement of different indoor environment parameters by the sensors should be performed near the occupants' desks [59]. It is also indicated that according to the building's characteristics, data should be collected on each floor and for each orientation [77].

According to ASHRAE 55 [86], thermal environment measurements in the floor plan should be made at a representative sample of locations where the occupants spend most of their time. Suppose occupancy distribution cannot be observed or estimated. In that case, the measurement locations shall include the centre of the room/space and 1 m inward from the centre of each room's walls. Suppose the case is exterior walls with windows. Thus, the measurement location shall be 1 m inward from the centre of the largest window. It is also mentioned that measurements can be taken in places with the most extreme thermal parameter values (e.g., potentially occupied areas near windows, diffuser outlets, corners, and entries). Suppose it is pretended to measure air temperature and average air speed. The values should be measured at 0.1, 0.6, and 1.1 m above the floor for seated occupants at the locations specified above and for standing occupants at 0.1, 1.1, and 1.7 m. How to measure operative temperature, floor temperature, and radiant temperature is also explained in ASHRAE 55 [86].

Watson and Watson study [141], a 15-month data collection, took place where the measurements were temperature and humidity at 30-minute intervals and electricity consumed by heating appliances. The temperature and humidity loggers were installed in every house. They collected data by putting one logger in the main living area, one in an important bedroom, and the other externally in a sheltered space. Setting another logger in another room depends on the house's layout. Additional data were collected, including housing observations of physical features that affect energy use and comfort, structured survey responses and semi-structured interview responses.

Stoppa & Touchie [145] studied two contemporary high-rise condominium buildings (59 suites) to characterize the relationship between occupant comfort and behaviours and HVAC operation.

Thermostat data (relative humidity and air temperature) were collected during 14 months at 5-minute intervals. They are installed in the suite's living area, set back from the façade and approximately 1.4 m above the floor. Additionally, participants completed an initial survey to collect their perceptions and understand the behaviour that they have to control the indoor conditions. Two interim surveys were conducted during the heating and cooling seasons during the monitoring period. These surveys asked occupants to report their perceived thermal comfort over the previous 24 hours. Upon monitoring period completion, a final survey was administered to understand occupant interventions used to mitigate thermal discomfort.

A Japanese dwellings thermal comfort study [89] performed measurements from the indoor thermal conditions in 120 dwellings during 4 years. For this, it is using data loggers that measure temperature and relative humidity at 10-minute intervals. The measurements occur in the living rooms and in the bedrooms. The occupants must also respond to a survey.

A nursing home study [91] performed the environmental measurements in the common areas such as the living, dining, therapy and gym-physiotherapy room. This study has an experimental campaign over three days during June, July, and August 2021, recording every 15 s between 15 and 60 min. The equipment was located in a central point of each room and 1.5 m above the ground. A nZEB houses study in Belgium [74] recorded air temperatures every 10 min in the living rooms and in the main bedrooms of each house for one year. Sensors were placed on top of the furniture at a minimal height of 80 cm, away from windows, to avoid direct solar radiation and away from other internal heat sources.

As described above, when studies carried out in residential buildings require the use of sensors, their location is not always the same. Can be simultaneous in the main living area, in an important bedroom, in a sheltered space and in another room, depending on the house's layout [141] or only in the living area [145], or yet in the living rooms and main bedrooms [74] [89] [154].

As mentioned in data collection from surveys/questionnaires (Chapter 2.4.1.1), data collection from sensors can also integrate different periods of the year when environmental conditions are more extreme (summer and winter). This depends on the type of study. ASHRAE 55 [86] indicates that measurement periods should be two hours or more and represent a total occupied hours sample in the selected period for evaluation or during periods determined to be the critical hours of anticipated occupancy. The European Standard EN 15251 [87] provides information on measuring the different comfort parameters and indicates other standards that provide information. Within many indications, it is described that to measure the thermal environment, the measurements should be done under representative weather conditions of cold and warm seasons, and the measurement period should be representative (e.g. 10 days). To measure the indoor air quality, namely the CO₂, this standard indicates that measurements should be made where the occupants spend most of their time.

There are more devices and sensors and methods for acquiring certain parameters values of the indoor environment than those described above. Data acquisition methods are often described in standards and studies. In Appendix A, the Table summarizes the variables and parameters of comfort and well-being of consulted literature studies, the methods of measuring and obtaining data, and the main conclusions.

2.4.2. Buildings energy performance assessment methods

The energy performance of buildings can be evaluated through the analysis of the energy certificate or in a detailed audit by taking energy measurements and collecting the characteristics of the building envelope and equipment. Consolidated regulatory methods exist for this assessment [36][37]. Still, the relationship between the energy efficiency of buildings and comfort and well-being in its various aspects

needs detailed studies [27]. Energy efficiency measures the amount of energy output for certain energy inputs and is closely related to technological advancement [27].

Building energy analysis simulation software such as TRNSYS [155] and EnergyPlus [113] using DesignBuilder to do the geometry [70] [109] [111] can be used during building planning and design phases before the building construction. This software calculates overall energy consumption, HVAC design, operation scheduling, lighting information, and others based on detailed building physical properties, occupancy schedule, geographical conditions, type of building and climatic parameters. However, the data needed for the simulation are often difficult to obtain [108]. Energy consumption can be measured using a plug-in electricity sensor on every heating device and/or a current clamp sensor placed on each circuit in the electrical meter board [141].

In buildings sustainability certification [29] (energy certification established by each country, LEED, BREEAM, and others), the evaluation is generally focused on the performance of the building, being less considered the evaluation of the comfort conditions, behaviour and feedback from the occupants [30][31][32]. On the other hand, certification focused on well-being, health, productivity, and indoor environmental quality (WELL) considers the building's characteristics, takes measurements and performs post-occupancy evaluation, considering less the energy performance of buildings [29][33]. Directive (EU) 2018/844 requires energy and comfort analysis [34] and as explained in Chapter 2.3.1 Decree-Law No. 101-D/2020 transposed these Directive and updated the methodology for calculating energy performance, the criteria for energy certification of buildings and the obligations of the intervening entities. This decree-law is complemented by other ordinances and orders, namely, Order No. 6476-H/2021 approving the SCE Manual that establishes the calculation methodology to assess the energy performance of buildings covered by the building energy certification system. There are other standards on energy performance in buildings but in Portugal this is the methodology applied. The energy certificate for buildings in Portugal provides an assessment of the energy performance of buildings and the identification of improvement measures for the energy class. Still, it does not include an assessment of the well-being and the impact of the "intelligence" of the building [156] for connection to energy grids and communities [157][158][159].

Energy use is taken as the most reliable indicator of the success of sustainable building design implementation. Rating systems for newly constructed high-performance buildings are based on certification in predicted energy performance acquired through simulation tools based on the proposed design. However, there is a gap between actual and predicted (simulated) energy consumption [20] [27]. This gap is influenced by occupants, technology, maintenance and management [27]. Theoretical/predicted energy consumption calculations ignore the energy expenditure determined by the occupant's lifestyle and behaviour. Actual energy consumption is obtained from the building's final energy bills and meters that reflect the consumption of all appliances, technologies, and behaviour [26]. In order to reduce the gap between the predicted and actual performance of buildings and to improve thermal comfort and buildings' energy efficiency, it is important to consider real, dominant occupancy patterns when evaluating the risks of overheating [111]. An appropriate occupant behaviour modelling is needed in building performance simulation. The Knowledge Discovery in Database (KDD) method is suitable for successful occupant behaviour profile extraction. KDD is a partially automated process of identifying valid, useful, and ultimately understandable patterns in data. It involves six steps: selection, cleaning and pre-processing, transformation, mining, interpretation and evaluation and extraction [155].

Knowing that the occupants' behaviour influences energy consumption and that lasting changes in occupant behaviour are challenging to achieve, new ways to foster energy efficiency have emerged. Technologies such as smart meters, dashboards, and mobile phone applications are available to measure,

store, and display energy information. They provide data that allows consumers to make informed and good choices [20]. Since occupancy-related information is recognized as an influential factor in buildings' energy operation, it is necessary to have occupant-centred strategies [113]. Further, since occupancy profiles can influence energy use, a survey questionnaire can be used to evaluate the influence of varying it [111].

Electricity data can be used to calculate average daily winter/summer heating power consumption (kWh/day). This measure, combined with temperature data, the Household Heating Efficiency (HHE) indicator arises and is expressed as °C/kWh/day. HHE is the ratio of average ΔT to average daily heating energy consumption. Another indicator is heating efficiency, the ratio of the time spent percentage in the comfort zone to average daily heating power consumption, expressed as %cz/kWh/day [141].

In Appendix A, there is a Table that summarizes the parameters and methods of evaluating the energy performance of the consulted literature studies.

2.5.Summary

As explained in the state of the art chapter, comfort and well-being are interconnected and subjective since a person can feel comfortable at one moment and uncomfortable at another with the same exact conditions. Also, people in the same space can have different perceptions and feelings about various parameters of comfort and well-being. This is because of contextual dynamism since people are influenced by multiple factors such as gender, age, country of origin, culture, life experiences, and humour, among others. Each person can have a perception according to their physical, psychological and experiential characteristics. Nevertheless, comfort is more related to regulated parameters that can be measured (temperature, humidity, noise, illuminance, and others) and well-being is more qualitative and involves parameters that cannot be measured, only questioned to people (view, biophilia, safety, furniture, and others).

In this study, comfort and well-being basically encompass various concepts such as comfort, well-being, satisfaction, and perception of occupants about the indoor environment. Although this study focuses on comfort and well-being in homes, the presented literature review cites studies on office buildings and other commercial and service buildings because there are studies that consider some factors of comfort and well-being that are little or non-existent in the context of housing. These studies can also help to study and understand some of the sensations and perceptions of home occupants.

From the literature review, it was possible to develop the methodology that will be implemented in this study, which is described in the next chapter. In this chapter on the state of the art, different parameters and factors that can influence comfort and well-being in a given indoor environment were presented. Methods to study these parameters were also mentioned. For this multiple comfort factors study, it was considered that the groups of factors to be studied would be: Thermal environment; Ventilation; Indoor air quality; Lighting; Acoustics/noise; Other housing characteristics; Furnishings, finishes and materials; Final considerations; and Respondent characteristics. The methods selected to assess the relationship between comfort, well-being and energy efficiency were measurements of some indoor environment parameters and energy consumption, and the application of surveys. Since this study aims to be comprehensive, considering various aspects of comfort and well-being in residential buildings, the selection of factors and parameters to be studied and surveyed is less in-depth than a study that aims to explore only one aspect of comfort and well-being.

The next chapter explains in detail the entire methodology for developing the method for assessing comfort, well-being and energy efficiency, namely the methodology for collecting data on the indoor environment, the methodology for acquiring and processing data, and the methodology for energy

simulation. The methodology to discover the comfort and well-being parameters to improve and the improvement measures on the indoor environment will be also described.

3. Methodology

The methodology is presented in two subchapters. The first addresses the methods that will be used and the parameters that will be studied based on the state of the art. The second subchapter describes how the selected methods were applied in practice. Firstly, will mention the data collection on the indoor environment via sensors and interviews, and the collection of dwellings occupants' satisfaction and perceptions through the application of surveys. It then discusses how the data collected was processed and how the comfort and well-being parameters to be improved in each case study were obtained. Finally, it explains how the simulation models for each case study were calibrated and which improvement measures will be studied across all the case studies to see their impact on the indoor environment. It also mentions why some measures are evaluated in simulation models and others are not.

3.1.Parameters and methods selection

This doctoral thesis aims to develop and test an integrated method for assessing comfort and well-being and its relationship with the energy efficiency of dwellings, establishing a new metric for evaluating buildings that focuses on the occupants. Since the research question is how to evaluate the comfort and well-being of occupants, integrating aspects and characteristics of the energy efficiency of buildings (construction aspects, energy systems, usage profiles, and others), it is necessary to identify:

- Comfort and well-being factors and parameters and their evaluation methods;
- Methods for evaluating the energy performance of buildings and strategies for making them more efficient;
- The relationship between the energy efficiency of buildings and comfort and well-being.

These points were explored in the literature review chapter, specifically in subchapters 2.1, 2.2, 2.4 and 2.4.2. In this study, when comfort and well-being are mentioned, it refers to the concepts of comfort, well-being, satisfaction and the occupant's perception of the interior environment. This literature review allowed the identification and selection of the most relevant parameters for this study, the factors that can affect the perception of occupants, the methods for assessing comfort, well-being and energy performance that are intended to be applied and how to do it are necessary points for the development and testing of the method.

The literature review was also fundamental to developing the methodology that will be implemented in this study. In this way, it will be possible to formulate recommendations for the post-occupancy evaluation of the comfort, well-being and energy efficiency of existing buildings and to provide recommendations for improvement in the operation and rehabilitation of residential buildings, making them more sustainable and comfortable for occupants. Despite this study being about comfort and well-being in the houses, the literature review includes studies on office buildings and other commercial and service buildings since there are more comprehensive studies that can help to explain and understand some of the sensations and perceptions of people in their homes. It should be noted that this study doesn't pretend to be a statistical validation but aims to ensure that the method developed responds to the different needs and specific characteristics of each case, requiring different inputs.

All things considered, the parameters and questions relevant to this study were selected. It should be noted that as this study aims to be comprehensive, considering various aspects of comfort and well-being in residential buildings, the selection of factors and parameters to be studied and surveyed is more comprehensive and less in-depth than a study that aims to explore only one aspect of comfort and well-being, for example, the thermal environment.

From the literature review, it was considered that the Post-Occupancy Evaluation (POE) method is widely used to collect the occupants' perceptions, satisfaction and preferences regarding their dwelling. This method generally uses surveys and/or interviews, as Chapter 2.4 describes. Data on energy consumption and/or other resources can also be collected as part of this POE methodology. Several building standards and surveys/questionnaires focused on energy consumption and occupant comfort were described in Chapter 2.4.1.1 and developed by organisations and/or presented in standards, scientific articles and articles that evaluate comfort and well-being. Considering the POE methodology and the surveys used in these standards and organisations, it was possible to develop the survey intended to apply in this study. Table 3.1 summarises the surveys that were analysed to construct the survey for this study, as well as the type of surveys to be applied, the questions to be asked, the periodicity, scales, and other points used in this study and those that weren't. The survey used in previous study [160] was also a starting point for the survey development that this study pretended to apply. That survey was applied in office buildings, and 310 people responded, allowing an analysis of it.

Considering all this, in this study, it was decided that it was necessary to conduct an initial interview, followed by two types of surveys: a right-now study applied at two points in time, summer and winter, and an extensive survey applied at the end of summer and winter. Data was collected on the home's energy consumption to support the home's energy efficiency assessment. In order to assess the relationship between comfort and well-being and energy efficiency and also interpret the results obtained from both the surveys and the energy consumption measurements, measurement campaigns of indoor environmental conditions (temperature, humidity, and CO₂ concentration) will be carried out. All these data acquisition methods are described in the state of the art, Chapter 2.4 and Chapter 2.4.2.

The following chapter discusses in more detail the entire methodology for developing the method for assessing comfort, well-being and energy efficiency, namely the methodology for collecting data on the indoor environment, the characteristics of the houses and the occupants, the methodology for energy simulation and data processing. Ten case studies were selected to implement the methodology of this study.

Table 3.1 - Points used from existing surveys to draw up the survey for the present study

	REF	What is used in this study	What wasn't used in this study
Standards			
ASHRAE 55-2017	[86]	• Satisfaction rate with the thermal environment on a 7-point satisfaction scale. • Environment acceptability is determined by who responded 'neutral' or 'satisfied' (0, +1, +2, or +3) • Question about 'overall' and/or 'average' environment comfort. • Survey applied in heating and cooling seasons. • Some questions, for example, about the clothes occupants are wearing at the moment, thermal sensation, and satisfaction with the thermal environment, among others. • Indoor conditions measurements	• Some types of questions, for example, about the level of physical activity at the time the occupant answers the questionnaire, location of the area of the building where they are (floor, if they are near windows or exterior walls, orientation of the façade, others), among others
EN 15251	[87]	• Thermal sensation rate on a 7-point scale • Thermal acceptability on a 4-point scale • Odor intensity rate on a 6-point scale • Question about how you would like the temperature to feel (higher, no change, lower)	• Question about the indoor air acceptability

Table 3.1 - Points used from existing surveys to draw up the survey for the present study (cont.)

	REF	What is used in this study	What wasn't used in this study
Organisations			
CBE Survey	[14] [54] [142] [147] [148]	• 7-point scale to gauge satisfaction with the survey areas with a neutral midpoint • The questions from the CBE survey were very important for constructing the study's survey. Some questions were adapted for housing. • Questions about the occupant's satisfaction with various factors: thermal comfort, indoor air quality, lighting, acoustics, overall building • Questions about air-conditioning systems, shading and more. • Indoor conditions measurements	• Questions related to the work environment
Building Use Studies (BUS) Methodology	[144][148]	• 7-point Likert scale to evaluate satisfaction in different parameters: temperature, lighting, noise, temperature, design	• Questions related to certain parameters of the environment where you work: productivity, health, image to visitors
World Green Building Council	[48]	• Some of the questions presented have been adapted for housing • Questions related to design and biophilia (view, nature) • Questions about the indoor environment (lighting, thermal comfort, indoor air)	• Questions related to the environment where you work, the location and amenities, employee engagement

3.2.Method implementation

This study has a data collection component, namely for collecting feedback from the occupants and data on the indoor environment, energy consumption and the construction and occupancy characteristics of the house. With this data collection, it will be possible to identify the comfort and well-being parameters that need to be improved in each case study considering the answers obtained in the surveys and then indicate the improvement measures that should be adopted. The simulation component of this study aims to understand the impact that some selected improvement measures will have on the thermal comfort. To verify the impact, it is necessary to perform simulations using EnergyPlus, starting with a model calibration process (temperature and energy).

Data collection

Firstly, it was performed an interview with the occupants of the dwellings and a visit to the dwelling to collect data on the occupancy of the home, the type of air conditioning equipment used, the energy-consuming equipment and control devices, the construction characteristics and dimensions, and to check whether the smart electricity meter was installed to decide whether it was necessary to use equipment to collect electricity consumption data. These smart meters make it possible to monitor and consult energy consumption.

Data on electricity consumption in the home can be collected in two ways: using a PEL device (Power Energy Logger) or, if there are smart meters, using the E-redes website, which provides the electricity consumption. Suppose other energy sources are also used, such as natural gas, bottled gas, biomass, renewable energies or others. In that case, these consumptions should also be recorded and, if possible, monitored. Only two case studies used electricity meters (PEL) in this study. The other eight had smart meters, so the E-redes website was used [161].

Regarding the measurement of indoor environmental conditions, monitoring the temperature and relative humidity of the living room in each case study was considered relevant. Over 1 year, values were recorded every 10 minutes, and HOBO sensors were used for this purpose. These sensors must be positioned approximately 1 m to 1.5 m above the floor and away from direct sources of heat or lighting.

In order to compare the indoor conditions with the outdoor conditions, data on the outdoor environment was collected using HOBO sensors. It is important to note that these outdoor sensors should not be exposed to direct sunlight and a safe location should be selected.

In order to find out the occupants' feedback on the perceived comfort and well-being of the dwelling, as well as their satisfaction, an extensive survey was carried out. This extensive survey concerns the home as a whole. It addresses questions relating to thermal comfort, acoustics, air quality and lighting, as well as broader questions relating to the view, furniture, building materials, and options that occupants prioritise, among other issues. The questions are divided into the following groups: Thermal environment; Ventilation; Indoor air quality; Lighting; Acoustics/noise; Other housing characteristics; Furnishings, finishes and materials; Final considerations; and Respondent characteristics. The first five groups are more related to comfort and the remaining to well-being. This survey was applied at two different times: at the end of winter and at the end of summer. Appendix B and Appendix C have the extensive survey applied in summer and the extensive survey applied in winter, respectively. The aim was to see if there were any differences in the perception of comfort and well-being in the more extreme seasons of the year. The first time this survey was implemented, the occupants completed the entire survey. The occupants only filled the five initial groups of questions the second time since the rest were irrelevant in this summer versus winter analysis. This survey was filled out individually by the occupants and was completed by all house permanent occupants who were over the age of 18. Permanent occupants are all those who live in the house most of the year.

The right-now survey is quick to complete and focuses essentially on one aspect of comfort, thermal comfort, which can be considered one of the main aspects of comfort and well-being in buildings. It addresses questions relating to the bedroom and living room when the occupant fills out the survey and during the day. The key questions in this survey are the status of windows and shades (open/closed), heating/cooling (on/off), thermal sensation and perceived discomfort. The occupants answered this survey every day from 9 p.m. for two continuous weeks, by the occupants sleeping in the house's main bedroom and are filled out individually. This survey was applied at two different times: two weeks in winter and two weeks in summer. The aim is to see if there are any differences in the perception of comfort and well-being in the year's more extreme/cooler seasons. The right-now survey applied in winter and summer can be found in Appendix D and Appendix E.

The intention of this right-now survey was also to find out whether there are significant differences in temperature and humidity in the main bedroom and the living room and to understand whether the occupants' perception of the indoor environment in these two rooms is the same or different. To be considered a main bedroom, it must be occupied most of the year by occupants over the age of 18. Suppose two bedrooms exist in a house used most of the year (permanently) by people over 18. In that case, the main bedroom is considered to be the one that is agreed to be the most uncomfortable. The living room and bedroom are typically where people spend the most time in a home and seek to feel comfortable and have a sense of well-being. This is how the right-now survey was developed.

At the same time as this right-now survey, measurements were taken of the indoor environment to compare the answers given with the temperature and relative humidity. The values were recorded every 5 minutes, day and night, both in the living room and the main bedroom of each case study. The equipment used was the HOBO in the bedroom to monitor temperature and relative humidity and the Rotronic in the living room, which records temperature (T), relative humidity (RH) and CO₂ concentration (CO₂). The Rotronic devices were not used to monitor the physical parameters in the bedrooms, as recording CO₂ concentration values could have intruded on the occupants' privacy and, therefore, compromised this part of the study. In the same way as Hobo sensors, Rotronic must be positioned at a height of approximately 1 m to 1.5 m and away from direct sources of heat or light. It

should be noted that the right-now survey and the respective monitoring of indoor environmental parameters lasted two weeks and did not occur simultaneously in all the case studies due to the geographical location of the case studies and for reasons related to the amount of equipment available.

Figure 3.1 illustrates the diagram of the methodology's application for collecting indoor environment data and occupant feedback, as described above. Table 3.2 shows the characteristics (range, accuracy, and resolution) of the various sensors and equipment used for data collection in this study. Figure 3.2 and Figure 3.3 show the HOBO sensors used to collect indoor temperature and humidity data over the course of a year. Figure 3.4 presents the sensor used to collect outdoor condition data (humidity and temperature). The Rotronic sensor, used during the right-now survey to collect data on temperature, humidity and CO₂ concentration, is shown in Figure 3.5. Finally, Figure 3.6 shows the PEL, equipment used for collecting data on electricity consumption.

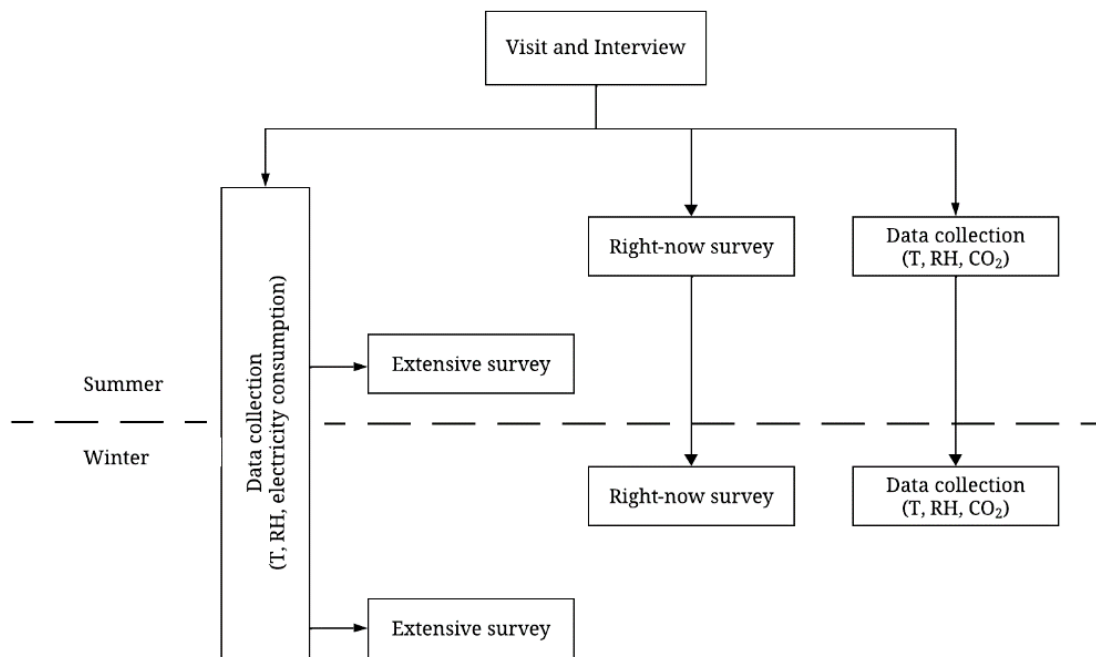


Figure 3.1 - Diagram of the application of the methodology for collecting indoor environment data and occupant feedback

Table 3.2 - Range, accuracy and resolution of the sensors and equipment used in the study

Equipment		Range		Accuracy	Resolution
		Min	Max		
Hobo UX100-003 (humidity and temperature data logger)	Humidity (%)	15	95	$\pm 3.5\%$ from 25% to 85% and $\pm 5\%$ below 25% and above 85%	0.07% at 25°C
	Temperature (°C)	-20	70	$\pm 0.21^\circ\text{C}$ from 0°C to 50°C	0.024°C at 25°C
Hobo U10-003 (humidity and temperature data logger)	Humidity (%)	25	95	$\pm 3.5\%$ from 25% to 85% (over the range 15°C to 45°C) and $\pm 5\%$ from 25% to 95% (over the range 5°C to 55°C)	0.07%
	Temperature (°C)	-20	70	$\pm 0.53^\circ\text{C}$ from 0°C to 50°C	0.14°C
Hobo MX2301A (exterior) (humidity and temperature data logger)	Humidity (%)	0	100	$\pm 2.5\%$ from 10% to 90% and $\pm 5\%$ below 10% and above 90%	0.01%
	Temperature (°C)	-40	70	$\pm 0.25^\circ\text{C}$ from -40 to 0°C	0.02°C
Rotronic (CO ₂ concentration, humidity and temperature data logger)	CO ₂ (ppm)	0	9999	$\pm 30\text{ppm} + 5\%$ of reading	1ppm
	Humidity (%)	0.1	99.9	$\pm 3.0\%$ % from 10% to 95% (25°C) and $\pm 5\%$ from other	0.1%
	Temperature (°C)	-20	60	$\pm 0.3^\circ\text{C}$	0.1°C
PEL	Voltage (V)	100	1000	$\pm 1\%$ Reading $\pm 3\text{V}$ (Typical)	0.1V
	Current (I)	A193 A***		-	-



Figure 3.2 - Hobo UX100-003



Figure 3.3 - Hobo U10-003



Figure 3.4 - Hobo MX2301A



Figure 3.5 - Rotronic



Figure 3.6 - PEL

In both types of surveys, it was mandatory to answer all the questions, and there was no anonymity since the goal was to study a specific house and a specific occupant. Of the ten case studies, in five, only one person responded to the surveys, while in the remaining five, two people from the same house responded. These occupants were considered, taking into account the characteristics mentioned above. Cases with more than one occupant responding allow for an analysis of the convergence or divergence of responses and to understand whether there is a common opinion regarding the interior conditions of the dwelling. Although it is not the main focus of this study and does not need to be explained, this analysis has enormous instrumental value for introducing the discussion of how to achieve consensus in the same dwelling. If there is convergence in the occupants' responses, it is, in principle, easier to solve discomfort problems. If there isn't, it becomes more complex since it is necessary to consider the discomfort of all occupants and not just one, with probably more comfort and well-being parameters and/or factors to consider. It should be remembered that comfort and well-being are subjective, as they depend on multiple factors (gender, age, experiences, among others), and so this analysis, while not a novelty or a priority, could be interesting in this study.

As mentioned, a home visit and an initial interview with the house's occupants were conducted for the house characteristics data collection. Sensors were used to collect data on the indoor environment, as described above. To collect feedback from the occupants the surveys (extensive and right-now) were developed in SurveyMonkey and distributed via Whatsapp messaging link. In the right-now survey, this message was sent after 9 p.m. to the occupants. When filling in the extensive survey, it was recommended that occupants respond via computer, as this is a more extended survey and also because of the layout of the survey itself, which is more user-friendly and has larger screens, thus not causing the platform itself to automatically readjust the type of questions. In the first version of this data collection method, GoogleForms was used. Still, SurveyMonkey was considered a more robust platform for this type of data collection. Table 3.3 summarises what has been described above concerning the two types of surveys.

After data collection, it is necessary to prepare the raw data in the format ready for the analyses considered necessary for this study. SPSS and Excel were used to prepare and analyse the data collected. In SPSS, it was necessary to validate that all the answers exported from SurveyMonkey were valid and to check for any errors or non-conformities. The data was analysed and processed in SPSS and Excel. With the tables generated from SPSS and others from Excel, it was possible to use Python to produce the graphical representations used in the results chapter of this thesis.

Table 3.3 - Main characteristics of the extensive and the right-now survey

		Extensive survey	Right-now survey
General characteristics	Type of analysis	Global	Specific
	Area under evaluation	Home	Main bedroom and living room
	Sample	Permanent occupants	Permanent occupants sleeping in the main bedroom
	Output	House characterisation	Specific characterisation of the living room and main bedroom
Survey	Parameters	Thermal; Air quality; Lighting; Acoustics/noise; Other housing characteristics; Furnishings, finishes and materials	Thermal
	Platform	SurveyMonkey	SurveyMonkey
	Period	Punctual, summer and winter	Two consecutive weeks in winter and another two weeks in summer
Measurements	Parameters	Temperature, relative humidity, electricity consumption	Temperature, relative humidity, CO ₂ concentration
	Equipment	Hobo	Hobo, Rotronic
	Data recording	Temperature and HR Records every 10 minutes	Temperature, HR and CO ₂ (the latter only in the living room) Records every 5 minutes
	Period	6 months	Two consecutive weeks in winter and another two weeks in summer

Identification of parameters to improve comfort and well-being

After this analysis, it was possible to establish which comfort and well-being parameters need to be improved according to the responses of the occupants. Of these parameters identified as needing improvement, it is considered necessary to categorise them into three priority classes:

- Class 1 - first parameters to improve
- Class 2 - second parameters to improve
- Class 3 - third parameters to improve

These priority classes are established regarding the level of satisfaction with the various parameters and the importance that the occupants attach to these parameters. So, it is necessary to create a methodology to understand which class the parameters will be included in. For this methodology, the level of satisfaction is represented by symbols in which symbol “✓” means when the occupants indicated they were satisfied (“Slightly satisfied”, “Satisfied”, “Very satisfied”), the symbol “±” when they indicated “Neutral” and “×” dissatisfied (“Slightly unsatisfied”, “Unsatisfied”, “Very unsatisfied”). The importance is represented with colours, green indicates that the occupant has answered that the parameter is important (“Slightly important”, “Important”, “Very important”), and orange that the parameter is “Not important”.

In the case studies in which two occupants responded (cases 6 to 10), it was enough for one of them to answer one of the three dissatisfaction scales to automatically be considered an “×”. When one of them answered “Neutral”, and the other was satisfied, it was considered ±. Regarding the importance, if one of the occupants indicated that it was important (one of the three levels of importance), the cell in the table is considered green.

The method is based on the simplified diagram shown in Figure 3.7. Firstly, it is necessary to check what type of parameter it is in analysis: a parameter that has a summer and winter evaluation (thermal, acoustic, lighting and air quality) or if it is a parameter that has an annual evaluation (privacy, maintenance and furniture and others). Then, following the diagram and checking the satisfaction and importance evaluation, it is possible to obtain the class of comfort and well-being parameters. Having that said, it's clear which parameters need to be improved from the occupant's point of view and it is

possible to indicate the measures to improve comfort and well-being and energy efficiency that should be implemented. In Chapter 7, this diagram is developed to provide a clearer explanation of the process at each decision stage.

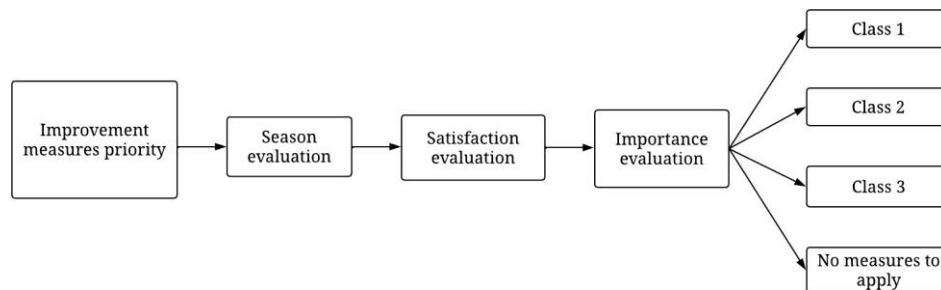


Figure 3.7 - Simplified diagram that reflects the method to classify the priority of the comfort and well-being parameters

Simulation models – Thermal comfort

As mentioned before, this study includes a simulation model component using EnergyPlus that develop simulation models for the 10 case studies and carry out parametric assessments of the building's comfort conditions. For that, it is necessary to calibrate the models using the collected temperature and energy use data, and then apply the identified measures by the surveys to improve comfort and energy efficiency and understand the impact this will have. Of the measures presented, only those related to thermal comfort will be analysed taking into account the results obtained in the simulation models. This is due to the fact that only data on the thermal component (temperature and humidity) was collected for one year, and no other comfort and well-being parameters were collected in order to calibrate a simulation model that would allow the impact of certain changes, i.e. improvement measures, to be verified. The impact on energy consumption will also not be evaluated because don't consider the desegregation of the uses (lighting, equipment, air conditioning systems) since it was not possible to collect information in this regard. However, the calibration of energy consumption is important because it helps establish the model's internal gains and, therefore, influences the house's interior temperature. Knowing that it is not possible to disaggregate energy consumption by use, it is not possible to know how much energy is used to air-conditioning the house, and therefore, it is not possible to know what the reduction in consumption will be after certain improvement measures are implemented. However, it is known that they impact comfort, energy consumption, and costs.

SketchUp Pro 2021 and OpenStudio were used to draw the geometry and indicate housing characteristics in each case study. In EnergyPlus 23.1.0, the model for each case study was further developed, and the desired results were obtained: energy consumption and temperatures inside the house. It should be noted that to carry out an energy simulation in EnergyPlus, an EPW climate file must be entered. This file was exported from an Excel sheet from the Direção Geral da Energia e Geologia, which provides climate files by municipality. Elements version 1.0.6 was then used to modify the data in the exported climate file relating to outside air temperature and relative humidity. This data comes from Hobo sensors placed outside the case studies and/or a weather station.

After obtaining these initial results, the calibration process began to ensure that the results obtained for energy consumption and temperatures were similar to those collected over a year (data from E-Redes/PEL and Hobo sensors placed in the living room). The raw data (temperature and energy consumption) were prepared in the format that is ready for the calibration process. In other words, with Python, routines were created to generate two Excel files: one for hourly temperature values and another for hourly energy consumption over a year. In this way, the data needed to start the calibration process

was prepared and organised. Thus, another Python routine was created so that monthly energy consumption values and monthly and hourly temperature values could be calibrated/compared with the results obtained from EnergyPlus. This is how the calibration process proceeded.

With the model calibrated, it became possible to apply the selected improvement measures. As previously stated, only the impact of the improvement measures on thermal comfort will be assessed since the calibration of the models is based on measurements taken over the course of a year. This made it possible to calibrate for that certain year, and to analyse the impact on temperature and number of discomfort hours after implementing the measures. Although various measures will be suggested for each case study based on the results, it is considered interesting for this study to analyse the impact of some measures to improve thermal comfort in the same way for all the case studies.

For all the case studies, the selected improvement measures that pretend to be analysed are the application of thermal insulation in the opaque envelope (walls, roof and floor, depending on the specifics of each case study), replacement of the windows and these two measures simultaneously. Heat recovery at the same time as replacing the windows and applying insulation is another measure to be studied. The heat recovery considered has an efficiency of 90% and is carried out by using a ventilation unit that produces a flow of air between an interior space and an exterior space and is equipped with both extraction and insufflation fans. Although this percentage is somewhat high, it was considered as it is indicated in Commission Regulation (EU) No 1253/2014 [162]. This measure is intended to be applied from January to May and from October to December. An analysis of the insulation with three different thicknesses is intended: 6cm, 8cm and 10cm. The insulation material selected was rock wool (thermal conductivity of 0.04 W/m°C). Compared to XPS, rock wool performs better in terms of fire resistance, is more sustainable, and is also acoustic in addition to being a thermal insulator. Also, for the analysis of the windows, it is considered PVC windows with low-emissivity double glazing with three thermal transmission coefficients: 2.5 W/m².°C, 2 W/m².°C and 1.5 W/m².°C.

It should be noted that the analysis should consider the mean monthly temperature in the living room and the hours of monthly discomfort are all those in which the temperature is not between 18°C and 25°C as recommended by Portuguese legislation. The 24 hours of a day should be taken into account and not just the hours when people are at home, since people's schedules are not always the same and so it was decided to do a broader analysis.

In order to understand how the dwellings behave under real conditions (calibrated model) and under nominal conditions (respecting the minimum requirements of the legislation), simulations of the models with the various improvement measures presented above will be carried out for four scenarios:

- Real scenario with HVAC: corresponds to the calibrated simulation model, i.e. with the uses of HVAC and with the air infiltrations that were taken into account so that the model was calibrated from the point of view of temperature and energy use;
- Real scenario without HVAC: real scenario with HVAC but considering that there is no use of HVAC;
- Nominal scenario with HVAC: takes into account the minimum infiltrations required by legislation (0.5 air changes per hour) and considers that there is always air conditioning in every room of the house for 24 hours so that the temperature is between 18 and 25°C;
- Nominal scenario without HVAC: is the Nominal scenario with HVAC but without HVAC conditioning.

In this way it will be possible to analyse the impact of the improvement measures in the real scenario and in the nominal scenario with or without HVAC. The next chapters present the case studies and then the results obtained from the implementation of this methodology.

4. Case studies

In this study, 10 case studies were selected to apply the presented methodology. They are all residential buildings in Portugal and include both apartments and villas. Case studies 1, 2, 4, 6, 7, 8 and 10 are apartments; of these, case studies 2, 4 and 8 are on the top floor of the building. Case studies 3, 5 and 9 are villas. The climatic zones and the characteristics of the construction and systems vary. The occupants of these dwellings have lived there for at least a year, and their ages are diverse.

The intention was to ensure diversity in terms of the occupant's profile, the building characteristics and the use of the dwelling since the aim was to test the method developed with different inputs. Homogeneity and generalisation are not of interest in this study because it is not intended to study relationships or correlations between certain characteristics of the occupants and/or the dwelling. Statistical validation is not the aim of this study. This study aims to determine if the developed methodology is able to address each case's different needs and specific characteristics, i.e., housing and occupants.

These case studies were also selected because they were dwellings that could be accessed at any time to gather information. This is an important condition for applying this methodology as it is being developed and tested. Table 4.1 presents the data obtained by the extensive survey regarding those who filled out the survey and the household. Table 4.2, Table 4.3, and Table 4.4 describe the construction features and types of house systems in the different case studies.

None of the occupants in this study reported having a disease related to the indoor environment in the last 3 years.

Table 4.1 - General characteristics of the case studies people

Case study	People surveyed		Households	Household income
	Gender	Age		
1	Male	46-55	1 adult	≥ 2705,60
2	Male	46-55	2 adult and 3 children	≥ 2705,60
3	Female	≥ 56	1 adult	1352,81 - 2029,20
4	Female	26-35	1 adult	1352,81 - 2029,20
5	Female	≥ 56	1 adult	676,40 - 1352,80
6	Male and female	26-35	2 adults	≥ 2705,60
7	Male and female	36-45	2 adults and 2 children	2029,21 - 2705,60
8	Male and female	≥ 56	2 adults	≥ 2705,60
9	Male and female	≥ 56	2 adults	1352,81 - 2029,20
10	Male and female	26-35	2 adults	2029,21 - 2705,60

Table 4.2 - General characteristics of the case studies

Case study	Location	Climate Zone	Construction year	Energy certification	Typology
1	Lisboa	I1;V2	1998	-	Apartment - T3
2	Lisboa	I1;V2	2003/2004	-	Apartment - T4
3	São Martinho do Porto	I2;V1	2010/2011	-	Villa - T4
4	Lisboa	I1;V2	≈1960	-	Apartment - T2
5	São Martinho do Porto	I2;V1	≈1960	-	Villa - T2
6	Lisboa	I1;V2	≈1960	-	Apartment - T1
7	Seixal	I1;V1	2005	D	Apartment - T3
8	Lisboa	I1;V2	≈1960	D	Apartment - T2
9	Cernache do Bonjardim	I2;V3	≈1975	-	Villa - T5
10	Almada	I1;V1	2004	C	Apartment - T3

Table 4.3 - Envelope characteristics of the case studies

Case study	Opaque envelope			Glazed envelope	WWR (%)	Shading
	Exterior Walls	Ceiling	Floor			
1	Double brick wall with air gap and insulation	Equal to the floor due to being between floors	Solid slab	Simple double-glazed windows with metal frames without thermal break	20	Plastic blinds from the outside
2	Double brick wall with air gap and insulation	Inclined reinforced concrete roof with insulation and Lusa tiles	Solid slab	Simple double-glazed windows with metal frames with thermal break	17	Plastic blinds from the outside
3	Double brick wall with air gap and insulation	Inclined reinforced concrete roof with Lusa tiles	Solid slab	Simple double-glazed windows with metal frames	17	Plastic blinds from the outside
4	Simple brick wall	Inclined reinforced concrete roof with Lusa tiles	Solid slab	Simple double-glazed windows with metal frames and simple double-glazed windows with plastic frames	70	Plastic blinds from the outside
5	Simple brick wall	Inclined reinforced concrete roof with Lusa tiles	Solid slab	Simple single-glazed windows with wooden frames	15	Plastic blinds from the outside
6	Simple brick wall	Equal to the floor due to being between floors	Solid slab	Simple double-glazed windows with metal frames	22	Plastic blinds from the outside
7	Simple brick wall	Equal to the floor due to being between floors	Solid slab	Simple double-glazed windows with metal frames	15	Plastic blinds from the outside
8	Simple brick wall	Inclined reinforced concrete roof with Lusa tiles	Solid slab	Simple double-glazed windows with plastic frames	12	Interior wood blinds
9	Simple brick wall	Inclined reinforced concrete roof with Lusa tiles	Solid slab	Mostly double-glazed windows with metal frames and simple double-glazed windows with plastic frames	10	Mostly plastic blinds from the outside
10	Double brick wall with air gap and insulation	Equal to the floor due to being between floors	Solid slab	Mostly simple double-glazed windows with plastic frames and double double-glazed windows	39	Mostly plastic blinds from the outside

Table 4.4 - Energy systems of the case studies

Case study	HVAC systems		Artificial light	Equipment	Renewable energy
	Heating	Cooling			
1	Electric	-	LED	Mostly with energy class C or better	-
2	Electric AC	Electric AC	LED	Mostly with energy class C or better	-
3	Biomass, Electric	-	Mainly LED	Mostly with energy class C or better	-
4	Electric	-	Mainly LED	Mostly with energy class C or better	-
5	Electric	-	Mainly LED	Mostly with energy class C or better	-
6	Electric	-	LED	Mostly with energy class B or better	-
7	Electric AC and Natural gas	Electric AC	LED	Mostly with energy class C or better	-
8	Electric AC and Natural gas	Electric AC	Mainly fluorescent	Mostly with energy class C or better	-
9	Biomass, Electric	-	LED	Mostly with energy class B or better	Thermal solar and Photovoltaic
10	Natural gas	-	LED	Mostly with energy class B or better	-

Not all of the case studies had architectural drawings available. Therefore, a representation of the rooms in each case study is presented below to make it easier to visualise the orientation and layout of the rooms (Figure 4.1 to Figure 4.10). The main bedroom and the living room are identified as the rooms to be studied. It also identifies the room where the sensors were placed to collect data on the indoor environment and compare it with the responses obtained during the right-now survey (RNS) and the extensive survey (ES). When the exterior line is red, it means that the façade is in contact with the outside, green means that it is adjacent to the neighbours, yellow means that it is in contact with the common areas of the building and blue means that it is in contact with the ground.



Figure 4.1 - Representation of case study 1



Figure 4.2 - Representation of case study 2

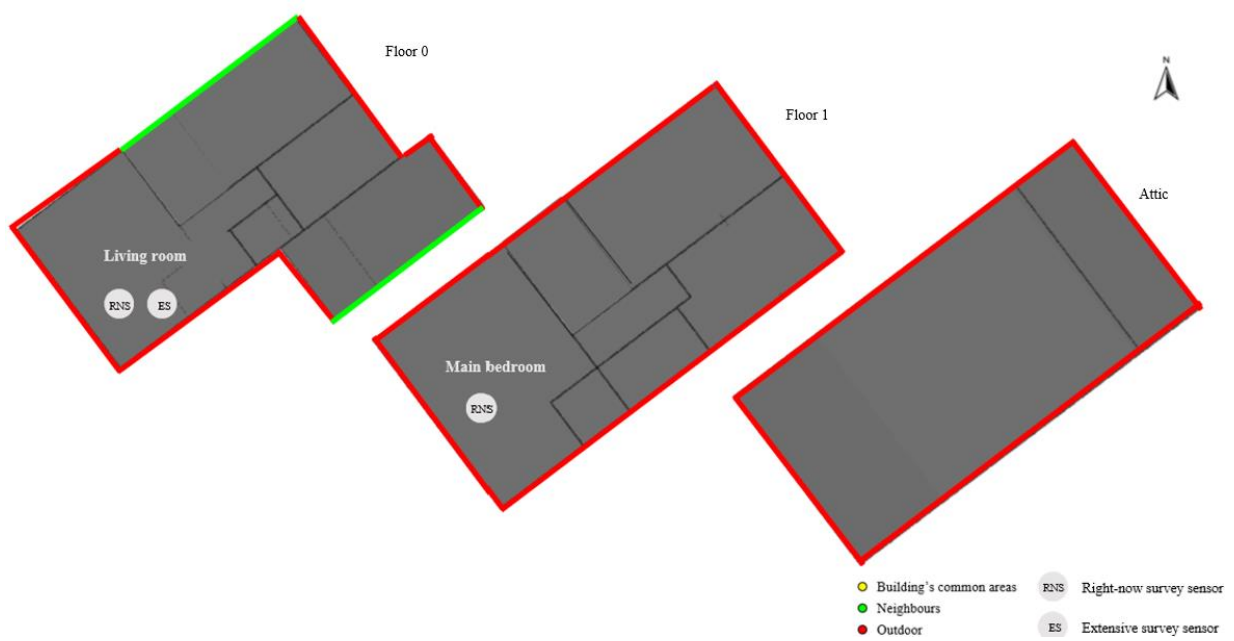


Figure 4.3 - Representation of case study 3

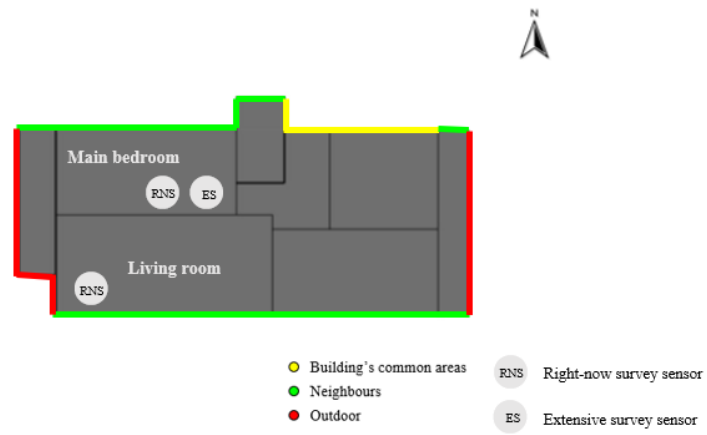


Figure 4.4 - Representation of case study 4



Figure 4.5 - Representation of case study 5



Figure 4.6 - Representation of case study 6



Figure 4.7 - Representation of case study 7



Figure 4.8 - Representation of case study 8



Figure 4.9 - Representation of case study 9

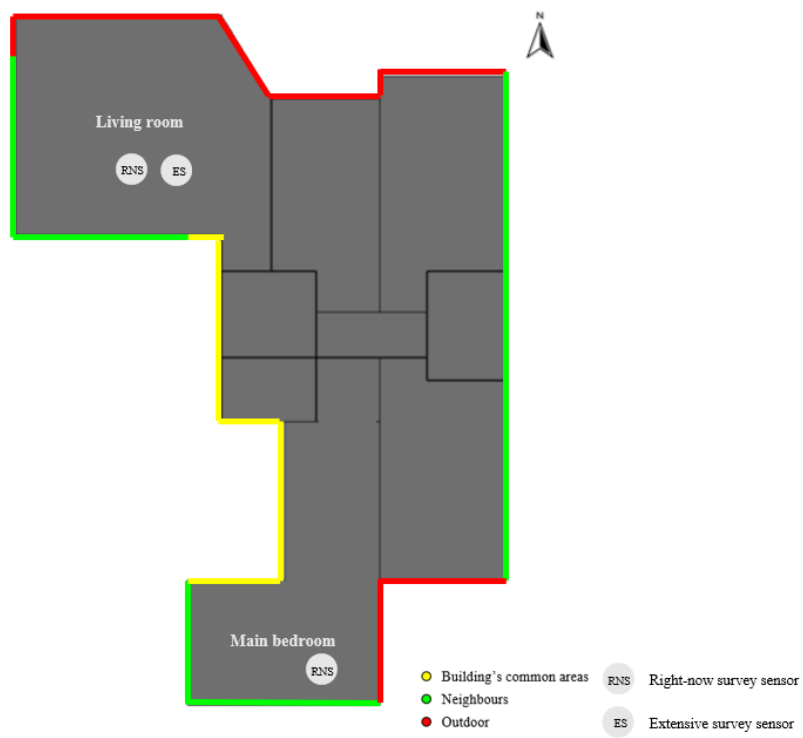


Figure 4.10 - Representation of case study 10

5. Right-now survey

The right-now survey focused essentially on thermal comfort, as mentioned above and was applied at two different times: two weeks in winter and two weeks in summer. It addresses questions relating to the bedroom and living room when the occupant fills out the survey and throughout the day. As described in the methodology, the questions are about the status of windows and shades (open/closed), heating/cooling (on/off), thermal sensation, and perceived discomfort when the person is filling out the survey. The number of people at home and what you think the weather was like when filled in the questionnaire are also questions asked. It should be remembered that occupants answered this survey every day from 9 p.m. for two continuous weeks. The right-now survey applied in winter and summer can be found in Appendix D and Appendix E, respectively.

At the same time that this right-now survey was taking place, measurements of the indoor environment were taken to compare the answers given with the temperature and relative humidity values recorded that day at night in the living room and the main bedroom of each case study. CO₂ concentration was also recorded in the living room. The right-now survey and the respective monitoring of indoor environmental parameters did not occur simultaneously in all the case studies due to the geographical location of the case studies and for reasons related to the amount of equipment available.

After this summary of the methodology for implementing this survey, the objectives of using the right-now survey and the indoor environment measurements in winter and summer are to understand:

- Which range of measurements of the indoor environment is relevant for the analysis of the two points above (all day, 9 p.m.-12 a.m., the time closest to when they answered the survey);
- Relationship between measured indoor temperature and people's perception;
- Whether people's perception of the indoor environment differs between the living room and the bedroom;
- Whether it is relevant to measure the temperature of the air in the bedroom and living room, taking into account the answers obtained by the right-now survey;
- Whether people's perception of thermal comfort in the indoor environment is different in the year's more extreme/cooler seasons.

5.1. Measured indoor environment data

Since it was impossible to simultaneously measure the indoor environment in the ten case studies, it is important to verify the outdoor temperature during the implementation of the right-now survey. This must be taken into account when analysing the results obtained. Table 5.1 shows the bedroom mean temperature (T_B), living room mean temperature (T_{LR}), mean outdoor temperature (T_{Out}) and the difference between the mean temperature values measured in the living room and outdoor (ΔT) during the period in which the right-now survey was applied. Table 5.2 shows the bedroom (B), living room (LR) and outdoor minimum and maximum temperatures during the period in which the right-now survey was applied.

Table 5.1 shows that during the application period of the right-now survey, the maximum difference in mean outdoor temperatures between the 10 case studies is 7.1°C in winter and 4.5°C in summer (T_{Out}). In winter, the difference in mean living room and bedroom temperatures is below 0.6°C (including) in eight case studies, 0.9°C in case study 8 and the biggest difference in mean temperature between these two rooms in the house is in the case study 6, with 1.9°C of difference. In summer, this difference is lower or equal to 0.6°C in nine case studies. In the case study 2, this difference is 1°C. The temperature

difference between the living room and the outside (ΔT) in winter is less than 6°C for all case studies, and in summer, less than 3°C, as shown in Table 5.1.

Table 5.2 also shows that the minimum outside temperatures in winter are similar, except for cases 7 and 9 ($T_{\min\text{Out}}$). Regarding the maximum outside temperatures in winter, the values are similar, with a difference between the maximum and minimum recorded value of 4.1°C ($T_{\max\text{Out}}$). In summer, the minimum outside temperatures are similar; in case 9, there is a greater difference than in the others ($T_{\min\text{Out}}$). There are disparate values in relation to maximum outside temperatures, with the difference between the minimum and maximum recorded values exceeding 13°C ($T_{\max\text{Out}}$).

Regarding the values recorded during the right-now survey, there is no case study in which the difference in mean relative humidity recorded in the bedroom and living room is greater than 11%, either summer or winter. The difference between the mean relative humidity recorded outside and in the living room is also not very significant, as shown in Table 5.3. In most cases, this difference is less than 10% (ΔHR). Table 5.4 also indicates that the minimum and maximum values recorded are not very different in the main bedroom and living room. In some case studies, the mean relative humidity recorded in the bedroom and/or living room is higher than outdoor. Some case studies have a mean relative humidity in the living room and bedroom, in summer and winter, that is not within the 50% to 70% range. Although this is the range established in Portugal, as stated in 2.3.2, it is common to see that other studies and standards consider between 40% and 60% to be comfortable and acceptable values.

Analysing the measured CO₂ concentration values in Table 5.5, it can be seen that in some of the study cases, the maximum values recorded during the implementation period of the right-now survey are very high. However, analysing the mean values, they are acceptable, although in some cases slightly high. It can also be seen that the average CO₂ concentrations are lower in summer. This could possibly be because windows are typically opened more often.

In this sense, the results obtained can be compared. However, care must be taken when analysing the results. These differences are justified not only by the fact that the temperature measurements were not taken simultaneously but also by the fact that the case studies had different geographical locations. Some have more extreme temperatures and climatic conditions than others.

Table 5.1 - Indoor and outdoor measured mean air temperatures during the right-now survey

Case study	T (°C)							
	Winter				Summer			
	T _B	T _{LR}	T _{Out}	ΔT	T _B	T _{LR}	T _{Out}	ΔT
1	17.5	16.9	13.1	3.8	25.2	24.7	26.2	1.5
2	18.4	19.0	15.6	3.4	24.2	25.2	23.2	2.0
3	16.5	17.0	13.4	3.6	23.3	23.2	22.7	0.5
4	16.2	16.1	13.5	2.6	26.5	26.3	26.2	0.1
5	16.5	16.3	15.2	1.1	24.9	24.5	24.0	0.5
6	17.4	19.3	13.5	5.8	26.6	27.2	27.2	0.0
7	18.7	19.1	16.3	2.8	27.1	27.4	24.7	2.7
8	18.8	19.7	15.3	4.4	24.6	25.0	22.9	2.1
9	14.8	14.7	9.2	5.5	25.6	25.5	24.6	0.9
10	18.2	18.6	15.1	3.5	25.3	25.2	23.0	2.2

Table 5.2. - Measured minimum and maximum indoor and outdoor air temperatures during the right-now survey

	T (°C)											
	Winter						Summer					
Case study	T min			T max			T min			T max		
	B	LR	Out	B	LR	Out	B	LR	Out	B	LR	Out
1	16.3	12.3	6.7	18.7	18.4	19.0	23.7	21.4	20.5	26.4	27.9	37.5
2	14.3	15.6	6.4	20.6	21.3	22.4	23.1	23.4	18.9	25.1	27.4	30.0
3	14.2	13.4	6.1	18.5	20.2	20.6	21.7	21.3	17.6	24.2	25.3	29.4
4	14.1	13.3	6.7	17.8	22.7	19.0	25.1	24.4	20.5	28.3	28.7	37.5
5	10.9	10.0	5.0	20.2	20.2	21.6	22.4	22.1	19.2	27.9	27.4	30.2
6	14.7	16.8	6.7	20.5	25.4	19.0	23.8	25.8	20.0	29.6	30.5	41.20
7	16.3	16.7	11.8	19.5	21.4	22.4	24.0	23.1	18.5	28.9	29.9	36.6
8	15.5	15.3	6.0	21.3	22.8	22.4	22.7	20.4	18.8	27.8	28.7	30.0
9	12.3	10.7	0.0	17.3	17.8	18.3	22.5	20.3	14.5	29.8	30.8	42.5
10	16.6	16.2	6.0	19.6	27.7	22.4	24.7	23.8	18.9	27.3	34.7	30.0

Table 5.3 - Indoor and outdoor measured mean relative humidity during the right-now survey

	RH (%)							
	Winter				Summer			
Case study	RH _B	RH _{LR}	RH _{Out}	ΔRH	RH _B	RH _{LR}	RH _{Out}	ΔRH
1	55.8	50.9	63.2	12.3	53.4	53.5	53.3	0.2
2	76.6	67.8	75.1	7.3	72.5	61.5	69.2	7.7
3	66.7	59.7	64.8	5.1	73.7	70.5	69.4	1.1
4	65.2	66.9	64.5	2.4	49.9	53.6	53.0	0.6
5	77.4	73.7	76.3	2.6	70.0	67.8	70.1	2.3
6	69.5	59.0	64.5	5.5	59.5	57.6	48.7	8.9
7	83.0	75.3	75.0	0.3	47.4	45.3	55.0	9.7
8	74.8	65.9	73.2	7.3	59.7	56.6	65.7	9.1
9	58.5	54.2	65.0	10.8	46.9	46.4	52.0	5.6
10	74.5	65.5	71.6	6.1	61.6	60.5	67.3	6.8

Table 5.4 - Measured minimum and maximum indoor and outdoor relative humidity during the right-now survey

	RH (%)											
	Winter						Summer					
Case study	RH min			RH max			RH min			RH max		
	B	LR	Out	B	LR	Out	B	LR	Out	B	LR	Out
1	41.7	34.3	34.8	68.8	65.7	87.5	36.5	34.2	27.9	70.4	74.2	78.0
2	49.2	35.0	35.2	87.8	81.8	92.1	59.0	44.1	40.9	78.9	74.6	84.6
3	46.2	45.8	34.4	77.4	66.1	88.7	59.8	50.6	36.2	84.7	80.2	86.1
4	60.0	53.0	34.8	76.2	77.4	87.5	41.8	44.3	27.9	65.5	66.9	78.0
5	60.1	61.8	52.8	88.8	86.0	92.4	60.7	58.9	51.0	79.6	76.3	85.8
6	48.8	39.0	34.8	83.5	75.0	87.5	35.5	46.4	18.0	75.4	74.3	75.8
7	67.6	51.0	35.2	87.8	83.0	92.1	32.8	30.5	25.0	64.7	61.2	78.8
8	43.9	40.8	30.1	93.1	79.0	92.1	40.7	37.2	38.4	81.0	73.1	84.6
9	34.1	27.9	31.0	72.3	67.3	93.9	24.1	24.8	14.9	74.5	75.9	84.2
10	52.9	41.2	30.1	84.8	77.1	92.1	38.9	41.8	38.4	75.7	73.9	84.6

Table 5.5 - Measured minimum, maximum, and mean living room CO₂ concentration during the right-now survey

Case study	CO ₂ (ppm)					
	Winter			Summer		
	Min	Max	Mean	Min	Max	Mean
1	392	845	501	398	840	463
2	389	2945	945	386	1000	490
3	355	4005	793	398	1238	676
4	410	2002	668	397	1662	586
5	370	1563	736	388	1227	638
6	405	2292	975	411	1933	905
7	427	1974	1050	399	1260	681
8	366	4103	951	386	1081	503
9	393	1956	703	390	648	432
10	384	1496	673	390	1548	616

5.2. Analysis of air temperature measurement intervals

As mentioned above, the living room and bedroom temperature values were recorded every 5 minutes. To process the data, and analyse the data obtained, it was considered the following time intervals:

- 9 p.m.-12 a.m: period during the time the occupants could answer the survey;
- Daily: all day;
- Closest hour: the closest time that occupant filled in the survey.

By averaging the recorded indoor temperatures, graphical representations were obtained for each case study by compartment (living room and main bedroom) and season (winter and summer), as shown in Figure 5.1 and Figure 5.2. Some case studies do not have the 14 days of evaluation period (x-axis) completed as they did not answer the survey on that day. Since in five case studies, only one person answered the survey and in the other five case studies there were two, the analysis of the right-now survey will have a part of the analysis where we want to check whether there is convergence or divergence of answers in the household where two people answered.

Both in summer and winter, the measurement intervals that have the closest values, in general, are between 9 a.m. and 12 p.m. and the closest hour the occupants answered the survey. On certain days when the occupants answered the survey, the daily values were closer to these other intervals, but this happens less often. This analysis applies to all the case studies. The fact that the "daily" time interval is generally further away from the others may be because it is a longer interval (24 hours) and may not reflect the use of HVAC equipment (heating and cooling). It should also be noted that in most of the cases analysed, the difference in temperature between these three-time intervals is around 0.5°/1° or less. In some cases, some days of the evaluation period have a greater difference and may reflect the use of air conditioning equipment or other actions carried out by the occupant.

Figure 5.1 and Figure 5.2 shows that the temperature profile of the three measurement periods in the living room does not always correspond to that of the bedroom, both in summer and winter, and this is more evident in some of the case studies. However, when we analyse it, it can be seen that the profile isn't always the same, but we're talking about scales of 0.5°C or 1°C, so it can be reflected in this way. It should also be noted that according to the analysis of Figure 5.1 and Figure 5.2, when comparing the temperatures obtained from the measurements in the living room and the bedroom, it turns out that there are no significant differences in mean temperature in the main bedroom and the living room (except in case studies 8 and 6 where these differences were more evident).

In Figure 5.2, the “Closest hour” data have two markers since two occupants of the same house answered the right-now survey. P1 are women, and P2 are men. These markers may not be close to each other because people could respond at different hours, resulting in different recorded temperatures.

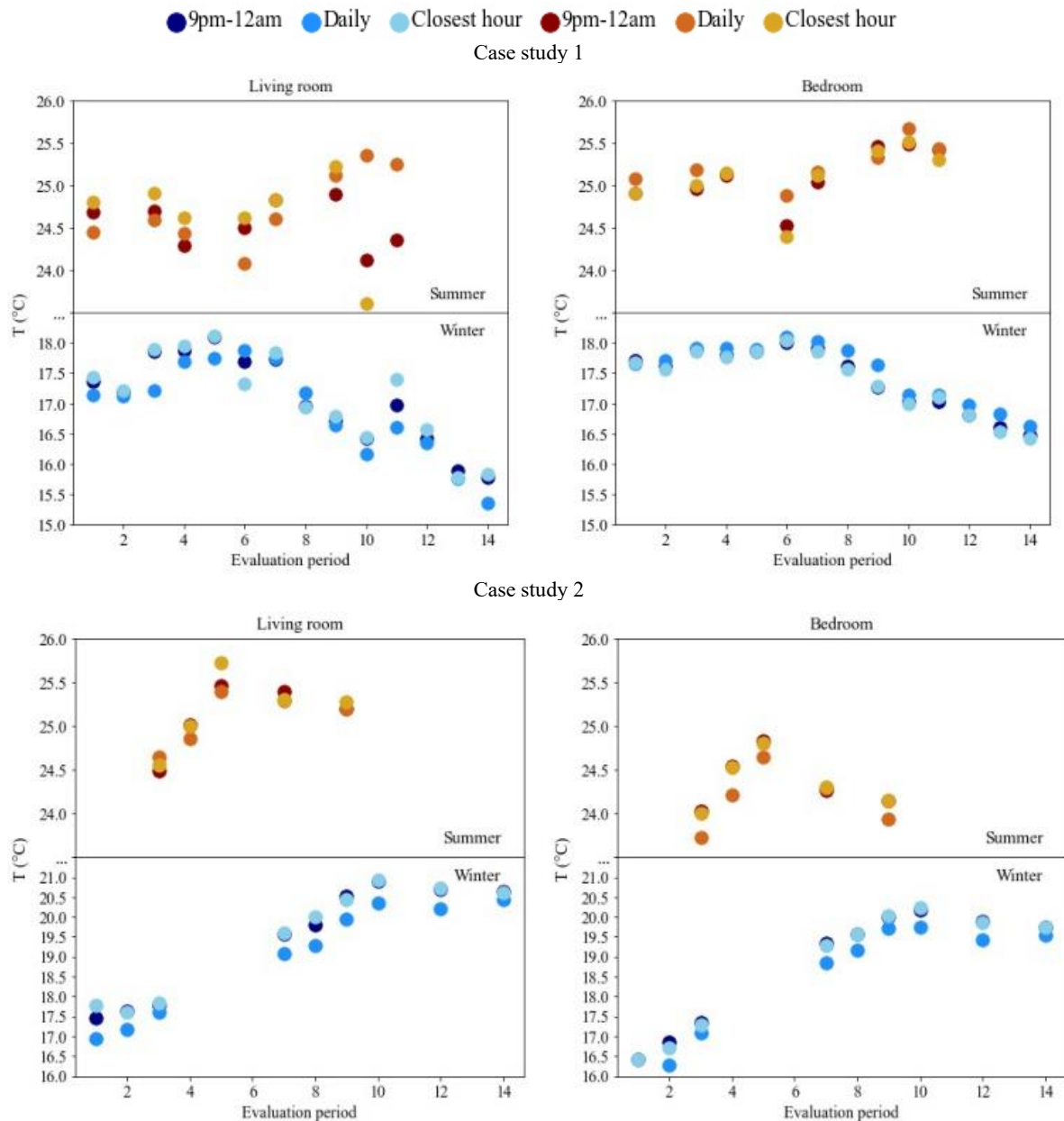
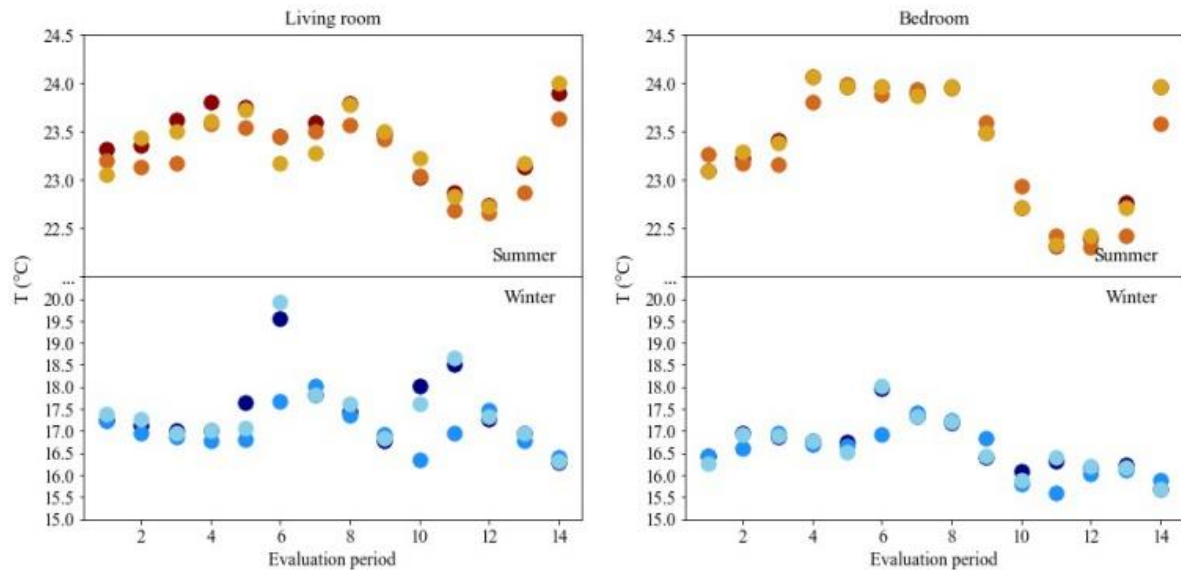


Figure 5.1 - Graphical representations of air temperature measurements intervals for each case studies (1-5) by compartment (living room and main bedroom) and by season (winter and summer)

Case study 3



Case study 4

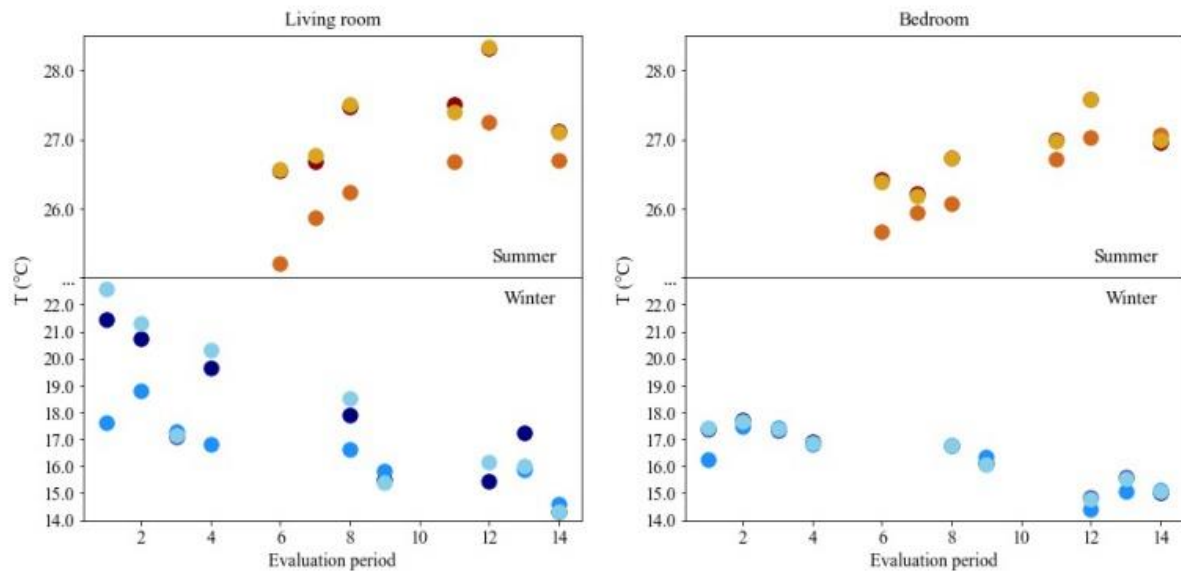


Figure 5.1 - Graphical representations of air temperature measurements intervals for each case studies (1-5) by compartment (living room and main bedroom) and by season (winter and summer) (cont.)

Case study 5

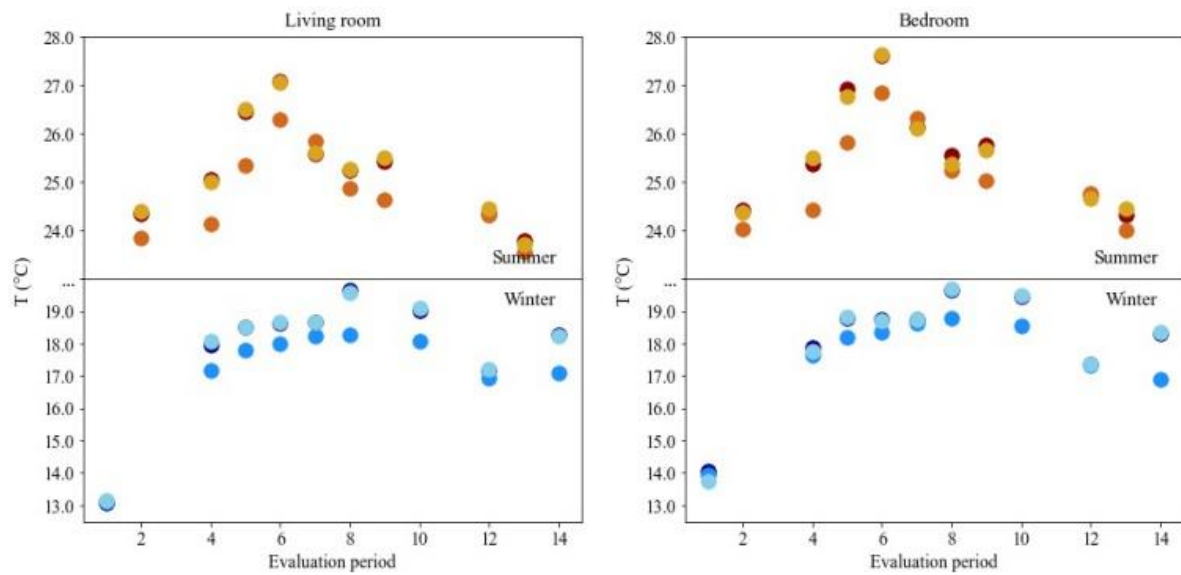


Figure 5.1 - Graphical representations of air temperature measurements intervals for each case studies (1-5) by compartment (living room and main bedroom) and by season (winter and summer) (cont.)

● 9pm-12am ◁ Closest hour P1 ● 9pm-12am ◁ Closest hour P1
 ● Daily + Closest hour P2 ● Daily + Closest hour P2

Note: P1 (◁) are women occupants and P2 (+) men occupants.

Case study 6

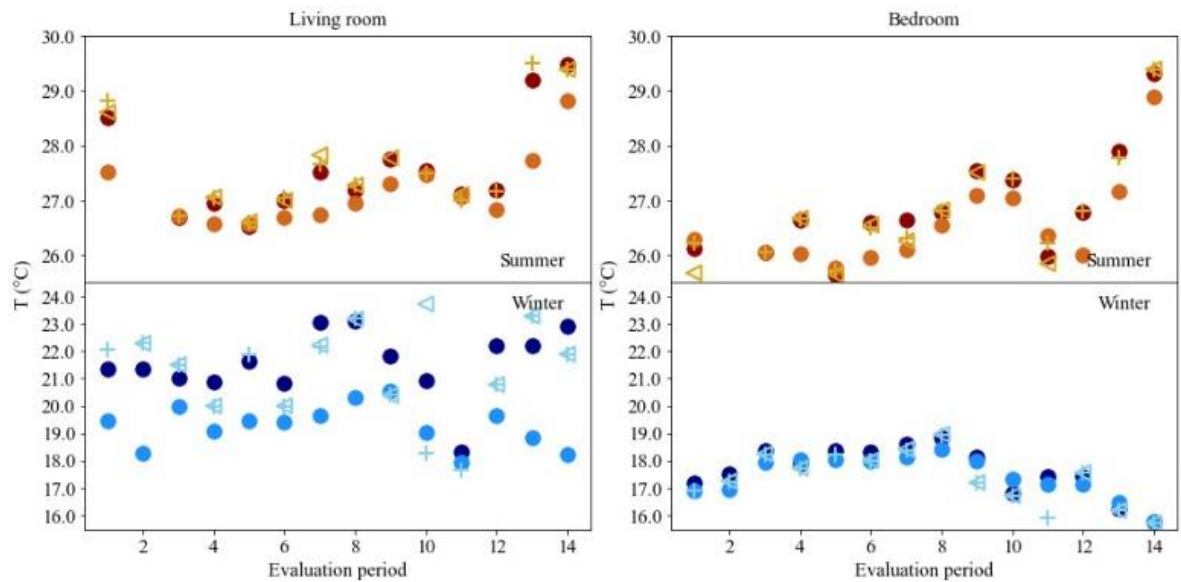
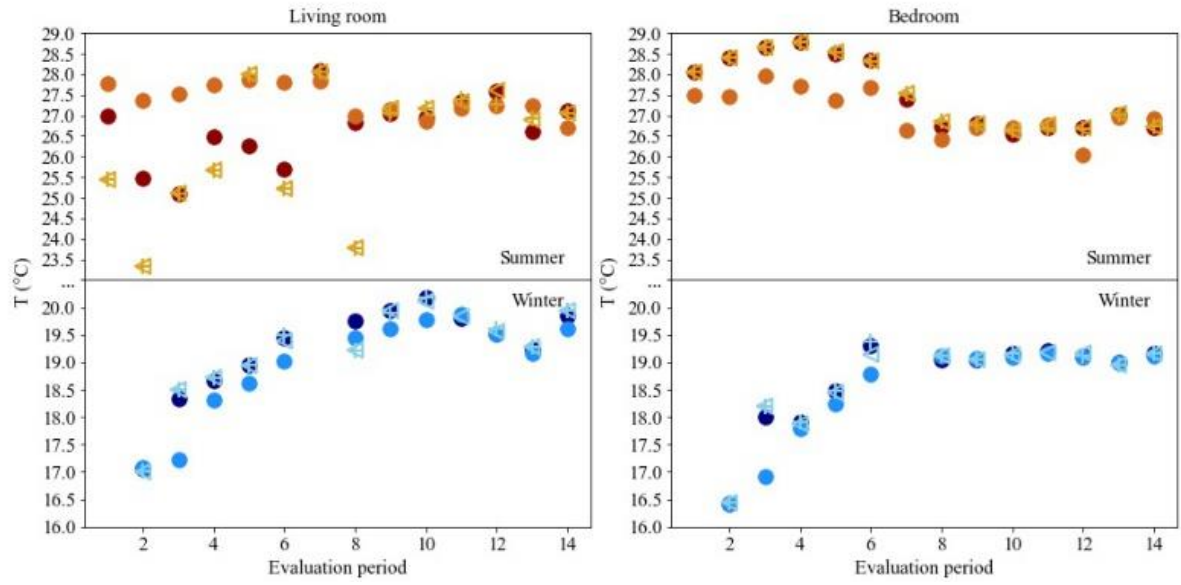


Figure 5.2 - Graphical representations of air temperature measurements intervals for each case studies (6-10) by compartment (living room and main bedroom) and by season (winter and summer)

Case study 7



Case study 8

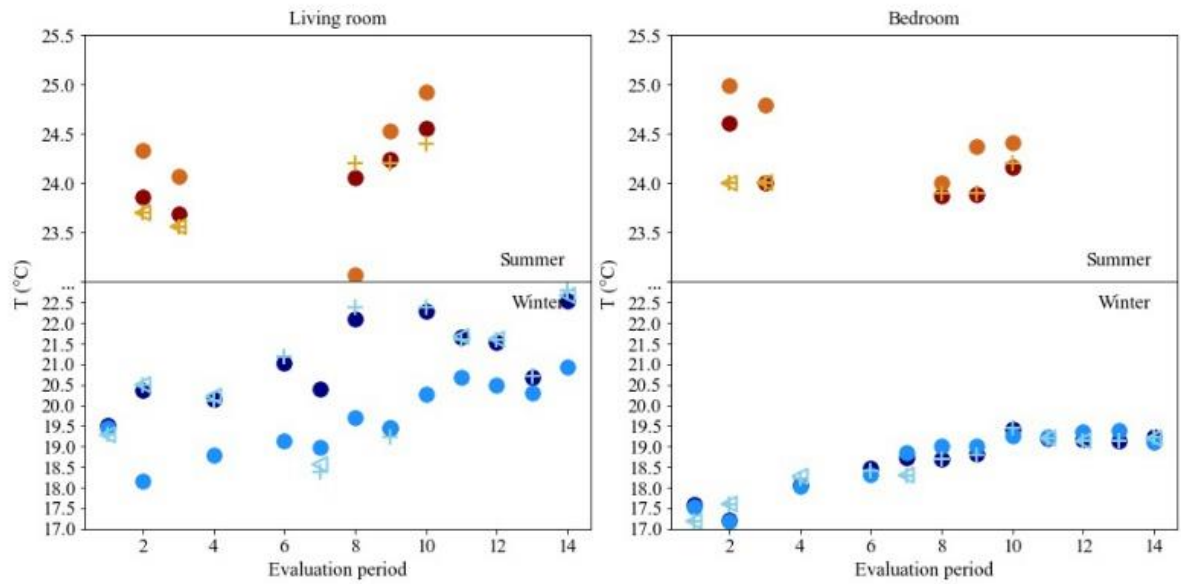
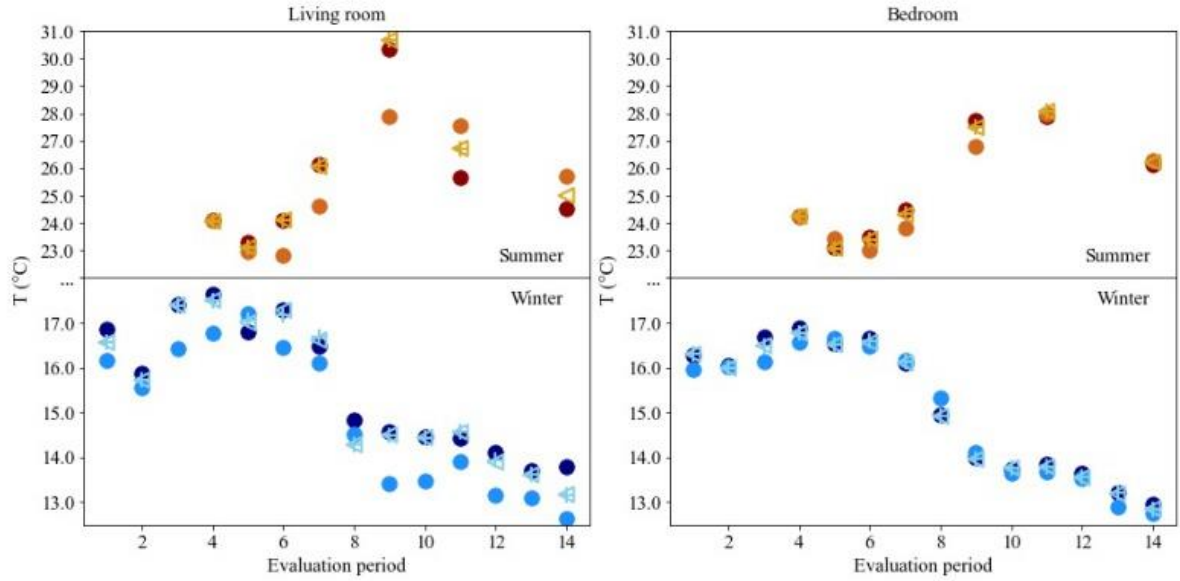


Figure 5.2 - Graphical representations of air temperature measurements intervals for each case studies (6-10) by compartment (living room and main bedroom) and by season (winter and summer) (cont.)

Case study 9



Case study 10

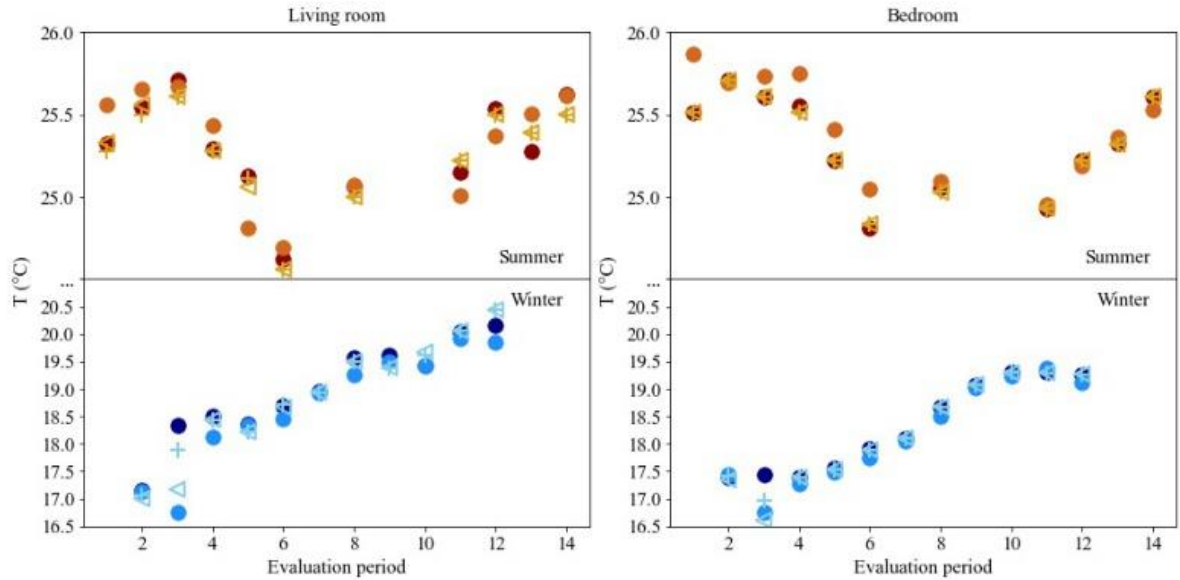


Figure 5.2 - Graphical representations of air temperature measurements intervals for each case studies (6-10) by compartment (living room and main bedroom) and by season (winter and summer) (cont.)

5.3. Measured indoor temperature and people's perception

This section is divided into the last four objectives listed in the beginning of the Chapter 5 to make the results more perceptible and intuitive. Knowing that one of the intentions of this right-now is to understand whether the occupants' perception of the indoor environment in the living room and bedroom is the same or different, it is necessary to consider the measured temperatures and the responses obtained in the survey. The temperature closest to the time when the occupants started answering the survey (Closest hour), the occupant's response to the thermal sensation at that moment and thermal comfort or discomfort were the variables considered to be obtained for each case study, the graphical representation shown in Figure 5.3 and Figure 5.4 (P1 is the indicator for women and P2 for men).

- **Relationship between measured indoor temperature and people's perception**

In case study 1, it can be seen that the occupant always indicates being slightly cool in the living room in the winter. In contrast, the occupant indicates being comfortable only a few times in the bedroom. However, they never said they felt uncomfortable with the temperature in these two rooms. Note that the occupant indicates being slightly cool and comfortable in the bedroom at the same/similar temperatures. In the summer, the occupant indicates that they are always comfortable.

The occupant of case study 2 indicates that in winter always feels neutral (comfortable) in the living room. In the bedroom, the occupant said that it was slightly cold and comfortable for same/similar temperatures. In the summer, the occupant indicates that sometimes was comfortable and sometimes was slightly hot (more so in the bedroom). The occupant never indicated discomfort with the living room and bedroom temperature to the thermal comfort/discomfort question.

In case study 3, it can be seen that the occupant indicates being slightly cold, slightly warm and comfortable in the living room in the winter. In the bedroom, the occupant said he was slightly cool but more often neutral (comfortable). In the summer, the occupant indicates that is more often neutral (comfortable) and sometimes slightly hot in the bedroom and living room. However, the occupant never indicates feeling uncomfortable with the bedroom and living room temperature but indicates different sensations in the living room and the main bedroom for the same/similar temperatures in winter and summer.

In case study 4, it can be seen that the occupant in winter indicates that the living room is slightly cold, slightly warm and comfortable. In the bedroom, the occupant said that was slightly cold more often and comfortable once. Sometimes, the occupant indicated feeling uncomfortable in terms of temperature in the bedroom and the living room when they indicated feeling slightly cold and even when indicated feeling comfortable. In summer, the occupant indicates that sometimes is comfortable and sometimes slightly warm and hot in the living room and slightly warm and hot in the bedroom. The occupant indicates different sensations and perceptions of comfort in the living room and bedroom for the same/similar temperatures in winter and summer. Therefore, the definition of comfort temperature ranges is not very clear, and it's challenging to make an analysis.

Generally, the occupant of case study 5 indicated that the living room and bedroom are neutral (comfortable) in winter and summer. Although, in summer, the occupant once indicated discomfort for a sensation "slightly warm". It should also be noted that when the occupant selects discomfort in the bedroom, on other days, he felt comfortable for the same/similar temperatures.

From here on, we'll look at case studies in which two people responded to the survey. In case study 6, it can be seen that in both winter and summer, occupant P2 identifies greater discomfort in the living room and bedroom compared to occupant P1. In general, it is in the bedroom where the discomfort is identified with more regularity and where the most extreme sensations (Hot and Cool) are indicated. This case study also shows that occupants identify different sensations for similar temperatures.

In case study 7, it can be seen that in winter, occupant P2 identifies greater discomfort in the living room and bedroom than occupant P1. In summer, both occupants reported feeling uncomfortable with the temperature in both rooms of the house. In general, it is in the bedroom where discomfort is most often identified. This case study also shows that occupants identify different sensations for similar/equal temperatures in the bedroom and the living room in summer and winter. In the figure, it's impossible to get a clear reading because the markers are all on "warm" with similar temperatures, but in the summer, in the bedroom, there are sensations identified as "warm" and a feeling of discomfort and others a feeling of comfort.

In case study 8, it can be seen that in winter, occupant P2 identifies greater discomfort in the bedroom than in the living room and also compared to occupant P1. In general, it is in the bedroom where discomfort is most often identified. It is also possible to see that the occupants identify different sensations for similar/equal temperatures in the bedroom and living room in both summer and winter. In summer, the analysis is done with little data collected, so it is necessary to be careful when analysing.

Case study 9 shows that occupants identify more discomfort in the bedroom than in the living room in both winter and summer. However, occupant P2 most often indicates that he doesn't feel "neutral (comfortable)" in winter. Overall, discomfort is most often identified in the bedroom. It also emerges that the occupants identify different sensations for similar/equal temperatures in the two rooms of the house in both summer and winter.

Finally, in case study 10, none of the occupants indicated feeling uncomfortable in any of the seasons or in any of the house's rooms being analysed. Occupant P2 said he felt "slightly warm" in the living room and bedroom in winter. Overall, the responses of the two occupants are similar, and there are no significant differences when analysing bedroom vs living room. As in the other cases, the occupants identify different sensations for similar/equal temperatures.

By analysing the recorded temperature and the answers of the occupants, it can be seen that in most case studies analysed, the occupants indicate two different sensations of the same/similar temperature; that is, sometimes, it is comfortable, and other times indicates, for example, slightly cool/hot. It also happens that occupants indicate the sensation neutral (comfortable) at a higher/lower temperature, and at an intermediate temperature, they indicate that they feel, for example, slightly cold or warm. Another finding is occupants are uncomfortable in temperatures that they've said they're comfortable in on another day. Having said that, this relationship between measured temperature and occupant sensation/perception is challenging to study and understand. However, this was expected since the literature already indicates that people's perception is subjective as it is affected by different variables such as how carefully they are answering the survey, their mood, and experiences, among others.

With regard to the case studies in which two people from the same house responded (case studies 6 to 10), the same can be seen in the previous paragraph. It can be seen that the occupants often disagree on the thermal sensation and comfort. This increases the complexity of analysing the case study because there are two different opinions/sensations for the same house, but it was also to be expected due to the subjectivity of analysing comfort and sensations.

For the purpose of simplifying the above analysis and drawing up comfort and discomfort ranges, taking into account the occupant responses (Table 5.6), the following was considered:

- Responses of feeling slightly cool, neutral and slightly warm are considered to be in the comfort range. When occupants select these sensations but indicate that they are uncomfortable (indicated by the "point/circle" marker in the graphical representations in Figure 5.3 and Figure 5.4), they are considered to be in a range of discomfort.
- Responses of cold, cool, warm and hot are always in the discomfort range, even if they didn't indicate discomfort. This decision was taken because it may have been an error not to indicate discomfort to those who may have responded to one of these four more extreme sensations.
- In the study cases in which two people responded, a discomfort range and a comfort range were created based on the responses of the two occupants and the above points.

Table 5.6 - Comfort and discomfort ranges for the case studies

Case study	Winter		Summer	
	Living room	Bedroom	Living room	Bedroom
1	Comfortable (15.8°C-18.1°C)	Comfortable (16.4°C-18.0°C)	Comfortable (23.3°C-25.2°C)	Comfortable (24.4°C-25.5°C)
2	Comfortable (17.6°C-20.9°C)	Comfortable (16.4°C-20.2°C)	Comfortable (24.6°C-25.7°C)	Comfortable (24.0°C-24.8°C)
3	Comfortable (16.3°C-19.9°C)	Comfortable (15.7°C-18.0°C)	Comfortable (22.7°C-24.0°C)	Comfortable (22.3°C-24.1°C)
4	Comfortable (15.4°C-22.6°C) Discomfortable (14.3°C-18.5°C)	Comfortable (16°C-17.4 °C) Discomfortable (14.8°C-17.4 °C)	Comfortable (26.8°C-27.5°C) Discomfortable (26.6°C-28.3°C)	Comfortable (26.8°C-27.5°C) Discomfortable (26.6°C-28.3 °C)
5	Comfortable (13.2°C-19.6°C)	Comfortable (13.7°C-19.7°C)	Comfortable (23.7°C-27.1°C)	Comfortable (24.4°C-27.6°C) Discomfortable (26.8°C)
6	Comfortable (20.0°C-23.7°C) Discomfortable (17.7°C-22.1°C)	Comfortable (15.7°C-19.0°C) Discomfortable (15.7°C-18.4°C)	Comfortable (26.6°C-28.6°C) Discomfortable (29.4°C)	Comfortable (25.7°C-27.8°C) Discomfortable (26.8°C-29.4°C)
7	Comfortable (17.0°C-20.2°C) Discomfortable (19.3°C)	Comfortable (16.4°C-19.4°C) Discomfortable (18.9°C)	Comfortable (23.3°C-28°C) Discomfortable (25.4°C-28.1°C)	Comfortable (26.7°C-27.0°C) Discomfortable (26.6°C-28.8°C)
8	Comfortable (19.3°C-22.7°C) Discomfortable (18.6°C)	Comfortable (17.6°C-19.4°C) Discomfortable (17.2°C-18.4°C)	Comfortable (23.6°C-24.2°C) Discomfortable (24.4°C)	Comfortable (23.9°C-24.2°C)
9	Comfortable (13.2°C-17.5°C) Discomfortable (17.5°C)	Comfortable (13.5°C-16.8°C) Discomfortable (12.9°C-13.2°C)	Comfortable (23.1°C-30.7°C) Discomfortable (26.1°C)	Comfortable (23.1°C-27.5°C) Discomfortable (24.3°C-28.1°C)
10	Comfortable (17.0°C-20.4°C)	Comfortable (16.6°C-19.3°C)	Comfortable (24.6°C-25.6°C)	Comfortable (24.6°C-25.7°C)

- **People's perception of the thermal environment between the living room and the bedroom and the relevance of measuring the air temperature in these two rooms, taking into account the survey answers**

When the perceptions obtained by the right-now survey are analysed between the bedroom and the living room, it can be seen that the perception of the thermal sensation felt in the living room and bedroom does not always coincide in all the case studies. This difference in responses occurs in the winter in case all the case studies except case study 5 and in the summer in all case studies except case studies 1 and 10. In case studies 7 and 10, the P2 occupants also reported no difference in winter, and in case studies 6 and 8, the P1 occupants also reported no difference in the summer. In some cases, this difference only occurs on one of the days when the right-now survey is implemented; in others, it occurs on more days.

Still, even when the recorded temperatures are analysed, there is no apparent justification regarding the difference in temperature between the bedroom and the living room as to why these perceptions are different. Possible justifications could be that people's perceptions are influenced by their state of mind, their mood, their experiences, the way they have lived through the day and also the way they view their home. In other words, a person may have the intrinsic feeling that the bedroom is colder than the living room, or vice versa, and in fact, the temperature recorded does not show this.

- **People's perception of thermal comfort in the indoor environment in the year's more extreme/cooler seasons**

By analysing the perception of thermal comfort felt by the occupants in the interior environment, from the data collected, it is impossible to say clearly whether the houses under analysis provide greater comfort or discomfort in summer or winter. However, in case study 1, it can be seen that the occupant feels more discomfort in winter than in summer. In case study 5, the occupant feels more discomfort in summer than in winter, just in the bedroom.

However, since the responses are not massive, there is doubt as to whether this discomfort indicated is really real or it is just for the day of the response. It may be that with the extensive survey, it is more accurate to see if the occupant indicates a greater discomfort in some of the more extreme seasons of the year since this right-now survey only analyses those days on which the right-now survey methodology has been implemented.

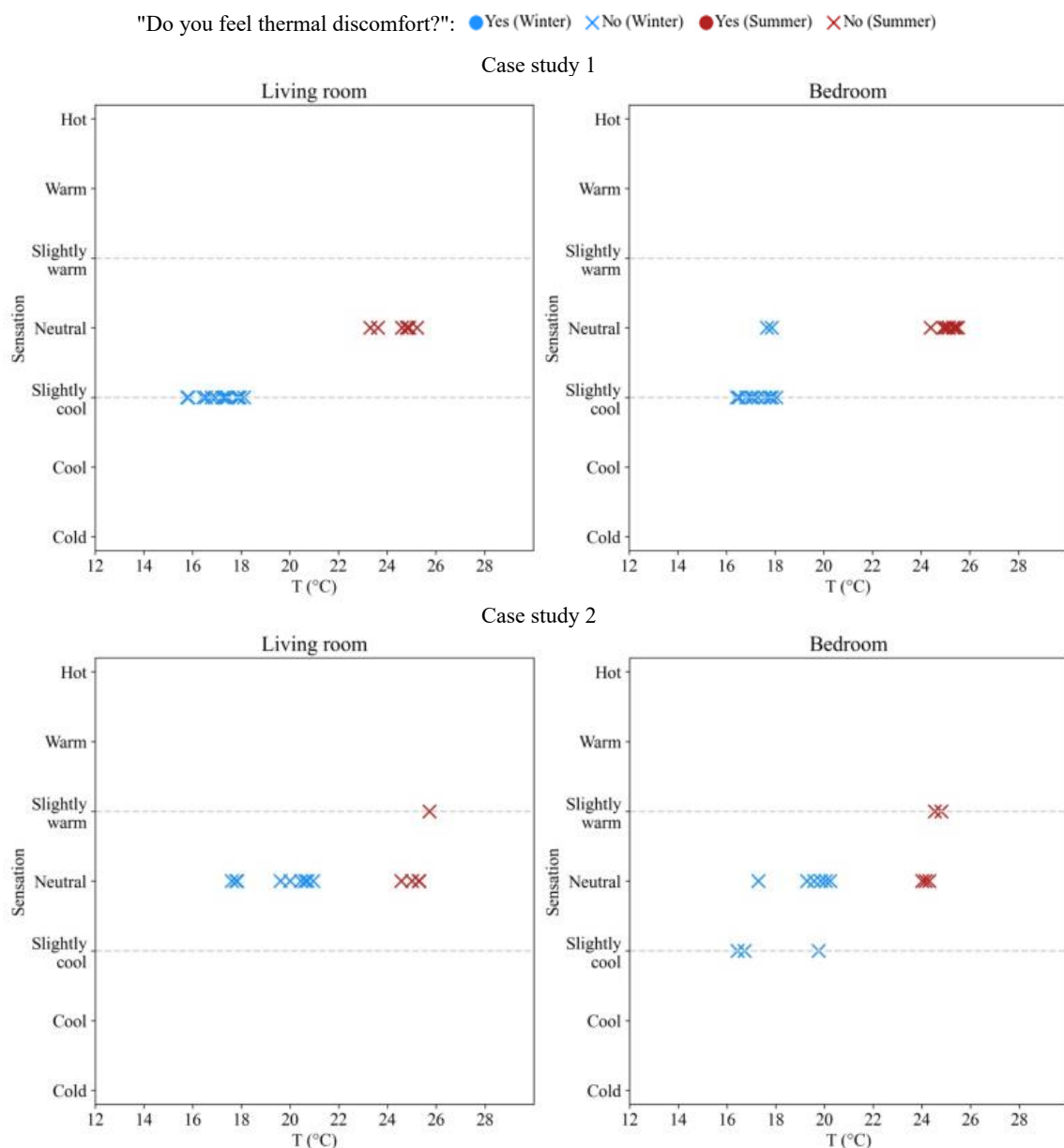


Figure 5.3 - Graphical representations of air temperature measurements and sensation for each case studies (1-5) by compartment (living room and main bedroom) and by season (winter and summer)

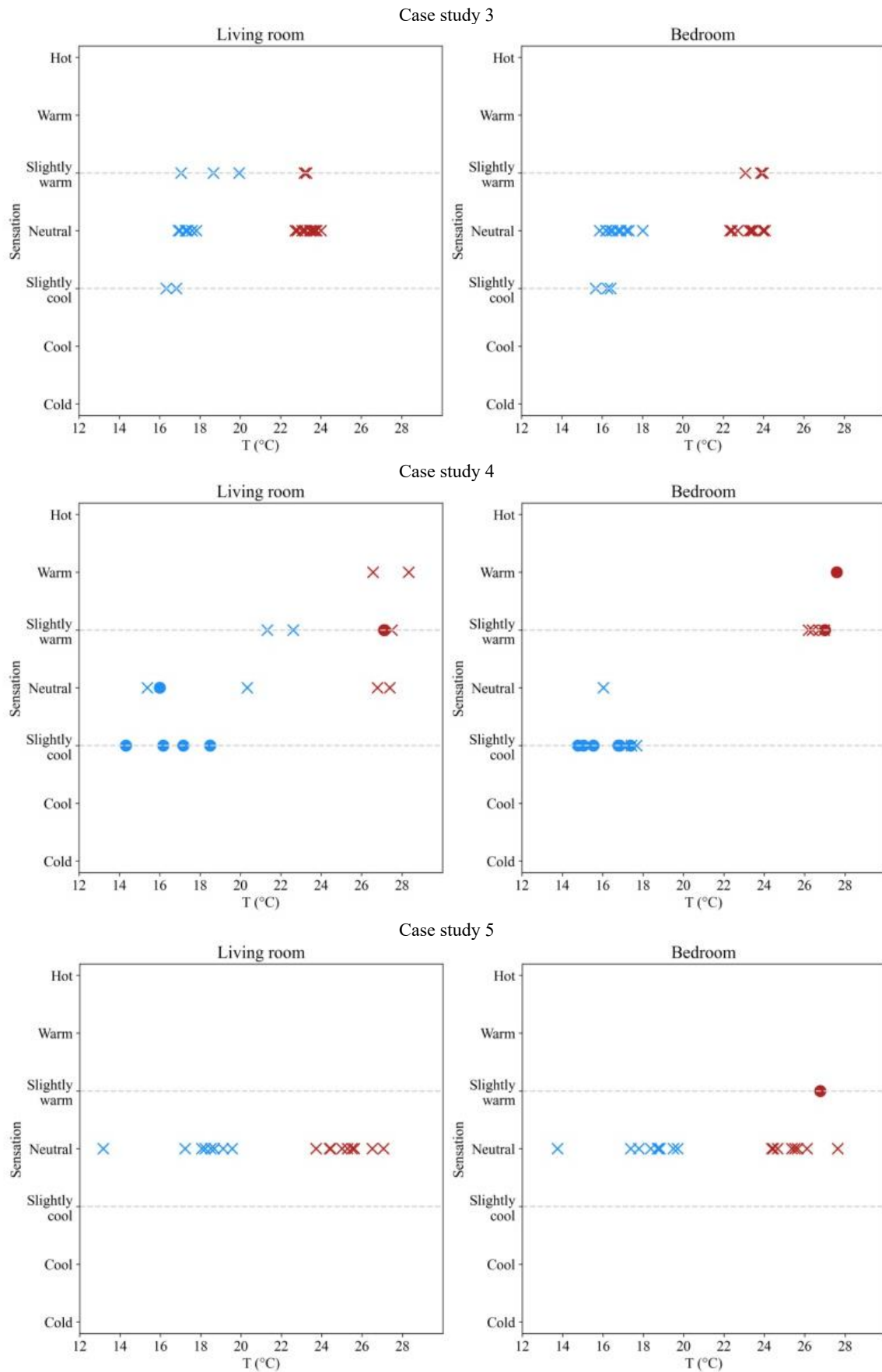


Figure 5.3 - Graphical representations of air temperature measurements and sensation for each case studies (1-5) by compartment (living room and main bedroom) and by season (winter and summer) (cont.)

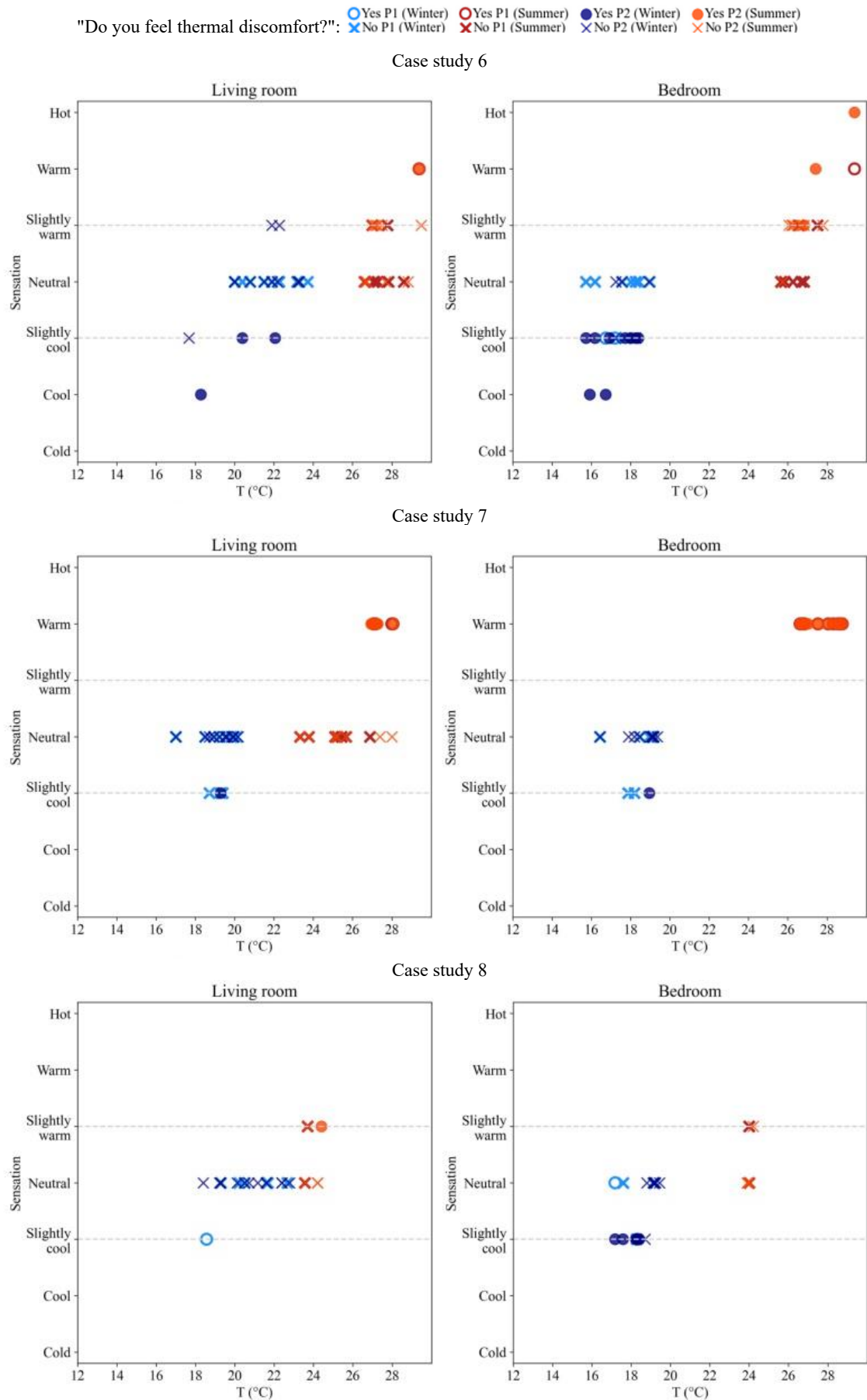


Figure 5.4 - Graphical representations of air temperature measurements and sensation for each case studies (6-10) by compartment (living room and main bedroom) and by season (winter and summer)

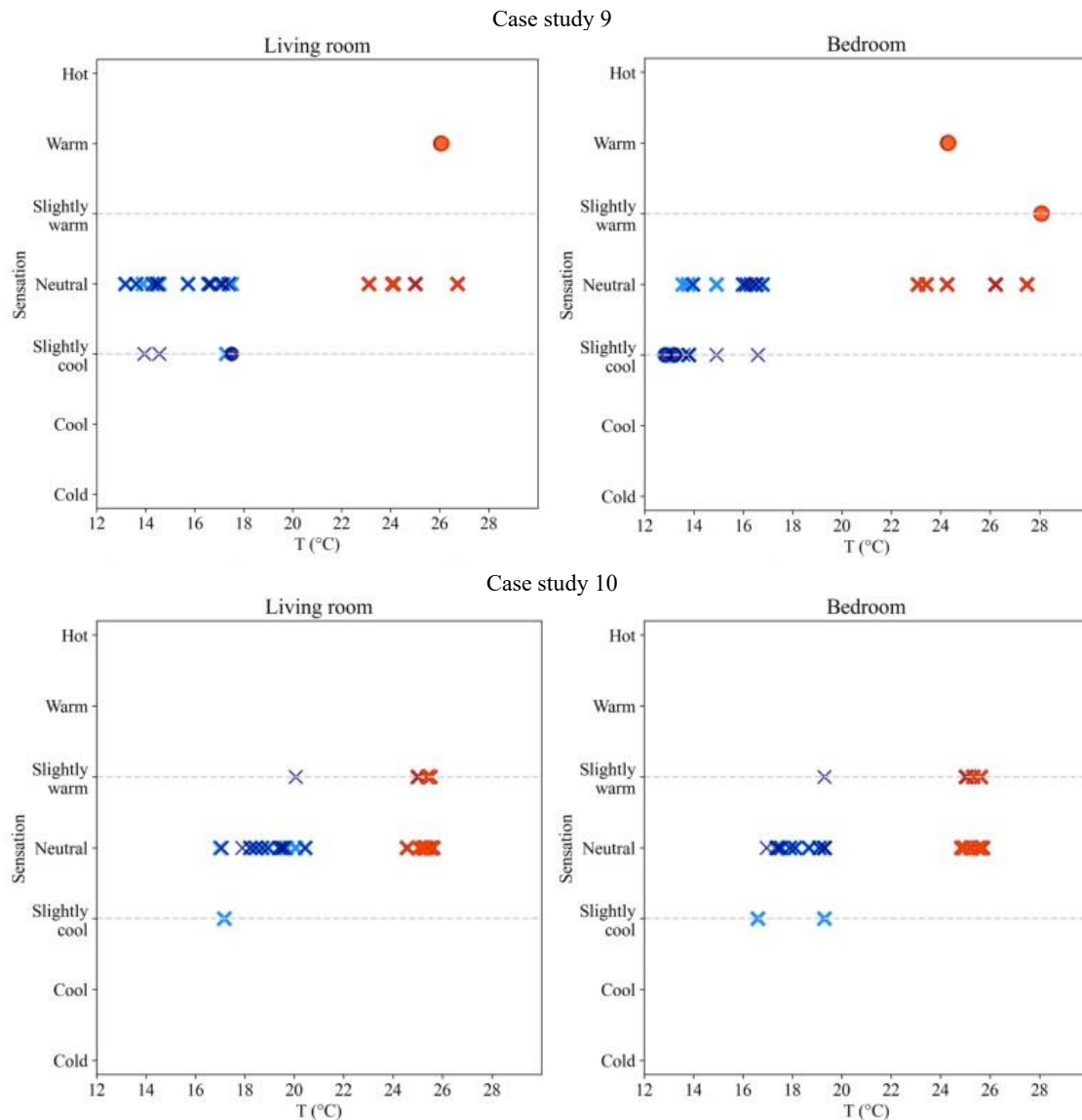


Figure 5.4 - Graphical representations of air temperature measurements and sensation for each case studies (6-10) by compartment (living room and main bedroom) and by season (winter and summer) (cont.)

When the occupants indicated that they felt thermally uncomfortable, they were asked what measures they could implement to stop being uncomfortable. Typically, the occupants of the various case studies indicated turning on the heating or cooling equipment, dressing warmly or wearing cooler clothes, closing or opening the windows to the outside or closing the external blinds.

Although this study has case studies with different constructions and locations, it is not possible to conclude that better constructions bring greater comfort. Some case studies of older construction present, for the measurement period, minimum and maximum temperatures more extreme and the occupant(s) indicated always or mostly felt comfortable, than other case studies with a more recent construction. This may be because the perception of a given person who lives in a given house depends a lot on that specific person, their perception of their home, and what your demands and life experiences are. Nevertheless, it is recognised that the conditions of more recent constructions with rigorous construction may be better for the occupants in all aspects of comfort.

5.4. Other survey topics

- **Discomfort**

To the question of whether the occupant feels discomfort at the moment they are answering the survey, there were hypotheses for discomfort such as temperature, lighting, indoor air, acoustics or others. Chapter 0 already analysed the answers obtained for thermal discomfort (shown in Figure 5.3 and Figure 5.4). The aim of this chapter is to realize whether occupants feel discomfort in other areas of comfort and well-being.

In the summer, only occupant P2 of case study 7 reported twice feeling uncomfortable with the indoor air in the bedroom and living room. In the living room, occupant P1 of the same case study identified being uncomfortable with the indoor air once. In no other case study was discomfort identified in the living room and/or bedroom in the summer when completing the survey. To avoid discomfort, the occupants of case study 7 indicated that the measures to be taken are to open the windows to the outside.

In winter, occupant P2 of case study 7 identified discomfort with indoor air nine times, lighting five times and humidity in the bedroom once. Occupant P1 of the same case study identified feeling uncomfortable with the indoor air in the bedroom once. To avoid this discomfort, the occupants indicated that opening the windows to the outside, turning on the dehumidifier, and opening the blinds would be measures to take. Occupant P2 of case study 6 also identified once feeling uncomfortable about the lighting in the bedroom and once about the whole air in the living room.

Having said that, it can be seen that only the occupants of case study 7 indicated feeling discomfort about factors other than temperature, as did occupant P2 of case study 6. All the other occupants of the other case studies never indicated feeling discomfort about factors other than temperature.

- **HVAC, blinds and windows use**

In the survey, the occupants were asked how often and how they used the windows, blinds and air conditioning equipment throughout the day in the living room and bedroom. They were also asked how these systems were at the time they were answering the survey.

When analysing Figure 5.5, it can be seen that the use of windows and blinds during the day is the same or very similar in all cases when comparing bedroom vs living room in winter. In summer there are more differences. Case studies 6 and 9 do not have these two columns filled in the living room since this compartment in these case studies is indoors and has no windows. Analysing the use of air conditioning equipment, it is more used in the living room during the day than in the bedroom, both in winter and summer.

Looking at the results obtained in Figure 5.6, it can be seen that at the moment the occupants answered the survey, in winter, the windows are generally closed in all the case studies, both in the bedroom and in the living room. In summer it is more common to find that the occupants have the window closed when they are answering the survey. As for the blinds, in winter, most of the time and most of the case studies have the blinds closed at the moment the occupants answered. In summer, they are more regularly open. As was seen in the questions about the use of air conditioning equipment during the day, these questions also show that at the moment they are answering the survey, air conditioning equipment is used more in the living room than in the bedroom in general in all cases, both in winter and summer.

Both in the analysis of Figure 5.5 and in the analysis of Figure 5.6, it is possible to see that in the case studies in which two people answered for the same house (case studies 6 to 10), there is not always convergence in the answers given. This may be because one of the occupants did not know precisely what happened at home during the day and assumed what had happened. The other occupant has more

information either because he was at home or does more of this type of work at home or for some other reason. Although there isn't always convergence on every day's response, looking from a general perspective and considering all the responses there is convergence in what is usual in the use of the systems.

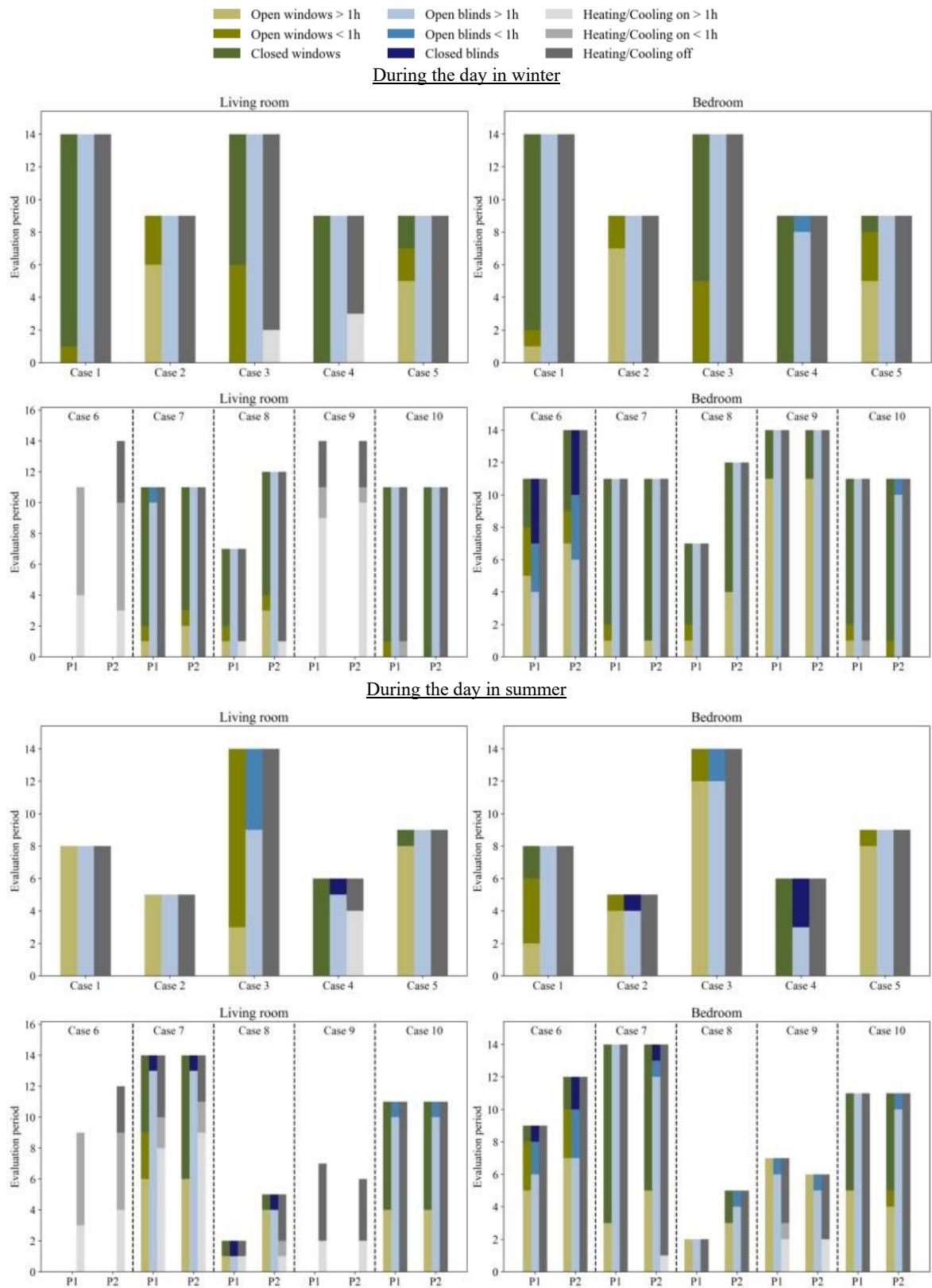


Figure 5.5 - Graphical representations of the use of windows, blinds and HVAC during the day for each case studies by compartment (living room and main bedroom) and by season (winter and summer)

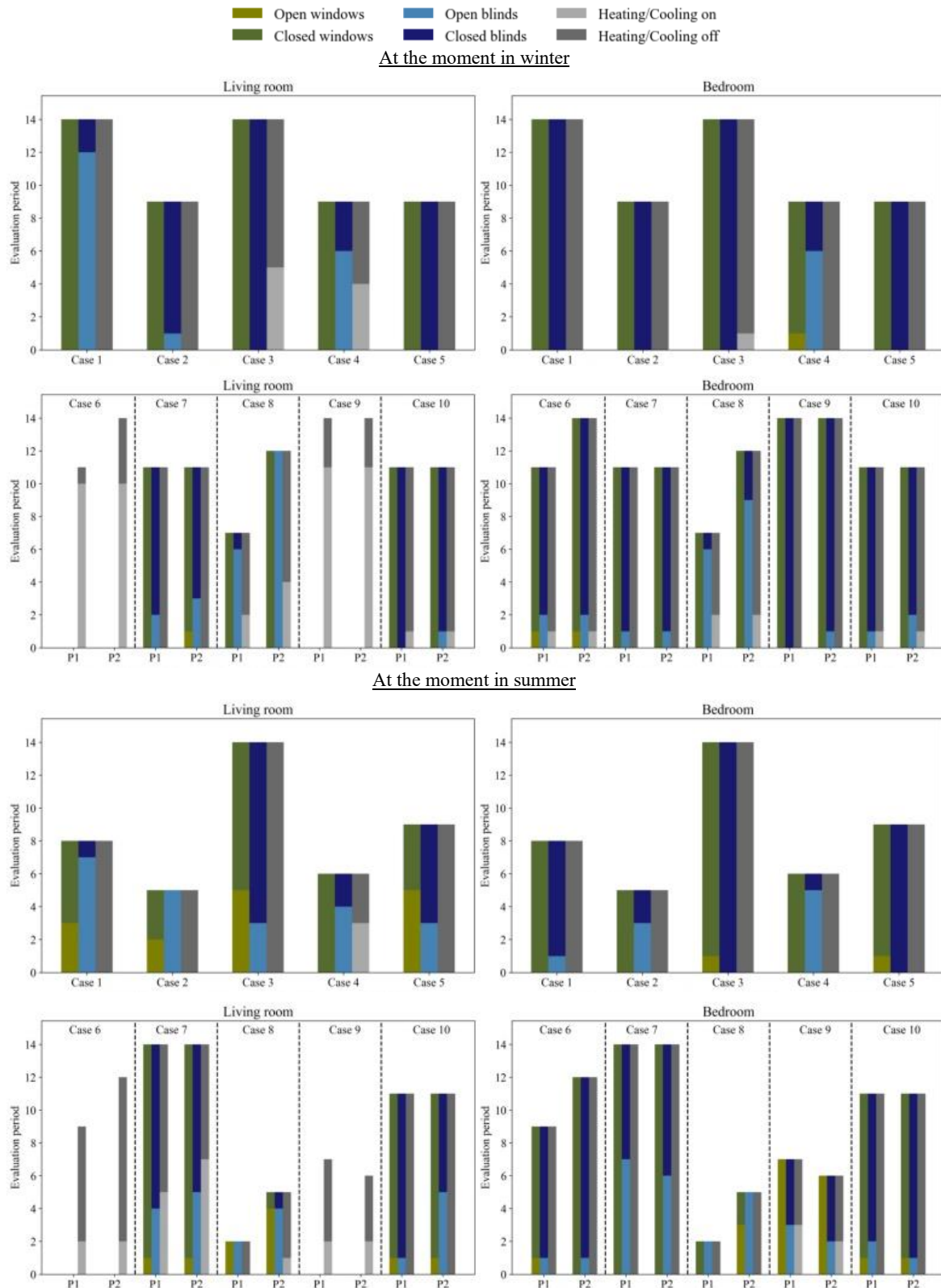


Figure 5.6 - Graphical representations of the use of windows, blinds and HVAC at the moment of filling the survey for each case studies by compartment (living room and main bedroom) and by season (winter and summer)

After this analysis, it was considered relevant to summarise the information in Table 5.7 and Table 5.8, checking whether there was a pattern in the answers given. Checking whether there is a pattern in the behaviour of using these systems is essential not only to compare with the answers obtained in the extensive survey but also to identify whether the people in a given house have a systematic behaviour, a habit, or not. This analysis can be relevant when proposing measures to improve energy efficiency.

The analysis of Table 5.7 and Table 5.8 shows that in most of the study cases the occupants showed a pattern in their behaviour towards the systems during the day and at the time they were filling in the survey. It can also be seen that by analysing the bedroom versus the living room, it is possible to verify that there are few case studies with behavioural differences concerning the systems. However, it should be emphasised that some cases have few responses, not enough to complete the 14-day right-now survey. Therefore, it is necessary to be cautious in this analysis, as these results can be compared and analysed with the results obtained in the extensive survey.

Table 5.7 - Typical behaviour regarding the use of windows, blinds and HVAC during the day occupants filled the right-now survey

		During the day					
		Winter			Summer		
Case study	Room	Windows	Blinds	Heating	Windows	Blinds	Cooling
1	LR	Closed	Open >1h	Off	Open >1h	Open >1h	Off
	B	Closed	Open >1h	Off	Closed/Open <1h/ >1h	Open >1h	Off
2	LR	Open >1h	Open >1h	Off	Open >1h	Open >1h	Off
	B	Open >1h	Open >1h	Off	Open >1h	Open >1h	Off
3	LR	Closed/Open <1h	Open >1h	Off	Open <1h	Open >1h	Off
	B	Closed	Open >1h	Off	Open >1h	Open >1h	Off
4	LR	Closed	Open >1h	Off	Closed	Open >1h	On >1h
	B	Closed	Open >1h	Off	Closed	Closed/Open >1h	Off
5	LR	Open >1h	Open >1h	Off	Open >1h	Open >1h	Off
	B	Open >1h	Open >1h	Off	Open >1h	Open >1h	Off
6	LR	-	-	On <1h/>1h	-	-	On <1h/>1h
	B	Open <1h/>1h	Closed/Open <1h	Off	Open >1h	Open >1h	Off
7	LR	Closed	Open >1h	Off	Closed	Closed	On >1h
	B	Closed	Open >1h	Off	Closed	Closed	Off
8	LR	Closed	Open >1h	Off	Open >1h	Open >1h	Off
	B	Closed	Open >1h	Off	Open >1h	Open >1h	Off
9	LR	-	-	On >1h	-	-	Off
	B	Open >1h	Open >1h	Off	Open >1h	Open >1h	Off
10	LR	Closed	Open >1h	Off	Closed	Open >1h	Off
	B	Closed	Open >1h	Off	Closed	Open >1h	Off

Table 5.8 - Typical behaviour regarding the use of windows, blinds and HVAC at the moment occupants filled the right-now survey

		At the moment					
		Winter			Summer		
Case study	Room	Windows	Blinds	Heating	Windows	Blinds	Cooling
1	LR	Closed	Open	Off	Closed	Open	Off
	B	Closed	Closed	Off	Closed	Closed	Off
2	LR	Closed	Closed	Off	Open/Closed	Open	Off
	B	Closed	Closed	Off	Closed	Open	Off
3	LR	Closed	Closed	Off	Closed	Closed	Off
	B	Closed	Closed	Off	Closed	Closed	Off
4	LR	Closed	Open	Off/On	Closed	Open	Off/On
	B	Closed	Open	Off	Closed	Open	Off
5	LR	Closed	Closed	Off	Open	Closed	Off
	B	Closed	Closed	Off	Closed	Closed	Off
6	LR	-	-	On	-	-	Off
	B	Closed	Closed	Off	Closed	Closed	Off

Table 5.8 - Typical behaviour regarding the use of windows, blinds and HVAC at the moment occupants filled the right-now survey (cont.)

		At the moment					
		Winter			Summer		
Case study	Room	Windows	Blinds	Heating	Windows	Blinds	Cooling
7	LR	Closed	Closed	Off	Closed	Closed	Off/On
	B	Closed	Closed	Off	Closed	Closed/Open	Off
8	LR	Closed	Open	Off	Open	Open	Off
	B	Closed	Open	Off	Closed/Open	Open	Off
9	LR	-	-	On	-	-	Off
	B	Closed	Closed	Off	Open	Closed/Open	Off/On
10	LR	Closed	Closed	Off	Closed	Closed	Off
	B	Closed	Closed	Off	Closed	Closed	Off

- Weather

The occupants were asked how they thought the day had been: cold, mild, hot, bad, average and/or good. Respondents could select more than one option. This question seeks to understand whether the occupant's perception of the day influenced or coincided with what they said about the thermal sensation in the living room and bedroom. Figure 5.7 shows that the occupants of case studies 1 and 5 have very standardised responses to the weather and the thermal sensation. In case studies 2, 3 and 4, although the occupants had more varied answers regarding the weather, it is not possible to verify that there is a strong correspondence with their answers regarding the thermal sensation in the bedroom and/or living room. On some days, this correspondence occurred but on others it did not.

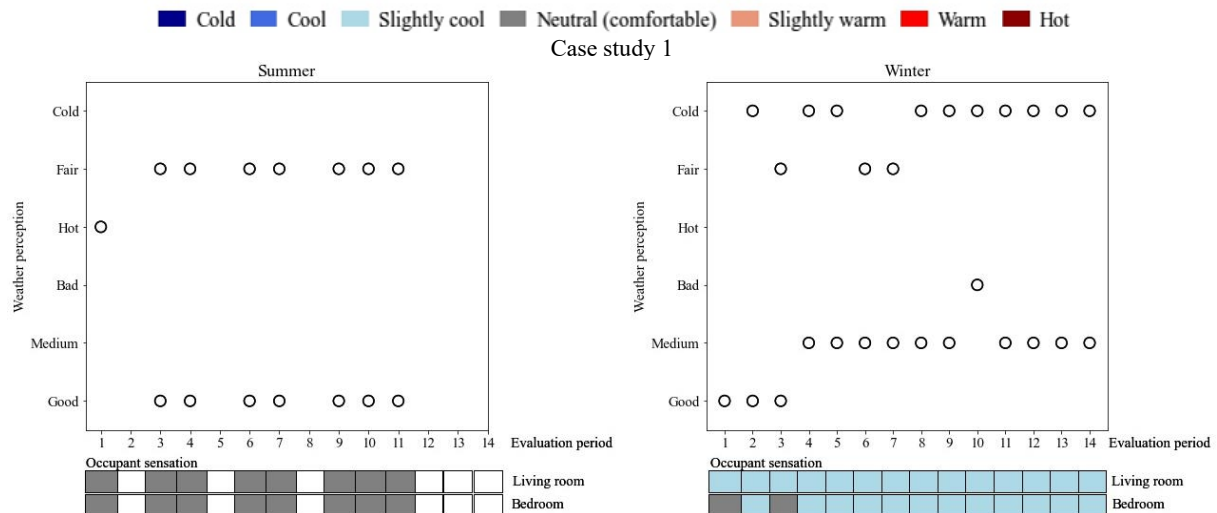


Figure 5.7 - Graphical representations of weather and thermal sensation perceptions for each case studies (1-5) by compartment (living room and main bedroom) and by season (winter and summer)

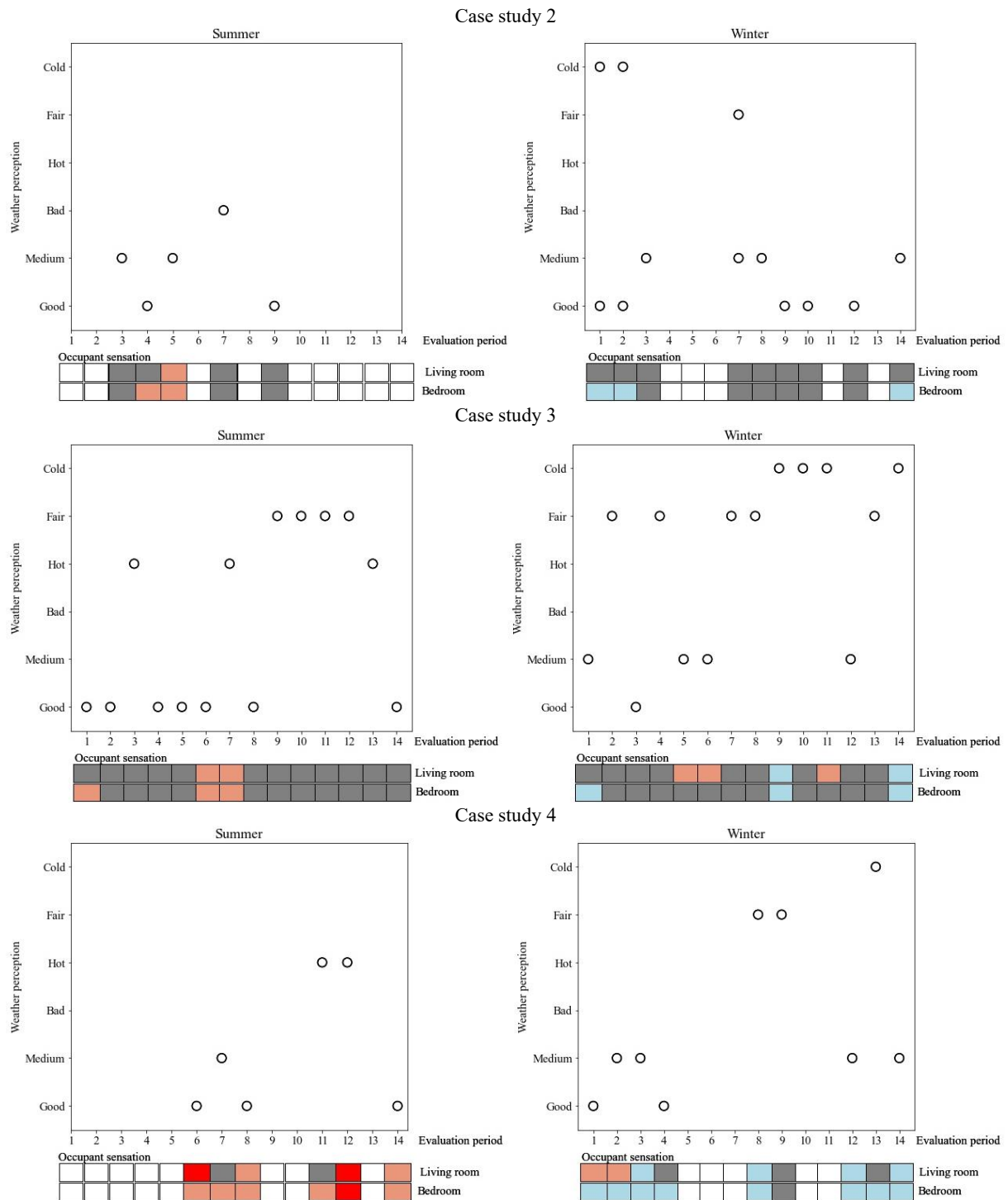


Figure 5.7 - Graphical representations of weather and thermal sensation perceptions for each case studies (1-5) by compartment (living room and main bedroom) and by season (winter and summer) (cont.)

Case study 5

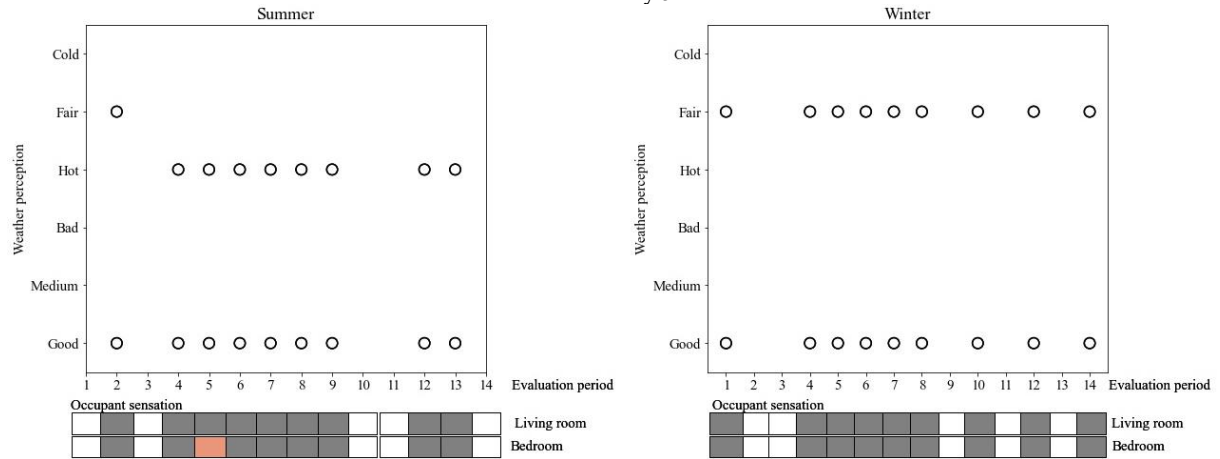


Figure 5.7 - Graphical representations of weather and thermal sensation perceptions for each case studies (1-5) by compartment (living room and main bedroom) and by season (winter and summer) (cont.)

Figure 5.8 also shows that the occupants of case studies 6 to 10 have varying responses relating to the weather. By analysing the correspondence with their answers regarding the thermal sensation in the bedroom and/or living room, it is not possible to verify that there is a relationship. On some days this correspondence/relationship occurs, but not on others.

■ Cold ■ Cool ■ Slightly cool ■ Neutral (comfortable) ■ Slightly warm ■ Warm ■ Hot
 Note: P1 (◁) are women occupants and P2 (+) men occupants

Case study 6

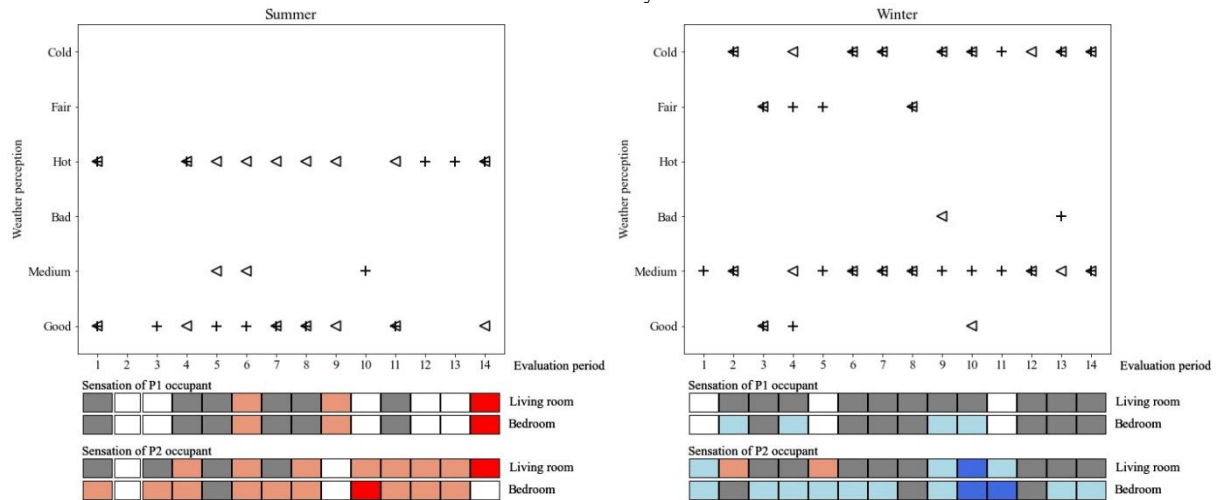


Figure 5.8 - Graphical representations of weather and thermal sensation perceptions for each case studies (6-10) by compartment (living room and main bedroom) and by season (winter and summer)

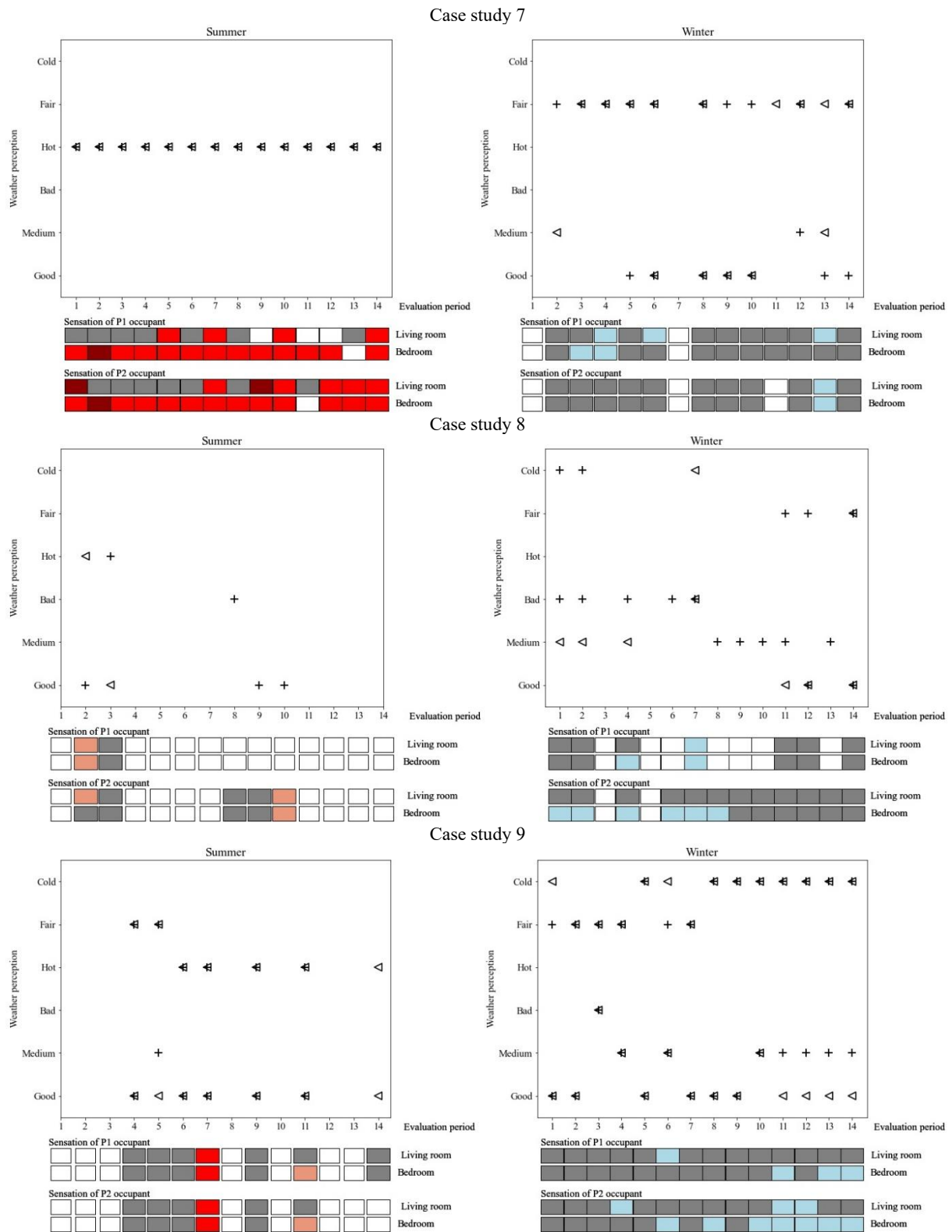


Figure 5.8 - Graphical representations of weather and thermal sensation perceptions for each case studies (6-10) by compartment (living room and main bedroom) and by season (winter and summer) (cont.)

Case study 10

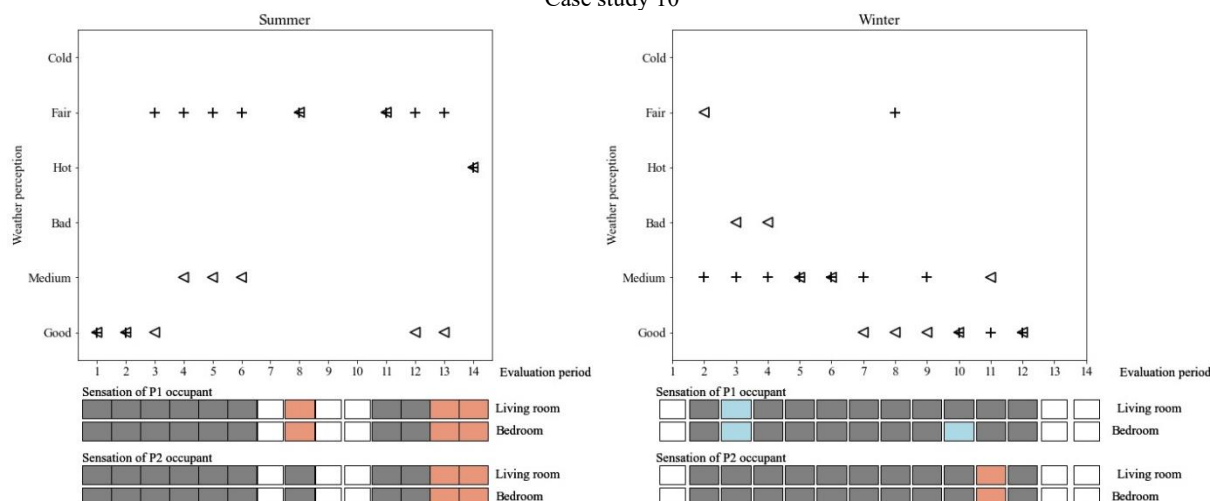


Figure 5.8 - Graphical representations of weather and thermal sensation perceptions for each case studies (6-10) by compartment (living room and main bedroom) and by season (winter and summer) (cont.)

• People in house

When asked how many people were at home during the survey, case studies 1, 5, 6, 8, 9, and 10 answered two people on most days. Case studies 3 and 4 answered one person. Case study 7 answered that three people were at home daily, while case study 2 answered that five were at home. This reveals that these are case studies with a diversity in the number of people who are typically at home. It was also found that there is consistency in the number of people who are usually in each house.

5.5. Conclusions of right-now survey

Comfort and well-being inside buildings, particularly homes, are increasingly important for construction and renovation. According to the literature, temperature is one factor that most influences home comfort and it was the parameter selected for this survey to be most focussed on. Knowing that the methodology used involved measurements of the indoor environment and daily surveys for 14 consecutive days in summer and winter, some conclusions were reached in the case studies analysed:

- In winter, the mean temperature of the living room and bedroom difference is below 0.6°C (including) in eight case studies, 0.9°C in case study 8 and the biggest difference in mean temperature between these two rooms is in case study 6, with 1.9°C of difference. In summer, this difference is below and including 0.6°C in nine case studies. In the case study 2, this difference is 1°C. Regarding the relative humidity, there is no case study in which the difference between the bedroom and living room is greater than 11% in summer or winter. Therefore, measuring two of the most used house rooms may not be justified since the temperature and relative humidity differences are not very significant. However, the maximum and minimum values recorded were quite different in some cases;
- The measurement intervals that have the closest values, in general, are between 9 a.m. and 12 p.m. and the closest hour the occupants answered the survey, both in summer and winter. The fact that the "daily" time interval is generally further away from the others may be because it is a longer interval (24 hours) and may not reflect the use of HVAC equipment during the day;
- The temperature profile of the three measurement periods in the living room does not always correspond to that of the bedroom in summer and winter. This is more evident in some of the case studies. However, when we analyse it, it can be seen that the profile isn't always the same, but we're talking about scales of 0.5°C or 1°C, so it can be reflected in this way. When comparing the mean temperature measurements during the right-now survey there are no significant

differences in the living room and the main bedroom (except in case studies 8 and 6, where these differences were more evident);

- Occupants indicate different sensations/perceptions for the same/similar air temperature. It also happens that occupants indicate the sensation neutral (comfortable) at a higher/lower temperature, and at an intermediate temperature, indicate that they feel slightly cold or warm. Also occurs that occupants indicate discomfort in temperatures that they've comfortable said in another day. Therefore, the relationship between measured temperature and occupant sensation/perception is challenging to study and understand because people's perception is subjective as it is affected by different variables, such as how carefully they answer the survey and their mood and experiences, among others;
- In case studies where two occupants respond to the survey, it was possible to verify that there is not always convergence in the answers regarding thermal sensation and comfort. This increases the complexity of analysing the case study since there are two different opinions/sensations for the same house. However, this was expected to happen since there is subjectivity in analysing comfort and sensation responses from occupants;
- Occupant perception of the bedroom and the living room thermal sensation does not always coincide in all the case studies despite the recorded temperatures not being significantly different between the bedroom and the living room. Possible justifications could be that people's perceptions are influenced by their state of mind, their mood, their experiences, how they have lived through the day, and how they view their house;
- From the data collected, it is not possible to say clearly whether the houses under analysis provide greater comfort or discomfort to the occupants in summer or winter. With the extensive survey some conclusions can probably be drawn, since there are more questions about thermal comfort in summer and winter. The right-now survey only analyses those days on which the right-now survey methodology has been implemented and the extensive survey refers to the entire seasons (winter and summer, general perception);
- From this study, it is not possible to conclude that better constructions bring greater comfort, even though it is recognised that more recent constructions with rigorous construction may be better for the occupants in all aspects of comfort. This could be due to the individual perception of each person, which depends a lot on their house perception, demands and life experiences;
- Regarding the case studies in which two people from the same house responded, it can be seen that the occupants do not always have a convergence in the answers. This could be because one of the occupants did not know precisely what happened at home during the day and assumed what had occurred. Although there isn't always convergence on every day's response, from a general perspective, considering all the responses, there is convergence in what is usual in the use of the systems;
- In most of the study cases, the occupants showed a pattern in their behaviour towards the systems (windows, blinds and HVAC) during the day and at the time they were filling in the survey. In the analysis of bedroom versus living room, it is possible to verify that there are few case studies with behavioural differences concerning the systems;
- Regarding the occupant's perception of the day weather influenced or coincided with their thermal sensation in the living room and bedroom, it is not possible to verify that there is a strong correspondence since some days this correspondence occurs, but not on others;
- All these conclusions or possible conclusions of the right-now survey are based on an analysis period of 14 days. The maximum number of possible responses was not reached in many case studies. Thus, it is necessary to be cautious in these analyses, and it will be important to check and compare with the results obtained in the extensive survey.

6. Extensive survey

The extensive survey pretends to evaluate the house as a whole and not a particular room. It addresses questions related to thermal comfort, acoustics, air quality and lighting, as well as broader questions relating to the view, furniture, building materials, and options that occupants prioritize, among other issues. As mentioned in the Methodology chapter, the questions are divided into groups: Thermal environment; Ventilation; Indoor air quality; Lighting; Acoustics/noise; Other housing characteristics; Furnishings, finishes and materials; Final considerations; and Respondent characteristics. The extensive survey was applied at two different times: at the end of winter and at the end of summer. Appendix B and Appendix C have extensive surveys applied in summer and winter, respectively.

The first time this survey was implemented, the occupants completed the entire survey. The second time, the occupants only filled out the 5 initial groups of questions (the other questions were irrelevant in summer versus winter comfort analysis). Over 1 year, the living room and outdoor temperature and relative humidity were monitored/recorded every 10 minutes in each case study.

After this summary of the methodology for implementing this survey, the objectives of using the extensive survey and the indoor environment measurements in winter and summer are to understand:

- Whether occupant's perception of comfort and well-being is different in the more extreme seasons of the year;
- The occupants' feedback on the perceived comfort and well-being of the dwelling, as well as their satisfaction with the various parameters;
- Which energy efficiency improvement measures should be considered, taking into account occupant feedback about the comfort and well-being of the dwelling;
- Relationship between measured indoor temperature and people's perception.

6.1. Measured indoor environment data

Over 1 year, the living room's indoor environmental data (temperature and relative humidity) was collected in each case study. The values were recorded every 10 minutes. Table 6.1 shows the mean temperature measurements for the four seasons. These values are essential for analysing the responses obtained in the extensive survey, particularly concerning thermal comfort. It can be seen that in winter and summer, in many of the study cases, the mean temperature is below 18°C and above 25°C, the range of values established by legislation. In some cases, they are only slightly outside the comfort range, but in other cases the difference is still significant. In some case studies they are outside the thermal comfort range in only one of the seasons and in other case studies in both seasons. In some case studies, mean relative humidity is not within the 50% to 70% range in at least one of the four seasons of the year. It should be noted that in winter there are case studies in which the range is slightly exceeded, but there is also a case in which the mean value does not reach 50%. The same in summer, where one case study exceeds 70% and the others that are not in the range indicated by the legislation are below 50 %.

Table 6.1 - Indoor measured mean air temperatures during one year, including during the extensive survey

Case study	Winter		Spring		Summer		Autumn	
	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
1	17.5	45.1	22.3	51.2	25.1	54.8	21.7	59.6
2	19.0	70.2	23.4	49.8	26.7	49.2	22.4	63.3
3	16.9	63.5	21.3	71.7	23.5	71.8	20.2	73.7
4	16.1	70.3	23.2	57.8	27.5	49.6	20.2	66.5
5	15.8	76.1	21.5	67.9	23.7	69.5	19.3	75.6
6	19.2	64.2	23.6	60.7	27.4	59.5	23.0	63.0
7	17.9	72.6	24.5	46.9	27.6	42.6	22.2	60.8
8	18.5	66.1	24.3	42.6	26.6	47.5	21.3	62.1
9	15.6	56.9	20.7	54.3	24.0	53.8	17.9	64.5
10	18.4	67.1	23.0	53.9	25.6	42.2	22.1	64.1

6.2.Satisfaction

In the survey, occupants were requested to indicate their level of satisfaction with the thermal comfort, air quality, lighting and acoustic quality of their home in summer and winter. From Figure 6.1 and Figure 6.2 and analysing all the cases together, it can be seen that thermal comfort is the most dissatisfying in both summer and winter. For some case studies, it is in summer that occupants indicate greater satisfaction with all these comfort parameters compared to winter. For other case studies, the opposite is true. It also occurs in case studies where more than one person responded that occupants have slightly and/or totally different levels of satisfaction. That said, it is necessary to evaluate each case individually. Since in five case studies, only one person answered the survey and in the other five case studies there were two, the analysis of the extensive survey will have a part of the analysis where we want to check whether there is convergence or divergence of answers in the household where two people answered.

Figure 6.1 shows that case study 1 did not indicate dissatisfaction with any of these comfort parameters in either summer or winter. On the other hand, case studies 2 and 3 did not indicate “slightly unsatisfied” in summer but did in winter with thermal comfort. Case study 2 occupant also indicated “slightly unsatisfied” with air quality. Case study 4 indicates “very unsatisfied” with thermal comfort in summer and “slightly unsatisfied” in winter, not only in thermal comfort but also in acoustics. Case study 5 indicates “slightly unsatisfied” in summer and winter with thermal comfort.

Analysing the case studies in which two people from the same house responded to the survey, Figure 6.2 shows that the level of satisfaction is not the same for the two occupants. In case study 6 it can be seen that both occupants are “slightly unsatisfied” with thermal comfort, but only occupant P1 is “slightly unsatisfied” with lighting in both seasons and occupant P2 with air quality in summer. Analysing case study 7, it can be seen that both occupants are “unsatisfied” with thermal comfort in the summer and occupant P2 identifies that it is “slightly unsatisfied” with air quality in the summer and “unsatisfied” with lighting in the winter. As for case study 8, only occupant P1 identifies feeling “slightly unsatisfied” in summer regarding air quality and acoustics. In case study 9, both occupants indicated they were “slightly unsatisfied” with thermal comfort in winter and only occupant P1 in summer. In case study 10, only occupant P1 is “slightly unsatisfied” with thermal comfort in the summer.

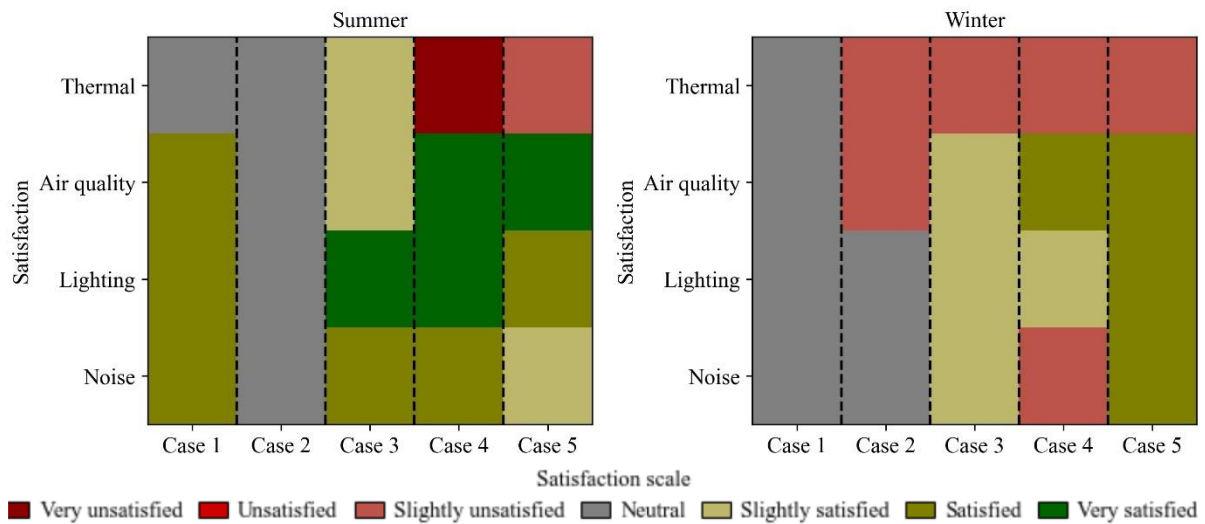


Figure 6.1 - Graphical representations of satisfaction for each case studies (1-5) by season (winter and summer)

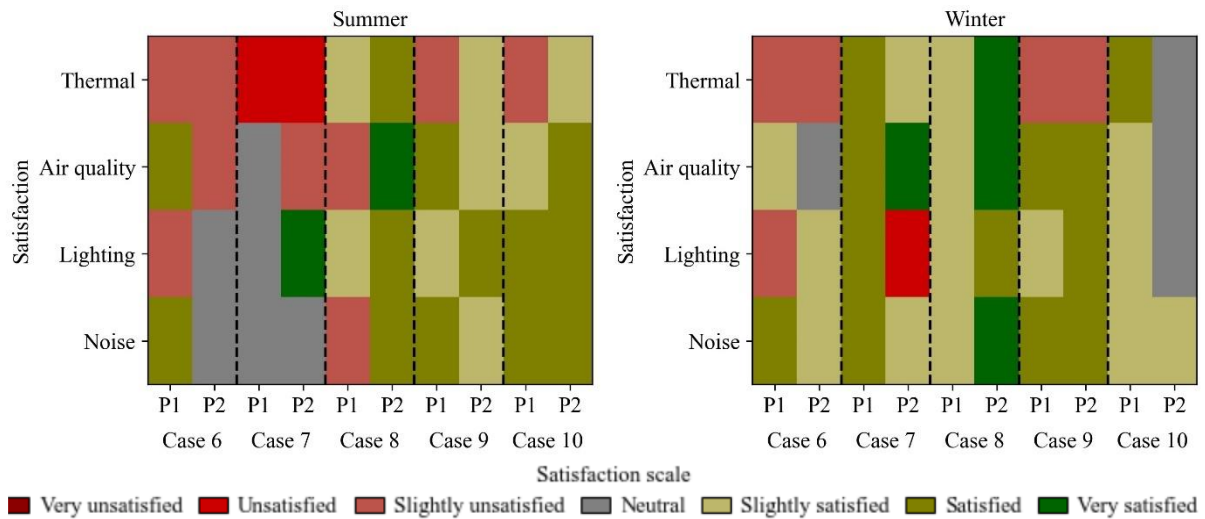


Figure 6.2 - Graphical representations of satisfaction for each case studies (6-10) by season (winter and summer)

In the survey, occupants were also asked to indicate their level of satisfaction with various parameters of comfort and well-being in their home throughout the year, namely privacy, maintenance of the home, furniture and other decorative and comfort elements inside the house, and finally, overall satisfaction with the home. These parameters were not differentiated by season (summer and winter). Figure 6.3 shows that case studies 1, 3, 4, 5 and 6 did not report any dissatisfaction. On the other hand, case study 2 indicated that it is “slightly unsatisfied” with privacy. Occupants P1 and P2 of case studies 8 and 10 also indicated “slightly unsatisfied” with privacy. In case study 7, occupant P2 is “very unsatisfied” with the maintenance of the house. Finally, occupant P1 of case study 9 indicates that he is “unsatisfied” with the maintenance and “slightly unsatisfied” with his home as a whole (Global).

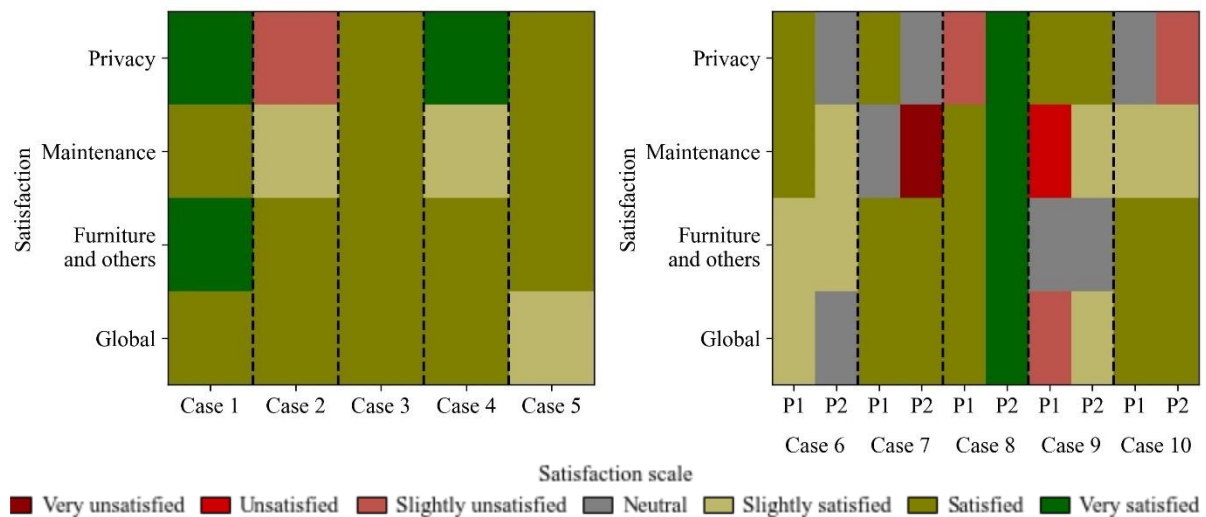


Figure 6.3 - Graphical representations of satisfaction for each case studies (1-10)

In case study 7, occupant P2 indicated that their satisfaction is "Very unsatisfied" with the maintenance of the house due to the lack of exterior paint on the building. In contrast, P1 indicated "Neutral" for the same cause as occupant P2. In case study 9, occupant P1 indicated that their satisfaction is "Unsatisfied" with the maintenance due to the state of the exterior paintwork and the roof.

The results obtained by analysing Figure 6.1, Figure 6.2 and Figure 6.3 are relevant to understanding which comfort and well-being parameters cause the greatest dissatisfaction among the occupants of the dwellings under study. Once these parameters have been identified, it is possible to draw up improvement measures for each case study, taking their perceptions into account so that they lead to an increase in the comfort and well-being of the occupants and an improvement in the energy efficiency of the dwelling. The following chapters aim to get to know some of these parameters in greater depth so that improvement measures can be drawn up in more detail and focus.

6.3. Thermal environment

Figure 6.4 and Figure 6.5 represent the thermal sensation that the occupant usually has inside the house, the level of clothing and the temperature preference, i.e. whether the occupant would prefer the house to be cooler, warmer or unchanged from what it usually is. The occupants were asked to indicate the level of clothing they typically wear inside their home since it is known that the level of clothing affects thermal insulation and the feeling of thermal comfort.

Figure 6.4 and Figure 6.5 shows that in summer, in all the case studies, the occupants usually wear cool clothes, and practically all of them indicate that the house is in one of the three options: slightly warm, warm or hot. Case study 1 and occupant P2 of case study 8 say they are usually neutral (comfortable). Almost all of them also indicate that they would like the temperature to be cooler than it usually is. In winter, in all the case studies, the occupants wear warmer clothes than in summer. In most case studies, the occupants indicate that the thermal sensation in their home is slightly cool, cool or cold. Only in case study 8 is indicated that the sensation is slightly warm and cases 1 and 10 indicate that they are neutral (comfortable). Occupant P1 of case study 7 also reports being comfortable. With the exception of case study 8 and occupant P1 of case study 7, who want the temperature to remain unchanged, all the other occupants say they prefer warmer temperatures than those they usually experience.

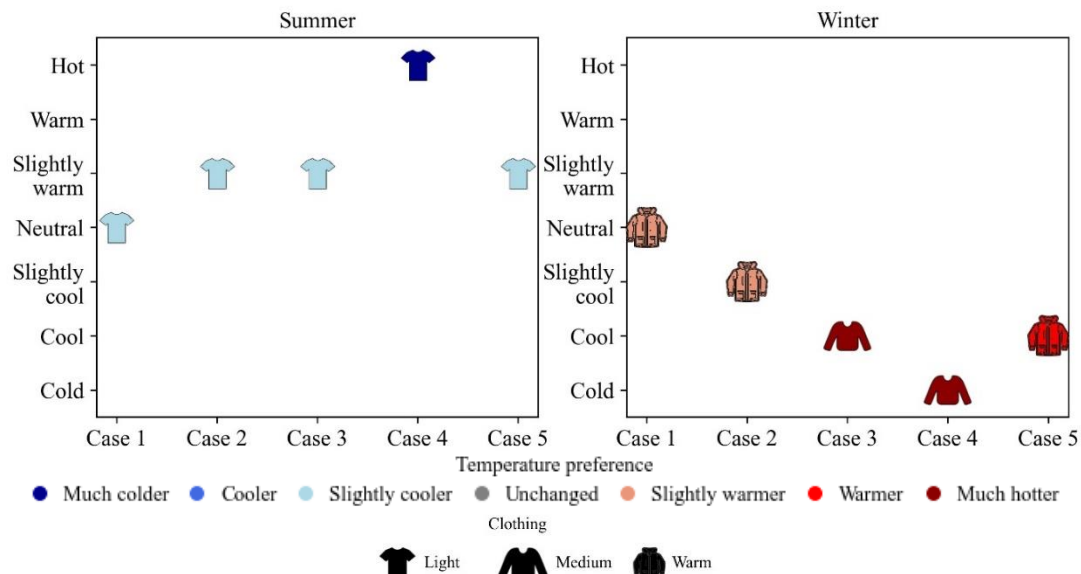


Figure 6.4 - Graphical representations of the indoors thermal sensation and preference and type of clothing that occupant usually wears indoors for each case study (1-5) by season (winter and summer)

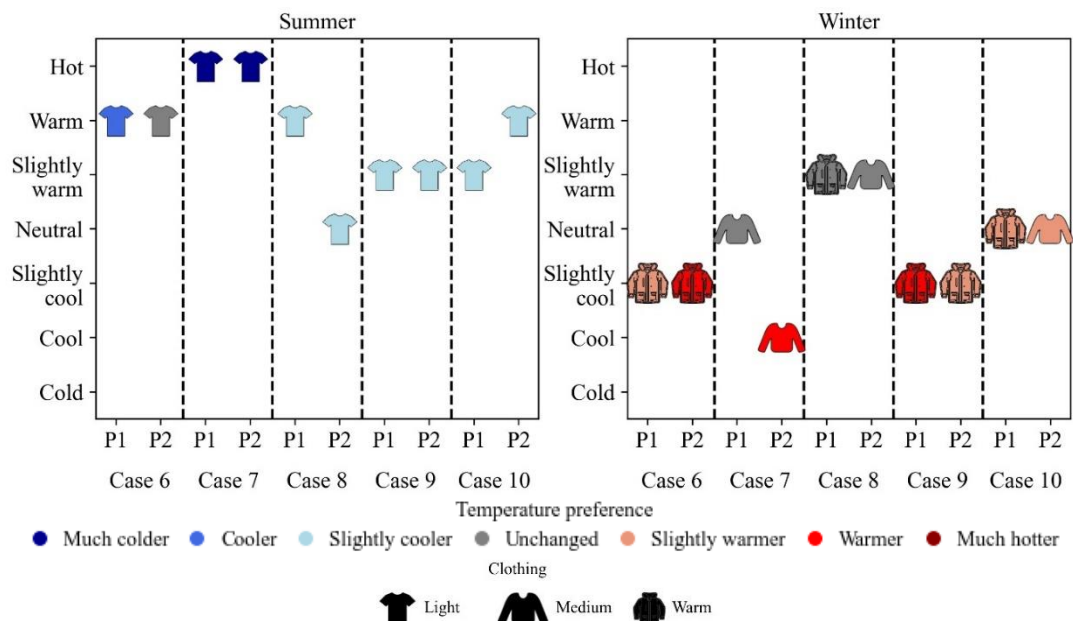


Figure 6.5 - Graphical representations of the indoors thermal sensation and preference and type of clothing that occupant usually wears indoors for each case study (6-10) by season (winter and summer)

House occupants were asked how often they use cooling and heating equipment in summer and winter. Figure 6.6 shows that in summer, the frequency of use of this equipment is “often or always”, with the exception of case studies 4 and 10, which indicate infrequently. Case studies 3 and 10 indicate that there is no heating equipment in winter; both only use biomass (fireplace) to heat their homes. In winter, the use of heating is more variable from case to case. Both in summer and winter, case studies 6 and 7 occupants do not agree on the frequency of heating and cooling equipment use.

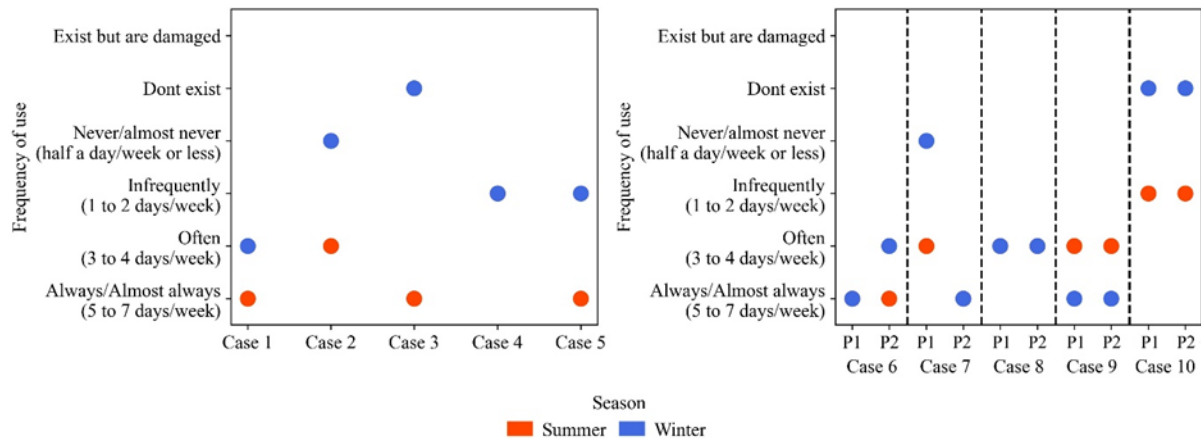


Figure 6.6 - Graphical representations of the frequency of use of air conditioning equipment for each case study by season (winter and summer)

6.4. Ventilation

Regarding the frequency of opening the windows of the dwellings in each case study, Figure 6.7 reveals that, in general, windows are opened more in summer than in winter, except in case studies 2, 3 and 9, which are always/almost always opened in both seasons. To the question of whether the occupants open the windows as much as they would like, there were different answers. However, in winter, the occupants generally indicate that they open them less often than they would like, except for case studies 1 and 2 and occupants P1 in case 6 and P2 in case studies 8 and 10.

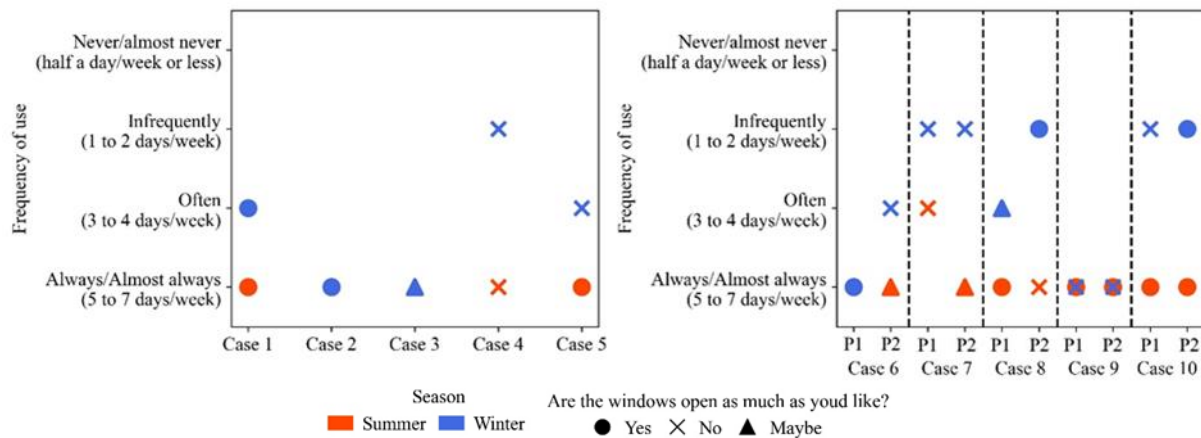


Figure 6.7 - Graphical representations of the frequency of open windows and opens up as much as would like for each case study by season (winter and summer)

Table 6.2 shows the main reasons why occupants don't open their home windows as much as they would like. Also shown are those who indicated "Maybe". In general, the main reasons are to maintain the house's temperature and prevent insects/mosquitoes and dust from entering. In winter, the fact that people are away from home more because of their work and the fact that it gets dark earlier is a reason for two of the case studies.

Table 6.2 - Main reasons for not opening windows as much as occupants would like for each case study by season (winter and summer)

Case study	Summer	Winter
1	-	-
2	-	-
3	To maintain house temperature and to prevent insects/mosquitoes from entering the house	Not being in the house
4	To prevent insects/mosquitoes from entering the house	To maintain house temperature and to prevent insects/mosquitoes from entering the house
5	-	To maintain house temperature
6	P1: - P2: To prevent insects/mosquitoes from entering the house and to avoid dust getting in the house	P1: - P2: To maintain house temperature
7	P1: To maintain house temperature (AC use) P2: To maintain house temperature (AC use)	P1: To maintain house temperature P2: To maintain house temperature and to prevent insects/mosquitoes from entering the house
8	P1: - P2: To prevent insects/mosquitoes from entering the house, to avoid dust getting in the house and to maintain house temperature	P1: To avoid dust getting in the house P2: -
9	P1: - P2: -	P1: To maintain house temperature P2: To maintain house temperature
10	P1: - P2: -	P1: Winter schedule P2: -

Table 6.3 identifies the rooms where the occupants reported dark stains and/or mould on the ceiling and/or walls in winter. Cells in the table with a dash (-) mean that the room does not exist in the dwelling. An "x" means that the dark spots and/or mould do not exist in that room of the house. In winter, case study 1 is the only one to indicate that there are no dark stains and/or mould on the ceiling and/or walls in the house. A general analysis of the 10 case studies shows that it is in the bathroom where these dark stains and/or mould usually appear and cause the most disturb (except in case studies 1, 3 and 8), followed by the bedrooms. In the summer, case study 2 indicated that there was mould in the main bedroom and in the secondary bedrooms, which caused him "Disturbing", and in the bathroom, which caused him "Slightly disturbing". Case study 4 also identified dark stains and/or mould in the main bedroom and living room, causing "Slightly disturbing" and in the bathroom causing "Disturbing". This data about the summer is not shown in the table.

Table 6.3 - Level of discomfort that dark stains and/or mould on the ceiling and/or walls cause the occupant in specific rooms of the house in winter

Case study	Main bedroom	Other bedrooms	Living room	Kitchen	Bathroom	Corridor	Glazed balcony
1	x	x	x	x	x	x	-
2	Slightly disturbing	Disturbing	x	x	Slightly disturbing	x	-
3	Slightly disturbing	x	x	x	x	x	-
4	Slightly disturbing	x	Slightly disturbing	x	Very disturbing	-	Disturbing
5	Disturbing	Disturbing	x	x	Disturbing	x	-
6	P1 Disturbing	-	x	x	Slightly disturbing	x	-
	P2 Very disturbing	-	x	Slightly disturbing	Disturbing	x	-
7	P1 Disturbing	Disturbing	Disturbing	Disturbing	Disturbing	Disturbing	-
	P2 Very disturbing	Very disturbing	Disturbing	Disturbing	Disturbing	Slightly disturbing	-

Table 6.3 - Level of discomfort that dark stains and/or mould on the ceiling and/or walls cause the occupant in specific rooms of the house in winter (cont.)

Case study		Main bedroom	Other bedrooms	Living room	Kitchen	Bathroom	Corridor	Glazed balcony
8	P1	x	Slightly disturbing	x	x	x	x	-
	P2	x	Slightly disturbing	x	x	x	x	-
9	P1	x	x	x	x	Very disturbing	x	-
	P2	x	x	x	x	Slightly disturbing	x	-
10	P1	x	x	x	x	Slightly disturbing	x	-
	P2	x	x	x	x	Disturbing	x	-

6.5. Indoor air quality

The occupants were asked about the intensity of odours inside the house. Figure 6.8 shows that in most case studies, the occupants do not consider that there is an odour or that there is a very weak odour. Only in case study 9 is indicated that the odour is moderate in winter, and for the same case study in summer, it is identified as moderate for occupant P1 and weak for P2. Also, in summer, case study 4 occupant indicated a moderate odour. It can also be seen that in most case studies there are no differences between odour intensity in summer and winter.

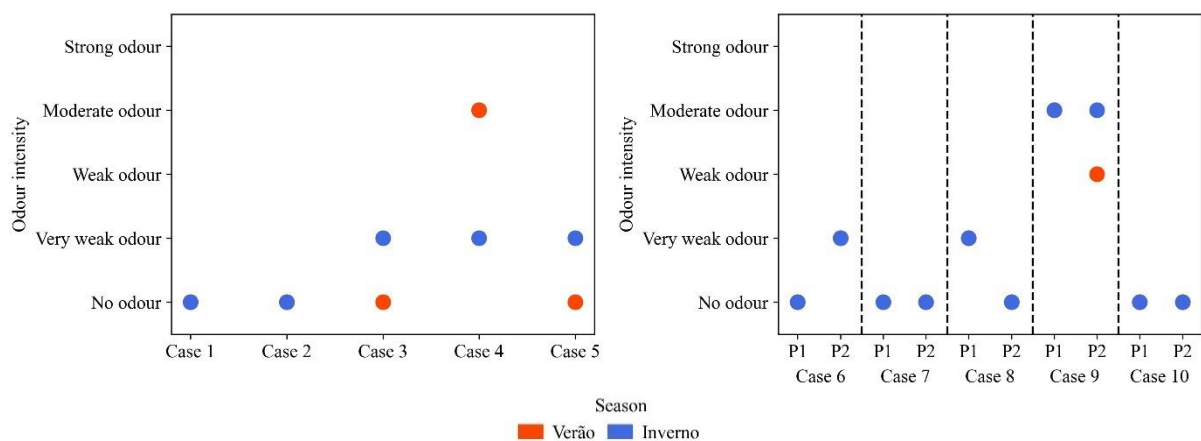


Figure 6.8 - Graphical representations of the odour intensity for each case study by season (winter and summer)

Occupants who answered that there was an odour in the house were asked whether the odour was pleasant, neutral or unpleasant. They were also asked whether they were persistent and recurrent (throughout the summer/winter and always present) or casual (they don't last throughout the summer/winter and aren't always present). As illustrated in Figure 6.9, the occupants of case studies 3 and 5 and the P2 occupants of case studies 6 and 9 indicated that the odour was neutral. On the other hand, the occupant of case study 4 and occupants P1 of case studies 8 and 9 indicated that the odour was unpleasant. Regarding the frequency of the odour, most of the occupants responded that it was casual, except for case study 4 in summer and occupant P2 in case 9 in winter.

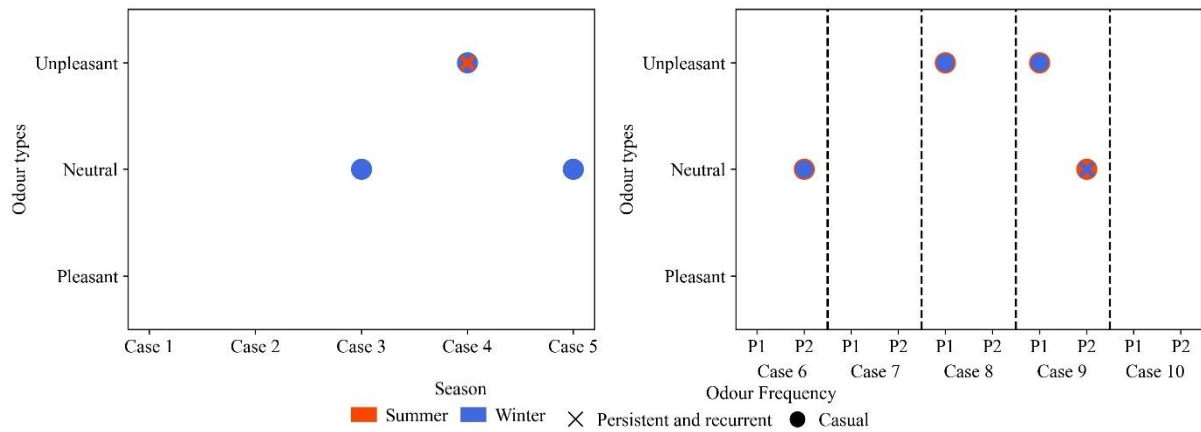


Figure 6.9 - Graphical representations of the odour type and frequency for each case study by season (winter and summer)

6.6. Lighting

The survey also included a section of questions about lighting. Figure 6.10 shows the responses of the occupants of case studies 1 to 5 regarding the natural lighting that typically exists inside the house and the use of artificial lighting in summer and winter. Case studies 2, 3 and 5 say that natural lighting is comfortable. They only switch on artificial lighting when it gets dark and only in the house's rooms with people, both in summer and winter. The occupant of case study 1 only switches on the artificial lighting when it gets dark and only in the house's rooms where there are people, both in summer and winter. As for natural lighting, in summer it is bright, and in winter it is comfortable. Analysing case study 4, it can be seen that the occupant considers natural lighting to be bright and switches on artificial lighting only when it gets dark, but in various rooms of the house. In winter, the occupant considers the natural lighting slightly bright but switches on the artificial lighting practically all day.

From these first five case studies, it can be seen that the houses have good natural lighting and occupants behave appropriately concerning artificial lighting since they all consider their homes to be bright, with the exception of the occupant of case study 4, who could use less or manage artificial lighting differently.

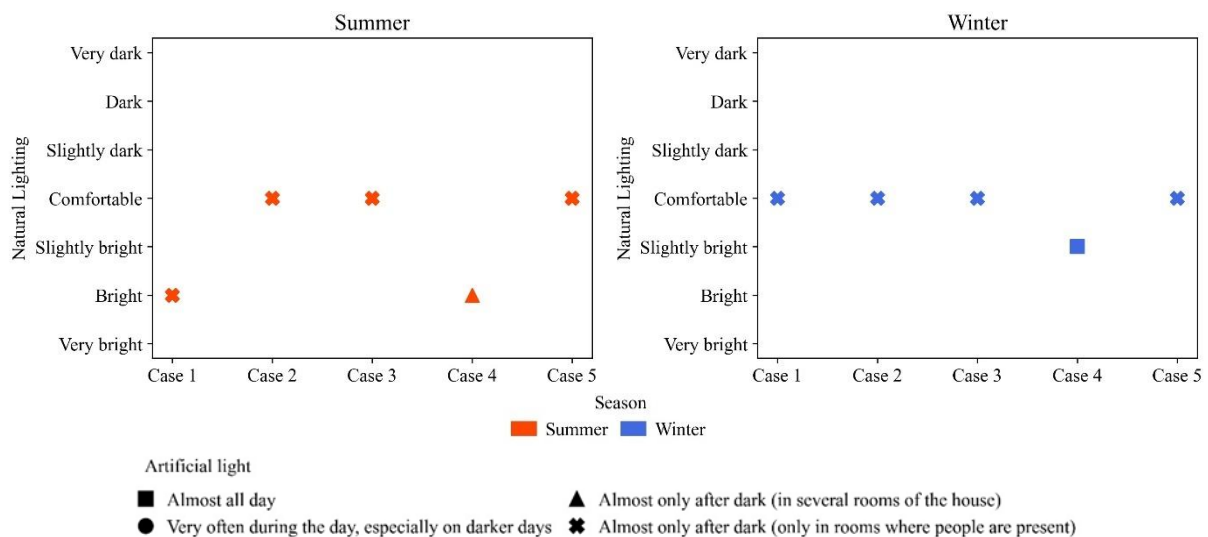


Figure 6.10 - Graphical representations of the natural lighting and use of artificial lighting for each case study (1-5) by season (winter and summer)

Figure 6.11 shows the occupants' responses of case studies 6 to 10 regarding the natural lighting that normally exists inside the house and the use of artificial lighting in summer and winter. The occupants of case study 6 consider the house to be slightly darker in summer and winter. In summer, they switch

on artificial lighting regularly during the day, especially on darker days. In winter, they switch it on for practically the whole day. In case study 7, the occupants have slightly different perceptions of natural lighting, especially in winter. One considers it to be slightly bright, and the other dark. As for the use of artificial lighting, in the summer, they only use it when it's dark and in rooms with people, and in the winter, occupant P2 says he uses it regularly during the day, especially on dark days, which is in line with his perception of natural lighting.

In case study 8, the two occupants consider that natural lighting is slightly bright in summer and winter. The two occupants indicate they only use artificial lighting when it starts to get dark, depending on whether it is in rooms where there are people or not. Case study 9 is a house with natural light in summer and winter. According to the occupants, they only use artificial lighting when it gets dark and in rooms where there are people. However, occupant P1 says that he switches on artificial lighting practically all day in winter. Finally, according to the answers obtained from the occupants of case study 10 in summer, the house is comfortable from the point of view of natural lighting, being brighter in summer and darker in winter. They indicate that they only use artificial lighting when it gets dark and in rooms where there are people in the summer and regularly during the day in winter time.

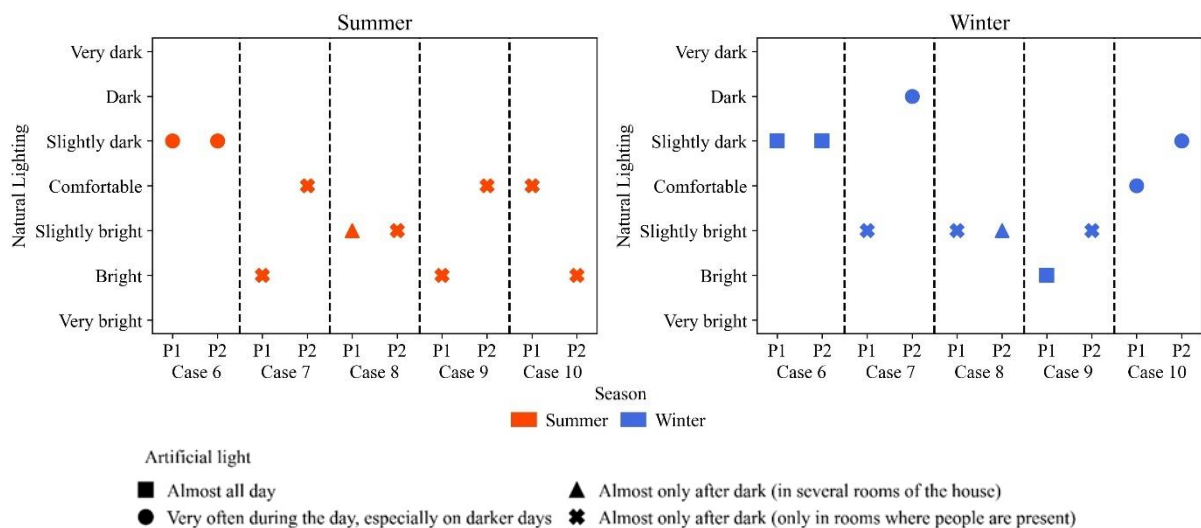


Figure 6.11 - Graphical representations of the natural lighting and use of artificial lighting for each case study (6-10) by season (winter and summer)

Figure 6.12 shows that in summer, in all the case studies, the occupants indicate that they always/almost always use solar shading (blinds, shutters, curtains, etc.) during the day. In winter, this pattern is also seen in almost all the case studies, with the exception of case studies 1, 2 and 4, which indicate that they use it never/almost never, infrequently and often, respectively. In case study 7, occupant P1 in winter has a completely opposite perception to P2, saying that he never/almost never uses it. In case study 8, there is also an opposite opinion from the occupants in winter (P1 says he uses it often, and P2 never/almost never).

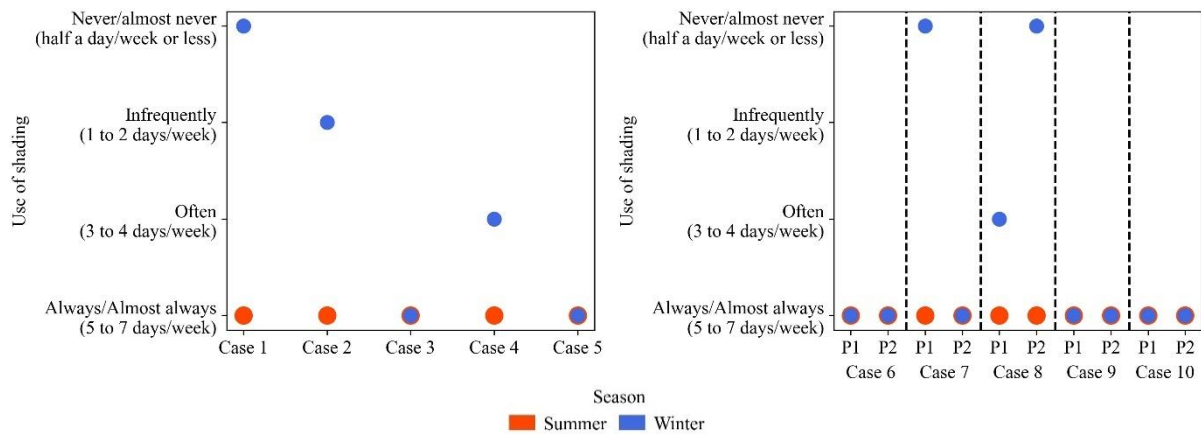


Figure 6.12 - Graphical representations of the use of shading for each case study by season (winter and summer)

6.7. Acoustics

Respondents were asked about their level of disturbance regarding the perceived noise inside their home caused by different factors in summer and winter. Figure 6.13 shows the results obtained for the first 5 case studies. The level of disturbance for each factor is quite different for each case study, and there are also differences between summer and winter in the same case study. It can be said that discomfort from noise coming from outside is the most identified, followed by neighbours' houses, in winter and summer.

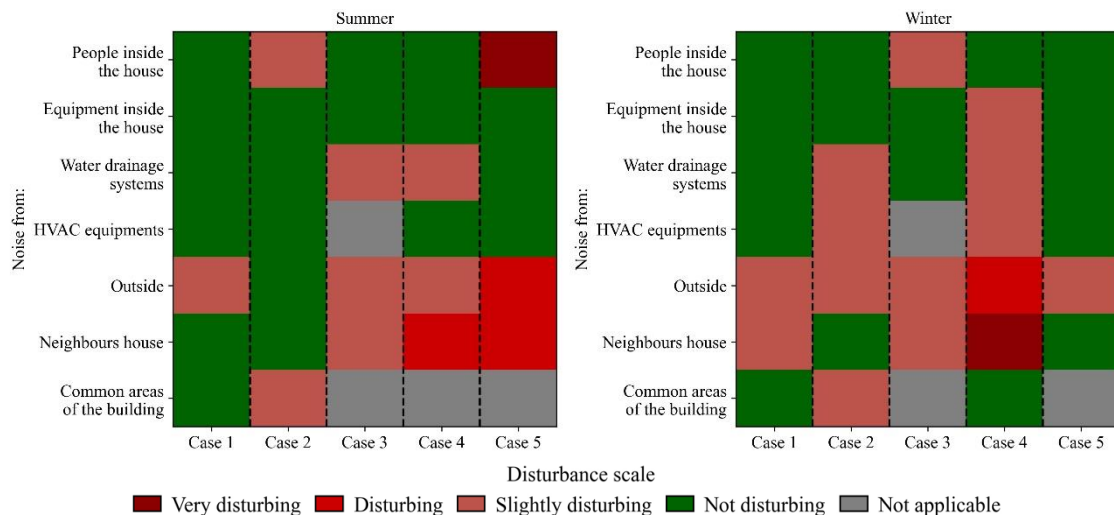


Figure 6.13 - Graphical representations of the level of disturbance regarding the perceived noise inside the home caused by different factors for each case study (1-5) by season (winter and summer)

Figure 6.14 shows the results obtained for case studies 6 to 10. Noise annoyance for each factor is quite different for each case study. It can also be seen that the occupants of the same house often have different perceptions of the annoyance level caused by a particular factor. There are also differences between the opinions given in summer and winter in the same case study. It can be said that discomfort from noise coming from outside is the most mentioned, followed by neighbours in summer. In winter, it is not possible to identify one or two factors mentioned as the source of the most significant noise, as the responses are pretty dispersed in the various case studies.

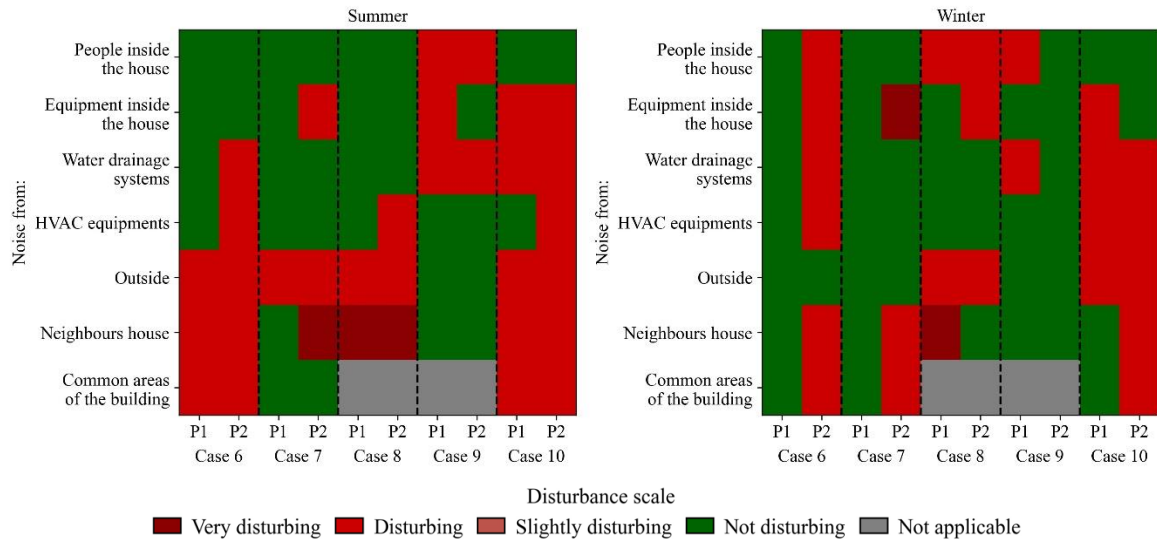


Figure 6.14 - Graphical representations of the level of disturbance regarding the perceived noise inside the home caused by different factors for each case study (6-10) by season (winter and summer)

6.8. Other parameters and features

The survey included two questions about the view: one aimed to determine the importance of the house outside view and the other the interest of the view (landscape with pleasant elements such as gardens, forest, sea, bridges, monuments, among others). As shown in Figure 6.15, all the occupants of the 10 case studies indicated that it was "Important" or "Very important" to have a view of a landscape with pleasant elements. However, only in case studies 1, 3, 7 and 10 occupants indicated that the view was "interesting" and/or "very interesting". Occupant P2 of case study 8 also considers the view "interesting". The occupants of case studies 2, 4 and 6 consider the view from their house to be "uninteresting" and/or "very uninteresting". The remaining occupants indicated "neutral" on the interest scale.

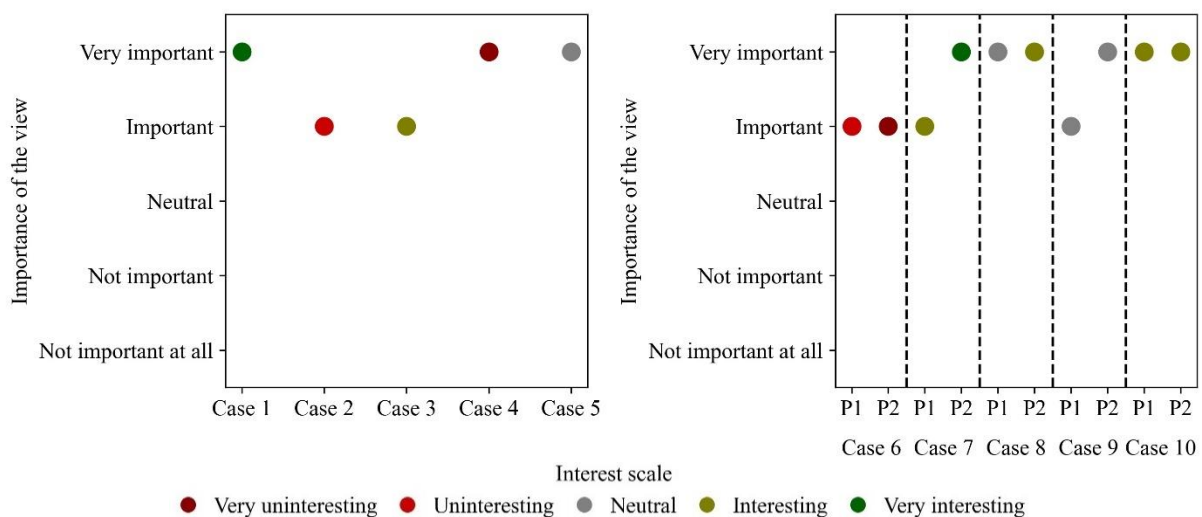


Figure 6.15 - Graphical representations of view importance for each case study

When asked about the importance of biophilia inside the house, i.e. the presence of plants, water features, light, animals, natural materials and others, the majority of occupants in the ten case studies indicated that it was "important" and/or "very important", except occupant P2 of case study 7, who didn't consider it to be important at all, and occupant P2 of case study 10, who considered the degree of importance to be neutral (Figure 6.16).

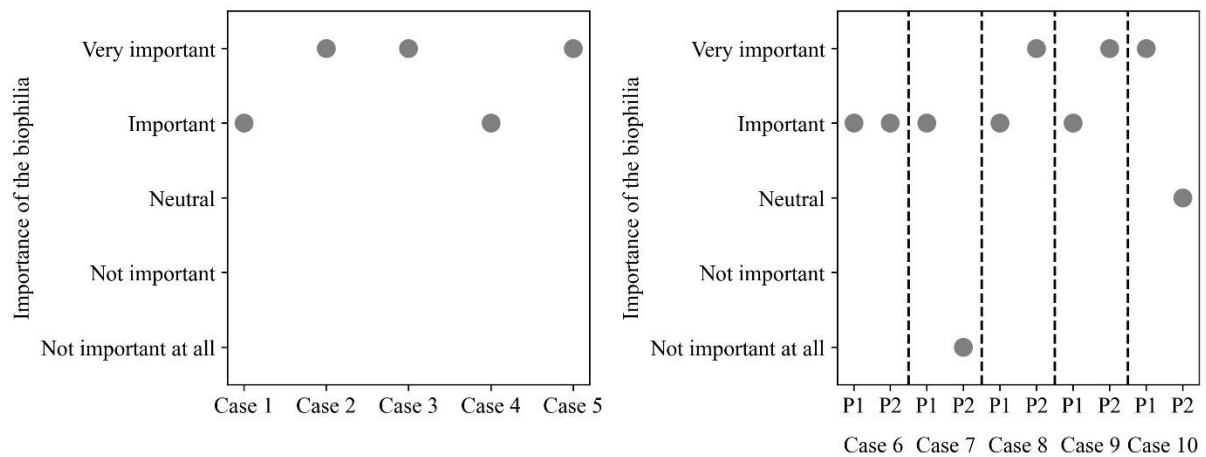


Figure 6.16 - Graphical representations of biophilia importance for each case study

The occupants of the case studies were asked about their preferences regarding the operation of the systems that are or could be in their home: automatic, manual, or simultaneously having the possibility of being automatic and manual. As shown in Figure 6.17, only the occupants of case studies 1, 5 and P1 of case study 8 preferred automatic systems in some house systems. The occupants of case studies 4 and 7, occupant P2 of case study 6 and P1 of case study 9 prefer manual systems for all (shading, lighting, ventilation and heating/cooling). The occupants in case study 10 and P1 in case study 6 prefer mixed systems, i.e. manual and automatic for all the systems in house. All the other occupants in at least one system prefer manual or both manual and automatic.

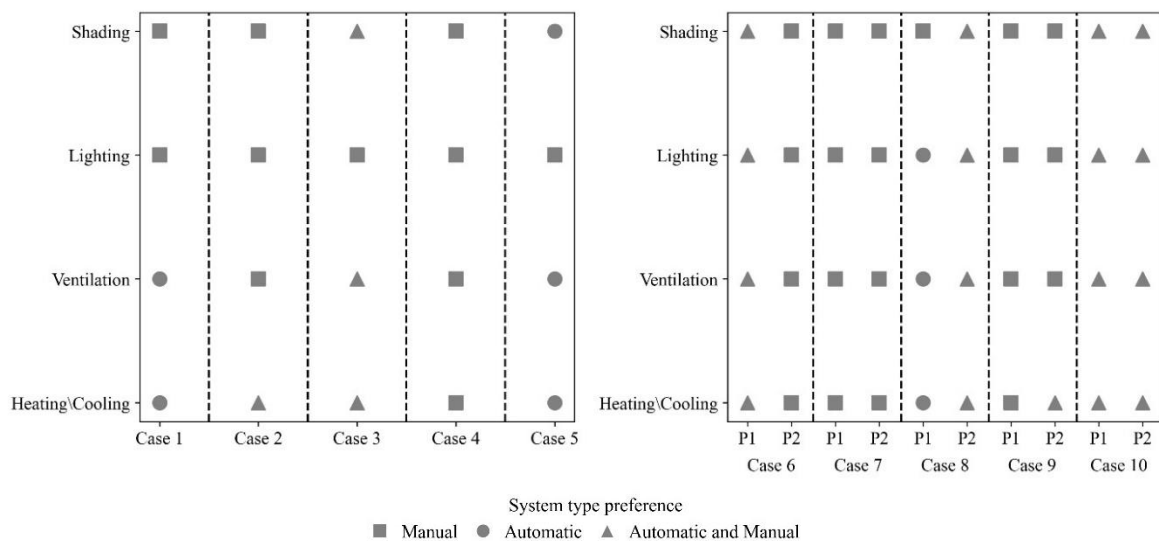


Figure 6.17 - Graphical representations of system type preference for each case study

The occupants of the case studies were asked about the importance of three different aspects: using or buying energy-efficient equipment; using or buying passive systems (systems that don't use energy to air-condition the house, for example); and choosing materials that incorporate recycled materials, that consume less energy to produce and pollute the environment less. As seen in Figure 6.18, all the case studies indicate that they have given importance or a lot of importance to using or acquiring more energy-efficient equipment. Concerning the use or buying of passive systems, most occupants have also been giving importance or a lot of importance to this aspect, except the occupants of case study 8 and occupant P1 of case study 7, who indicate that they have not given any importance. Regarding the last aspect related to the materials chosen, the occupants of case studies 1, 2 and 8 and occupant P2 of case

study 10 have not given it any importance. The remaining occupants indicate that this is an aspect that they have given importance or a lot of importance.

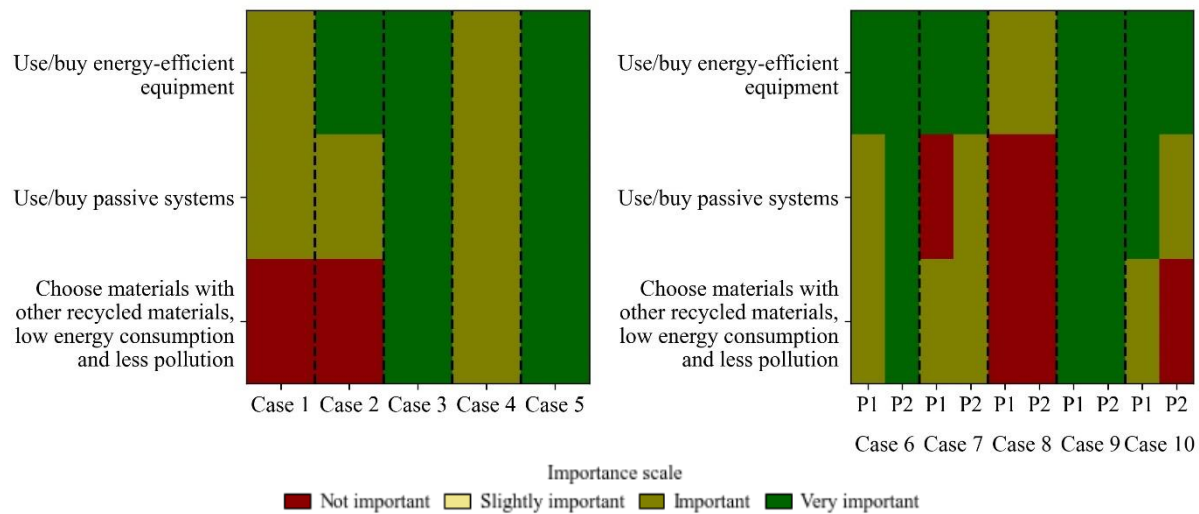


Figure 6.18 - Graphical representations of the importance of three aspects for each case study

In order to understand the importance that the occupants attach to the different groups of comfort and well-being parameters that were asked about during the survey, they were asked to indicate the degree of importance for their comfort inside the house on a scale of four options. Figure 6.19 shows that case studies 1, 3 and 5 identified all the parameters as very important. The occupant of case study 2 considers all the parameters “very important” except lighting, acoustics and other features, which he considers “not important” for comfort and well-being. The occupant of case study 4 considers the thermal environment, acoustics and furniture, finishes, and materials to be “very important” and the other groups of parameters to be “not important” at all. Case studies 6 to 10, the occupants indicate that some parameters are “very important” and others are “important”, except occupant P2 in case study 6, who indicates that acoustics and furniture, finishes, and materials are “not important” at all.

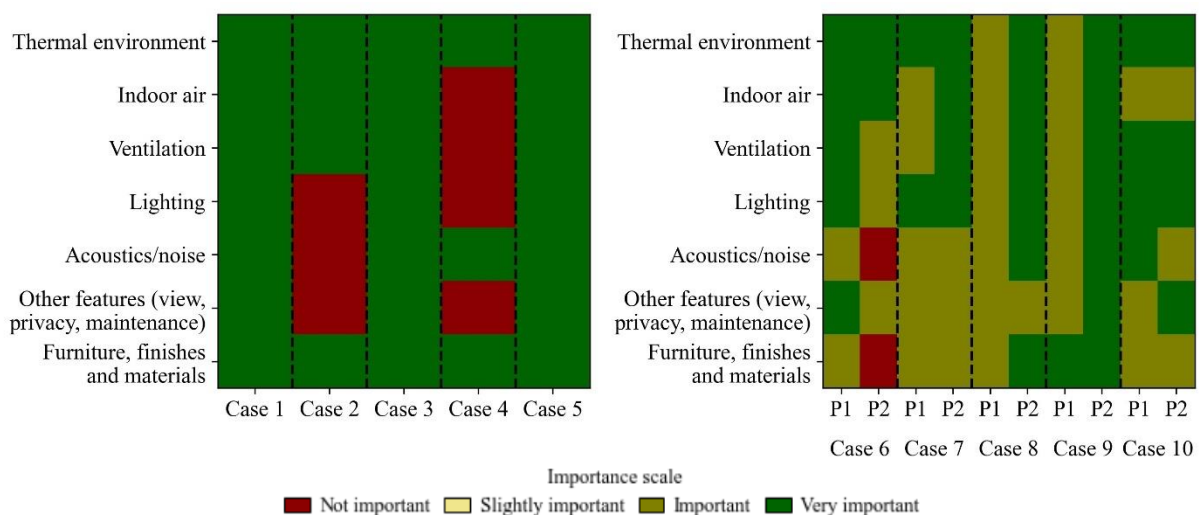


Figure 6.19 - Graphical representations of the importance of comfort and well-being parameters for each case study

To identify the energy efficiency measures that the occupants consider to be a priority in their home and those they have already carried out, they were asked to identify the measures indicated on a priority scale. It's important to emphasise that some of these measures may already be in place in the house, and the occupants may not be aware of them or need to be reinforced. Figure 6.20 shows that the answers obtained are very different from one case study to another. Within the case studies with two people

answering, it can also be seen that these occupants have very different opinions on the priority of the measures in some cases.

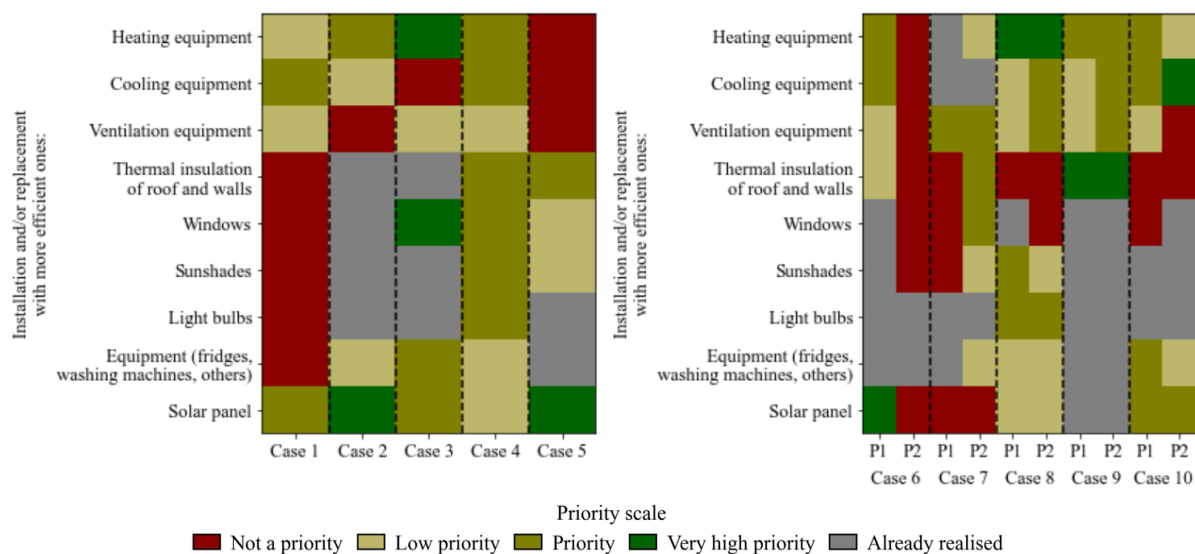


Figure 6.20 - Graphical representations of improvement measures priority for each case study

Finally, the occupants were asked to indicate the most important positive and negative points about the house from their perspective. These points may not have been covered in the survey. In this way, the results shown in Table 6.4 were obtained.

Table 6.4 - Positive and negative points of the houses according to the occupants

Points that are most important for the occupant		
Case study	Positive	Negative
1	Comfort, view, sun exposure	Degradation of materials, broken appliances, condominium
2	Furniture, acoustic, lighting	View, winter thermal comfort, humidity
3	Location (far from the city centre), privacy, central vacuum, pre-installation for AC and central heating	Wood-burning fireplace, aluminium tilt windows
4	Location, interior furnishings and well-oriented	Humidity/Mould, old floors, plumbing odours
5	Small areas, garden, location	Old, not connected to basic sanitation
6	P1: Location, indoor finishes	Small areas, interior living room
	P2: Recently renovated; small (easy to maintain); rental value	Rear orientation; layout of rooms difficult to make changes between rooms; interior bathroom
7	P1: Natural light, view, typology T3	High temperatures in summer, lack of lift, lack of exterior painting of the building
	P2: Natural light, areas, laundry	Lack of roof waterproofing (top floor of the building); interior bathrooms and corridor without natural light and ventilation
8	P1: Light; quality of materials; state of conservation; outdoor deck	Lack of storage room
	P2: Duplex; only one unit with neighbours; riverside location	A airshaft that reverberates the noise caused by the neighbour's dogs; no storage room/garage
9	P1: Rooms area, garden	Lots of stairs, interior rooms (living room and bathroom)
	P2: Rooms area	Stairs
10	P1: House layout, solar orientation, absence of noise	Lack of cooling system, constructive quality of the walls, inefficient boiler
	P2: View, acoustics and thermals quality	No AC, privacy, more balconies

6.9. Conclusions of extensive survey

This survey focused on the comfort and well-being of occupants in their homes. For this purpose, several questions were asked to determine the respondents' perceptions of various parameters and comfort factors concerning their homes. These parameters present in the survey were selected according to the state of the art. In this way, and after applying the surveys at the end of summer and winter, the following main conclusions were reached:

- The mean temperature in winter is below 18°C and in summer above 25°C in many case studies (although some case studies fall slightly outside the range). It also turns out that a case study can be in discomfort in only one of the seasons or both. Regarding relative humidity, in some case studies, mean relative humidity is not within 50% - 70% in at least one of the four seasons of the year;
- Analysing the satisfaction of parameters such as thermal comfort, air quality, lighting and acoustic quality in summer and winter, it was concluded that thermal comfort is the most dissatisfying parameter in summer and winter. For some case studies, summer occupants indicate greater satisfaction with all these comfort parameters than in winter. For other case studies, it is the opposite. The occupants' response to satisfaction throughout the year with privacy, maintenance of the house, furniture and other decorative and comfort elements inside the house, and overall satisfaction with the house varies from case studies. Five case studies did not report any dissatisfaction; the others indicated some dissatisfaction;
- Regarding the thermal environment, it was found that most occupants reported that their house in summer is slightly warm, warm or hot, and only a minority of occupants said they felt comfortable. Almost all of them also indicate that they would like the temperature to be cooler than it usually is. In most case studies in winter, the occupants indicate that the thermal sensation in their home is slightly cool, cool or cold. A minority said it is typically comfortable, and one occupant indicated it is slightly warm. All the occupants say they prefer warmer temperatures to those they usually experience, except one occupant who wants the temperature to remain unchanged. The clothing worn by the occupants in both seasons is appropriate;
- From the responses obtained regarding the frequency of use of cooling and heating equipment in the respective seasons, it can be seen that in summer, the frequency of use of this equipment is often or always, except in two case studies, which indicate infrequently. In winter, the use of heating is more variable from case to case;
- Regarding the frequency of window opening, it was found that windows are opened more in summer than in winter, except in three case studies, which are always/almost always opened in both seasons. In winter, the occupants generally indicate that they open the windows less often than they would like (except for five occupants). In general, this is because the occupants want to maintain the house's temperature and prevent insects/mosquitoes and dust from entering;
- Most of the case studies indicate dark stains and/or mould on the ceiling and/or walls in winter in the house, except case study 1. A general analysis of the case studies shows that it is in the bathroom where these dark stains and/or mould usually appear and cause the most disturbance, followed by the bedrooms. In summer, only two case studies indicated the presence of dark stains and/or mould on the ceiling and/or walls;
- In most case studies, the occupants indicated that there was a weak odour or considered that odour didn't exist. In most case studies, there are no differences between the intensity of odour in summer and winter. However, indicated that there was an odour, that odour was neutral or unpleasant; nobody noted that it was pleasant. Most of the occupants revealed that the odour was casual;

- All case studies have good natural lighting except one. Occupants behave appropriately concerning artificial lighting since they all consider their homes to be bright, except a minority number of occupants from two different case studies, who could use less or manage artificial lighting differently;
- In all case studies, the occupants indicate that in summer they always/almost always use solar shading (blinds, shutters, curtains, etc.) during the day. This pattern is also seen in almost all case studies except three in winter;
- It can be said that generally, the discomfort from noise coming from outside is the most identified, followed by neighbours' houses, in both winter and summer;
- All the occupants of the case studies indicated that it was "Important" or "Very important" to have a view of a landscape with pleasant elements. However, a few occupants indicated that the view was "interesting" and/or "very interesting". When asked about the importance of biophilia inside the house (plants, water features, light, animals, natural materials and others), the majority of occupants indicated that it was "important" and/or "very important";
- Regarding the preference for shading, lighting, ventilation, and heating/cooling systems operation, only three occupants preferred automatic systems in some house systems. Five occupants of the case studies prefer manual systems for all systems. Three prefer manual and automatic for all the systems in house. All the other occupants in at least one system prefer manual or both manual and automatic;
- All the case studies indicate that they have given importance or a lot of importance to using or acquiring more energy-efficient equipment. Regarding the use or buying of passive systems, most occupants have also been giving importance or a lot of importance to this aspect, except a minority of occupants. Regarding the chosen materials, there is a greater diversity of responses; some occupants consider them important, and others do not;
- In case studies where two occupants responded to the survey, it was verified that the answers did not always converge. This was expected to happen since this is a subjective analysis. The responses depend on various occupants' personal factors, and occupants can also respond based on what they think happens rather than what actually happens. This increases the complexity of the case study analysis since there are two different opinions/perceptions of the same house;
- The satisfaction and level of importance of some groups of comfort and well-being results are relevant to understanding which comfort and well-being parameters cause the greatest dissatisfaction among the occupants of the dwellings under study and which parameters the occupants consider most important for feeling comfortable. Once these parameters have been identified, it is possible to draw up improvement measures for each case study, taking their perceptions into account so that they lead to an increase in comfort and well-being and an improvement in the energy efficiency of the dwelling. The priority that the occupants give to the energy efficiency measures presented in the survey is also fundamental to cross-reference with the feedback they gave regarding the comfort they said they felt in their homes;
- From the data collected, it's not possible to encompass all the results and say whether the case studies being analysed provide more comfort in summer or winter. However, when analysing each case study individually, it is possible to see that in some cases, with regard to thermal comfort, acoustics, air quality and lighting, there is more discomfort in one season than in the other, but in other cases, there is discomfort in both seasons;
- All these conclusions or possible conclusions of the extensive survey are based on the analysis of these ten case studies.

After analysing the results of the extensive survey and considering those from the right-now survey, the focus now shifts to a comparative analysis of both. It is important to recall that the extensive survey

provides a broader assessment of comfort and well-being parameters, covering a wider range of questions. This survey also considers occupants' perceptions of their homes throughout the entire winter and summer periods. In contrast, the right-now survey focuses primarily on thermal comfort, aiming to identify potential differences or similarities between the main bedroom and the living room. Data for this survey is collected over a shorter timeframe, specifically two weeks in winter and two weeks in summer. Based on this analysis, the following conclusions can be drawn:

- The thermal sensation most frequently reported in the right-now survey across the majority of case studies does not align with that indicated in the extensive survey. This discrepancy can be observed in both winter and summer. One possible explanation is that, when completing the extensive survey, occupants provide a global assessment of their home based on memory and overall perception of thermal sensation. In contrast, responses in the right-now survey reflect their immediate, real-time experience. Furthermore, the thermal sensations reported in the right-now survey are influenced by the specific conditions of the evaluation period. As a result, the responses may not be fully representative of typical winter and summer conditions, as the assessed period could coincide with atypical weather patterns. These same conclusions can also be applied to the use of HVAC equipment;
- In certain case studies, the mean temperature measured over the entire winter and summer periods is similar to that recorded during the right-now survey implementation period (two weeks). However, in some cases, the difference between these mean temperatures exceeds 1°C and can reach up to 1.5°C in other cases. The largest discrepancies in mean temperatures vary across case studies, occurring in summer for some and in winter for others.

7. Comfort and well-being improvement: parameters and measures

The previous two chapters present the results of the right-now survey and the extensive survey. This chapter aims to identify which comfort and well-being parameters require improvement to enhance occupants' comfort and well-being at home considering the occupant's feedback collected through the surveys. Once the comfort and well-being parameters to be improved have been identified, it is possible to suggest measures that will contribute to increase energy efficiency, overall comfort and satisfaction.

7.1. Comfort and well-being parameters to be improved

In order to find the comfort and well-being parameters that need to be improved, the questions results of the satisfaction levels (Figure 6.1, Figure 6.2, and Figure 6.3) and importance that the occupants assigned to each parameter (Figure 6.19) were crucial according to the methodology developed.

Table 7.1 was therefore created based on occupant feedback, presenting the responses in a concise and structured manner. Remembering what was described in the chapter 3.2, the symbol “✓” represents when the occupants indicated they were satisfied (“Slightly satisfied”, “Satisfied”, “Very satisfied”), the symbol “±” when they indicated “Neutral” and “x” dissatisfied (“Slightly unsatisfied”, “Unsatisfied”, “Very unsatisfied”). When the background of the cell is green, it indicates the occupant has answered that the parameter is important (“Slightly important”, “Important”, “Very important”) and orange “Not important”. In the case studies in which two occupants responded (cases 6 to 10), it was enough for one of them to answer one of the three dissatisfaction scales to automatically be considered an “x”. When one of them answered “Neutral”, and the other was satisfied, it was considered “±”. Regarding the importance, if one of the occupants indicated that it was important (one of the three levels of importance), the cell in the table is considered green.

Table 7.1 - Summary of the satisfaction and importance that the occupants attached to comfort and well-being parameters

			Case study 1	Case study 2	Case study 3	Case study 4	Case study 5	Case study 6	Case study 7	Case study 8	Case study 9	Case study 10
Satisfaction	Thermal comfort	Summer	±	±	✓	x	x	x	x	✓	x	x
		Winter	±	x	x	x	x	x	✓	✓	x	±
	Air quality	Summer	✓	±	✓	✓	✓	x	x	x	✓	✓
		Winter	±	x	✓	✓	✓	±	✓	✓	✓	±
	Lighting	Summer	✓	±	✓	✓	✓	x	±	✓	✓	✓
		Winter	±	±	✓	✓	✓	x	x	✓	✓	±
	Acoustic	Summer	✓	±	✓	✓	✓	±	±	x	✓	✓
		Winter	±	±	✓	x	✓	✓	✓	✓	✓	✓
	Privacy		✓	x	✓	✓	✓	±	±	x	✓	x
	Maintenance		✓	✓	✓	✓	✓	✓	x	x	x	✓
	Furniture and others		✓	✓	✓	✓	✓	✓	✓	✓	±	✓
	Overall satisfaction		✓	✓	✓	✓	✓	±	✓	✓	x	✓

Based on Table 7.1, it was possible to identify the priority that the comfort and well-being parameters have for each case study that would give an order of intervention to improve the parameters. The classification of comfort and well-being parameters to be improved is the following:

- Class 1 - first parameters to improve
- Class 2 - second parameters to improve
- Class 3 - third parameters to improve

The method is based on the diagram shown in Figure 7.1. It is necessary to check whether the parameters have a summer and winter evaluation (the first four in Table 7.1) or whether the parameters have an annual evaluation (the last in Table 7.1). Then, following the diagram and checking the symbols and colours in Table 7.1, it is possible to obtain the class of comfort and well-being parameters by underlaying the symbols and colours. Note that in the summer and winter case parameters, there only needs to be one “x” to follow this diagram path. The same goes for “±”. If, for example, in summer, a given parameter has an “x” and in winter a “±”, then it is the path of the “x” that has to follow.

For a better understanding of this method, the following describes how it is applied, using case study 2. From Table 7.1, it can be observed that thermal comfort and air quality have an "x" in winter and a "±" in summer. Since these are evaluation parameters for winter and summer, and given that there is an "x" in winter and the table cells are filled in green, it is concluded that these are Class 1 parameters. Considering lighting and acoustics, Table 7.1 shows that these two parameters have table cells filled in orange and are marked with the symbol "±". According to the detailed diagram presented in Figure 7.1, these are classified as Class 3 parameters. Regarding parameters evaluated annually (privacy, Maintenance, and Furniture and others), it can be seen that privacy, having the symbol "x" and an orange color, is classified as a Class 2 parameter. Maintenance is also marked in orange but has the symbol "✓", indicating that it does not require improvement. In the case of furniture and others, as it is filled in green and marked with the symbol "✓", it is also not necessary to be improved, and therefore, no improvement measures need to be suggested. That said, the results about classifying the priority of the comfort and well-being parameters for all the case studies were obtained and shown in Table 7.2.

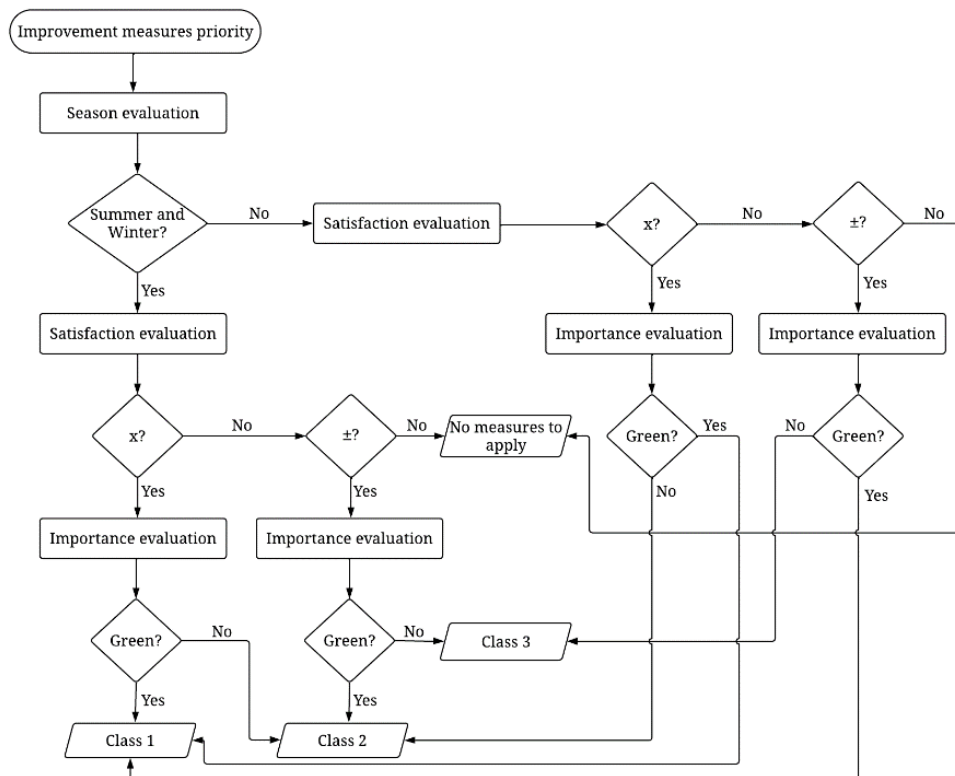


Figure 7.1 - Diagram that reflects the method to classify the priority of the comfort and well-being parameters

Table 7.2 - Classification of the priority of the comfort and well-being parameters

Case study	Class 1	Class 2	Class 3
1	-	Thermal, air quality, lighting, acoustic	-
2	Thermal, air quality	Privacy	Lighting, acoustics
3	Thermal	-	-
4	Thermal, acoustic	-	-
5	Thermal	-	-
6	Thermal, air quality, lighting	Acoustics, privacy	-
7	Thermal, air quality, lighting, maintenance	Acoustics, privacy	-
8	Air quality, acoustics, privacy	-	-
9	Thermal, maintenance	Furniture	-
10	Thermal, privacy	Air quality, lighting	-

Knowing now which parameters need to be addressed to improve occupant comfort and well-being, all the information obtained from occupant feedback (behaviour, perceptions, preferences, priorities, etc.) and measurements of the indoor environment were systematised in tables in Annex F. These tables are organised by case study and considering the satisfaction parameters that are evaluated in winter and summer: Thermal comfort, Air quality, Lighting and Acoustics. Privacy, Maintenance, Furniture and other decorative, comfort elements inside the house, and overall satisfaction with the home are asked only once in the first extensive survey and are present in a separate table for each case study. In this way, it is possible to indicate the measures to improve all the comfort and well-being parameters identified and the energy efficiency measures that should be implemented.

7.2. Proposed measures

Once the comfort and well-being parameters that need to be improved have been identified by priority class, it is possible to indicate measures to improve the indoor environment. The occupants' feedback has been taken into account, as mentioned above.

Below are reflections and suggestions for improvement measures for each case study. Although these were not simulated in the calibrated model, they are known to impact comfort, well-being, energy consumption and costs. Following on from these reflections and suggestions for improvement measures, Table 7.3 summarises for each case study the parameters identified for improvement, the results of the measurements taken during the surveys, the problems identified, the priorities that the occupants have indicated in terms of improvement measures and the proposal for improvement measures. In the last column of proposed improvement measures, were present those that the occupants prioritised, but also all the others that are considered relevant but that the occupants did not indicate.

• Case study 1

This case study does not have class 1 priority comfort and well-being parameters to be improved; they are all class 2, and they are thermal, air quality, lighting and acoustics (Table 7.2). For the analysis of the indoor environment measurements during one year (Table 6.1), it appears that the mean temperatures in spring and autumn seasons are acceptable, between 18-25°C as recommended by Portuguese legislation, but in summer and winter, the mean temperatures are outside this range, but close enough, to be considered within the range. Analysing the data recorded for the right-now survey periods (Table 5.2), it is noted that in winter, the minimum temperature recorded in the bedroom and living room is low (16.3°C and 12.3°C respectively), and the maximum temperature in summer is high (26.4°C and 27.9°C respectively).

From the information gathered, the opaque façade is constituted by a double brick wall with air gap and insulation. The glazed windows are simple double-glazed windows with metal frames and without

thermal break. However, the occupant does not consider insulating the walls and roof a priority. Nevertheless, it is proposed to install thermal insulation in the exterior walls from the inside, as not all the neighbours may agree with insulating the outside of the building. Since acoustics has also been identified as a parameter to be improved, the insulating material should be acoustic and thermal. The sources that occupants identify as causing the most noise disturbance is the outside and the neighbours. Thus, the walls adjacent to the neighbours can also be insulated. The selected thermal and acoustic insulator is rock wool. The occupant also indicates that it is not a priority to replace the windows. Nevertheless, it is proposed to replace the existing windows with PVC ones with double-glazing Low-E. This will improve thermal and acoustic parameters. For the occupant, it is a priority to install the cooling equipment and solar panels. Thus, installing solar panels will reduce the electricity bill or attenuate when cooling is being carried out.

Air quality is one of the parameters to be improved. However, the occupant states that there is no humidity in the house (even though the relative humidity measurements from the right-now survey are from just two weeks, Table 5.4 shows that the maximum values recorded during this period are acceptable) and that he ventilates the house more in summer than in winter, but often in winter. The occupant also states that there is no odour in the house. Table 5.5 also shows that the CO₂ concentration values collected over two consecutive weeks in summer and winter are also acceptable. Therefore, it is not possible to determine the air quality problem and it is necessary to understand the issue with the occupant afterwards.

Regarding lighting, one of the parameters identified for improvement, and considering the occupants' answers to the survey, it can be seen that the natural light is bright in summer and comfortable in winter and uses always/almost always solar shading in summer. It is suggested to substitute or add interior blinds that reduce brightness whenever the occupant wishes. To do this, it is necessary to consider the colour, type of fabric and material.

- **Case study 2**

In this case study, the parameters of comfort and well-being identified to be improved (Table 7.2) were thermal and air quality (class 1). The class 2 parameter to be considered when applying comfort improvement measures is privacy, and the class 3 parameters are lighting and acoustics. For the analysis of the measurements of the indoor environment during one year (Table 6.1), it appears that the mean temperatures in spring, autumn and winter seasons are acceptable, between 18-25°C as recommended by the Portuguese legislation, but in summer, the mean temperature is outside this range. The data recorded for the right-now survey periods (Table 5.2) shows that in winter, the minimum temperature recorded in the bedroom and living room is low (14.3°C and 15.6°C respectively), and the maximum temperature in summer is high in the living room, 27.4°C (in the bedroom the maximum recorded is 25.1°C).

According to the information collected, it is known that there is no insulation on the opaque façade, but the roof has it, and the windows are simple double-glazed with metal frames with thermal break. Although the occupant has identified that it has already applied insulation, it is suggested that insulating the walls and roof (on the top floor of the building) is the first measure to improve thermal comfort and acoustics. Thermal and acoustic insulation should be inside the exterior walls since this case study is an apartment (not all the neighbours may agree with insulating the outside of the building). As mentioned at the beginning of the chapter, rock wool is the insulation selected for all case studies given its insulating thermal and acoustic insulator characteristics and is a material that is compatible with environmental concerns compared to others. The noise sources that occupants identify are multiple: the outside, the neighbours, common areas of the building, inside the house and water drainage. Thus, in addition to the

roof and exterior walls, it is recommended to insulate the walls that are adjacent to the common areas of the building and with the neighbours. Although the occupant indicates that the windows have already been replaced, it is proposed to replace them with PVC ones with double glazing Low-E for thermal and acoustic improvement.

Insulation will also make it possible to improve the presence of humidity and mould in the home, but it is recommended that the occupant naturally ventilate the rooms more, although according to the surveys, the occupant always/opens the windows in summer and winter. The relative humidity measurements from the right-now survey from the two weeks in winter show that (Table 5.4) the maximum values recorded during this period are high, and the mean value, especially in the bedroom, is also high (Table 5.3). In the case of the bathroom, it is recommended to check if there is better mechanical ventilation equipment than the installed one since it is a room without a window and has been identified as a place with humidity. In the bedrooms, ventilation should be more frequent, and insulation should be sufficient. Reducing or eliminating the presence of mould in the home will improve indoor air quality, a parameter identified as a class 1 priority for improvement. The CO₂ concentration values collected over two consecutive weeks in summer and winter show that the maximum value recorded is high and that the mean value in winter is also high (Table 5.5). So, the idea of naturally ventilating the house, especially in winter, is reinforced.

Concerning the lighting parameter identified for improvement, it is necessary to understand the potential for improvement since the occupant indicated that the natural light is comfortable in the summer and winter. So, it's difficult to understand the problem. It is necessary to analyse this point in more detail, but it is worth emphasising that this is a class 3 parameter to improve. Regarding privacy, it is a comfort and well-being parameter of class 2 to be improved, and it is suggested that the occupants put up interior blinds that allow for privacy when needed but do not make the house seem to have less natural light because it can influence the comfort that the occupant indicates.

For the occupant, improving the heating equipment is a priority and installing solar panels is very priority. Installing solar panels will reduce the electricity bill at the end of the month and contribute to using electricity from renewable sources.

• Case study 3

Thermal comfort is the only parameter identified to be improved (Table 7.2). The measurements of the indoor environment over the year (Table 6.1) show that the mean temperature in spring, autumn and summer seasons is acceptable (between 18°C and 25°C). In winter, the mean temperature is outside this range. When analysing the data recorded for the right-now survey periods, it can be seen that even in winter, the minimum temperature recorded in the living room and bedroom is low (Table 5.2). The relative humidity measurements from the right-now survey from the two weeks in winter show that the mean values are acceptable (Table 5.3).

According to the information collected, the roof has no insulation, unlike the walls, which have insulation, and the glazed windows are made of metal frames with double glazing. Therefore, it is essential to install thermal insulation in this house (exterior walls and roof) to correct a discomfort identified not only by the house occupant but also reflected in the measurements of the indoor environment. The insulation can be applied from the outside on the walls since it is a villa.

Although the occupant doesn't say that it is slightly disturbing with the acoustics in the house, say that the noise from outside and from the neighbours is slightly disturbing. As explained at the beginning of the chapter, rock wool insulation is also an acoustic insulator and will, therefore, resolve the occupant's discomfort. Additionally, the occupant also mentions in the survey that it is considered important to

choose recycled materials with low energy consumption and less polluting, and mineral wool is a material compatible with these environmental concerns. Insulation will also make it possible to improve the presence of humidity and mould in the home. However, it is recommended that the occupant opens the window more, especially in winter, although it is open always/almost always the window. Replacing the windows with PVC windows with Low-E double glazing will also improve thermal and acoustic parameters. This is a very priority improvement measure identified by the house's occupant.

In order to reduce energy consumption, it is also recommended that the occupants replace equipment such as fridges, washing machines, and laundry machines. Basically, equipment used frequently may be old and consume much energy. Installing solar panels will reduce the electricity bill at the end of the month. The occupant identifies these measures as a priority. Also, it identifies that replacing the heating equipment is very priority. Since the occupant uses electricity and wood-burning equipment to heat the house, it is recommended to install heating equipment that uses electricity and, with the benefit of solar panels, does not have a higher electricity cost or opt for a passive system.

- **Case study 4**

After analysing the surveys, the comfort and well-being parameters identified in Table 7.2 as the main ones to be improved were thermal and acoustic comfort. Analysis of the measurements of the indoor environment over the course of a year (Table 6.1) shows that the mean temperatures in the spring and autumn seasons are acceptable, between 18-25°C as recommended by the Portuguese legislation, but in winter and in summer, the average temperatures are outside this range. When analysing the data recorded for the right-now survey periods, it can be seen that even in winter, the minimum temperature recorded in the living room and bedroom is too low (Table 5.2). The relative humidity measurements from the right-now survey from the two weeks in winter show that the mean values are acceptable (Table 5.3).

According to the information collected, there is no insulation on the opaque façade, and the glazed windows are made of metal frames with double glazing. It is, therefore, essential to install thermal insulation in this house (walls and roof) to correct a problem identified not only by the house's occupant but also reflected in the measurements of the indoor environment. However, since acoustics has also been identified as a parameter to be improved, the insulation should be acoustic, not just thermal. As this is a house in a building, it's best to insulate the outside walls from the inside, as not all the neighbours may agree with insulating the outside of the building. Analysing what the occupant answered in the extensive survey, it can be seen that the sources that cause the most discomfort are the neighbours and outside noise. Therefore, in addition to the roof and walls in contact with the outside, it is also necessary to insulate those adjacent to neighbours.

As mentioned at the beginning of this chapter, the choice of rock wool as an insulator seems a suitable solution since it is a thermal and acoustic insulator. Additionally, the occupant also mentioned in the survey that she considers it important to choose recycled materials with low energy consumption and that are less polluting, and mineral wool is a material compatible with these environmental concerns. Insulation will also make it possible to improve the presence of humidity and mould in the home. However, it is recommended that the occupant opens the window more, especially in winter, as it is infrequent to open it. In the case of the bathroom, it is recommended that mechanical ventilation equipment is installed if possible since it is a room without a window and has been identified as a place with a higher presence of humidity.

Replacing the windows with PVC windows with Low-E double glazing will also improve thermal and acoustic parameters. These are two improvement measures the house's occupant has identified as priorities. The occupant also indicates that it is important to install sunshading (a passive system that also considers important). So, putting shades on the windows that don't have is also a measure to improve

thermal comfort and to improve lighting comfort since the occupant indicated that natural light is bright in summer and slightly bright in winter.

Although the occupant indicates that indoor air, ventilation and lighting are not important parameters, the recommendations above are given. Since the occupant has indicated that improving the heating and cooling equipment and the light bulbs is a priority, it is recommended that they replace them with more energy-efficient ones.

In order to reduce energy consumption, it is also recommended that the occupant replace equipment such as fridges, washing machines and laundry machines, basically equipment that is used frequently and that may be old and consume a lot of energy. Installing solar panels will reduce the electricity bill at the end of the month. However, the occupant identifies this measure as a low priority and the collection of monthly consumption shows that there is little energy consumption in most months. Therefore, this may not make much sense from a financial return point of view.

- **Case study 5**

According to the data collected through the surveys, the comfort and well-being parameter identified in Table 7.2 as the main one to be improved was thermal comfort. Analysis of the measurements of the indoor environment over the course of a year (Table 6.1) shows that the mean temperatures in spring, autumn and summer seasons are acceptable, between 18°C and 25°C as recommended by the Portuguese legislation, but in winter, the average temperatures are outside this range. When analysing the data recorded for the right-now survey periods, it can be seen that in winter, the minimum temperature recorded in the living room and bedroom is too low and although, on average, the temperature recorded in summer is in the comfort range, there are maximum values recorded above this range (Table 5.2).

According to the information collected, there is no insulation on the opaque façade, and the glazed windows are made of wood frames with simple glazing. It is essential to install thermal insulation in walls and roof in this house (occupant identifies it as a priority) and substitute the windows to correct a thermal problem identified not only by the occupant of the house but also reflected in the measurements of the indoor environment. The occupant indicated that heard disturbing noises, especially in the summer, but also indicated that was slightly satisfied with the acoustics in the room. Therefore, it is not considered necessary for the insulation to be acoustic, but since the choice is rock wool (as mentioned and justified at the beginning of the chapter), it will also be a thermal and acoustic insulator and is in line with the occupant's concern about the material's environmental sustainability. Replacing the windows with PVC ones with Low-E double glazing will also improve thermal and acoustic parameters, although the occupant considers it a low priority.

Since this is a villa, the roof will be insulated without any obstructions, and it's best to insulate the outside walls from the outside to eliminate/reduce thermal bridges. Since there is a basement below the house, it is also recommended to insulate the roof of this basement so that there is less heat loss through the floor. Insulation will also make it possible to improve the presence of humidity and mould in the home. However, it is recommended that the occupant opens the window more regularly in all the rooms of the house where there is the greatest presence of humidity, especially in winter and when there are activities where more water vapour is produced than usual (bathing, sleeping, drying clothes, others.). Still, as the occupant identifies that prefer automatic ventilation systems, it can be install mechanical ventilation, especially in the bathroom. The relative humidity measurements from the right-now survey from the two weeks in winter confirm this idea of humidity in the house since the maximum values recorded during this period are high (Table 5.4), and the mean value, especially in the bedroom, is also high (Table 5.3).

In order to reduce energy consumption, it is also recommended that the occupant replace old equipment that consumes more energy than the new ones, although the occupant says that already made these replacements. Installing solar panels will reduce the electricity bill at the end of the month, and it's a measure that the occupant considers a high priority.

- **Case study 6**

After analysing the surveys, the principal comfort and well-being parameters identified to be improved (Table 7.2) were thermal, air quality and lighting. Next, the class 2 parameters to be considered when applying comfort improvement measures are acoustics and privacy. For the analysis of the measurements of the indoor environment during one year (Table 6.1), it appears that the mean temperatures in spring, winter and autumn seasons are acceptable, between 18°C and 25°C as recommended by Portuguese legislation, but in summer, the mean temperatures are outside this range. Analysing the data recorded for the right-now survey periods (Table 5.2), it is noted that even in winter, the minimum temperature recorded in the bedroom and living room is low (17.7°C and 16.8°C respectively), and the maximum temperature in summer is too high (29.6°C and 30.5°C respectively). It should be noted that the occupants of this house use the heater frequently, as they mentioned in Figure 5.5, Figure 5.6 and Figure 6.6, and therefore, the mean temperature may be higher than if they didn't use heating.

From the information gathered, there is no insulation on the opaque façade, and the glazed windows are made of metal frames with double glazing. However, the occupants do not consider insulating the walls and ceiling a priority. Nevertheless, it is proposed to install thermal insulation in the exterior walls and the roof of the bedroom (only the compartment where the roof has contact with the outside) to correct a problem identified not only by the occupants of the house but also reflected in the measurements of the indoor environment. Since the building's garage is underneath the house, insulating the garage ceiling would also be important. Since acoustics has also been identified as a parameter to be improved, the insulating material should be acoustic and thermal. This case study is an apartment, part of a building. Thus, it's best to insulate the outside walls from the inside, as not all the neighbours may agree with insulating the outside of the building. The bedroom walls can be insulated from the outside as they are not part of the original façade of the building. The sources that occupants identify as causing the most noise disturbance are the common areas of the building, the outside and the neighbours. Therefore, in addition to the garage ceiling, the bedroom roof and exterior walls, it is also necessary to insulate the walls adjacent to the common areas of the building and with the neighbours.

As mentioned in other case studies, rock wool is a thermal and acoustic insulator for this house. Additionally, the occupants indicated in the survey that recycled materials with low energy consumption and less polluting are important to consider, and mineral wool is a material compatible with these environmental concerns. Insulation will also make it possible to improve the presence of humidity and mould in the home, especially in the bedroom. It is also recommended that the occupants naturally ventilate the bedroom more, especially in winter, although often open the window according to the extensive survey. However, the right-now survey shows no pattern in the window's opening, so there is a margin for improvement. In the case of the bathroom, it is recommended to check if there is better mechanical ventilation equipment than the installed one since it is a room without a window and has been identified as a place with humidity. The relative humidity measurements during the two weeks of the right-now survey show that the maximum values recorded during this period are high, especially in the main bedroom (Table 5.4). Reducing or eliminating mould in the home will improve indoor air quality, a parameter identified as a priority for improvement in view of the responses obtained in the survey. However, the dissatisfaction with this parameter is more in the summer on the part of one of the occupants (slightly unsatisfied), and couldn't figure out why. Maybe it is due to the CO₂ concentration

since the values collected over two consecutive weeks in summer and winter show high mean values (Table 5.5).

As with the insulation of walls and ceilings, which the occupants consider a low priority, they indicate that replacing the windows is not a priority since they consider that this improvement measure has already been carried out. Nevertheless, the existing windows are proposed to be replaced with PVC ones with double-glazing Low-E. This will improve thermal and acoustic parameters.

Improving the heating and cooling equipment is a priority for one of the occupants, but for the other, it is not. Since there is no air conditioning in the house and high temperatures are reached indoors in the summer, it is recommended that air conditioning be installed in this house to help improve thermal comfort. Although insulation helps to improve thermal comfort, installing this equipment can be useful when harsher temperatures are experienced. One of the occupants also considers installing solar panels a high priority. Thus, installing solar panels will reduce the electricity bill at the end of the month.

Regarding lighting, and knowing that it is one of the parameters identified for improvement, it is necessary to understand what the problem is. Looking at the occupants' answers to the survey, it can be seen that the occupants indicate that there is little natural light in both summer and winter, and this may be due to the fact that the living room is an interior compartment with no window to the outside. This gives the occupants this perception; adding up, the bedroom has a small window. In this case study, the lack of natural light is structural since the house has few windows and the living room has no window to the outside. In this sense, it is not possible to make a recommendation that does not involve major renovations.

As for privacy, not being one of the most necessary parameters to intervene (class 2), it is suggested that the occupants put up interior blinds that allow for privacy when needed but do not make the house seem to have less natural light. Paying attention to the colour and type of fabric helps with this balance of privacy vs. natural light.

- **Case study 7**

In this case study, the parameters of comfort and well-being identified to be improved (Table 7.2) were thermal, air quality, lighting and maintenance. Next, the class 2 parameters to be considered when applying comfort improvement measures are acoustics and privacy. For the analysis of the measurements of the indoor environment during one year (Table 6.1), it appears that the mean temperatures in the spring and autumn seasons are acceptable, between 18-25°C as recommended by Portuguese legislation, but in winter and summer, the mean temperatures are outside this range. However, the average winter temperature can be considered within this comfort range as it is 17.9°C. The data recorded for the right-now survey periods (Table 5.2) shows that in winter, the minimum temperature recorded in the bedroom and living room is low (16.3°C and 16.7°C respectively), and the maximum temperature in summer is high (28.9°C and 29.9°C respectively).

According to the information collected, it is known that there is no insulation on the opaque façade, and the glazed windows are made of metal frames with double glazing. One of the occupants considers insulating the walls and ceiling a priority, and this is the first measure proposed to improve the thermal comfort and acoustics. Thermal and acoustic insulation should be inside the exterior walls since this case study is an apartment, part of a building, and not all the neighbours may agree with insulating the outside of the building. The roof can be insulated since the floor above the house is a storage area for everyone in the building. As mentioned at the beginning of the chapter, rock wool is the insulation selected for all case studies, given its insulating thermal and acoustic insulator characteristics. It is a material compatible with environmental concerns that the occupants consider important to use. The

noise sources that occupants identify as causing the most noise disturbance are the outside, the neighbours and common areas of the building. In addition to the ceiling and exterior walls, it is recommended to insulate the walls that are adjacent to the common areas of the building and with the neighbours. One of the occupants indicates that replacing the windows is a priority and a proposed thermal and acoustic improvement measure. As in other cases, we suggest replacing the windows with PVC with double-glazing Low-E.

Insulation will also make it possible to improve the presence of humidity and mould in the home but it is recommended that the occupants naturally ventilate the rooms, especially in winter, since they infrequently open the windows according to the extensive survey. The relative humidity measurements during the two weeks of the right-now survey show that the mean and maximum values recorded during this period are high in winter (Table 5.3 and Table 5.4). In the case of the bathroom, it is recommended to check if there is better mechanical ventilation equipment than the installed one since it is a room without a window and has been identified as a place with humidity. Reducing or eliminating mould in the home will improve indoor air quality, a parameter identified as a priority for improvement, given the responses obtained in the survey. However, the dissatisfaction with this parameter is more in the summer on the part of one of the occupants (slightly unsatisfied), and it is not possible to understand why. The CO₂ concentration values collected over two consecutive weeks in summer and winter show that the mean value in winter is very high, but in summer it is acceptable (Table 5.5).

Improving the ventilation equipment is a priority for the occupants. Since there is air conditioning in some rooms in the house, it is recommended that it be installed in other rooms to help improve thermal comfort and ventilation.

Knowing that lighting is one of the parameters identified for improvement, it is necessary to understand the potential for improvement. The analysis of the surveys shows that in the summer, one of the occupants identified it as comfortable, and another identified it as clear. In winter, one identifies it as light and the other as dark. So, it's a bit difficult to tell whether it's dark or light in winter. However, it is suggested to substitute or add interior blinds that can reduce brightness whenever the occupants wish. To do this, it is necessary to consider the colour, type of fabric and material so that it doesn't affect the occupant who feels that there isn't too much natural light in winter. Privacy is a comfort and well-being parameter of class 2 that needs to be improved, and it is suggested that the occupants put up interior blinds that allow for privacy when needed but do not make the house seem to have less natural light. Paying attention to the colour and type of fabric helps with this balance of privacy vs natural light.

Knowing that maintenance was one of the parameters identified for improvement, and since the suggestion of applying insulation to the walls and ceiling and replacing windows, the maintenance of the opaque and glazed envelope will be resolved. The maintenance of the house's interior will have to be evaluated by the occupants, and priorities and the best options must be identified.

From the point of view of using electricity from renewable sources, specifically solar panels, the occupants indicated that installing these panels was not a priority. However, installing solar panels will reduce the electricity bill at the end of the month.

• Case study 8

After analysing the surveys, the comfort and well-being parameters identified to be improved (Table 7.2) were air quality, acoustics, and privacy, all class 1 parameters. For the analysis of the measurements of the indoor environment during one year (Table 6.1), it is verified that the mean temperatures in spring, autumn and winter seasons are acceptable, between 18°C and 25°C as recommended by the Portuguese legislation, but in summer, the mean temperature is outside this range. The data recorded for the right-

now survey periods (Table 5.2) shows that in winter, the minimum temperature recorded in the bedroom and living room is low (15.5°C and 15.3°C respectively), and the maximum temperature in summer is high in the bedroom and the living room (27.8°C and 28.7°C respectively). The relative humidity measurements from the right-now survey from the two weeks in winter show that the mean values are acceptable in the living room but a little bit high in the bedroom (Table 5.3).

Although only the mean summer temperature is outside the established comfort range, the mean winter temperature is only 0.5°C higher. Bearing this in mind and knowing that this parameter was not one of those indicated as being for improvement, it is still recommended that it be applied insulation on the opaque façade and replacing the windows because there is no insulation on this house, and the windows are simple double-glazed with plastic frames. These measures will improve thermal comfort and acoustic comfort, a parameter that is indicated as being important to improve (class 1). It is suggested that the exterior walls be insulated from the inside since they are part of one building, and the neighbours may disagree with insulating the outside of the building and insulating the roof since it is on the top floor of the building. As previously mentioned, rock wool is the insulation selected for all case studies, given its insulating thermal and acoustic insulator characteristics. It is a material that is compatible with environmental concerns compared to others. The noise sources that occupants identify are the outside, the neighbours and inside the house (equipment and people). Thus, in addition to the roof and exterior walls, it is recommended that the walls adjacent to the neighbours be insulated. Although the occupants indicate that they have already replaced the windows, replacing them with PVC ones with double-glazing, Low-E is proposed for thermal and acoustic improvement.

Insulation, as well as improving thermal and acoustic comfort, can also enhance the quality of air in the sense that it can reduce the presence of humidity in the home. However, it is recommended that the occupant naturally ventilate the rooms more, especially in winter, since the occupants indicated that they infrequently/often open the windows. However, in addition to humidity, the unpleasant odour reported by one of the occupants can also be associated with air quality discomfort. In this sense, the source of the problem should be addressed. It should also be noted that the CO₂ concentration values collected during two consecutive weeks in summer and winter show that the mean value in winter is high. Still, in summer, it is acceptable (Table 5.5).

Privacy is a comfort and well-being parameter that needs to be improved, and it is suggested that the occupants analyse what bothers them about this parameter. However, installing interior blinds that allow more privacy when needed is a measure. These blinds' colour and type of fabric must be considered to not affect the natural lighting. This measure may even favour the improvement of the lighting parameter since the occupants identify that the natural lighting is slightly bright in summer and winter.

To reduce energy consumption and address one of the occupants' priorities, the light bulbs should be replaced. Although the occupants don't identify installing solar panels as a priority, this measure will reduce the electricity bill at the end of the month. What's more, the occupant has indicated that installing HVAC in the house is a priority, which will increase energy consumption.

• Case study 9

Thermal and maintenance were the principal comfort and well-being parameters identified to be improved (Table 7.2). Then, furniture is the class 2 parameter to be considered when applying comfort improvement measures. Analysing the indoor environment measurements of the study year (Table 6.1), it appears that the mean temperatures in spring and summer seasons are acceptable, between 18°C and 25°C as recommended by the Portuguese legislation, but in winter and autumn, the mean temperatures are outside this range, although in autumn is practically 18°C. Analysing the data recorded for the right-now survey periods (Table 5.2), it is noted that in winter, the minimum temperature recorded in the

bedroom and living room is too low (12.3°C and 10.7°C respectively), and the maximum temperature in summer is too high (29.8°C and 30.8°C respectively). It should be noted that the occupants of this house use the heater almost every day in winter, as mentioned in Figure 5.5, Figure 5.6 and Figure 6.6. Therefore, the mean temperature may be lower if they didn't use heating.

From the information gathered, the opaque façade is not insulated, and some of the glazed windows are made of metal frames with double glazing, while others are PVC. To improve the thermal comfort identified not only by the house occupants but also reflected in the measurements of the indoor environment, thermal insulation is proposed to be installed in the exterior walls, the ceiling of the basement, and the roof of the house. The walls can be insulated from the outside since it is a villa.

As mentioned above in other case studies, rock wool is a thermal and acoustic insulator. It is suggested to apply and is compatible with the environmental concerns of the occupants since they indicate that recycled materials, with low energy consumption and that are less polluting, are important to consider. Insulation will also make it possible to improve the presence of humidity and mould in the home. It is also recommended that the occupant naturally ventilate the house more, especially in winter, despite the occupant's concerns about maintaining the house temperature. In the case of the bathroom, it is recommended that mechanical ventilation equipment be installed since it is a room without a window and has been identified as a place with the presence of humidity. The measurements of the relative humidity during the two weeks of the right-now survey show that the mean values recorded during this period are acceptable in winter, but the maximum values recorded in the bedroom are high (Table 5.3 and Table 5.4). Reducing or eliminating mould in the home will improve indoor air quality, a parameter identified as important in the survey filled by the occupants. The CO₂ concentration values (air quality) collected during the right-now survey in summer and winter show that the mean values are acceptable (Table 5.5). Although the occupants indicated they had already replaced the windows with better ones, some have not yet been replaced. In this way, replacing the existing windows with PVC ones with double-glazing Low-E is proposed. This will improve thermal and acoustic parameters.

Improving the heating and cooling equipment and ventilation is a priority for the occupants. Since there is no air conditioning in the house and high temperatures are reached indoors in the summer, it is recommended that air conditioning be installed in this house to help improve thermal comfort. Although insulation helps to improve thermal comfort, installing this equipment can be useful when harsher temperatures are experienced. Since solar panels are installed, the electricity bill may not be increased at the end of the month. Just as it is recommended to install ventilation in the bathroom for reasons of humidity accumulation, it is also recommended to install a ventilation system in the living room as it is a windowless room, or even to put in a window to improve the ventilation of the house, a priority indicated by the occupants even though they say they are satisfied with this comfort parameter.

Knowing that maintenance was one of the parameters identified for improvement, and since the suggestion of applying insulation to the walls and ceiling and replacing windows, the maintenance of the exterior of the building will be resolved. As for the maintenance of the house's interior, it will have to be evaluated by the occupants as well as the replacement of furniture, a parameter also identified for improvement (class 2), identifying the priorities and the best options. It should be noted that the occupants indicate some noise disturbance from the house and plumbing systems, so when considering interior maintenance, measures can be taken to improve this aspect.

- **Case study 10**

After analysing the surveys, the comfort and well-being parameters identified in Table 7.2 as the main ones to be improved were thermal comfort and privacy (class 1). The class 2 parameters identified to be improved were air quality and lighting. The measurements of the indoor environment over the course of

a year (Table 6.1) show that the mean temperatures in the spring, winter and autumn seasons are acceptable, between 18°C and 25°C as recommended by the Portuguese legislation, but in summer, the mean temperature is outside this range. When analysing the data recorded for the right-now survey periods (Table 5.2), it can be seen that in summer, the maximum temperature recorded in the living room and bedroom is high (34.7°C and 27.3°C, respectively).

According to the information collected, there exists insulation on the opaque façade, and the windows are mostly simple double-glazing with plastic frames. However, it is recommended that thermal insulation in exterior walls be reinforced to improve thermal comfort, a problem identified by the occupants. As this is a house in a building, it's best to insulate the outside walls from the inside, as not all the neighbours may agree with insulating the outside of the building. Although the acoustics are not a parameter to be improved, the survey shows that there is a problem with the noise from the neighbours. Therefore, installing acoustic insulation in the walls adjacent to the neighbours will also help to correct this issue. As mentioned at the beginning of this chapter, the insulator will be rock wool as it is a thermal and acoustic insulator and is more sustainable than other insulators. The occupants also consider it important to choose recycled materials with low energy consumption that are less polluting, and mineral wool is a material compatible with these environmental concerns. Insulation will also make it possible to improve the presence of humidity and mould in the home. The relative humidity measurements during the two weeks of the right-now survey show that the mean values recorded during this period are acceptable in winter in the living room but in the main bedroom is high (Table 5.3). The maximum values recorded for the two rooms are high (Table 5.4). Thus, it is recommended that the occupant opens the window more in winter, as it infrequently opens the window. In the case of the bathroom, it is recommended that mechanical ventilation equipment is installed, if possible since it is a room without a window and has been identified as a place with the presence of humidity. These proposed improvements will allow air quality improvement, a parameter also identified as one of those to be improved. It should be noted that the CO₂ concentration values collected during two consecutive weeks in summer and winter show that the mean values are acceptable; however, the recorded maximum value is high for the two seasons (Table 5.5).

Replacing the windows with PVC windows with Low-E double glazing will also improve thermal comfort. The occupant also indicates that it is a priority to install heating equipment and, very important cooling equipment. Thus, installing air conditioning is a solution. However, energy consumption will increase. To mitigate this effect, installing solar panels will be a solution since it will reduce the electricity bill at the end of the month. Also, the occupants identify this measure as a priority measure. In order to reduce energy consumption and align with what the occupants consider to be a priority, it is also recommended that the occupant replace equipment such as fridges, washing machines and laundry machines. Equipment's used frequently may be old and consume a lot of energy.

Privacy is a comfort and well-being parameter to be improved, and it is suggested that the occupants put up interior blinds that allow for privacy when needed but do not make the house seem to have less natural light since lighting is also a parameter to improve. So, paying attention to the colour and type of fabric is necessary to help with this balance of privacy vs. natural light. Regarding lighting (class 2 of comfort and well-being parameters to improve), knowing that it is one of the parameters identified for improvement, it is necessary to understand the potential for improvement. The analysis of the surveys shows that in the summer, one of the occupants identified it as comfortable, and another identified it as bright. In winter, one identifies it as comfortable and the other as slightly dark. However, it is suggested to substitute or add interior blinds that can reduce brightness whenever the occupants wish. To do this, it is necessary to consider the colour, type of fabric and material so that it doesn't affect the occupant who feels that is slightly dark in winter.

Table 7.3 - Systematisation of the parameters to be improved, problems identified and proposed improvement measures for each case study

Case Study	Parameters to Improve	Indoor Measurements	Identified problems	Occupant Priorities	Proposals Improvement (occupant priorities/extra)
1	Class 2: Thermal, Air Quality, Lighting, Acoustic	- Acceptable temperatures in spring/autumn and in summer/winter very close to this range - Acceptable humidity levels	- Air quality: not identified - Thermal comfortable in summer and winter but prefers slightly cooler in summer and slightly warmer in winter - Noise disturbance: outside and neighbours - Natural light: bright in summer and comfortable in winter	- Installation of air conditioning - Installation of solar panels	- Installation of air conditioning - Installation of solar panels
					- Installation of thermal/acoustic insulation in the exterior walls from the inside and in the walls adjacent to neighbours - Replacement of windows - Installation/replacement of interior/exterior shading
2	- Class 1: Thermal, Air Quality - Class 2: Privacy - Class 3: Lighting, Acoustic	- Acceptable temperatures except in summer - Acceptable humidity levels	- Thermal discomfort in summer and winter and prefers slightly cooler in summer and slightly warmer in winter - Noise disturbance: outside, common areas of the building, inside the house and water drainage systems. - Mould: bedrooms and bathroom - Lighting: not identified	- Installation of air conditioning - Installation of solar panels - Replacement of house equipment	- Installation of solar panels - Installation of air conditioning - Replacement of equipment with efficient versions
					- Installation of thermal/acoustic insulation in the exterior walls from the inside, interior walls that are adjacent to common areas of the building and neighbours and roof - Replacement of windows - More natural/mechanical ventilation - Installation/replacement of interior/exterior shading considering the colour and material (compromise between light and privacy)
3	Class 1: Thermal	- Acceptable temperatures except in winter - Acceptable humidity levels, however slightly above the required values	- Thermal discomfort in summer and winter and prefers slightly cooler in summer and much hotter in winter - Noise: Despite satisfied, indicates noise disturbance - Mould: bedroom	- Installation of heating and ventilation system - Installation of solar panels - Replacement of windows - Replacement of house equipment	- Installation of air conditioning - Installation of solar panels - Replacement of windows - Replacement of equipment with efficient versions
					- Installation of thermal/acoustic insulation in the roof and exterior walls from the outside - More natural/mechanical ventilation

Table 7.3 - Systematisation of the parameters to be improved, problems identified and proposed improvement measures for each case study (cont.)

Case Study	Parameters to Improve	Indoor Measurements	Identified problems	Occupant Priorities	Proposals Improvement (occupant priorities/extra)
4	Class 1: Thermal, Acoustic	- Acceptable temperatures except in winter/summer - Acceptable humidity levels	- Thermal discomfort in summer and winter and prefers much colder in summer and much hotter in winter - Noise disturbance: neighbours, outside, inside the house, and water drainage systems - Mould: bedroom, bathroom, glazed balcony and living room	- Installation of air conditioning - Installation of solar panels - Installation of thermal insulation - Installation/Replacement of sunshades - Replacement of house equipment - Replacement of lighting - Replacement of windows	- Installation of air conditioning - Installation of solar panels - Installation of thermal/acoustic insulation in the exterior walls from the inside, interior walls that are adjacent to the neighbours and the roof - Replacement of windows - Installation/replacement of interior/exterior shading - Replacement of equipment with efficient versions - Replacement of light bulbs - More natural/mechanical ventilation
5	Class 1: Thermal	- Acceptable temperatures except in winter - High humidity in winter and autumn	- Thermal discomfort in summer and winter and prefers slightly cooler in summer and warmer in winter - Noise: Despite satisfied, indicates noise disturbance - Mould: bedrooms and bathroom	- Installation of solar panels - Installation/Replacement of sunshades - Installation of thermal insulation - Replacement of windows	- Installation of thermal/acoustic insulation in the roof, floor, and exterior walls from the outside - Replacement of windows - Installation/replacement of interior/exterior shading - Installation of solar panels - More natural/mechanical ventilation
6	- Class 1: Thermal, Air quality, Lighting - Class 2: Acoustics, Privacy	- Acceptable temperatures except in summer - Acceptable humidity levels	- Insufficient natural light in winter and summer (living room is an interior compartment with no window to the outside, and the bedroom has a small window) - Noise disturbances: common areas, outside, neighbours and others identified for only one occupant - Thermal discomfort in summer and winter - Mould: bedroom, kitchen and bathroom	- Installation of solar panels* - Installation of thermal insulation * - Installation of air conditioning *	- Installation of thermal/acoustic insulation in roof, floor, some of the exterior walls from the outside and others from the inside and interior walls adjacent to common areas of the building and neighbours - Installation of air conditioning - Installation of solar panels - More natural/mechanical ventilation - Replacement of windows - Installation/replacement of interior/exterior shading considering the colour and material (compromise between light and privacy) - Lighting: recommendations involve major renovations

Table 7.3 - Systematisation of the parameters to be improved, problems identified and proposed improvement measures for each case study (cont.)

Case Study	Parameters to Improve	Indoor Measurements	Identified problems	Occupant Priorities	Proposals Improvement (occupant priorities/extra)
7	- Class 1: Thermal Air quality Lighting, Maintenance - Class 2: Acoustics, Privacy	- Acceptable temperatures except in summer and in winter very close to this range - Acceptable humidity levels except in winter; however, in summer and spring, the mean value is below the reference values	- Thermal discomfort in summer and winter - Natural light: In summer, one occupant identified as comfortable, and the other clear. In winter, one identifies as light and the other as dark. Difficult to tell whether it's dark or light in winter - Noise disturbances: outside and others identified for only one occupant - Mould: bedrooms, living room, kitchen, corridor and bathroom	- Installation of heating * and ventilation system - Installation of thermal insulation* - Installation/Replacement of sunshades * - Replacement of windows* - Replacement of house equipment *	- Installation of thermal/acoustic insulation in roof, exterior walls from the inside and interior walls adjacent to common areas of the building and neighbours - Installation/replacement of interior/exterior shading considering the colour and material (compromise between light and privacy) - Replacement of windows - Installation of air conditioning - Replacement of equipment with efficient versions
8	Class 1: Air quality, Acoustics, Privacy	- Acceptable temperatures except in summer - Acceptable humidity levels; however, in summer and spring, the mean value is below the reference values	- Thermal discomfort in summer and winter - Noise disturbances: outside, neighbours, inside the house and others identified for only one occupant - Mould: bedroom	- Installation of air conditioning - Installation/Replacement of sunshades - Installation of solar panels - Replacement of light bulbs - Replacement of house equipment	- Installation/replacement of interior/exterior shading considering the colour and material (compromise between light and privacy) - Replacement of light bulbs - Installation of air conditioning - Installation of solar panels - Replacement of equipment with efficient versions
9	- Class 1: Thermal, Maintenance - Class 2: Furniture	- Acceptable temperatures except in winter and in autumn very close to this range - Acceptable humidity levels	- Thermal discomfort in summer and winter - Noise: Despite satisfied, indicates noise disturbance - Mould: bathroom	- Installation of air conditioning - Installation of thermal insulation	- Installation of thermal/acoustic insulation in the ceiling of the basement, roof, and exterior walls from the outside - Installation of air conditioning
					- Replacement of windows - Installation of solar panels - Ensure regular maintenance of building and interiors and upgrade furniture for better comfort - More natural/mechanical ventilation

Table 7.3 - Systematisation of the parameters to be improved, problems identified and proposed improvement measures for each case study (cont.)

Case Study	Parameters to Improve	Indoor Measurements	Identified problems	Occupant Priorities	Proposals Improvement (occupant priorities/extra)
10	- Class 1: Thermal, Privacy - Class 2: Lighting, Air quality	- Acceptable temperatures except in summer but very close to this range - Acceptable humidity levels; however in summer, the mean value is below the reference values	- Thermal discomfort in summer and winter - Natural light: In summer, one occupant identified as comfortable, and the other as bright. In winter, one identifies as comfortable and the other as slightly dark - Mould: bathroom - Noise: Despite satisfied, indicates noise disturbance	- Installation of air conditioning - Installation of solar panels - Replacement of house equipment	- Installation of air conditioning - Replacement of equipment with efficient versions - Installation of solar panels
					- Installation of thermal/acoustic insulation in exterior walls from the inside and interior walls adjacent to neighbours - More natural/mechanical ventilation - Replacement of windows - Installation/replacement of interior/exterior shading considering the colour and material (compromise between light and privacy)

7.3.Conclusions of parameters and measures

After identifying the comfort and well-being parameters to be improved, assigning priority classes, and then suggest improvement measures to improve the indoor environment and energy efficiency, as indicated above for each case study, it is possible to draw the following conclusions:

- Of the parameters analysed in winter and summer, it can be seen that thermal comfort is the parameter that needs to be improved the most, according to the occupants' responses, which were identified in 9 of the 10 case studies. This was followed by acoustics and indoor air quality. Finally, lighting was identified as a parameter for improvement in 5 of the 10 case studies. Of the parameters analysed once a year, as the season does not affect perception, privacy most needs improvement, having been identified in 5 of the 10 case studies. This was followed by maintenance and, finally, furniture;
- Although the improvement measures indicated have not been studied using simulation models, it is known from other studies and daily experience that they impact the indoor environment parameters. Many of these measures also reduce energy consumption or, at least, the energy bill.

8. Case studies simulation models

The simulation model's component of this study pretends to develop simulation models for the case studies using EnergyPlus. These models gave results concerning energy consumption and indoor temperature conditions. Firstly, initial results were obtained. Then, the calibration process began to ensure that the results obtained for consumption and temperatures were similar to those collected over one year (data from E-Redes/PEL and Hobo sensors).

After the models for the ten case studies had been calibrated, both from an energy and temperature point of view, it became possible to apply the selected improvement measures more directed towards thermal comfort and, which will be applied equally to all case studies (Chapter 3.2). With the results obtained by introducing the selected improvement measures, it was possible to verify their impact on occupant thermal comfort, allowing the chosen options to be validated and evaluated.

8.1.Simulation models

In Chapter 4 representations of the rooms in each case study are presented (Figure 4.1 to Figure 4.10), where the main bedroom and living room are identified. Considering the model boundaries, when the exterior line is red, it indicates that the façade is in direct contact with the outside. Green means that it is adjacent to the neighbours, yellow indicates contact with the common areas of the building, and blue indicates contact with the ground. This section presents the 3D models derived from OpenStudio for each case study (Figure 8.1 to Figure 8.10). However, in these models, it is not possible to verify the adiabatic surfaces and other considerations made, so it is necessary to check the colours of the exterior lines in Figure 4.1 to Figure 4.10.

For each case study, specific schedules were set based on occupants' reports of occupancy, natural ventilation, and equipment and lighting use. Equipment and system characteristics were considered with reference to site visits and occupant feedback. Shading was characterised based on visits and use reported by occupants. For opaque and glazed envelope elements, thermal conductivity and other properties (density, specific heat, etc.) were considered, primarily based on ITE50. Table 4.3 and Table 4.4 in Chapter 4 detail these characteristics for each case study, including the type of heating or cooling present. Table 8.1 presents the overall heat transfer coefficients (U) for each envelope element, without listing the materials for each case study.

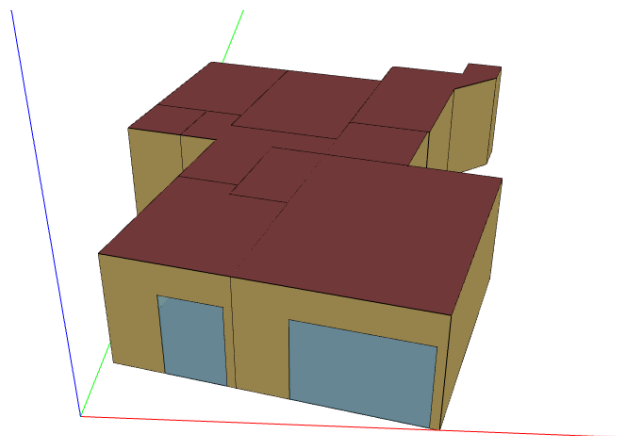


Figure 8.1 - 3D model of case study 1

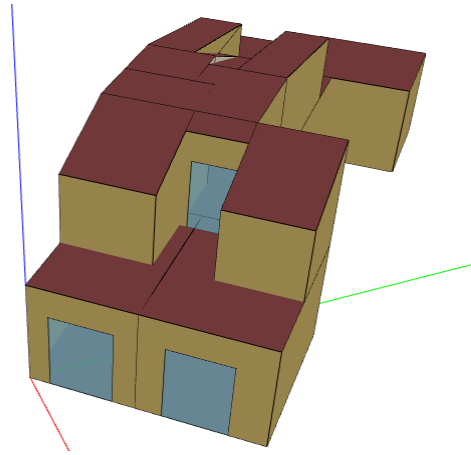


Figure 8.2 - 3D model of case study 2

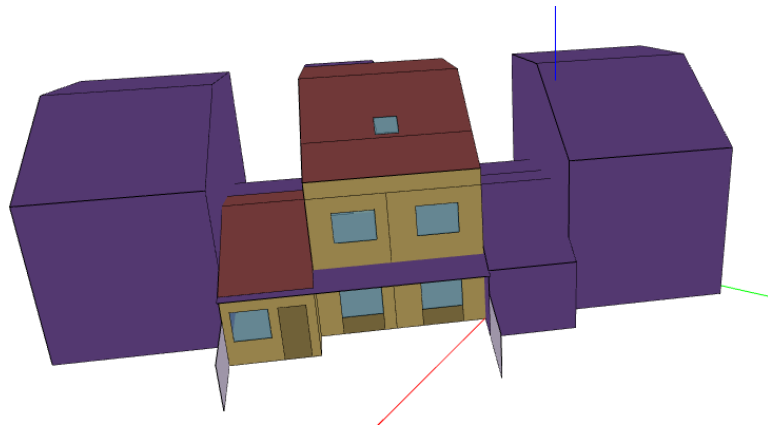


Figure 8.3 - 3D model of case study 3

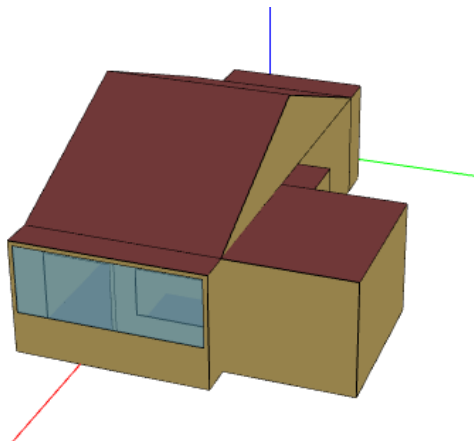


Figure 8.4 - 3D model of case study 4

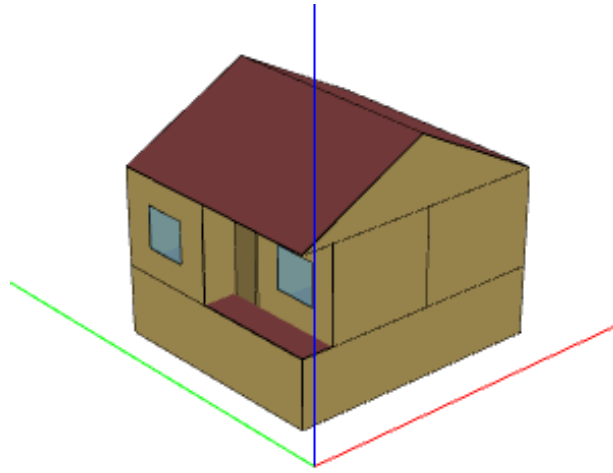


Figure 8.5 - 3D model of case study 5

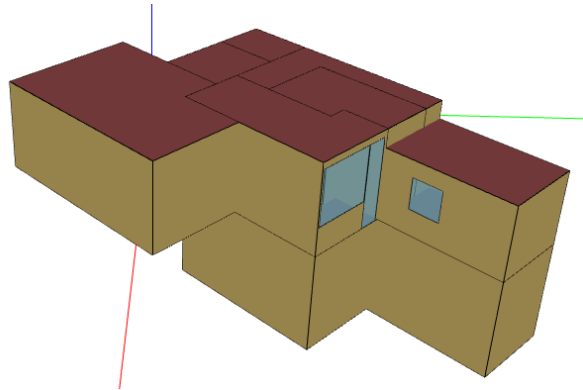


Figure 8.6 - 3D model of case study 6

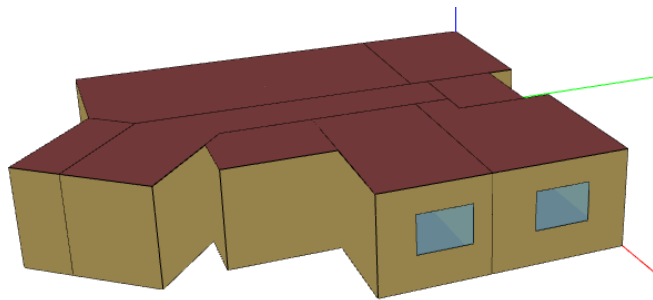


Figure 8.7 - 3D model of case study 7

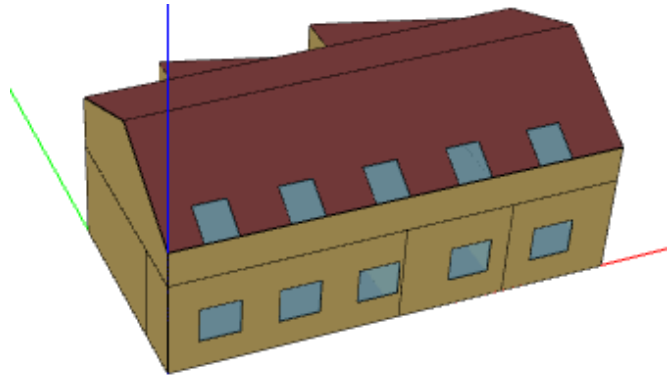


Figure 8.8 - 3D model of case study 8

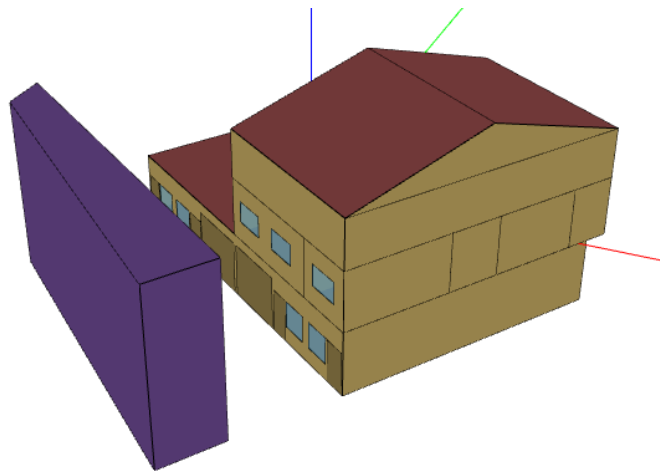


Figure 8.9 - 3D model of case study 9

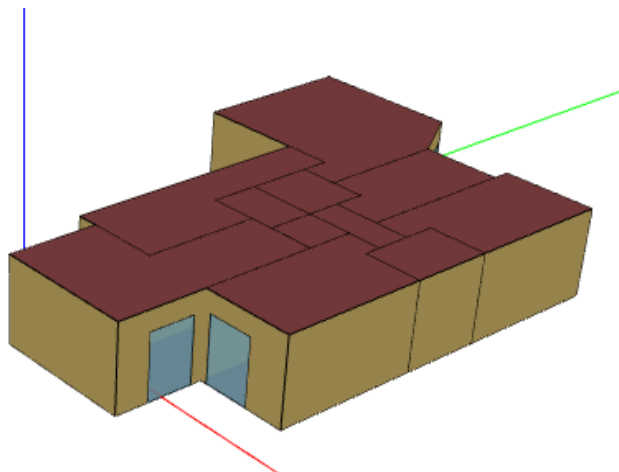


Figure 8.10 - 3D model of case study 10

Table 8.1 - Simulation models envelope characteristics of the case studies

Case study	Opaque envelope			Glazed envelope
	Exterior Walls	Ceiling	Floor	
1	U=1.7 W/(m ² .K)	U=3.3 W/(m ² .K)	U=3.3 W/(m ² .K)	U=4 W/(m ² .K)
2	U=0.8 W/(m ² .K)	U=1.1 W/(m ² .K)	U=4.4 W/(m ² .K)	U=3.7 W/(m ² .K)
3	U=0.8 W/(m ² .K)	U=7.4 W/(m ² .K)	U=3.5 W/(m ² .K)	U=3.7 W/(m ² .K)
4	U=1.8 W/(m ² .K)	U=3.4 W/(m ² .K)	U=2 W/(m ² .K)	U=4.3; 4.5 and 3.7 W/(m ² .K)
5	U=1.8 W/(m ² .K)	U=3.4 W/(m ² .K)	U=2 W/(m ² .K)	U=5.1 W/(m ² .K)
6	U=1.8 W/(m ² .K)	U=3 W/(m ² .K)	U=3 W/(m ² .K)	U=3.7 W/(m ² .K)
7	U=1.7 W/(m ² .K)	U=3.3 W/(m ² .K)	U=3.3 W/(m ² .K)	U=4 W/(m ² .K)
8	U=1.7 W/(m ² .K)	U=7.4 W/(m ² .K)	U=3 W/(m ² .K)	U=3.2 W/(m ² .K)
9	U=1.8 W/(m ² .K)	U=3.4 W/(m ² .K)	U=3.5 W/(m ² .K)	U=4.5 and 2.7 W/(m ² .K)
10	U=0.7 W/(m ² .K)	U=3 W/(m ² .K)	U=3 W/(m ² .K)	U= 2.7 and 1.6 W/(m ² .K)

As explained in Chapter 3.2, to realize the energy simulation in EnergyPlus for the case studies, an EPW climate file must be entered. This file was exported from an Excel sheet from the Direção Geral da Energia e Geologia, which provides climate files by municipality and modified on Elements version 1.0.6. The modified data are the outside air temperature and relative humidity metered using an exterior Hobo sensor placed outside in some case studies and/or a weather station.

In the case studies located in São Martinho do Porto (case studies 3 and 5), the EPW file for the municipality of Alcobaça was downloaded from the Direção Geral da Energia e Geologia excel sheet. The parameters mentioned above were then altered in order to carry out the simulation and calibration of the model. However, due to data acquisition problems, only data for June and a few days in May and July are missing for the year 2023. Therefore, for the days on which there is no data collected by the Hobo sensor, it was decided to use the data in the file exported from the excel sheet from the Direção Geral da Energia e Geologia.

For case study 10, the EPW file of the municipality of Almada was downloaded from the Direção Geral da Energia e Geologia excel sheet. The temperature and relative humidity values recorded by the Hobo sensor were altered in order to simulate and calibrate the model. However, due to data acquisition problems, there was a lack of data for July to October and some days in the month of June and November 2023. Therefore, for the days on which there is no data collected by the sensor, it was decided to use the data from the file exported from the excel sheet of the Direção Geral da Energia e Geologia.

In Lisboa case studies (case studies 1, 2, 4, 6 and 8), the EPW file for the municipality of Lisboa was downloaded from the excel sheet of the Direção Geral da Energia e Geologia. The temperature and relative humidity values recorded by a weather station were then altered in order to simulate and calibrate the model. However, due to data acquisition problems, there was a lack of data for November and December and some days in the month of October 2023. Therefore, for the days on which there is no data collected by the weather station, it was decided to use the data from the file exported from the excel sheet of the Direção Geral da Energia e Geologia.

In case study 7, there was no possibility of placing any exterior sensor to acquire data and there was also no weather station where the recorded data could be accessed. In this way, the data used was the one of the EPW file for the municipality of Seixal (downloaded from the excel sheet of the Direção Geral da Energia e Geologia).

Lastly, in the case study located in Cernache do Bonjardim (case study 9), the EPW file for the municipality of Sertão was downloaded from the Direção Geral da Energia e Geologia excel sheet. The parameters mentioned above were then altered in order to carry out the simulation and calibration of the model.

8.2.Models' calibration

Calibration evaluates the simulation's accuracy and the building's metered data regarding the building simulation outputs. It is crucial to perform this step during building simulation to ensure the maximum accuracy of results. The goal is to reduce the gap between the metered building's data and the values obtained from the model simulation. Defining schedules for occupancy, equipment, lighting, and others in a residential building can be difficult since the living environment inside the dwelling can change daily and may not lead to an hourly, weekly or even monthly pattern. This fact can lead to complex calibration of the simulated model.

ASHRAE Guideline 14-2002 [163] provides a minimum acceptable performance level in residential buildings' energy and demand savings measurement. The guideline recommends collecting utility bills, spanning at least a year or 12 continuous months, to calibrate the simulation outputs with the metered data. To have a broader understanding of the simulation results accuracy, calibrated models need to be validated based on their compliance with statistical indices within acceptable tolerances. For this study, the model validation was performed using two statistical indices, Mean Bias Error (MBE) and Coefficient of variance of the root mean squared error (CV(RMSE)).

Root Mean Square Error (RMSE) represents the differences between the simulation results and the measured data, where m_i is the measured data, s_i is the simulated results, and N_p is the total number of observations:

$$RMSE(\%) = \sqrt{\frac{\sum_{i=1}^{N_p} (m_i - s_i)^2}{N_p}} \quad (1)$$

Although RMSE shows the average differences, an index is still needed to determine how well a building performance simulation model fits the data. CV(RMSE) illustrates the similarity of measurements and simulation results and is used to closely reflect the accumulated magnitude of the error where $\bar{m}$ is the average of all measurements:

$$CV(RMSE)(\%) = \frac{\sqrt{\sum_{i=1}^{N_p} (m_i - s_i)^2 / N_p}}{\bar{m}} \quad (2)$$

MBE is an overall measure of how influenced the data is and is also a good indicator of how much error will likely be introduced in the annual energy consumption estimates since positive and negative errors will cancel each other out. MBE is a useful indicator for identifying the overall bias of the responses.

$$MBE(\%) = \frac{\sum_{i=1}^{N_p} (m_i - s_i)}{\sum_{i=1}^{N_p} (m_i)} \quad (3)$$

Different standards/guidelines have prepared standard criteria to assess the validity of calibrated models. Table 8.2 shows these requirements. As it turns out, the MBE and CV(RMSE) can be calculated for the calibrated model for monthly and/or hourly time frames ($N_p=12$ and/or $N=8760$, respectively).

Table 8.2 - Model calibration criteria

Standard/guideline	Monthly criteria (%)		Hourly criteria (%)	
	MBE	CV(RMSE)	MBE	CV(RMSE)
ASHRAE Guideline 14 [163]	± 5	± 15	± 10	± 30
IPMVP [164]	± 20	-	± 5	± 20
FEMP [165]	± 5	± 15	± 10	± 30

In this study, to calibrate the electricity simulation models it was compared the real consumption, metered data of monthly electricity consumption from the bills during twelve consecutive months (1st January 2023 to 31 December 2023), and the simulation consumption model. Due to the lack of an hourly consumption pattern and a lack of consumption disaggregation, it was not possible to perform hourly calibration criteria. The electricity consumption data for eight case studies were available on the electricity distribution grid operator's website (E-redes website). For two case studies, the electricity consumption data were collected using electricity meters (PEL). The results obtained from the calibration process are shown in Table 8.3.

Usually, the desired tolerances are not achieved in the first simulation model. Then, it follows an iterative process where it is identified and verified which parameters and schedules can be readjusted to have similar values between the simulated and metered data. The values of MBE and CV(RMSE) for the final energy model calibration are presented in Table 8.4.

To evaluate the accuracy of the indoor temperature of the living room obtained in the simulation, it is necessary to compare them with the real case. The results obtained from the calibration process are shown in Table 8.5. For this, data obtained from the sensor placed in the living room was used. The recorded values are during year 2023. The values of MBE and CV(RMSE) for the temperature calibration are presented in Table 8.6. Figure 8.11 shows the monthly calibrations for each case study.

By analysing the MBE and CV(RMSE) values obtained for each case study, both in the calibration of electricity consumption and in the calibration of living room temperature (Table 8.4 and Table 8.6, respectively), it is possible to verify that the criteria established in ASHRAE, IPMVP and FEMP were satisfied (Table 8.2).

Table 8.3 - Real and simulation monthly energy consumption of each case study (kWh)

Case study		Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Real	211.7	161.8	182.6	169.4	170.9	159.8	172.7	156.3	180.9	187.8	170.3	279.7
	Simulation	219.3	188.4	171.9	164.6	164.9	160.1	168.8	166.0	162.1	174.1	178.4	288.7
2	Real	242.0	178.1	191.6	211.0	205.3	282.1	206.3	170.4	215.4	216.2	181.2	207.6
	Simulation	238.1	194.9	194.6	211.9	227.8	246.5	204.5	169.4	210.2	216.1	183.0	207.9
3	Real	272.0	240.2	206.6	223.9	215.4	197.4	189.2	229.4	214.4	248.0	280.9	292.6
	Simulation	270.4	244.5	266.1	221.1	179.2	176.8	186.6	222.2	238.2	247.3	242.1	308.6
4	Real	188.8	120.7	53.8	30.3	35.0	27.3	26.8	31.9	40.3	35.4	42.5	118.6
	Simulation	189.0	120.8	52.2	31.9	32.9	32.6	32.8	33.6	39.5	36.9	42.0	117.6
5	Real	242.0	141.9	131.2	119.8	106.2	113.9	111.4	117.2	103.8	119.4	158.3	336.3
	Simulation	244.5	143.4	130.9	113.1	104.7	102.9	115.5	104.1	103.3	119.0	163.3	359.2
6	Real	311.1	329.4	253.6	109.5	95.2	111.2	93.6	112.3	119.0	174.9	248.9	344.8
	Simulation	313.8	310.4	251.1	116.8	112.8	110.8	119.9	113.3	113.2	178.4	274.8	335.2
7	Real	288.0	273.4	275.7	268.7	258.6	303.0	327.3	391.7	300.3	272.6	288.5	312.5
	Simulation	293.4	265.9	286.1	261.5	276.8	294.4	328.4	389.9	297.9	282.7	287.0	308.5
8	Real	570.6	282.0	264.9	254.4	256.9	99.6	104.9	86.5	228.1	74.9	297.8	528.1
	Simulation	536.5	276.0	244.2	274.1	262.2	99.8	106.3	102.3	223.3	105.3	297.0	526.5
9	Real	302.7	196.0	90.1	79.9	69.4	74.8	86.6	338.3	338.2	230.2	328.4	383.6
	Simulation	302.4	194.9	86.8	85.6	75.3	72.1	83.1	323.9	315.5	227.2	323.4	381.7
10	Real	225.2	211.1	207.1	176.1	166.9	166.6	165.6	180.0	164.1	185.7	192.2	212.2
	Simulation	224.6	176.8	194.3	162.1	162.9	158.9	167.1	163.4	159.9	190.4	203.7	221.2

Table 8.4 - Energy model calibration of each case study

Case study	Monthly	
	MBE (%)	CV(RMSE) (%)
1	-0.2	6.5
2	0.1	6.4
3	0.3	10.8
4	-1.4	4.1
5	-0.1	5.8
6	-2.0	7.1
7	-0.3	2.7
8	-0.2	6.5
9	1.8	4.0
10	3.0	7.1

Table 8.5 - Real and simulation living room monthly temperature of each case study (°C)

Case study		Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Real	17.5	16.7	18.6	21.5	22.8	24.7	25.1	25.7	24.4	24.2	20.4	18.2
	Simulation	17.2	16.8	18.4	21.9	21.9	24.4	24.5	25.9	24.3	24.4	20.5	18.3
2	Real	20.7	21.1	21.8	23.5	23.4	25.2	25.2	26.1	24.8	23.2	21.6	20.3
	Simulation	18.2	19.0	21.4	23.7	23.6	25.6	25.2	25.9	23.7	23.2	20.9	18.1
3	Real	16.8	16.5	17.5	19.4	20.6	22.6	23.3	24.0	23.2	22.5	18.9	16.9
	Simulation	16.7	17.2	19.2	21.0	21.8	22.6	23.7	24.5	23.3	21.8	18.6	15.6
4	Real	16.1	15.6	18.0	22.1	23.8	26.5	26.7	27.8	24.6	23.3	18.1	15.1
	Simulation	16.6	16.1	17.5	21.0	22.2	25.3	26.8	27.2	24.5	23.8	18.0	15.6
5	Real	17.8	17.8	18.7	20.0	19.9	21.8	22.1	22.5	21.8	20.5	18.9	16.6
	Simulation	16.9	16.2	17.8	19.6	19.9	20.5	22.4	24.5	22.6	20.9	18.0	15.7
6	Real	23.8	21.2	21.9	23.1	24.0	25.8	25.9	26.6	24.8	24.0	22.9	20.8
	Simulation	22.8	21.5	21.6	23.4	24.0	25.6	26.3	26.7	24.9	24.4	22.7	21.2
7	Real	17.9	18.0	19.2	23.7	25.3	27.2	28.0	27.9	26.3	25.0	20.5	18.1
	Simulation	17.0	17.8	20.0	23.0	25.1	26.9	28.1	27.9	26.8	25.1	20.7	18.4
8	Real	18.3	18.5	20.3	23.9	24.7	26.6	26.9	28.2	24.9	23.8	19.9	17.6
	Simulation	18.2	18.1	20.3	23.9	24.4	27.0	27.0	27.6	25.0	23.7	20.0	17.8
9	Real	15.6	15.9	16.8	19.7	21.8	23.4	24.3	24.9	22.1	20.7	16.2	14.5
	Simulation	15.4	15.8	16.4	19.7	23.5	23.5	25.0	24.9	22.4	20.9	16.6	14.7
10	Real	20.2	19.9	20.8	22.5	23.0	24.5	24.2	23.4	23.9	23.2	21.4	19.8
	Simulation	19.4	20.1	20.2	23.4	23.0	24.3	25.3	24.7	23.3	23.1	20.4	18.5

Table 8.6 - Temperature model calibration of each case study

Case study	Monthly		Hourly	
	MBE (%)	CV(RMSE) (%)	MBE (%)	CV(RMSE) (%)
1	0.4	1.8	0.5	9.1
2	3.1	5.3	3.0	16.3
3	-1.5	4.5	-1.5	6.3
4	1.3	3.6	1.5	10.3
5	1.4	5.1	1.3	17.6
6	-0.1	1.7	-0.2	13.7
7	0.1	2.0	0.1	13.9
8	0.3	1.2	0.4	11.7
9	-1.3	3.0	-1.3	13.4
10	0.5	3.6	0.7	16.3

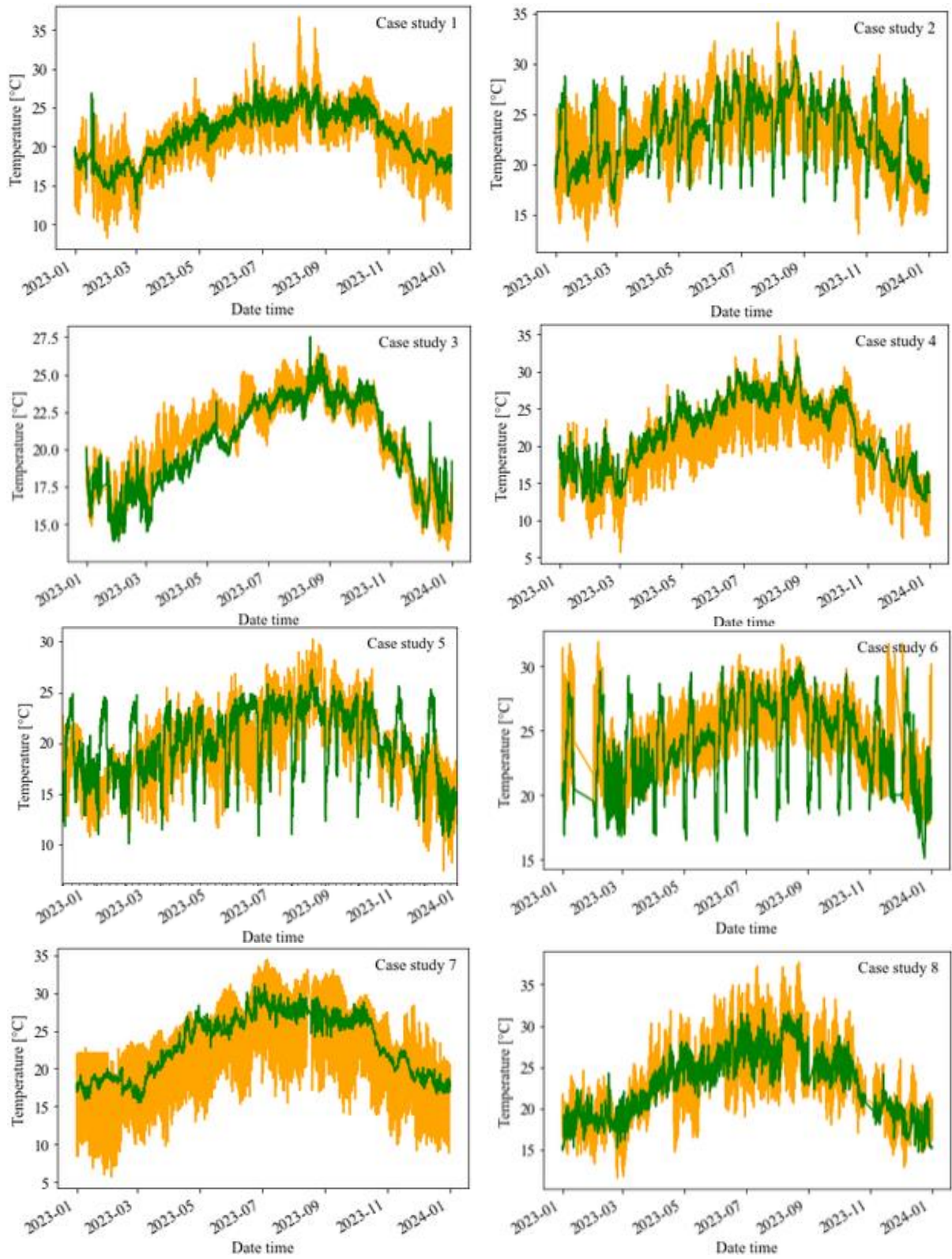


Figure 8.11 - Hourly temperature model calibration of each case study

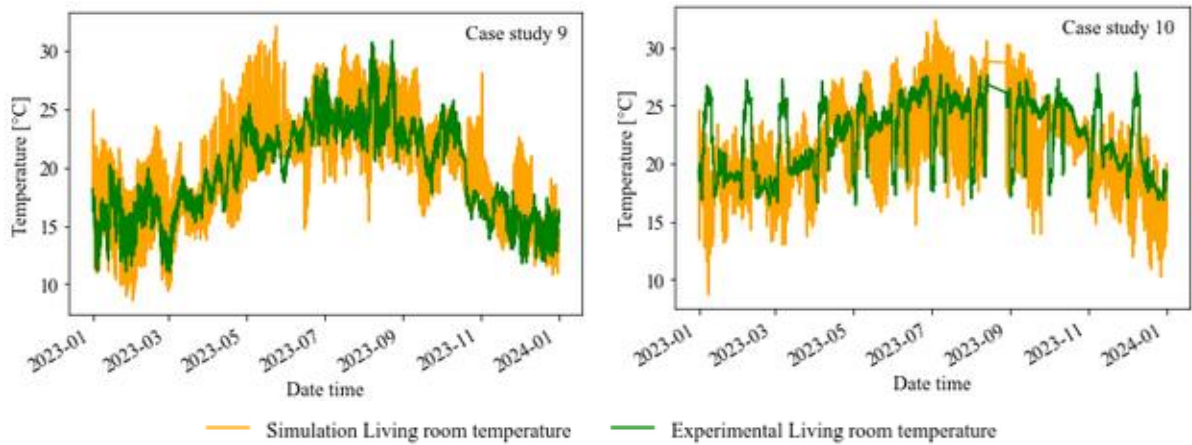


Figure 8.11 - Hourly temperature model calibration of each case study (cont.)

8.3.Improvement measures

With all the case studies calibrated, both from an energy and temperature point of view, it is possible to analyse the impact on occupant comfort of the selected improvement measures mentioned in Chapter 3.2 (thermal insulation application, windows replacement and heat recovery). The impact on energy consumption will not be evaluated because although energy consumption was calibrated, it was not done considering the uses (lighting, equipment, air conditioning systems) since it was not possible to collect information in this regard, as mentioned in Chapter 3.2. However, the calibration of energy consumption was important to establish the internal gains of the model and, therefore, influences the house's interior temperature. Having said that, when improvement measures are applied in relation to the calibrated model, it doesn't mean that the reduction in consumption is exactly what it is in reality, but rather what was established in the calibrated model. That said, the improvement measures applied to the simulation model, which has already been calibrated, aim to understand their impact on the temperature inside the house.

From the results obtained in Table 7.2, it can be seen that in practically all the case studies, with the exception of case study 8, thermal comfort needs to be improved. However, as mentioned in Chapter 3.2, for all the case studies, it is intended to carry out an analysis of measures that contribute to increasing thermal comfort, namely placing thermal insulation in the opaque envelope (walls, roof and floor, depending on the specifics of each case study), replacing windows and these two measures simultaneously. Other measure to be studied is heat recovery with windows replacement and insulation application. The heat recovery is carried out by using a ventilation unit that produces a flow of air between an interior and an exterior space and is equipped with extraction and insufflation fans. This analysis aims to verify the impact on temperature and number of discomfort hours after implementing these measures. It should be noted that this analysis considers the mean monthly temperature in the living room, and the hours of monthly discomfort are all those in which the temperature is not between 18°C and 25°C as recommended by Portuguese legislation. The 24 hours of a day were taken into account, not just the hours when people are at home; since people's schedules are not always the same, it was decided to do a broader analysis.

The insulation of the opaque envelope considers three different thicknesses: 6cm, 8cm and 10cm. The insulation material selected was rock wool (thermal conductivity of 0.04 W/m°C). Depending on the case study, it is sometimes applied from the outside and sometimes from the inside. Compared to XPS, rock wool performs better in terms of fire resistance, is more sustainable, and is also acoustic in addition to being a thermal insulator. As for the windows, the analysis considered PVC windows with low-emissivity double glazing with three thermal transmission coefficients: 2.5 W/m².°C, 2 W/m².°C and 1.5

W/m².°C. The analysis also considers replacing the windows and applying insulation simultaneously. When analysing heat recovery simultaneously with the application of insulation and the replacement of windows, it is always done considering an efficiency of 90%. As mentioned previously, this percentage is somewhat high but it was considered since is indicated in Commission Regulation (EU) No 1253/2014 [162]. The heat recovery is applied from January to May and from October to December.

As mentioned in Chapter 3.2, the simulations of the improvement measures were carried out for four scenarios: real with and without HVAC and nominal with and without HVAC. The real scenario with HVAC corresponds to the calibrated simulation model, i.e. with the uses of HVAC and with the air infiltrations that were taken into account so that the model was calibrated from the point of view of temperature and energy use. The real scenario without HVAC is only with the infiltrations considered and without use of HVAC. The nominal scenario with HVAC takes into account the minimum infiltrations required by legislation (0.5 air changes per hour) and considers there is always air conditioning in every room of the house for 24 hours so the temperature is between 18 and 25°C. The nominal scenario without HVAC takes into account the minimum infiltrations required by legislation and does not include air conditioning.

The results obtained for each case study are shown below. Cost analysis, consumption reduction and life cycle assessment were not carried out in this study.

- **Case study 1**

Figure 8.12 presents the mean monthly temperature in the living room of the calibrated model based on the measurements taken and all the simulation results obtained after the introduction of the improvement measures. Figure 8.13 represents the percentage of the monthly discomfort hours considered all those in which the temperature is not between 18°C and 25°C as recommended by the Portuguese legislation. The 24 hours of a day were considered, not just the hours when people are at house.

From Figure 8.12, it can be seen that in the real (calibrated) simulation, in almost every month, the mean monthly temperature is within the thermal comfort range considered, except in January, February, August and December. This applies to both the real and nominal scenarios. Also, it can be seen that replacing the windows causes a greater temperature increase in the room than applying insulation to the outside walls from the inside. This is because the existing windows have a thermal transmission coefficient that is further away from those of the improvement measures when compared to the walls. However, as expected, applying these two measures simultaneously (insulation in the opaque envelope and windows) increases the average monthly temperature of the living room. Heat recovery, in addition to the application of insulation and the replacement of windows, also leads to a greater increase in the average monthly temperature in the winter months.

In general, it can be seen that in the real scenario, with or without HVAC, it is possible for the living room to be in the thermal comfort range with the exception of a few summer months. However, these are not very far from this range. Therefore, from the real scenario without HVAC, it can be concluded that if the occupant stops using heating in the winter, with the implementation of measures to improve insulation and windows or even heat recovery, the occupant will continue to be in the comfort range. In the summer months, they may use cooling. If consider the minimum infiltration of 0.5 air changes per hour, and there is no use of HVAC, the results are already different (Nominal without HVAC). Not all winter months are within the comfort range if don't take into account the heat recovery associated with applying insulation and replacing windows. However, the temperatures in the summer months are closer to the comfort range. This could be due to the fact that the calibrated model takes into account the opening of the windows according to the feedback from the occupants and considers an infiltration of 0.5 air changes per hour. However, when improvement measures are applied that impact infiltration, it

is reduced to below 0.5 air changes per hour. In the nominal scenario, increasing the infiltration causes the temperature to drop slightly. Therefore, there may be space for improvement if the occupant opens the windows to cool the house, especially at night.

Analysing Figure 8.13, it can be seen that in January, February, March and December the percentage of discomfort hours decreases after the introduction of comfort improvement measures, as expected. However, in April, May and November, despite the temperature being within the comfort range with the application of the improvement measures, the hours of discomfort increased. However, the percentage of hours of discomfort in these months is less than 5% for all scenarios (real and nominal). In the hottest months, June, July, August, September and October, as would be expected, these hours of discomfort also increased because they were months in which the mean temperature was already very close to 25°C.

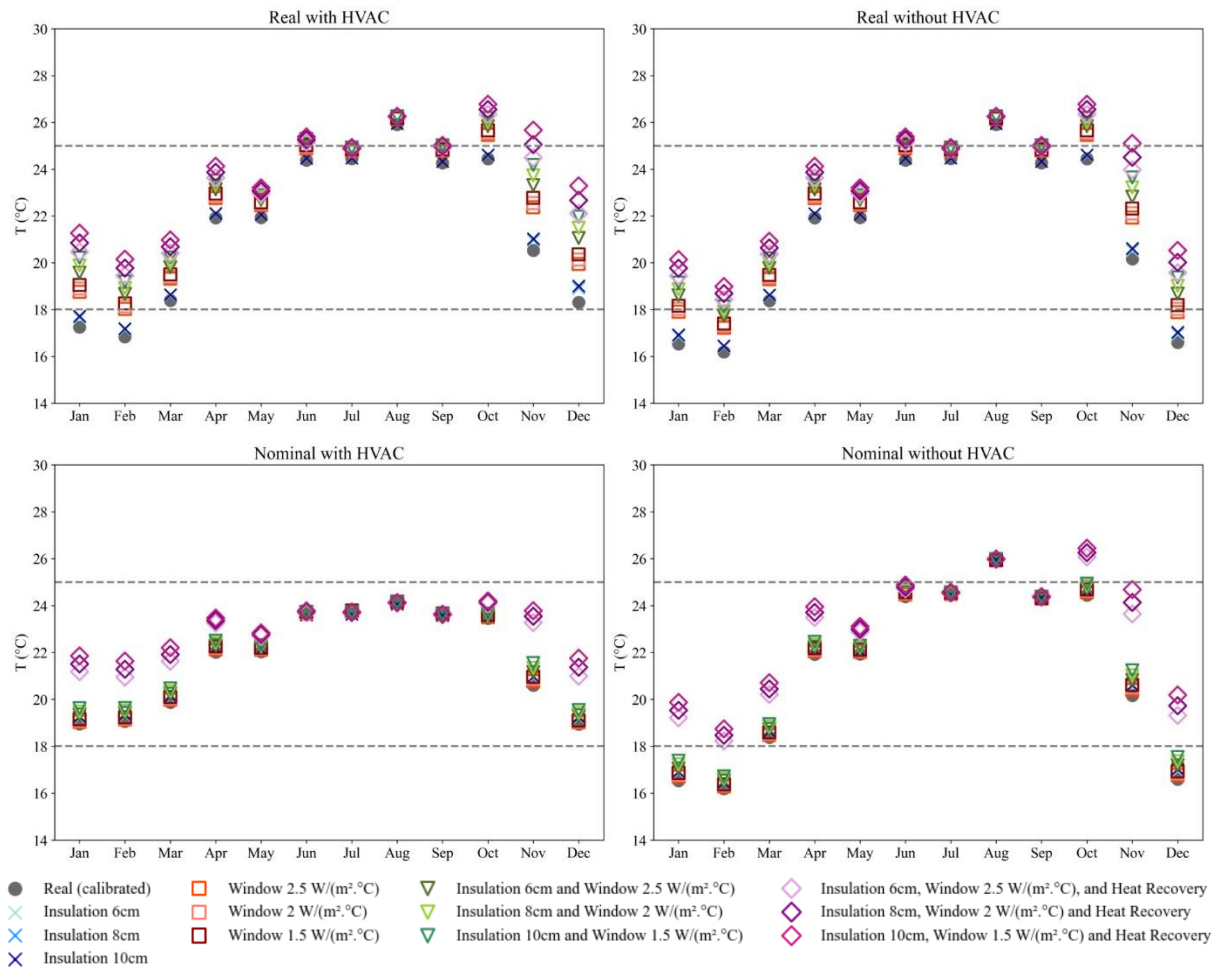


Figure 8.12 - Living room temperature after improvement measures in case study 1 for real and nominal scenarios with and without using HVAC

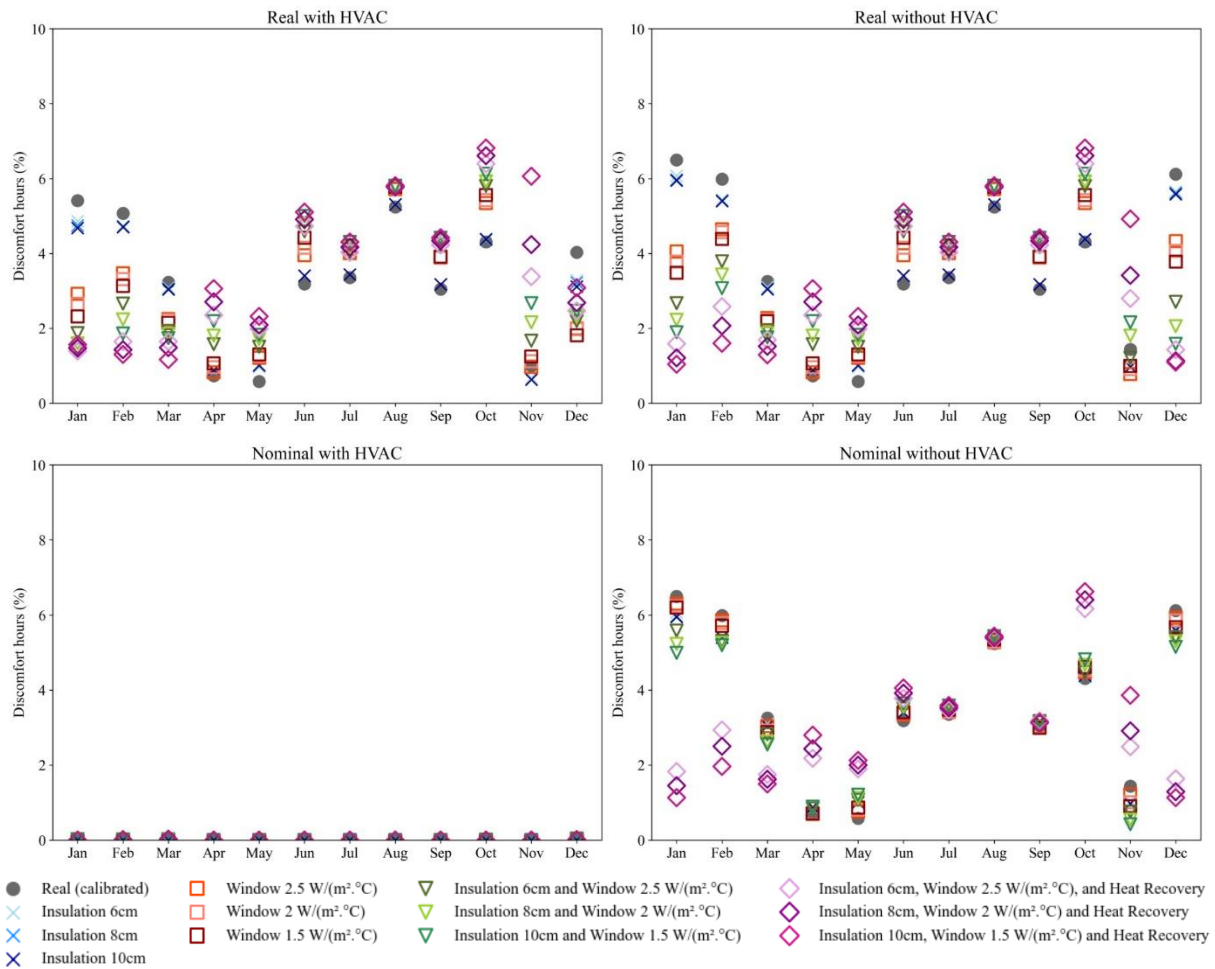


Figure 8.13 - Living room discomfort hours after improvement measures in case study 1 for real and nominal scenarios with and without using HVAC

• Case study 2

Figure 8.14 and Figure 8.15 show the mean monthly temperature in the living room and the percentage of the monthly discomfort hours, respectively, of the calibrated model and all the simulation results obtained after introducing the improvement measures. The discomfort hours were obtained considering the 24 hours of the day and whenever the temperature is not between 18°C and 25°C, as recommended by the Portuguese legislation. As mentioned before, the improvements were carried out for four scenarios: real with and without HVAC and nominal with and without HVAC.

From Figure 8.14, it can be seen that in this case study, the real simulation (calibrated) in the real scenario with HVAC, in almost all months, the mean monthly temperature is within the thermal comfort range considered, with the exception of June, July and August. However, the real and nominal scenarios without HVAC are different. Some months are no longer within the range, and others have moved into the thermal comfort range. The Figure also reveals that applying insulation to the outside walls from the inside and in the roof causes a greater temperature increase in the living room than replacing the windows. This is because the wall and roof area is substantial. However, as expected, applying these two measures simultaneously (insulation in the opaque envelope and windows) increases the mean monthly temperature of the living room. Heat recovery, in addition to applying insulation and replacing windows, also leads to a greater increase in the mean monthly temperature in the winter months. However, in some months, it exceeds the comfort range (18°C - 25°C).

It can be verified that for the real scenario with or without the HVAC, the living room is in the thermal comfort range almost all the months, except a few summer months. However, these are not very far from the thermal comfort range considered. Therefore, from the real scenario without HVAC, it can be concluded that if the occupant doesn't use heating in the winter, with the implementation of measures to improve insulation and windows or even heat recovery, the occupant will continue to remain in this comfort range. In the summer months, the occupant may use cooling. However, the occupant doesn't currently use it in the living room, but in other rooms of the house, the occupant does, and it is expected that they will continue to do so. Considering the minimum infiltration of 0.5 air changes per hour and no use of HVAC, the results are similar (Nominal without HVAC). These results could be due to the fact that the calibrated model takes into account the opening of the windows according to the feedback from the occupants and considers an infiltration below 0.5 air changes per hour and when improvement measures that have an impact on infiltration are applied, the infiltration value is lower. In the nominal scenario, increasing the infiltration to 0.5 air changes per hour causes the temperature to drop slightly. Therefore, there may be space for improvement if the occupant opens the windows to cool the house, especially at night. In contrast to case study 1, it is unnecessary to consider heat recovery associated with applying insulation and replacing windows in all winter months, which are in the comfort range in the nominal scenario without HVAC. This can be due to many reasons, mainly the characteristics of the opaque envelope that already exists in the house. The temperatures in the summer months are similar to the real scenarios.

Analysing Figure 8.15, it can be seen that in January, February and December, the percentage of discomfort hours decreased after the comfort improvement measures' introduction, as expected. In contrast to the results obtained in case 1, in the hottest months, June, July, August and September, these hours of discomfort also decreased. In this case study, introducing measures to improve thermal comfort also reduces the number of hours of discomfort in the summer months. However, in March, April, May, October and November, despite the temperature being within the comfort range with the application of the improvement measures, the hours of discomfort increased. However, this is a general statement; it doesn't apply to all the improvement measures, and it doesn't apply to all the months mentioned, but it is most evident in November. In general, the percentage of hours of discomfort in all months is less than 5% for all scenarios (real and nominal) when applying the improvement measures (except the heat recovery combined with the insulation and the replacement of the windows in some months).

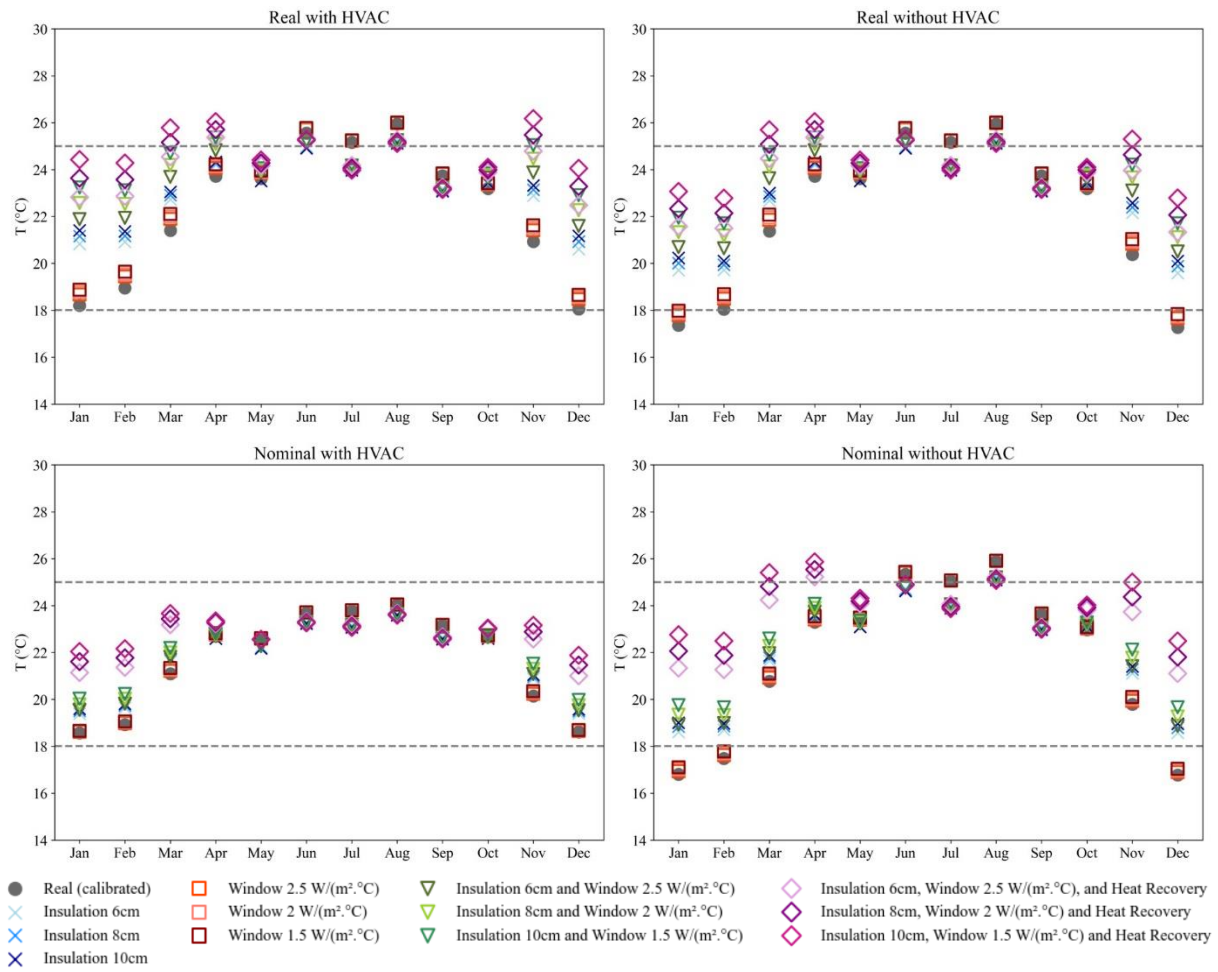


Figure 8.14 - Living room temperature after improvement measures in case study 2 for real and nominal scenarios with and without using HVAC

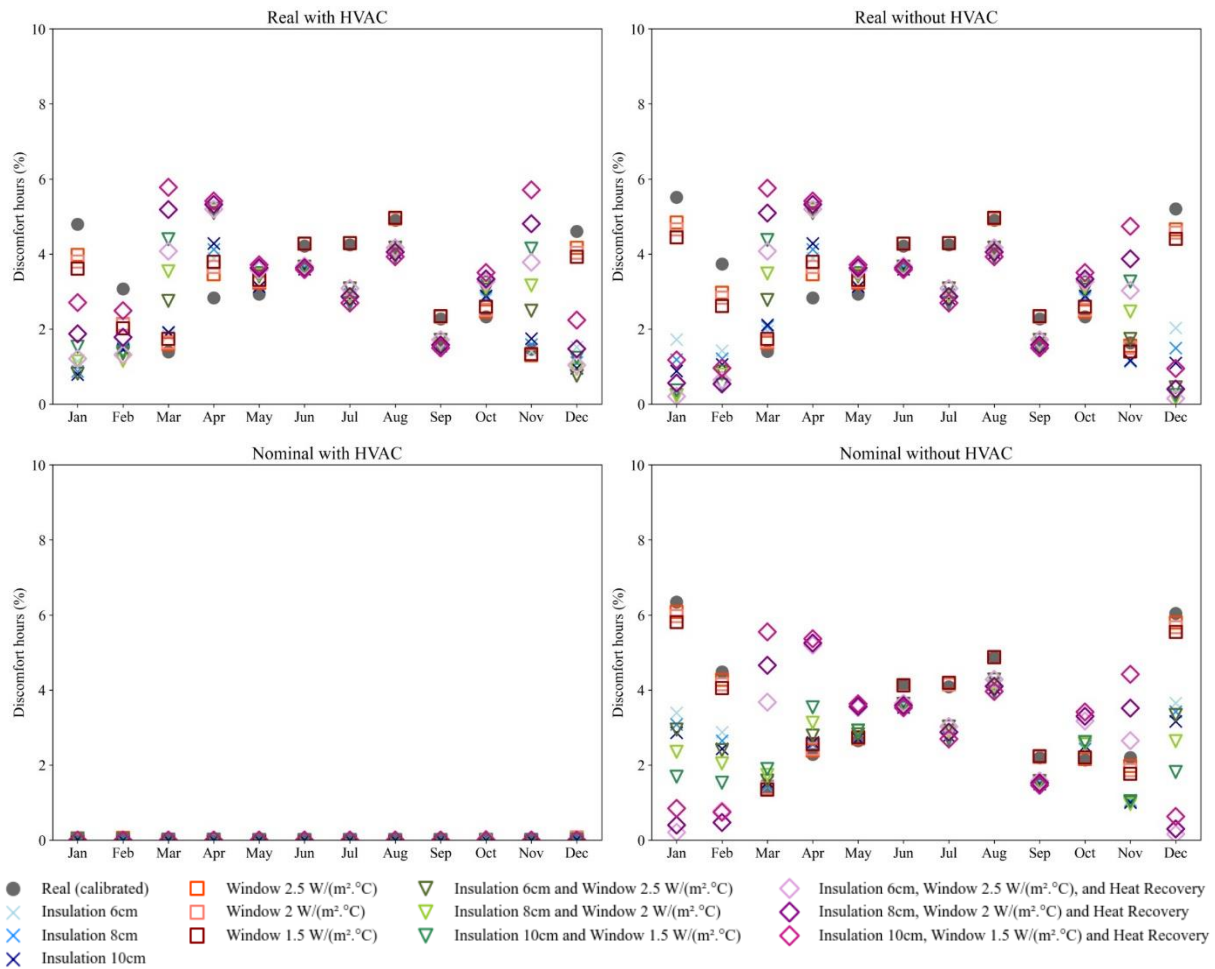


Figure 8.15 - Living room discomfort hours after improvement measures in case study 2 for real and nominal scenarios with and without using HVAC

• Case study 3

Figure 8.16 and Figure 8.17 represent the mean monthly temperature in the living room and the percentage of the monthly discomfort hours, respectively, of the calibrated model and all the simulation results obtained after introducing the improvement measures considering real and nominal scenarios. Remember that the real scenario with HVAC corresponds to the calibrated simulation model, i.e. with the uses of HVAC and with the air infiltrations that were taken into account so that the model was calibrated from the point of view of temperature and energy use and the real scenario without HVAC is the calibrated model without using HVAC. The nominal scenario takes into account the minimum infiltrations required by legislation (0.5 air changes per hour), and when speaking with HVAC, it considers that there is always HVAC in every room of the house for 24 hours so that the temperature is between 18 and 25°C and the nominal scenario without HVAC is the nominal model without using HVAC. As already mentioned, the discomfort hours are all the 24 hours of the day when the temperature is not between 18°C and 25°C.

By analysing Figure 8.16, it can be seen that not all the months in the real (calibrated) simulation are within the established thermal comfort range, namely January, February and December. This applies to the real and nominal scenarios without HVAC. It can also be noted that for this case study, applying insulation to the outside walls from the outside and the roof causes a greater increase in the living room temperature than replacing the windows. This is because the opaque envelope's area is larger than the glazed area. Nevertheless, as expected, these two improvement measures applied together (insulation in

the opaque envelope and windows) increase the mean monthly temperature of the living room. Heat recovery, in addition to applying insulation and replacing windows, also leads to a more significant increase in the mean monthly temperature in winter months. This case study also reveals that introducing the improvement measures described in the summer months brings down the temperature in the living room in summer.

It can be verified that for the real scenario with or without the HVAC, the living room is in the thermal comfort range almost all the months, but in January, February, and December, it is more challenging to be in the comfort range considered. However, in December, it's only by recovering heat, insulating the opaque envelope and replacing the windows that the mean temperature of 18°C is reached. The results are similar in the nominal scenario without HVAC (infiltration of 0.5 air changes per hour). However, in January, February and December, you only reach 18°C with heat recovery, insulation and windows replacement simultaneously. This can be due to many reasons, but in particular to the characteristics of the opaque envelope that already exists in the house and the fact that this case study is located in a climate where winter is colder than in case studies 1 and 2. It should be noted that the summer is less severe than those in case study locations 1 and 2. The results between real and nominal scenarios are similar, and this could be due to the fact that the infiltration is not very different in the scenarios. However, in real with HVAC, it is below 0.5 air changes per hour, and when improvement measures that impact infiltration are applied, the infiltration value is lower. In the nominal scenario, increasing the infiltration to 0.5 air changes per hour causes the temperature to drop slightly.

Figure 8.17 reveals that the percentage of discomfort hours decreases after thermal comfort improvement measures are introduced in all months, contrary to case studies 1 and 2. In January, February, November and December, the percentage of hours of discomfort in all months is less than 8% for all scenarios (real and nominal) when applying the improvement measures, and from March to November, this percentage is less than 5%.

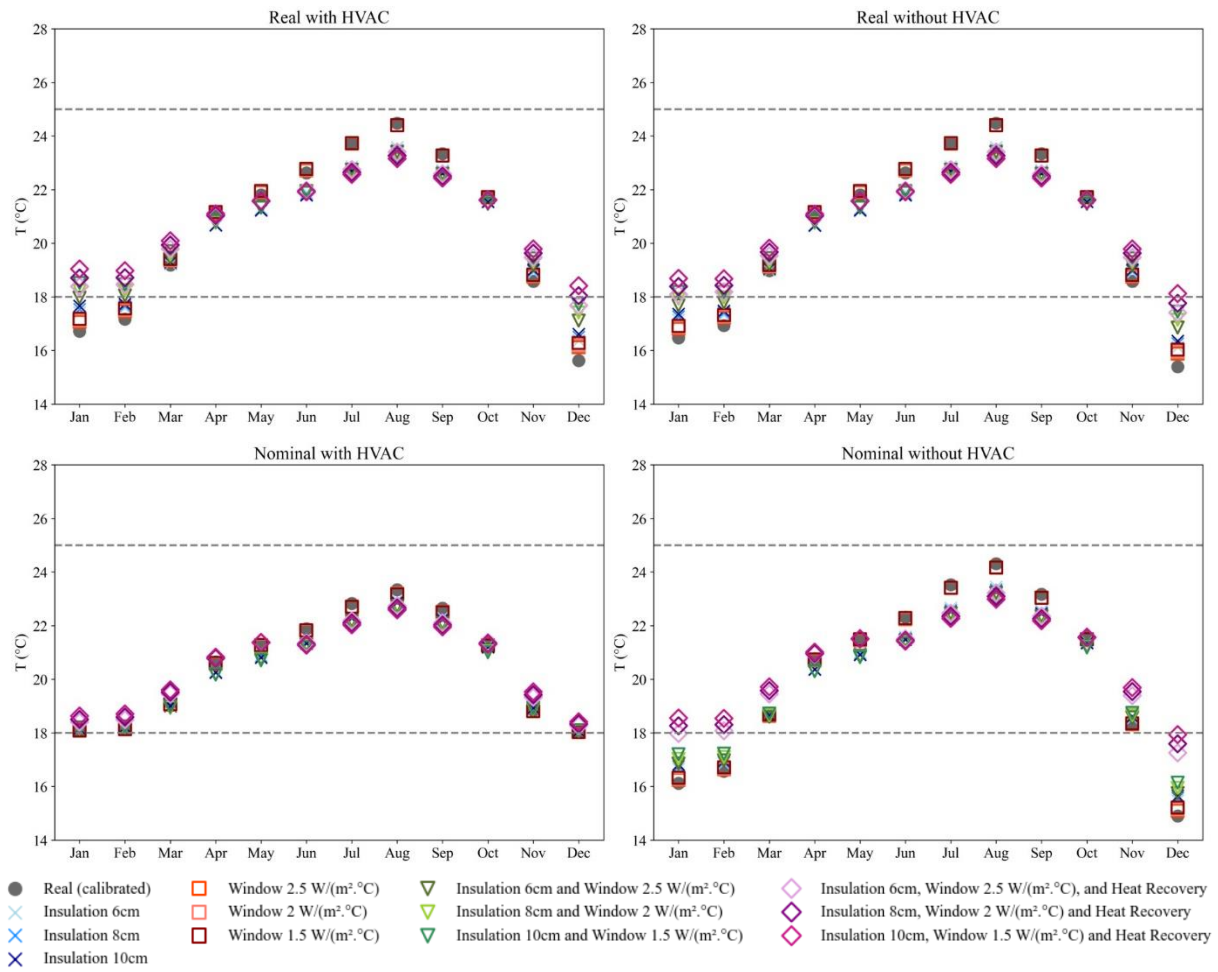


Figure 8.16 - Living room temperature after improvement measures in case study 3 for real and nominal scenarios with and without using HVAC

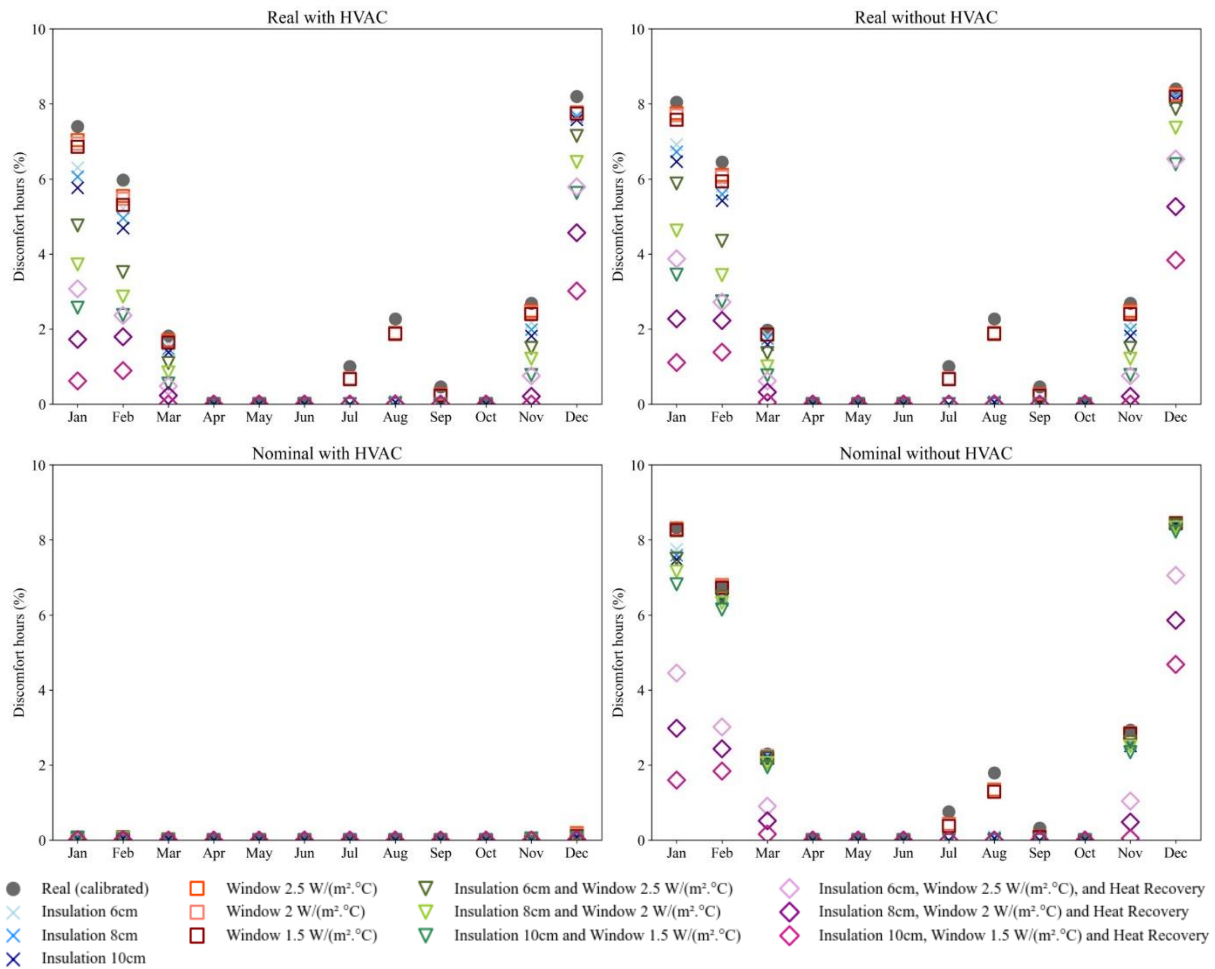


Figure 8.17 - Living room discomfort hours after improvement measures in case study 3 for real and nominal scenarios with and without using HVAC

• Case study 4

Figure 8.18 presents the mean monthly temperature in the living room of the calibrated model based on the measurements taken and all the simulation results obtained after the introduction of the improvement measures. Figure 8.19 represents the percentage of the monthly discomfort hours which are considered all those in which the temperature is not between 18°C and 25°C considering the 24 hours of the days. The simulations of the improvement measures were carried out for 4 different scenarios: real with and without HVAC and nominal with and without HVAC.

From Figure 8.18, it can be seen that only April, May, September and October are the months of the real (calibrated) simulation within the established thermal comfort range. This applies to the real and nominal scenarios without HVAC, although in the latter scenario June can also be considered within the thermal comfort range. From this Figure, it is also verified that applying insulation to the outside walls from the inside and in the roof causes a greater temperature increase in the living room in winter than replacing the windows. This is because the opaque envelope's area is larger than the glazed area. Nevertheless, as expected, these two improvement measures applied together (insulation in the opaque envelope and windows) increase the mean monthly temperature of the living room and adding heat recovery leads to a greater increase in the mean monthly temperature in the winter months. In the summer months, the introduction of the improvement measures decreased the temperature in the living room.

From the real scenario, it can be seen that with HVAC, the living room is in the thermal comfort range in all the winter months when applying some improvement measures, but without HVAC in December,

the thermal comfort range is not reached. Both in one scenario and in the other, comfort is not achieved in August either with the implementation of the improvement measures. In the winter and summer months, if comfort temperatures cannot be reached or are more difficult, HVAC can be used. The results are similar in the nominal scenario without HVAC (infiltration of 0.5 air changes per hour). However, in January and February, it's only with heat recovery plus insulation in the opaque envelope and replacing the windows that you reach a comfortable monthly mean temperature. Although it can have several causes, the main ones are the characteristics of the opaque envelope that already exists in the house and the fact that the infiltration is not very different in the scenarios. In real with HVAC scenario, the infiltration is below 0.5 air changes per hour. When improvement measures that have an impact on infiltration are applied, the infiltration value is more lower. In the nominal scenario, increasing the infiltration to 0.5 air changes per hour makes the temperature drop slightly. Note that this case study has the same climate as case studies 1 and 2.

According to the results shown in Figure 8.19, in most months, the number of discomfort hours decreases with the introduction of improvement measures, except in October and punctually a given measure in a given month. The percentage of discomfort hours in all months is less than 8% for all scenarios (real and nominal) when applying the improvement measures but it's possible to get it down to 6% or less when heat recovery plus insulation in the opaque envelope and replacing the windows is applied.

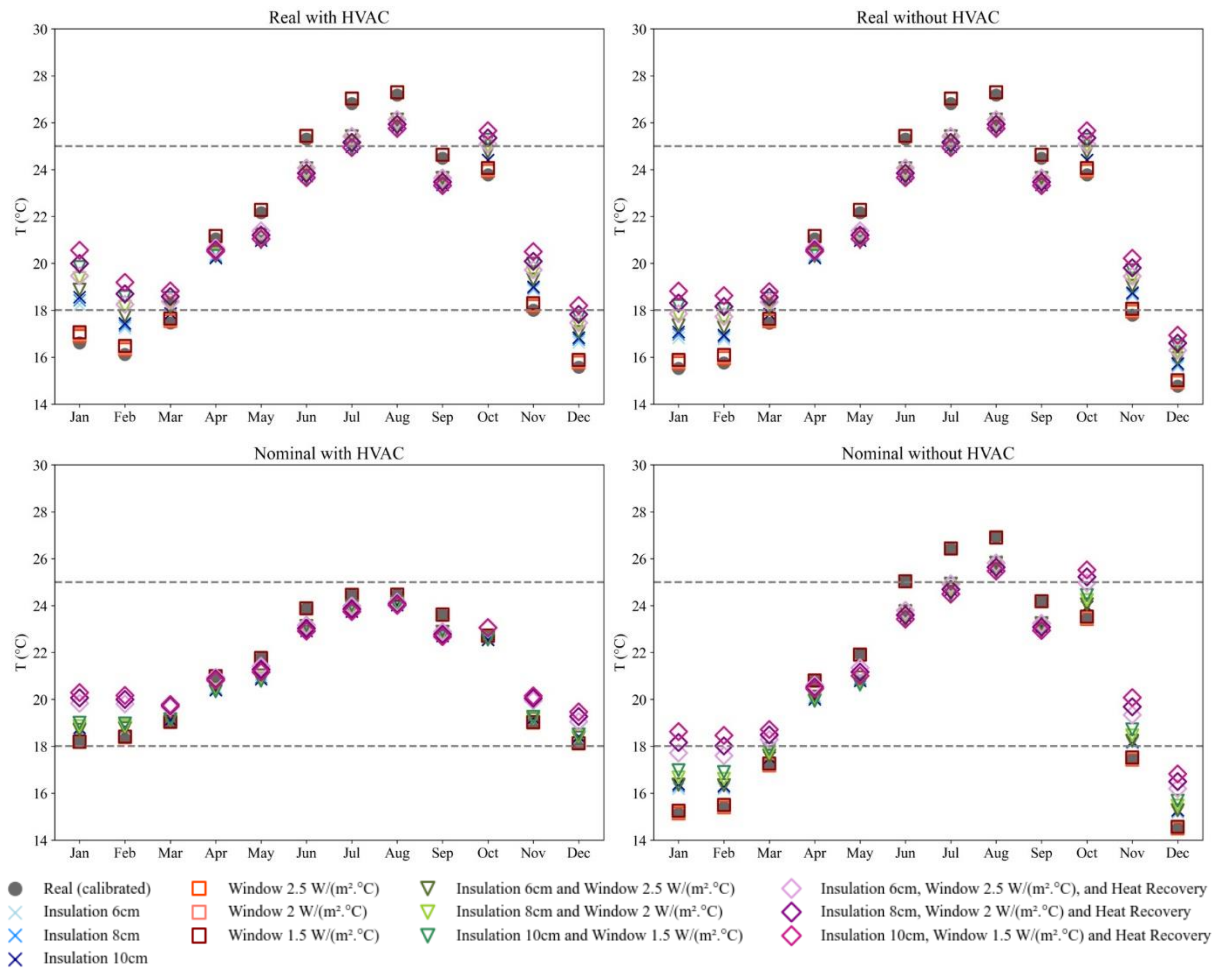


Figure 8.18 - Living room temperature after improvement measures in case study 4 for real and nominal scenarios with and without using HVAC

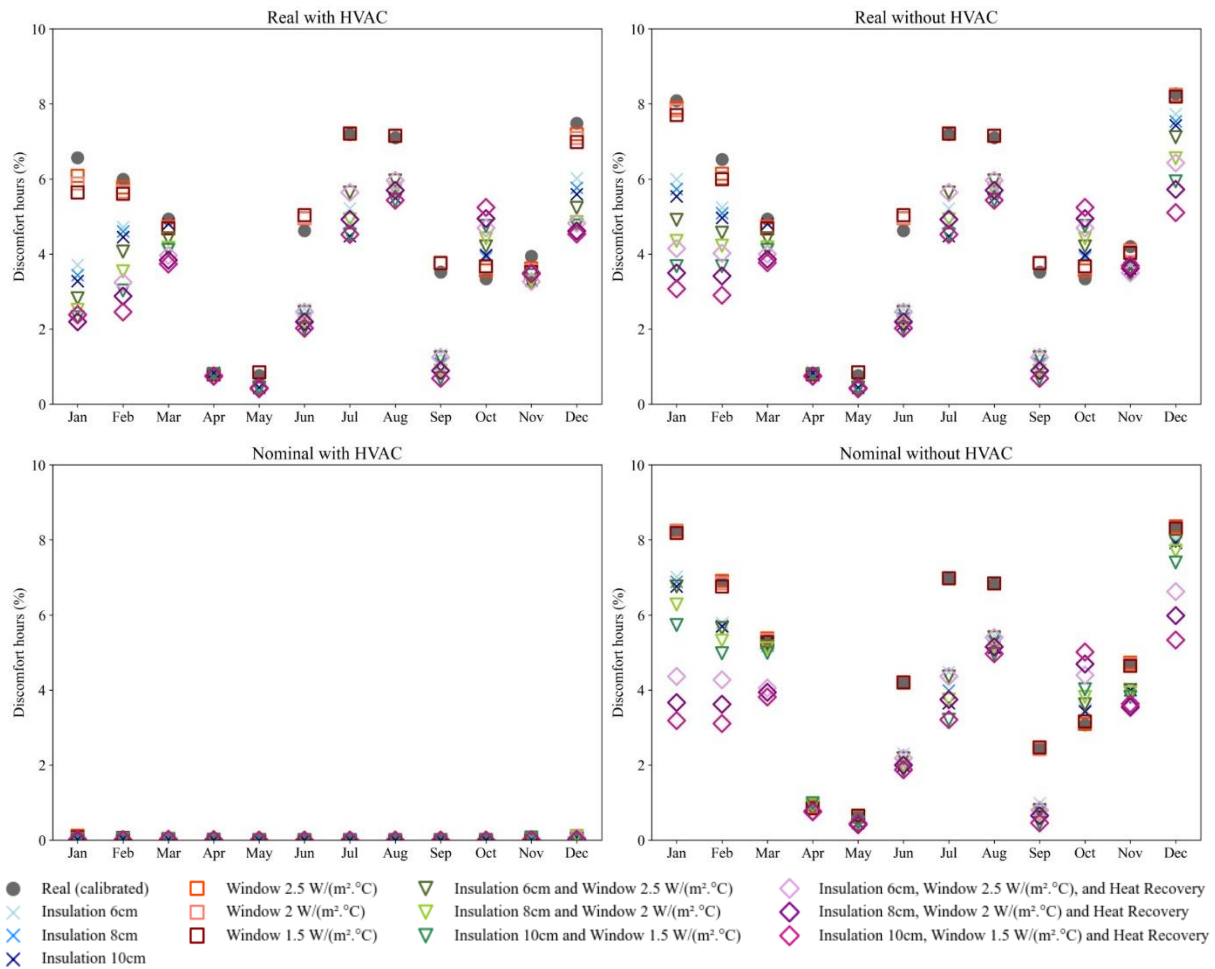


Figure 8.19 - Living room discomfort hours after improvement measures in case study 4 for real and nominal scenarios with and without using HVAC

• Case study 5

Figure 8.20 and Figure 8.21 represent the mean monthly temperature in the living room and the percentage of the monthly discomfort hours, respectively, of the calibrated model and all the simulation results obtained after introducing the improvement measures considering real and nominal scenarios. As already mentioned, the discomfort hours are all the 24 hours of the day when the temperature is not between 18°C and 25°C. The simulations were conducted for four scenarios: real with and without HVAC and nominal with and without HVAC.

From the results obtained and presented in Figure 8.20, it can be seen that in some months of the year, the average monthly room temperature values of the real (calibrated) simulation are not within the established thermal comfort range. January, February, March and December are months when the mean temperature is not within the thermal comfort range in the real scenarios with and without HVAC. In the case of the nominal scenario without HVAC, it is only in January, February and December that the real simulation does not have an average temperature within the thermal comfort range. The results also show that for this case study, replacing the windows causes more increase in the living room temperature than applying insulation to the outside walls from the outside, in the roof of the house and in the ceiling of the basement. But for some months, the opposite has been observed. Knowing that this house is a villa with more opaque envelope area than glazed envelope area, it is expected that insulating the envelope would have more impact than replacing the windows. However, the existing windows are single-glazed wooden ones with high air permeability and, therefore, high air infiltration. Thus, by

replacing the windows with much better ones, air infiltration is greatly reduced, and thermal resistance is greatly improved so that in many months, this improvement measure will have more impact than applying insulation.

Analysing the real scenario with or without the HVAC, the living room is in the thermal comfort range in all the months when some measures were applied. However, in December, it's only by recovering heat, insulating the opaque envelope and replacing the windows that the mean temperature of 18°C is reached. The results are similar in the Nominal scenario without HVAC (infiltration of 0.5 air changes per hour). This can be due to many reasons, but in particular to the characteristics of the opaque envelope that already exists in the house and due to the fact that the infiltration is not very different in the scenarios, although in real with HVAC is above 0.5 air changes per hour and when improvement measures that have an impact on infiltration are applied, the infiltration value is more lower. In the nominal scenario, increasing the infiltration in the to 0.5 air changes per hour causes the temperature to drop slightly. This figure also reveals that in the summer months, the introduction of improvement measures has brought down the temperature in the living room. The location of this house is the same as the case study 3.

Figure 8.21 reveals that the percentage of discomfort hours decreases after the introduction of thermal comfort improvement measures in all months. Generally, the percentage of discomfort hours in all months can reach values lower than 5% for all scenarios (real and nominal).

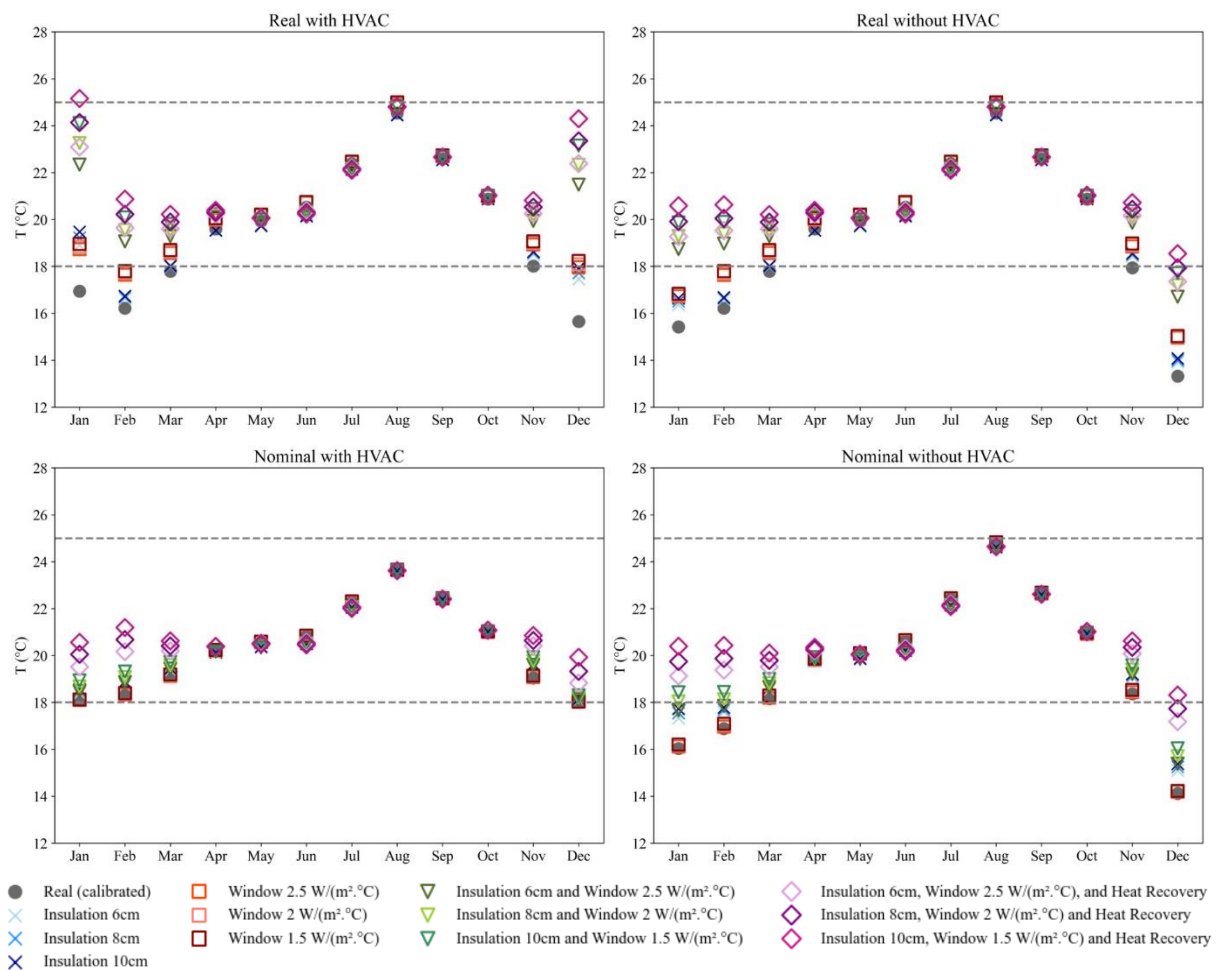


Figure 8.20 - Living room temperature after improvement measures in case study 5 for real and nominal scenarios with and without using HVAC

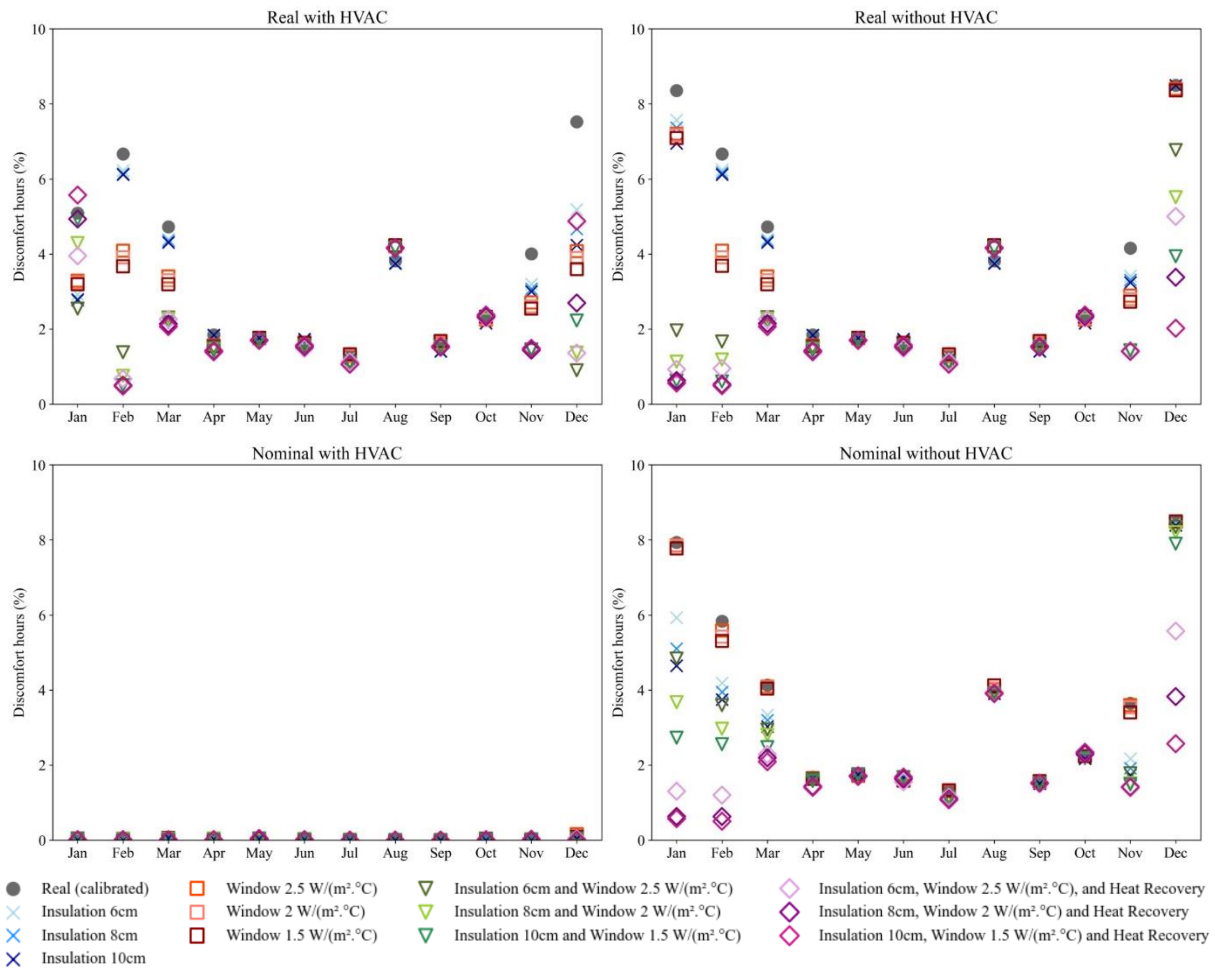


Figure 8.21 - Living room discomfort hours after improvement measures in case study 5 for real and nominal scenarios with and without using HVAC

• Case study 6

Figure 8.22 presents the results of the mean monthly temperature in the living room of the calibrated model and all the twelve simulation results obtained after the introduction of the improvement measures. Figure 8.23 represents the percentage of the monthly discomfort hours (all the hours of the day that the temperature is not between 18°C and 25°C) for all of these simulations. The simulations consider four scenarios: real and nominal with and without HVAC. In real scenarios, the infiltration considered for this case study is below 0.5 air changes per hour, and when improvement measures impact the infiltration, the value is even lower. In the nominal scenario, the infiltration is always 0.5 air changes per hour, as the legislation requires. When the nominal scenario uses HVAC, it considers that there is always HVAC in every room of the house for 24 hours so that the temperature is between 18 and 25°C, and the nominal scenario without HVAC is the nominal model without using HVAC.

Figure 8.22 shows that in almost every month, the real (calibrated) simulation is in the thermal comfort range established. The mean temperature is out of this range in June, July and August in the two real scenarios and in the nominal scenario without HVAC. From this Figure, it is also verified that applying insulation to the outside walls from the inside and outside (depending on the rooms in the house) and on the bedroom roof causes a more significant temperature increase in the living room in winter than replacing the windows. This is due to the fact that the area of the glazed area is lower than the opaque envelope adjacent to the outside. As expected, these two improvement measures applied together (insulation in the opaque envelope and windows) increase the mean monthly temperature of the living

room and adding heat recovery leads to a greater increase in the mean monthly temperature in the winter months, in many months it exceeds an average of 25°C.

From the real and nominal scenario, it can be seen that the living room is not always in the thermal comfort range, even when some improvement measures are applied. June, July and August never reached this comfort range. The use of HVAC is the solution, and increasing the infiltration and/or ventilation of the house at night also allows the house to lower the mean temperature, as can be seen in the nominal case where the value considered in the infiltrations is higher than that considered in most of the simulations of the real scenarios. Furthermore, it should be noted that these results are also due to the fact that the room is an interior compartment with no window to the outside.

Figure 8.23 shows that almost all the improvement measures implemented increase the discomfort hours every month. However, in some months and for some measures, the opposite is true in real scenarios and nominal scenarios without HVAC. The percentage of hours of discomfort in all months is less than 9% for all scenarios (real and nominal) when applying the improvement measures.

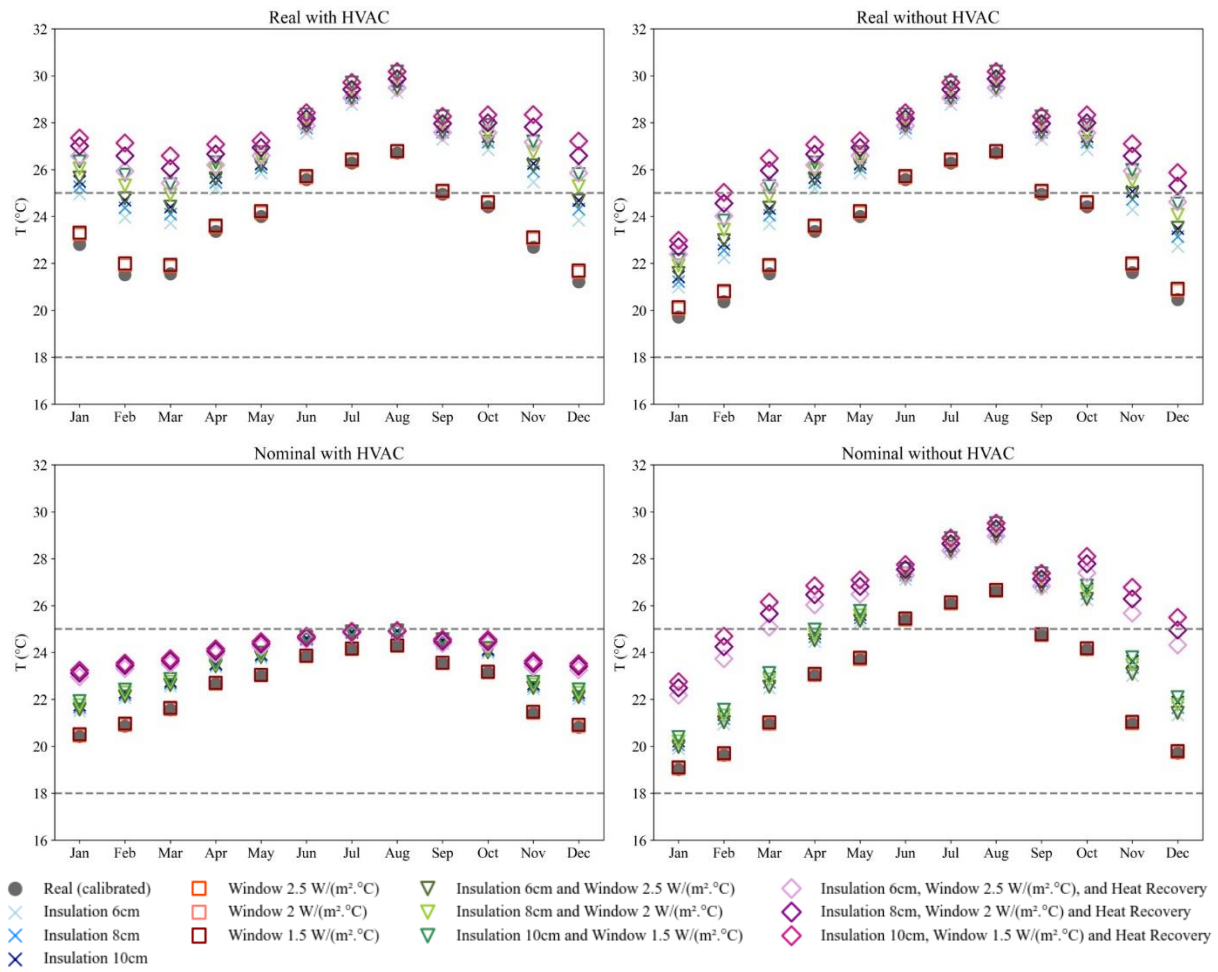


Figure 8.22 - Living room temperature after improvement measures in case study 6 for real and nominal scenarios with and without using HVAC

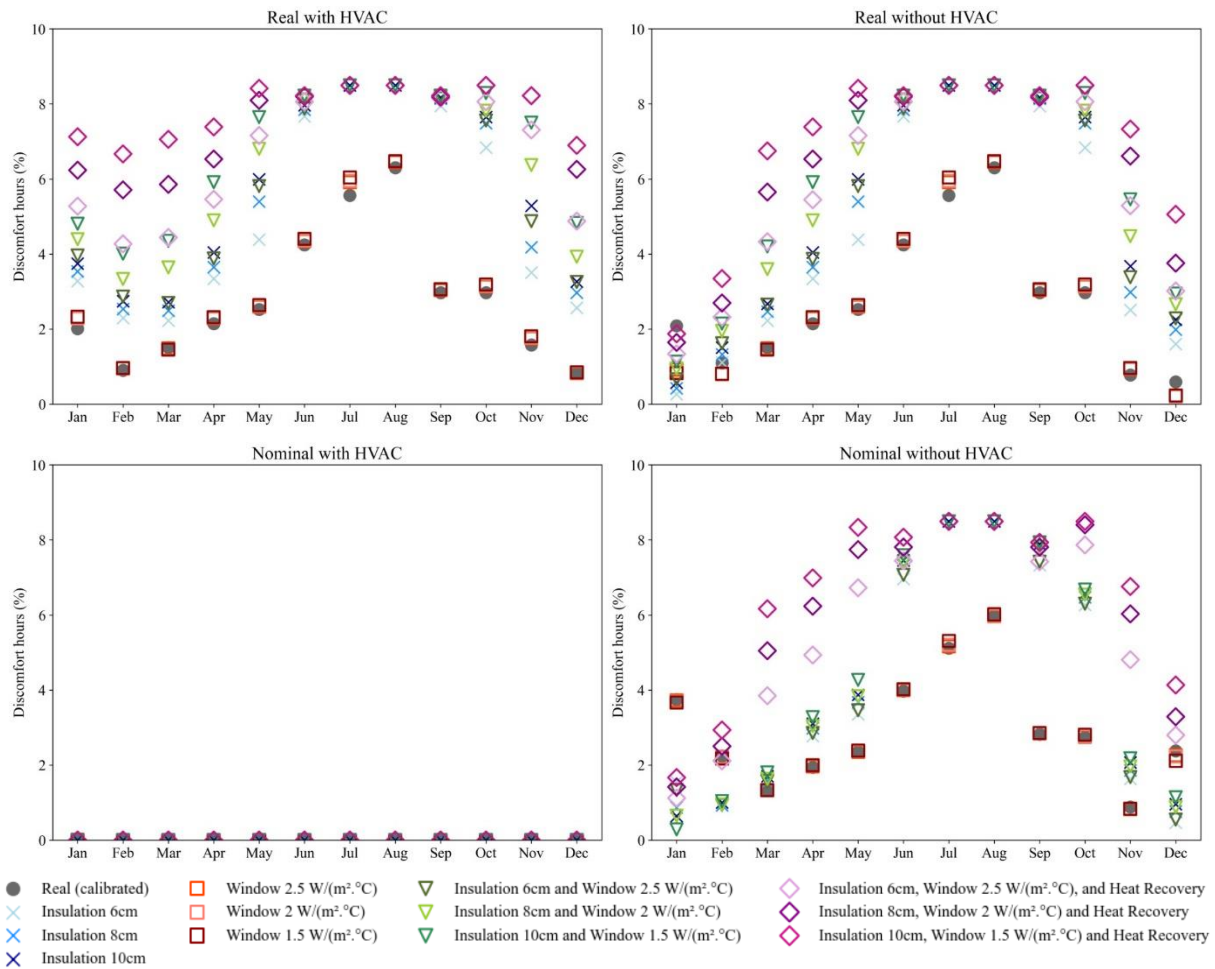


Figure 8.23 - Living room discomfort hours after improvement measures in case study 6 for real and nominal scenarios with and without using HVAC

• Case study 7

Figure 8.24 presents the mean monthly temperature in the living room of the calibrated model based on the measurements taken and all the twelve simulation results obtained after the introduction of the improvement measures. Figure 8.25 represents the percentage of the monthly discomfort hours (all the hours of the day that the temperature is not between 18°C and 25°C). The improvement measures simulations were carried out for four different scenarios: real and nominal with and without HVAC.

From Figure 8.24, it can be seen that in almost all the months, the real (calibrated) simulation is out of the thermal comfort range established. The months in which the mean temperature is within this range are March, April, November and December in the real scenario with HVAC, while in the real and nominal scenarios without HVAC, December is already outside this range. From this Figure, it is verified that replacing the windows causes a greater temperature increase in the living room in winter than applying to the outside walls from the inside and on the floor of the storage rooms at the top of the house. This is because the area of the glazed area is significant, and replacing the windows with ones that are significantly better thermally. Nevertheless, as expected, these two improvement measures applied together (insulation in the opaque envelope and windows) increase the living room's mean monthly temperature. Adding heat recovery leads to a greater increase in the mean monthly temperature in the winter months. In the summer months, introducing the improvement measures increased the temperature in the living room. However, in the nominal scenario, this increase is less marked than in the real scenarios with and without HVAC due to the infiltration considered. In real scenarios, the

infiltration considered for this case study is 0.5 air changes per hour. When improvement measures that have an impact on infiltration are applied, the infiltration value is more lower. In the nominal scenario, increasing the infiltration to 0.5 air changes per hour for all simulations makes the temperature drop slightly.

From the real and nominal scenario, it can be seen that the living room is not always in the thermal comfort range, even when some improvement measures are applied. May, June, July, August, September and October are the months that never reached this comfort range. However, the thermal comfort range has not been reached without HVAC in December. In summer months, the mean comfort temperature range is not reached; using HVAC is the solution. However, increasing the infiltration and/or ventilation of the house at night also allows the house to lower the mean temperature, as can be seen in the nominal case where the value considered in the infiltrations is higher than that considered in most simulations of the real scenarios. The infiltration value is 0.5 air changes per hour in real and nominal scenarios. However, when improvement measures impact infiltration, the infiltration value is lower than 0.5 in real scenarios. This case study has the same climate as case study 10, a less severe climate since the winter is classified as I1 and the summer as V1.

According to the results shown in Figure 8.25, only in January, February and December the number of hours of discomfort decrease with the introduction of improvement measures in all scenarios, except March in a nominal scenario without HVAC in some measures decreased and in others, increased. The percentage of hours of discomfort in all months is less than 8% for all scenarios (real and nominal) when applying the improvement measures, but in winter months, this percentage is lower.

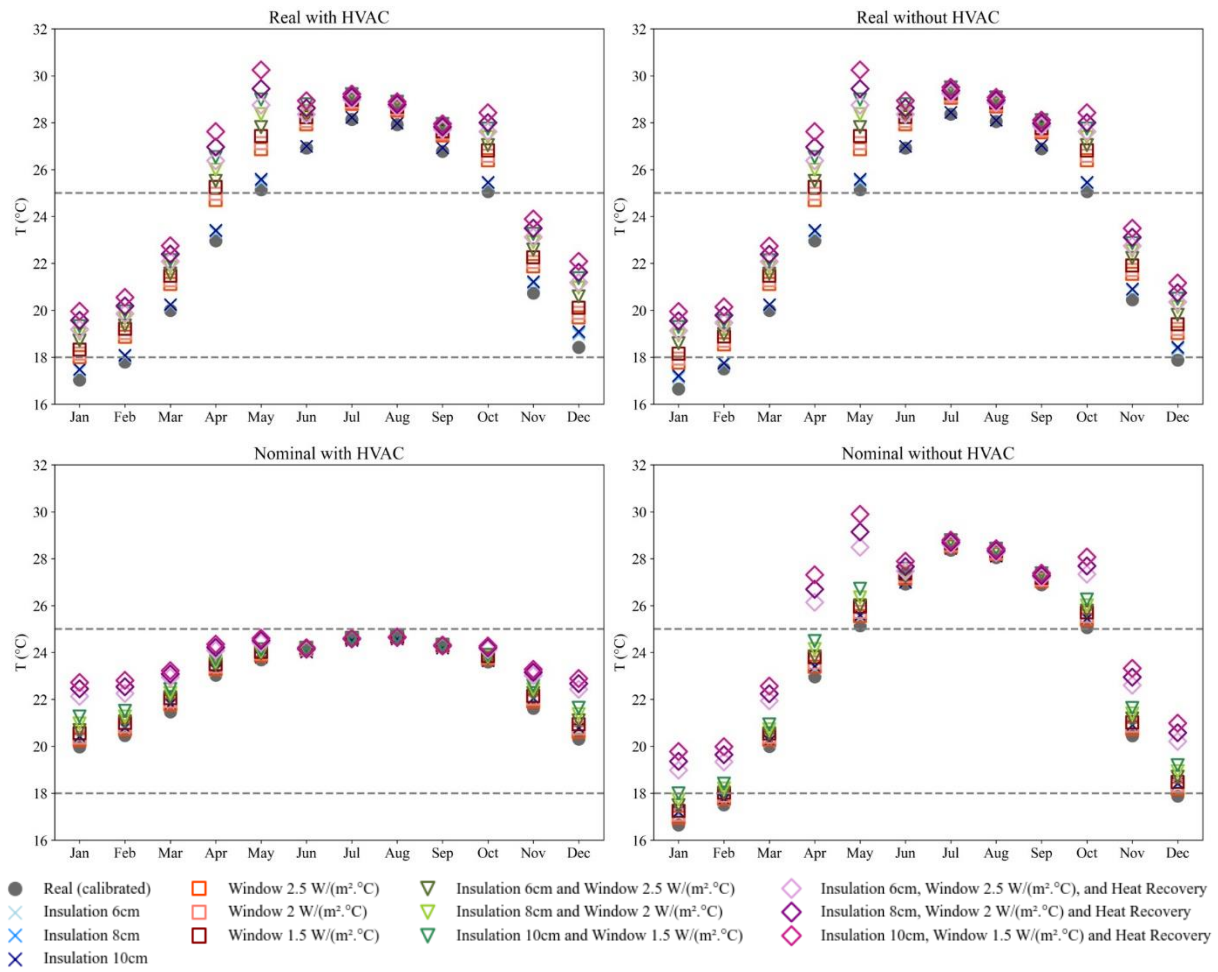


Figure 8.24 - Living room temperature after improvement measures in case study 7 for real and nominal scenarios with and without using HVAC

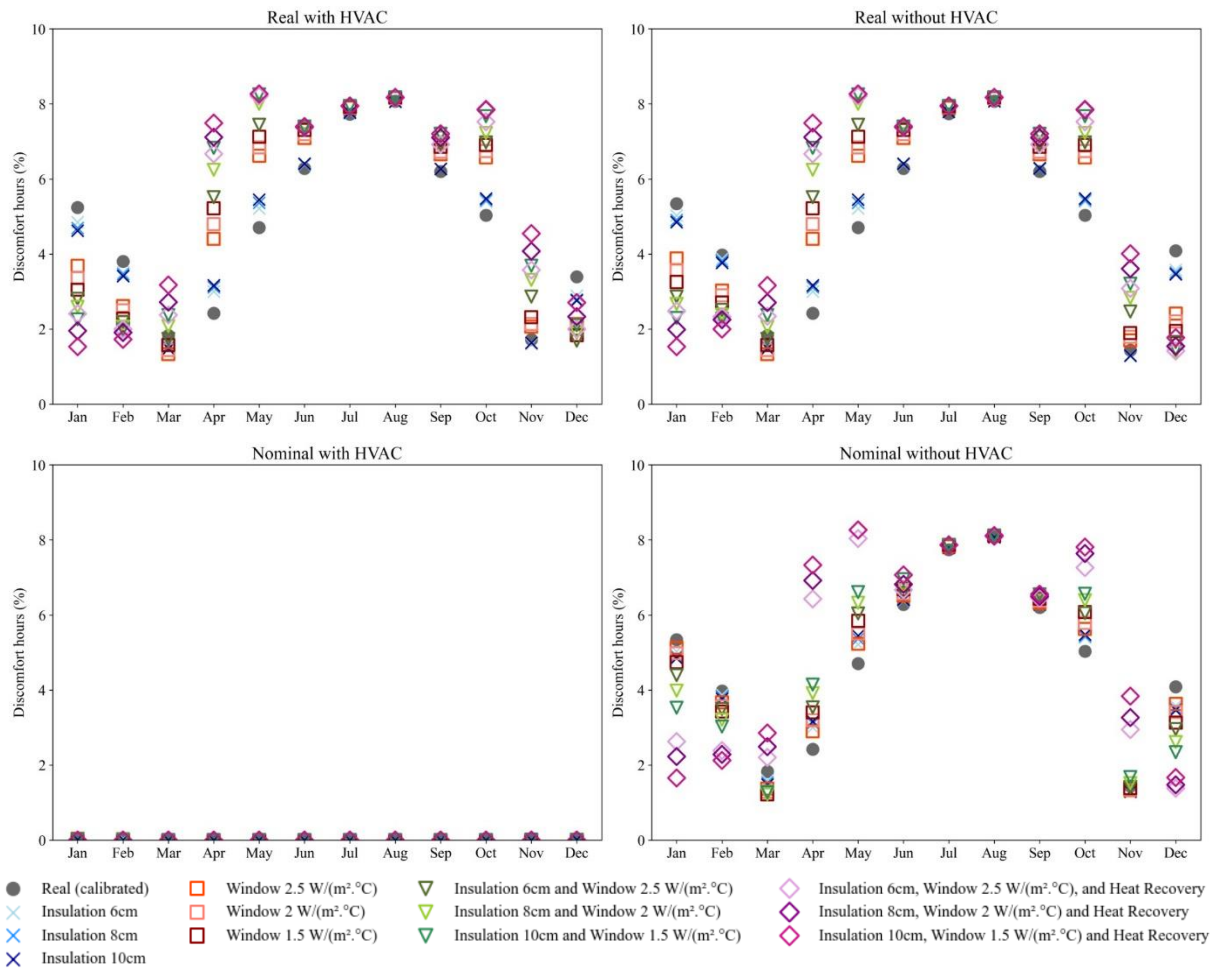


Figure 8.25 - Living room discomfort hours after improvement measures in case study 7 for real and nominal scenarios with and without using HVAC

• Case study 8

Given the occupants' responses in this case study, thermal comfort it is not identified as a parameter to be improved. As this is the only case study of the ten that does not consider temperature as a parameter to be improved, it was also considered important to carry out this analysis to verify the results that would be obtained since the annual temperature measurements indicate that the temperature is not within the established comfort range (18-25°C).

Figure 8.26 presents the mean monthly temperature in the living room of the calibrated model and all the other simulation results obtained after the introduction of the thermal improvement measures. Figure 8.27 represents the percentage of the monthly discomfort hours that the temperature is not between 18°C and 25°C. As in the other case studies, the simulations of the improvement measures were carried out for four scenarios: real and nominal with and without HVAC.

From Figure 8.26, it can be seen that in almost all the months, the real (calibrated) simulation is in the thermal comfort range established for the real scenario with HVAC. The mean temperature is out of this range in June, July, August and December. In the real and nominal scenarios without HVAC, January and February are also outside the thermal comfort range. This Figure also verifies that applying insulation to the outside walls and on the roof causes a greater temperature increase in the living room than replacing the windows. In some summer months, the application of certain measures results in a mean decrease in temperature, but in others, it causes an increase. This is because the area of the opaque envelope area is significant compared with the glazed area. Nevertheless, as expected, these two

improvement measures applied together (insulation in the opaque envelope and windows) increase the mean monthly temperature of the living room and adding heat recovery leads to a greater increase in the mean monthly temperature in the winter months, leading even in many cases to mean temperatures above 25°C.

From the real and nominal scenario, it can be seen that the living room is not always in the thermal comfort range in summer, even when some improvement measures are applied. June, July and August never reached this comfort range, so using HVAC is the solution. However, increasing the infiltration and/or ventilation of the house at night also allows the house to lower the mean temperature, as can be seen in the nominal case where the value considered in the infiltrations is higher than that considered in the simulations of the real scenarios. In real scenarios, the infiltration value is below 0.5 air changes per hour, and when improvement measures impact infiltration, the infiltration value is even lower. In nominal scenarios, the infiltration is considered 0.5 air changes per hour.

According to the results shown in Figure 8.27, in a real scenario with HVAC, some measures lead to an increase in the number of hours of discomfort and others to a decrease in some months. In real and nominal scenarios without HVAC, the hours of discomfort vary differently. The percentage of hours of discomfort in all months is less than 6% for all scenarios (real and nominal) when applying the improvement measures, but in winter months, this percentage is lower.

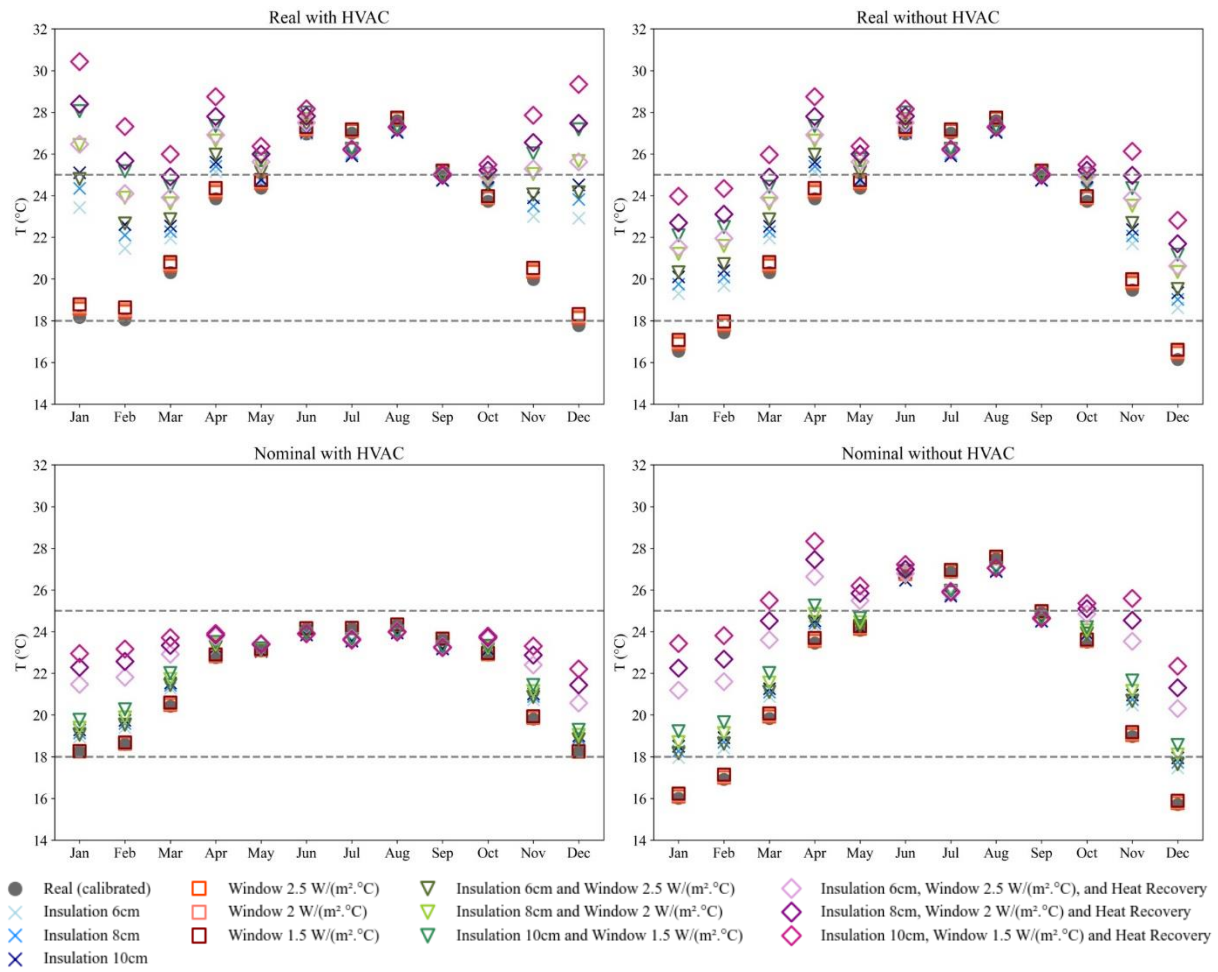


Figure 8.26 - Living room temperature after improvement measures in case study 8 for real and nominal scenarios with and without using HVAC

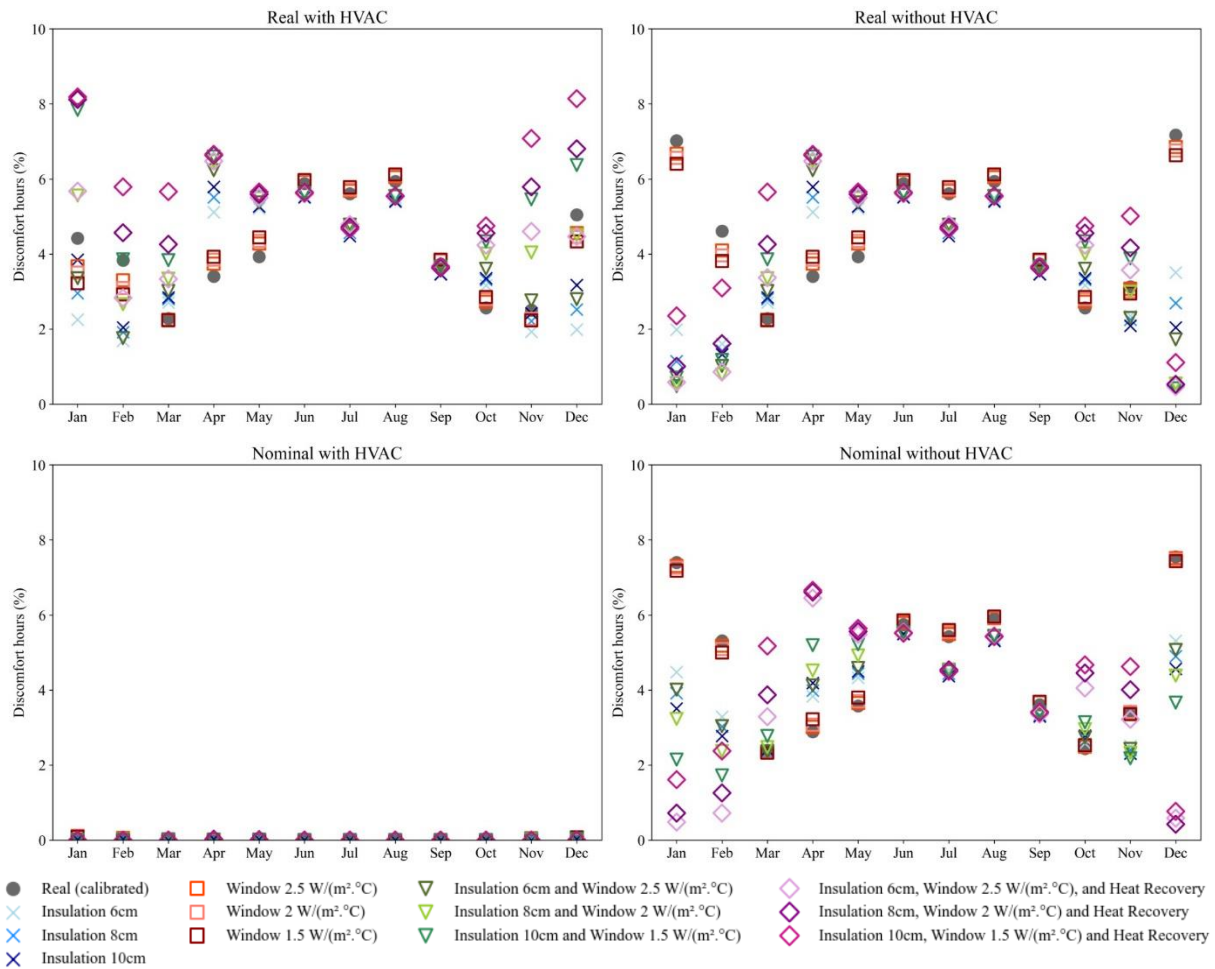


Figure 8.27 - Living room discomfort hours after improvement measures in case study 8 for real and nominal scenarios with and without using HVAC

• Case study 9

Figure 8.28 and Figure 8.29 reveal the mean monthly temperature in the living room and the percentage of the monthly discomfort hours, respectively, of the calibrated model and all the simulation results obtained after introducing the improvement measures. The discomfort hours were obtained considering the 24 hours of the day and when the temperature is not between 18°C and 24°C. As said before, the improvements were carried out for four scenarios: real with and without HVAC and nominal with and without HVAC.

Figure 8.28 shows that in the real simulation (calibrated) in the real scenario with HVAC, in some months, the mean monthly temperature is within the thermal comfort range considered, except in January and February, March, November and December. April is also outside the thermal comfort range in real scenarios without HVAC. In the nominal scenario without HVAC, the months that don't reach this temperature range are January, February, March, April, July, November and December. The Figure also reveals that generally, in real scenarios, replacing the windows causes an improvement in temperature compared to applying insulation to the outside walls from the outside, on the roof and the ceiling of the basement in the living room. In nominal scenario without HVAC, the opposite is verified. This is because the living room has an area of opaque envelope exposed to the outside that is very small. It's a room that can be considered interior. It should also be noted that the considered infiltration in the real simulation is above 0.5 air changes per hour, and when improvement measures that impact infiltration are applied, the infiltration is below 0.5. In the nominal scenario, the infiltration is always

0.5 air changes per hour. As expected, applying insulation in the opaque envelope and replacing windows simultaneously increases the mean monthly temperature of the living room. Heat recovery, in addition to applying insulation and replacing windows, also leads to a greater increase in the mean monthly temperature in the winter months.

By analysing the two real scenarios, it is possible to verify that the occupants of this house use a lot of heating in the living room. That's why there are so many differences in the graphical representation. After applying some measures, it can be verified that for the real scenario with HVAC, almost all months are within the thermal range. The real and nominal scenarios without HVAC in the living room, even with heat recovery in some months, don't reach the thermal range. Thus, it can be concluded that if the occupant doesn't use heating in the winter, with the implementation of measures to improve insulation and windows or even heat recovery, the occupant will not reach this comfort range. These results could be because the calibrated model considers the windows opening according to the occupants' feedback and considers an infiltration above 0.5 air changes per hour. When improvement measures that impact infiltration are applied, the infiltration value is lower than 0.5. In the nominal scenario, the infiltration is 0.5 air changes per hour. It should be noted that this case study is in the harshest climate of all the case studies.

Analysing Figure 8.29, it can be seen that the percentage of discomfort hours generally decreases after the introduction of comfort improvement measures, except for some summer months in real scenarios. In the nominal scenario without HVAC, generally, the percentage of discomfort hours decreases in all months. The discomfort hours are generally less than 8% for all scenarios when applying the improvement measures.

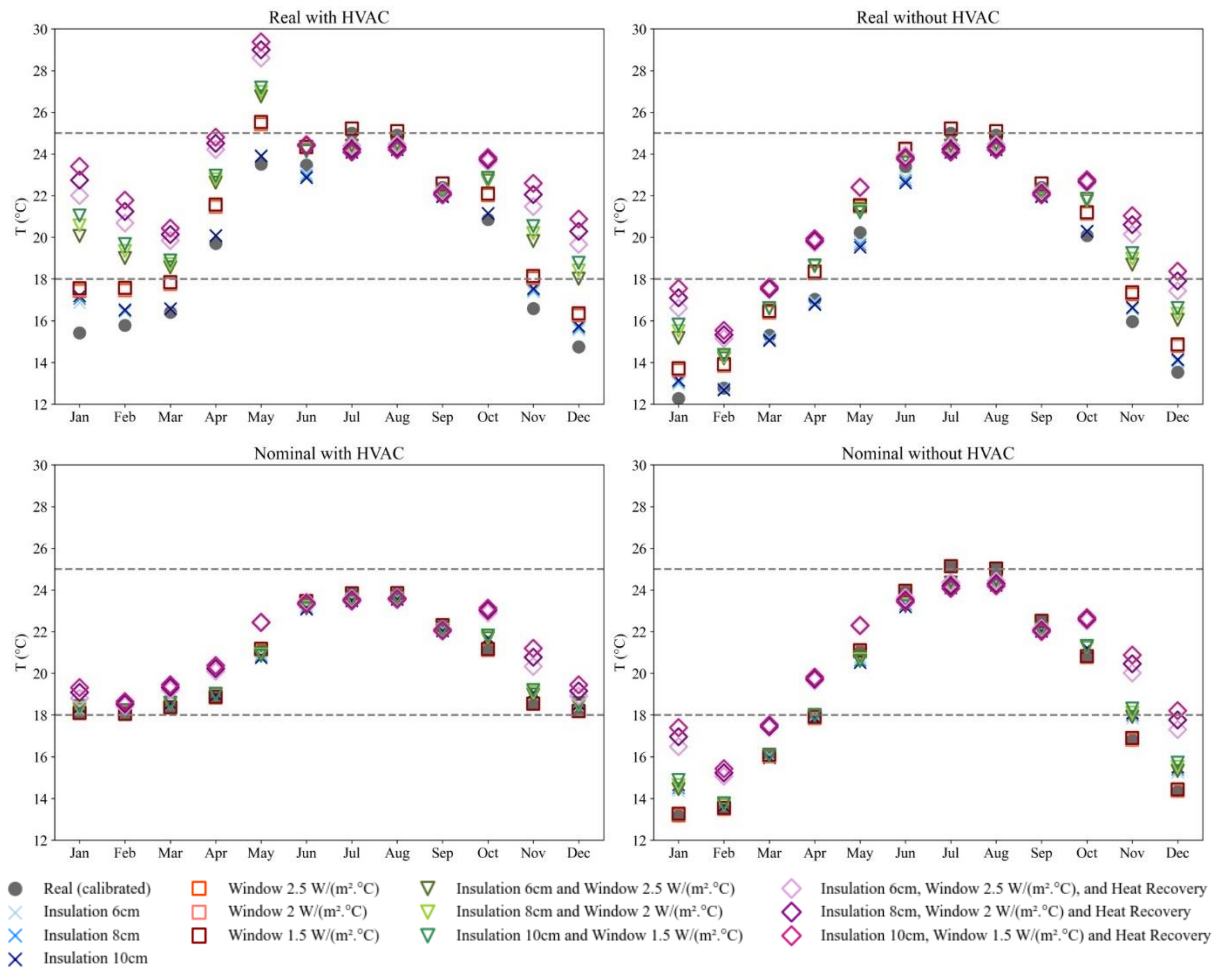


Figure 8.28 - Living room temperature after improvement measures in case study 9 for real and nominal scenarios with and without using HVAC

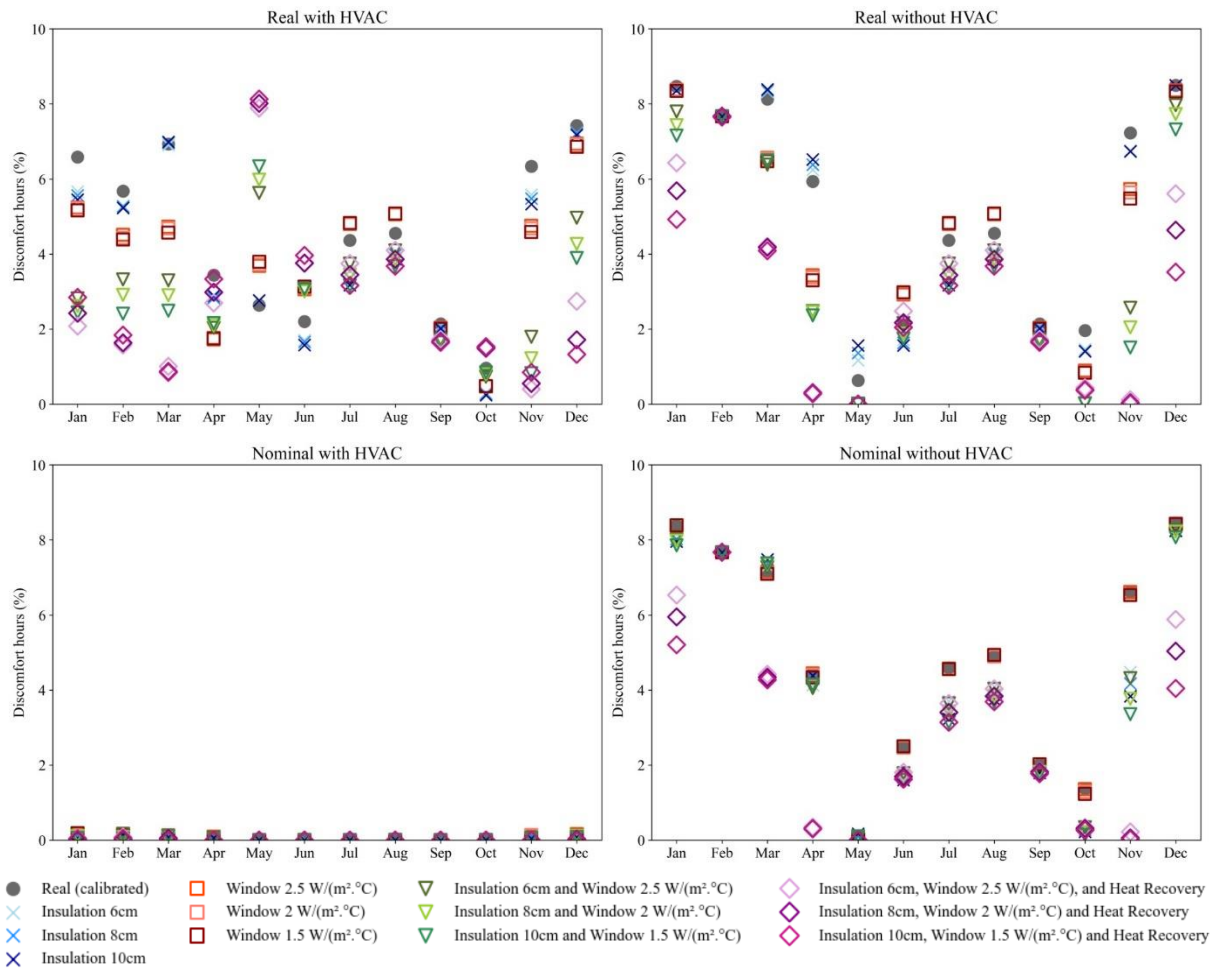


Figure 8.29 - Living room discomfort hours after improvement measures in case study 9 for real and nominal scenarios with and without using HVAC

• Case study 10

The mean monthly temperature in the living room of the calibrated model based on the measurements taken and all the simulation results obtained after the introduction of the improvement measures are presented in Figure 8.30. Figure 8.31 presents the percentage of the monthly discomfort hours, which are considered all those in which the temperature is not between 18°C and 25°C as recommended by Portuguese legislation considering the 24 hours of a day. This analysis was carried out for four different scenarios as described in all the case studies and described at the beginning of the chapter: real with and without HVAC and nominal with and without HVAC.

Figure 8.30 shows that in the real scenario with HVAC, the real simulation (calibrated) is within the established comfort range in all months except July. Regarding the real and nominal scenarios without HVAC, January and December are not within the range in addition to this month. From the figure, it is possible to conclude that replacing the windows increases the mean temperature in the living room more than applying insulation to the outside walls from the inside. This is because the area exposed to the outside is bigger regarding the glazing envelope because the opaque envelope is more exposed to the neighbours than to the outside. However, as expected, applying insulation in the opaque envelope and replacing windows simultaneously increases the mean monthly temperature of the living room but exceeds the established thermal comfort limit in some months. Heat recovery, in addition to applying insulation and replacing windows, also leads to a greater increase in the mean monthly temperature in the winter months, even exceeding 25°C in some months.

In general, it can be seen that in the real scenario, with or without the HVAC, it is possible for the living room to be in the thermal comfort range except for a few summer months when the measures were applied. However, these are not very far from this range; in the summer months, they may use cooling since the improvement measures do not contribute to lowering the temperature. Therefore, from the real scenario without HVAC, it can be concluded that if the occupant stops using heating in the winter, with the implementation of measures to improve insulation and windows or even heat recovery, the occupant will continue to be in the comfort range. If considering the minimum infiltration of 0.5 air changes per hour, and there is no use of HVAC, the results are already different in winter (Nominal without HVAC). The living room's mean temperature is lower than the real scenarios. However, the temperatures in the summer months are slightly closer to the comfort range. This could be because the calibrated model considers the windows opening according to the occupants' feedback and considers an infiltration of 0.5 air changes per hour. However, when improvement measures are applied that impact infiltration, it is reduced to below 0.5 air changes per hour. In the nominal scenario, increasing the infiltration causes the temperature to drop slightly in winter and summer. Therefore, there may be space for improvement in summer if the occupants open the windows more at night to cool the home, and in winter, close them more or use the heating equipment.

By analysing Figure 8.31, it can be seen that in most months, the percentage of discomfort hours in real scenarios increases after the comfort improvement measures, except in December and some measures in one or two months. In nominal scenarios, generally, in January, February, March, November and December, the hours of discomfort decreased. In the other months these hours increase. However, the percentage of hours of discomfort in the months can be generally less than 7% for all scenarios (real and nominal). These results are because the mean monthly temperature values for most months of the year are already within the established thermal comfort range.

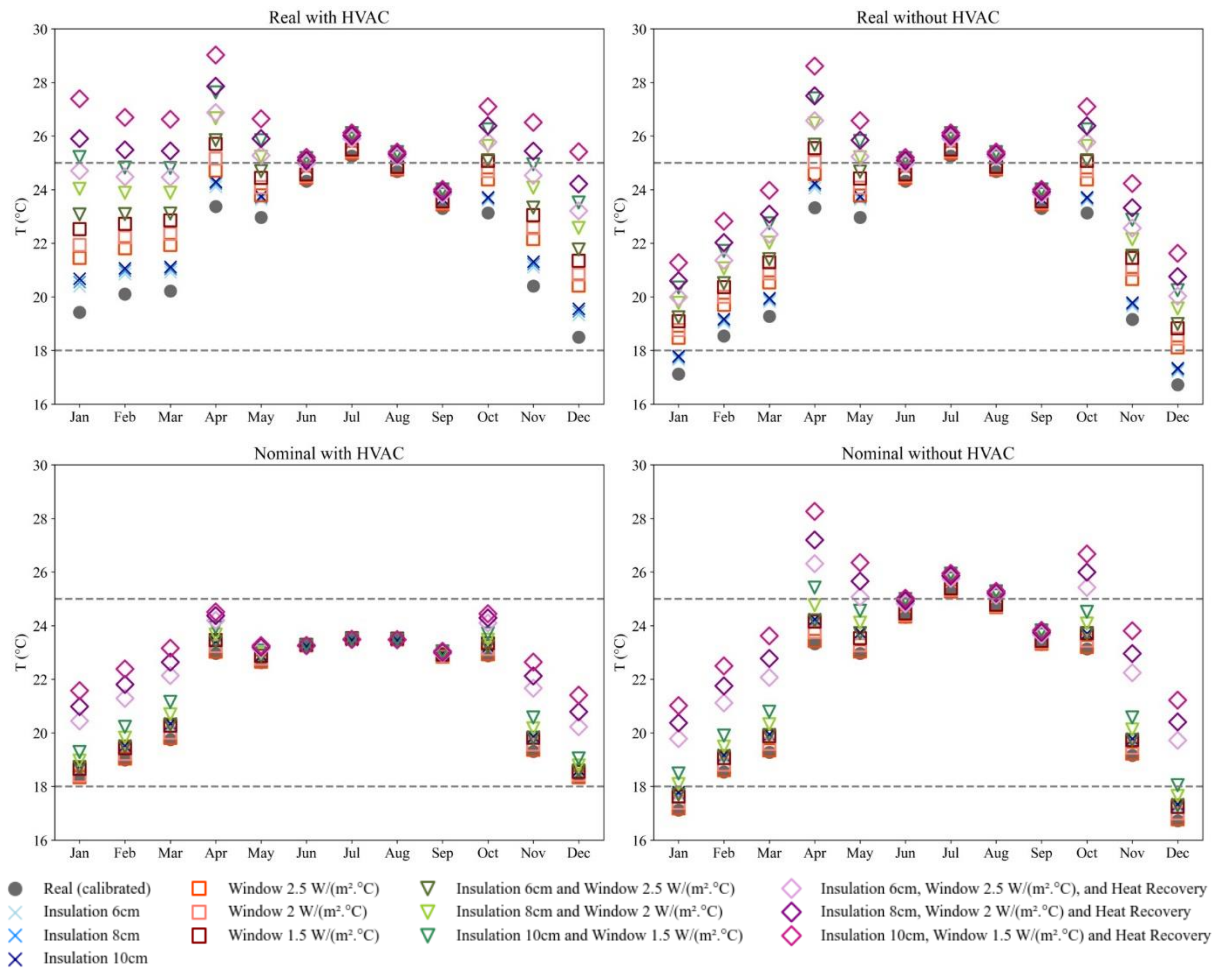


Figure 8.30 - Living room temperature after improvement measures in case study 10 for real and nominal scenarios with and without using HVAC

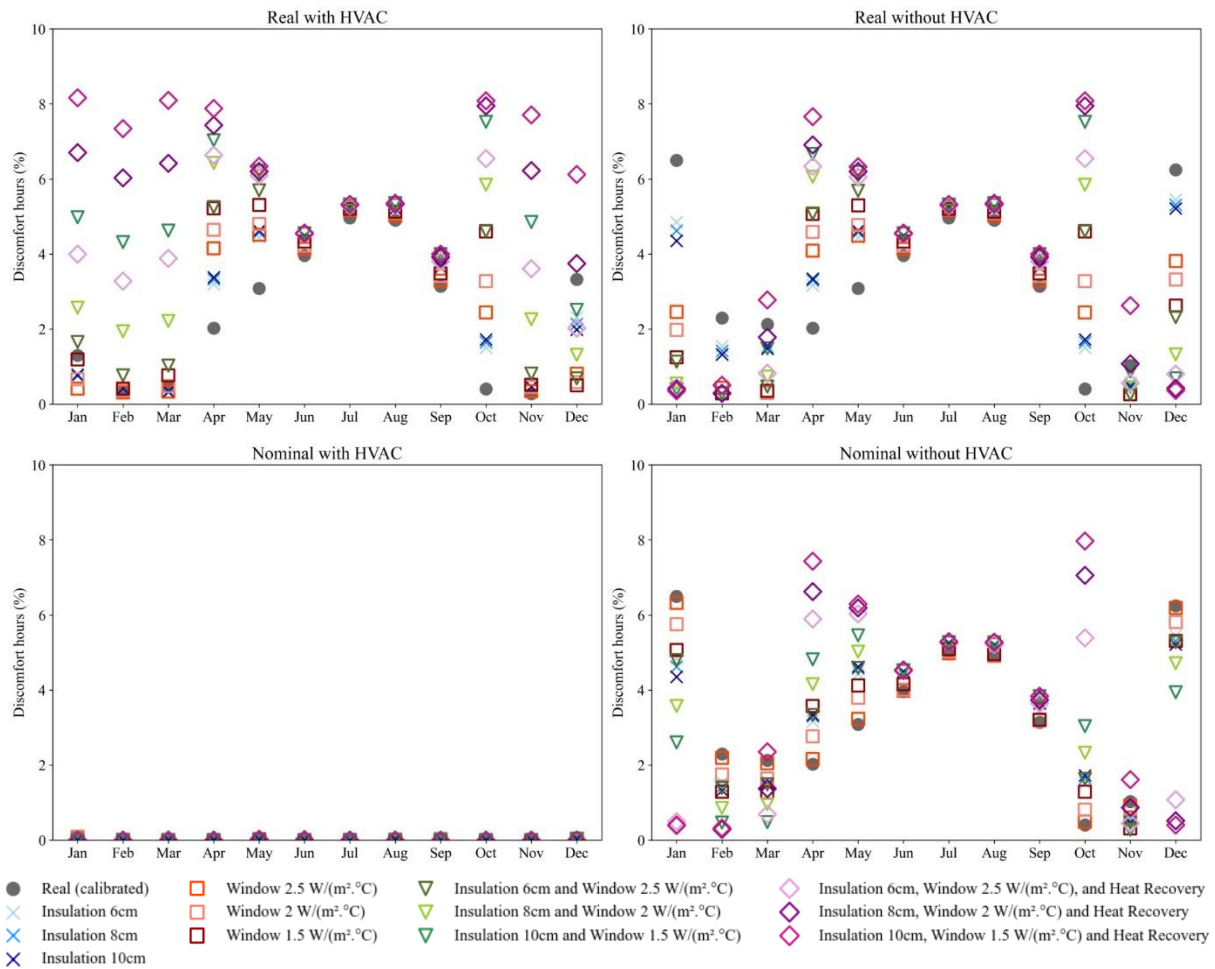


Figure 8.31 - Living room discomfort hours after improvement measures in case study 10 for real and nominal scenarios with and without using HVAC

8.4. Conclusions of simulation models

For this study, it is intended to know the results of energy consumption and indoor temperature. To this end, the first results were obtained based on the information gathered on the construction characteristics of the house and its use. The model was calibrated based on temperature and electricity consumption values collected over a consecutive year, considering the MBE and CV(RMSE) values established in ASHRAE, IPMVP and FEMP.

The impact on occupant thermal comfort was evaluated (models calibrated for this comfort parameter). As mentioned previously, the impact on energy consumption was not evaluated since it was not possible to collect disaggregated information on the different uses. However, the calibration of energy consumption is important because it helps establish the model's internal gains and, therefore, influences the house's interior temperature. Also, improvement measures in terms of energy efficiency and reducing energy consumption were indicated above in each case study.

As mentioned at the beginning of the chapter, it was intended to carry out a more specific analysis of measures that contribute to increasing thermal comfort since, in most case studies, this is a parameter identified as a margin for improvement. In this way, and after applying the improvement measures for the four scenarios (Real with HVAC, Real without HVAC, Nominal with HVAC and Nominal without HVAC), the following main conclusions were reached:

- In some case studies, the real (calibrated) simulation (i.e. before any thermal comfort improvement measures have been implemented) is within the established comfort range (18-25°C) in most months both in real and nominal scenarios. It is in the summer and winter months when temperatures are more extreme that it often happens that the comfort range is not achieved. However, there are other case studies where this is not the case;
- In some case studies, replacing the windows causes a greater temperature increase in the interior, and in other case studies, is the insulation to the opaque envelope. This is because, in some houses, there is a more exposed area to the outside of the glazing or opaque envelope (in some case studies, the opaque envelope is not exposed to the outside but to the neighbours). It also contributes to the fact that, in some cases, the windows and/or the opaque surroundings have a heat transmission coefficient that is higher than that applied in the improvement measures;
- As expected, applying insulation in the opaque envelope and replacing windows simultaneously increases the rooms' mean monthly temperature. Heat recovery, in addition to applying insulation and replacing windows, also leads to a greater increase in the mean monthly temperature in the winter months;
- In almost all case studies, it has been found that simply insulating the opaque envelope or replacing the windows may not be enough to stay within the thermal comfort range considered in the winter months. Usually, it is the application of these measures together that ensures that the comfort temperature range is maintained. In addition to these measures, heat recovery in some case studies is the only measure that ensures it reaches 18°C in winter, and in other case studies, in some months, it exceeds 25°C, exceeding the thermal comfort range even in scenarios where the use of heating in winter was not considered. In some case studies, introducing these improvement measures increases the mean summer temperature; in other case studies, it improves it by lowering the value. Therefore, in some cases where the mean temperature is above the range, there may be space for improvement since, in some studies, the occupants may open the windows more at night to cool the home. Or, as a last instance, air conditioning guarantees the thermal comfort range in both summer and winter;
- Considering the real scenarios (with or without the HVAC), in almost all case studies, it is possible for the living room to be in the thermal comfort range in winter (except in case study 4) at least if one of the improvement measures applied. In almost all case studies, there is at least one summer month in which thermal comfort is not achieved, except for case studies 3 and 5, where comfort is always attained in summer with at least one of the applied improvement measures. The case studies in which a particular month does not achieve thermal comfort are not far off the range. Therefore, from the real scenario without HVAC, it can be concluded that if the occupant doesn't use heating in the winter, with the implementation of measures to improve insulation and windows or even heat recovery, the occupant will continue to be in the comfort range except one month in case study 4. In the case studies, the summer months don't reach 25°C or lower temperatures; occupants may use cooling to be within the comfort range;
- Considering the nominal scenario (minimum infiltration of 0.5 air changes per hour) without using HVAC, the results in some case studies are different than the real scenario but similar in other cases. This is due to the infiltration considered when calibrating the initial simulation model. In some case studies, the value was higher than 0.5 air changes per hour; in others, it was lower, and in others, the same. However, when improvement measures are applied that impact infiltration, it is reduced in all case studies to below 0.5 air changes per hour and in the nominal scenarios, this infiltration is 0.5 air changes per hour. The greater the difference

between the infiltration value used in real and nominal scenarios, the greater the difference between the results;

- Usually, in winter months, the percentage of discomfort hours decreases after comfort improvement measures are introduced, as expected. In some case studies in the hottest months, these hours of discomfort increased or decreased depending on the mean temperature, which was already very close to 25°C and depending on the infiltration and ventilation considered in the calibrated model. The climate in which the house is located also influences it. In some case studies, in some months, despite the temperature being within the comfort range with the application of the improvement measures, the hours of discomfort increased. This could happen because the mean monthly temperature values of the calibrated model are already within the established thermal comfort range. However, the percentage of hours of discomfort in most case studies is less than 5% for all scenarios (real and nominal) when applying the improvement measures, except case studies 3, 4 and 10. In some months, the percentage of hours of discomfort is less than 8%;
- No cost-benefit analyses were carried out in this study. However, the thermal comfort improvement measures analysed in the simulation models indicate that, in many case studies, they tend to increase indoor temperatures during winter and decrease them during summer. Thus, less energy will be needed for air-conditioning homes to be in the comfort range of 18°C-25°C.

9. Conclusions and future work

This final chapter aims to set out the main conclusions of this research, explore future work that could be carried out, and what can be improved, considering this research and the methodology developed.

9.1. Conclusions

This research aimed to develop and test an integrated method for evaluating multiple parameters of comfort and well-being and their relationship with building energy efficiency. This method revealed which comfort and well-being parameters need to be improved in all case studies, according to feedback from occupants and the impact that the improvement measures can have on the indoor environment.

Thus, having achieved the objective of this research, it is possible to answer the main research question of this doctoral thesis. To evaluate the occupant's comfort and well-being in their houses, integrating aspects and characteristics of the energy efficiency of buildings, it is necessary to collect feedback from the occupants through surveys and interviews, to collect data about the construction aspects, energy systems, usage profiles, and others and monitor parameters of the indoor environment. Monitoring these parameters are deemed necessary to verify that what the occupants indicate corresponds to the comfort ranges established by studies and/or legislation, to performed simulation models and to check the impact of certain improvement measures. Monitoring energy consumption is essential to understanding the real consumption of a particular house, helping design simulation models, and checking the impact of specific measures.

With the answer to the central question, it turns out that the relationship between energy efficiency, characteristics of buildings, comfort, and well-being is undeniable but also subjective since people's perceptions are affected by their experiences, their emotional state, and other subjective factors. In some cases, the various comfort parameters depend on each other, so a particular occupant's perception of one parameter can affect their perception of another. These perceptions of comfort also contribute to an increase or a decrease of energy consumption, especially in thermal comfort and lighting. It has also been found that houses with poorer construction characteristics are not necessarily the ones with poorer satisfaction ratings. This is due to the experiences that the occupants of each case study have with the surroundings of the house itself.

This study also found that, in most case studies, the thermal sensation most frequently reported in the right-now survey differs from that indicated in the extensive survey. This discrepancy is linked not only to subjectivity but also to the different scopes of the surveys. The right-now survey captures a momentary assessment, whereas the extensive survey provides a broader evaluation of winter and summer conditions. To identify the comfort and well-being parameters requiring improvement, the extensive survey is essential, as it includes questions covering a wide range of parameters. If only the right-now survey had been conducted, developing the method would not have been possible, given that this survey focuses almost exclusively on thermal comfort. Nevertheless, the right-now survey played a crucial role in highlighting differences in occupant analysis and perception, as well as other discrepancies discussed in the results analysis chapter, including variations in perception between the main bedroom and the living room.

After the post-occupancy evaluation, comfort and well-being parameters were identified to be improved, and it was possible to formulate recommendations for improving residential buildings' indoor environment, making them more sustainable and comfortable for the occupants that live there. Of these recommendations, it can be seen that some impact more than one comfort and well-being parameter and impact energy consumption. However, other suggestions for improvement do not affect energy

consumption or the energy bill but contribute to the general comfort of the home. Although many of the improvement measures have not been studied from the real point of view of their impact on comfort and energy consumption, using simulation models, it is known from other studies and daily experience that they impact the indoor environment and can reduce energy consumption or, at least, the energy bill. The thermal comfort improvement measures were evaluated through simulation models and showed that the temperature inside the house generally increases in winter and decreases in summer. Thus, less energy will be needed for air-conditioning homes to be in the comfort range of 18°C-25°C.

This research contributes to the field of comfort and well-being in residential buildings since it considers occupant feedback as a starting point for improving the indoor environment and explores improvement measures that increase the comfort experienced by occupants and energy efficiency. This integrated assessment of comfort, well-being, energy efficiency, and their relationship is innovative and essential for decarbonising the building stock. Residential buildings have the potential to reduce energy consumption by adopting construction solutions that provide comfort and well-being with the minimum use of resources, using and managing energy resources with a vision of sustainability and the use of renewable sources.

9.2.Future work

Considering the methodology developed and the results obtained, improvements are needed, and various directions can be taken. In terms of improvements, it is highlighted:

- The need to apply the methodology developed to more case studies to have a greater diversity of results and to understand whether the methodology developed is sufficiently robust;
- Not all the questions in the extensive survey are necessary to conclude which comfort and well-being parameters should be improved in the dwelling being analysed and what the source of the discomfort or dissatisfaction is. Therefore, reviewing the questions to be asked might be a point to consider in order to reduce the length of the survey and make it more targeted. However, for this to happen, it is important to apply this methodology to more case studies, as has already been mentioned;
- That disaggregating energy consumption is essential to understand the impact of the various improvement measures on energy consumption, specifically in the case of thermal comfort, where many of the measures have an effect on the temperature of the home and, therefore, the increase or reduction in energy consumption would be important to know. Without energy desegregation, this analysis would not have been very accurate;
- Taking measurements of the indoor environment, particularly those focusing on acoustics, lighting and air quality, would be important to help make decisions on improvement measures. However, the measurements that have been carried out essentially of the thermal environment can be made more consistent and more robust by continuing the measurements so that the average monthly values are based on more years than just one, which may be atypical.

Many directions can be taken from this study. Some are listed below:

- The methodology developed can be applied, with the necessary adjustments, to commercial and service buildings;
- The surveys presented and the case studies can serve as a starting point for other broader studies or for studies that are more focused on a given comfort parameters, such as thermal comfort, acoustics, air quality, lighting or others, rather than considering all the parameters;

- Development a dashboard or tool that automatically uses the answers given by the occupants and based on measurements of the indoor environment to indicate the comfort and well-being parameters to be improved and the recommended improvement measures;
- Perform a cost-benefit analysis of each measure to improve the indoor environment.

References

- [1] PNAEE, ‘Plano Nacional de Ação para a Eficiência Energética - Terceiro PNAEE | 2017 - 2020’, *Diário da República*, 2017.
- [2] Governo de Portugal, ‘Plano Nacional Energia e Clima 2021-2030’, 2019.
- [3] DL 101-D, ‘Decreto-Lei n.º 101-D/2020 de 7 de dezembro’, *Diário da República - I Série*, no. 2, pp. 3179–3182, 2020.
- [4] Parlamento Europeu e o Conselho da União Europeia, ‘Directiva 2010/31/UE do Parlamento Europeu e do Conselho de 19 de Maio de 2010 relativa ao desempenho energético dos edifícios (reformulação)’, *Jornal Oficial da União Europeia*, pp. 1–35, 2018.
- [5] P. Isolani, ‘Eficiência energética nos edifícios residenciais’, p. 48, 2008.
- [6] H. Gonçalves and J. M. Graça, *Conceitos Bioclimáticos para os Edifícios em Portugal*, DGGE / IP-. 2004.
- [7] J. Alker, M. Malanca, C. Pottage, and R. O’Brien, ‘Health, Wellbeing & Productivity in Offices’, *World Green Building Council*, p. 46, 2014.
- [8] K. Fabbri, *Indoor Thermal Comfort Perception. A Questionnaire Approach Focusing on Children*. Springer International Publishing AG Switzerland, 2015. doi: 10.1007/978-3-319-18651-1.
- [9] S. Gaspar, ‘O impacto do suporte no trabalho percebido pelos trabalhadores’, Instituto Superior de Psicologia Aplicada, 2011.
- [10] L. Lambert, H. A. Passmore, and M. D. Holder, ‘Foundational Frameworks of Positive Psychology: Mapping Well-Being Orientations’, *Canadian Psychology*, vol. 56, no. 3, pp. 311–321, 2015, doi: 10.1037/cap0000033.
- [11] R. Coelho do Vale and I. Moreira, ‘Estudo de Satisfação e Bem-estar à Sociedade Portuguesa’, 2016.
- [12] Y. Alhorr, M. Arif, A. Kaushik, A. Mazroei, M. Katafygiotou, and E. Elsarrag, ‘Occupant productivity and office indoor environment quality: A review of the literature’, *Build Environ*, vol. 105, no. February 2017, pp. 369–389, 2016, doi: 10.1016/j.buildenv.2016.06.001.
- [13] L. Pastore and M. Andersen, ‘Building energy certification versus user satisfaction with the indoor environment: Findings from a multi-site post-occupancy evaluation (POE) in Switzerland’, *Build Environ*, vol. 150, no. January, pp. 60–74, 2019, doi: 10.1016/j.buildenv.2019.01.001.
- [14] UC Davis - Student Community Center, ‘Average Scale Scores by Category - CBE Survey’, 2014.
- [15] Z. Zhang, Y. Zhang, and A. Khan, ‘Thermal comfort of people from two types of air-conditioned buildings - Evidences from chamber experiments’, *Build Environ*, vol. 162, no. April, p. 106287, 2019, doi: 10.1016/j.buildenv.2019.106287.
- [16] M. Pazhoohesh and C. Zhang, ‘A satisfaction-range approach for achieving thermal comfort level in a shared office’, *Build Environ*, vol. 142, no. June, pp. 312–326, 2018, doi: 10.1016/j.buildenv.2018.06.008.

- [17] S. D. Mangan, G. K. Oral, I. Sozen, and I. E. Kocagil, 'Evaluation of settlement textures in terms of building energy , economic performance , and outdoor thermal comfort', *Sustain Cities Soc*, vol. 56, no. October 2019, p. 102110, 2020, doi: 10.1016/j.scs.2020.102110.
- [18] M. A. Ortiz, S. R. Kurvers, and P. M. Bluysen, 'A review of comfort, health, and energy use: Understanding daily energy use and wellbeing for the development of a new approach to study comfort', *Energy Build*, vol. 152, pp. 323–335, 2017, doi: 10.1016/j.enbuild.2017.07.060.
- [19] C. Randall, A. Corp, and A. Self, 'Measuring National Well-Being: Life in the UK', *Office for National Statistics*, no. February, pp. 1–52, 2014.
- [20] A. Paone and J. P. Bacher, 'The impact of building occupant behavior on energy efficiency and methods to influence it: A review of the state of the art', *Energies (Basel)*, vol. 11, no. 4, 2018, doi: 10.3390/en11040953.
- [21] E. Hoxha, C. Liardet, and T. Jusselme, 'Office densification effects on comfort, energy, and carbon lifecycle performance: An integrated and exploratory study', *Sustain Cities Soc*, vol. 55, no. January, 2020, doi: 10.1016/j.scs.2020.102032.
- [22] S. Willems, D. Saelens, and A. Heylighen, 'Comfort requirements versus lived experience: combining different research approaches to indoor environmental quality', *Archit Sci Rev*, vol. 0, no. 0, pp. 1–9, 2020, doi: 10.1080/00038628.2019.1705754.
- [23] W. H. Ko *et al.*, 'The impact of a view from a window on thermal comfort, emotion, and cognitive performance', *Build Environ*, vol. 175, no. February, p. 106779, 2020, doi: 10.1016/j.buildenv.2020.106779.
- [24] IEA EBC, 'Iea Ebc Annex 72', no. September 2019, 2017.
- [25] A. Boodi, K. Beddiar, M. Benamour, Y. Amirat, and M. Benbouzid, 'Intelligent systems for building energy and occupant comfort optimization: A state of the art review and recommendations', *Energies (Basel)*, vol. 11, no. 10, 2018, doi: 10.3390/en11102604.
- [26] M. A. Ortiz, S. R. Kurvers, and P. M. Bluysen, 'A review of comfort, health, and energy use: Understanding daily energy use and wellbeing for the development of a new approach to study comfort', *Energy Build*, vol. 152, pp. 323–335, 2017, doi: 10.1016/j.enbuild.2017.07.060.
- [27] P. Šujanová, M. Rychtáriková, T. S. Mayor, and A. Hyder, 'A healthy, energy-efficient and comfortable indoor environment, a review', *Energies (Basel)*, vol. 12, no. 8, pp. 1–37, 2019, doi: 10.3390/en12081414.
- [28] A. S. of H. R. and A. E. (ASHRAE), 'ANSI/ASHRAE Standard 55-2013 - Thermal environmental conditions for human occupancy.', p. 56, 2013.
- [29] K. G. Jensen *et al.*, *Guide to Sustainable Building Certifications*, 1st ed. 2018.
- [30] N. Alborz and U. Berardi, 'A post occupancy evaluation framework for LEED certified U.S. higher education residence halls', *Procedia Eng*, vol. 118, pp. 19–27, 2015, doi: 10.1016/j.proeng.2015.08.399.
- [31] C. Ward, A. Yates-Bre, J. Whitaker, S. Ramesh, and N. Stodola-Iwbi, 'Assessing Health and Wellbeing in Buildings', *Bre; Iwbi*, p. 16, 2017.
- [32] 'LEED v4: Interior Design + Construction Guide | USGBC'. Accessed: Apr. 07, 2020. [Online]. Available: https://www.usgbc.org/guide/idc?fbclid=IwAR0GjiRaJiK4qQh8JTWLfze6ZB64gxAeY5BLXW6_IdbAk-2ZH8vmXacm6yQ

- [33] I. W. B. I. Pbc., ‘The WELL Building Standard’, 2020.
- [34] Parlamento Europeu e o Conselho da União Europeia, ‘Diretiva 2018/844 do Parlamento Europeu e do Conselho de 30 de maio de 2018 que altera a Diretiva 2010/31/UE relativa ao desempenho energético dos edifícios e a Diretiva 2012/27/UE sobre a eficiência energética’, *Jornal Oficial da União Europeia*, vol. L156, pp. 75–91, 2018.
- [35] SCE, ‘Sistema de Certificação Energética dos Edifícios - Decreto-Lei n.º 118/2013, de 20 de agosto’, *Diário da República*, vol. 159, 2013.
- [36] RECS, ‘Regulamento de Desempenho Energético dos Edifícios de Comércio e Serviços (RECS) — Requisitos de conceção para edifícios novos e intervenções - Portaria n.º 349-D/2013, de 2 de dezembro’, *Diário da República N.º 233, 1.ª série*, no. 40, pp. 40–73, 2013.
- [37] REH, ‘Regulamento de Desempenho Energético dos Edifícios de Habitação (REH)—Requisitos de conceção para edifícios novos e intervenções - Portaria n.º 349-B/2013’, *Diário da República N.º 232, 1.ª série*, vol. 11, no. 29, pp. 18–29, Lisboa, Portugal (in Portuguese), 2013.
- [38] Technical Committee CEN/TC 169 ‘Light and Lighting’, ‘Light and lighting - Lighting of work places - Part 1: Indoor work’, *European Standard 12464*, vol. 3, pp. 1–43, 2002, doi: <http://www.din.de>.
- [39] G. Brager, H. Zhang, and E. Arens, ‘Evolving opportunities for providing thermal comfort’, *Building Research and Information*, vol. 43, no. 3, pp. 274–287, 2015, doi: 10.1080/09613218.2015.993536.
- [40] M. S. Andargie, M. Touchie, and W. O’Brien, ‘A review of factors affecting occupant comfort in multi-unit residential buildings’, *Build Environ*, vol. 160, no. June, p. 106182, 2019, doi: 10.1016/j.buildenv.2019.106182.
- [41] A. L. Pisello *et al.*, ‘Test rooms to study human comfort in buildings: A review of controlled experiments and facilities’, *Renewable and Sustainable Energy Reviews*, vol. 149, no. May, p. 111359, 2021, doi: 10.1016/j.rser.2021.111359.
- [42] S. Pinto, L. Fumincelli, A. Mazzo, S. Caldeira, and J. C. Martins, ‘Comfort, well-being and quality of life: Discussion of the differences and similarities among the concepts’, *Porto Biomed J*, vol. 2, no. 1, pp. 6–12, 2017, doi: 10.1016/j.pbj.2016.11.003.
- [43] J. F. Nicol and M. A. Humphreys, ‘Adaptive thermal comfort and sustainable thermal standards for buildings’, *Energy Build*, vol. 34, no. 6, pp. 563–572, 2002, doi: 10.1016/S0378-7788(02)00006-3.
- [44] W. de L. Machado and D. R. Bandeira, ‘Bem-estar psicológico: definição, avaliação e principais correlatos’, *Estudos de Psicologia (Campinas)*, vol. 29, no. 4, pp. 587–595, 2012, doi: 10.1590/s0103-166x2012000400013.
- [45] S. Altomonte *et al.*, ‘Ten questions concerning well-being in the built environment’, *Build Environ*, vol. 180, p. 106949, 2020, doi: 10.1016/j.buildenv.2020.106949.
- [46] J. Zitars, B. Spadafore, S. Coulombe, M. Riemer, B. C. Dreyer, and S. Whitney, ‘Understanding the psycho-environmental potential functions of a green building to promote employee health, wellbeing and productivity: A theoretical perspective’, *Build Environ*, vol. 205, no. June, p. 108268, 2021, doi: 10.1016/j.buildenv.2021.108268.
- [47] UK Green Building Council, ‘Health and Wellbeing in Homes’, *UK Green Building Council*, no. July, pp. 1–37, 2016, doi: 10.1007/978-3-319-78328-4.

- [48] World Green Building Council, 'Health, Wellbeing & Productivity in Offices', *World Green Building Council*, vol. 1, no. September, p. 46, 2014.
- [49] P. S. Burge, 'Sick building syndrome', *Occup Environ Med*, vol. 61, no. 2, pp. 185–190, 2004, doi: 10.1136/oem.2003.008813.
- [50] F. Monika and P. Wargocki, *Human comfort and self-estimated performance in relation to indoor environmental parameters and building features*. 2011.
- [51] Global Centre for Healthy Workplaces, 'Working at Home Wellbeing Survey - Summary Report of Global Findings', 2020.
- [52] S. W. Ornstein, 'Avaliação Pós-Ocupação aplicada em edifícios de escritórios: Alguns aspectos metodológicos e resultados', 1995.
- [53] S. Hu, D. Yan, and E. Azar, 'A systematic review of occupant behavior in building energy policy', *Build Environ*, vol. 175, no. March, p. 106807, 2020, doi: 10.1016/j.buildenv.2020.106807.
- [54] S. Schiavon and S. Altomonte, 'Influence of factors unrelated to environmental quality on occupant satisfaction in LEED and non-LEED certified buildings', p. 17, 2014.
- [55] LEED, 'LEED - Rating System', Consultado: Abril 2021 em <https://www.usgbc.org/credits?Version=%22v4.1%22&Rating+System=%22New+Construction%22>.
- [56] BREEAM, 'Introduction to BREEAM', Consultado: Abril 2021 em https://www.breeam.com/BREEAMUK2014SchemeDocument/#01_introduction_newcon/2introductiontobreeam_nc.htm%3FTocPath%3DIntroduction%2520to%2520BREEAM%7C____0.
- [57] WELL, 'WELL v2', Consultado: Abril 2021 em <https://v2.wellcertified.com/wellv2/en/concepts>.
- [58] WELL, 'Explore features within each WELL concept', Consultado: Abril 2021 em <https://legacy.wellcertified.com/en/explore-standard>.
- [59] C. Duarte Roa, S. Schiavon, and T. Parkinson, 'Targeted occupant surveys: A novel method to effectively relate occupant feedback with environmental conditions', *Build Environ*, vol. 184, no. June, p. 107129, 2020, doi: 10.1016/j.buildenv.2020.107129.
- [60] A. Wagner and L. O'Brien, 'Occupant behaviour-centric building design and operation EBC Annex 79', *IEA EBC*, no. October, 2018.
- [61] E. Mlecnik, T. Schütze, S. J. T. Jansen, G. De Vries, H. J. Visscher, and A. Van Hal, 'End-user experiences in nearly zero-energy houses', *Energy Build*, vol. 49, pp. 471–478, 2012, doi: 10.1016/j.enbuild.2012.02.045.
- [62] M. Boubekri, *Daylighting, Architecture and Health Building Design Strategies*, vol. 1, no. September 2013. 2008.
- [63] José A. Vasconcelos de Paiva, 'Medidas de reabilitação energética em edifícios', in *Reabilitação energética de edifícios em zonas urbanas: O caso da habitação social*, LNEC, Ed., Lisboa, 2000, p. 28.
- [64] A. J. Santos, S. Almeida, M. Rebelo, and C. A. Pina dos Santos, 'Aspectos subjectivos do conforto visual : Percepções e Expectativas', 2010.

- [65] C. V. T. Barbosa, 'Percepção da Iluminação no Espaço da Arquitetura : Preferências Humanas em Ambientes de Trabalho', p. 238, 2010.
- [66] J. Morales-Bravo and P. Navarrete-Hernandez, 'Enlightening wellbeing in the home: The impact of natural light design on perceived happiness and sadness in residential spaces', *Build Environ*, vol. 223, no. June, p. 109317, 2022, doi: 10.1016/j.buildenv.2022.109317.
- [67] Jorge Patrício, *Acústica nos edifícios - 7ª Edição, Revista e Aumentada*, 7th ed. Engebook, 2018.
- [68] L. Cirrincione, A. Marvuglia, and G. Scaccianoce, 'Assessing the effectiveness of green roofs in enhancing the energy and indoor comfort resilience of urban buildings to climate change: Methodology proposal and application', *Build Environ*, vol. 205, no. July, p. 108198, 2021, doi: 10.1016/j.buildenv.2021.108198.
- [69] A. Barros and S. Schiffer, *Manual de conforto térmico*, 5th ed. Studio Nobel, 2006.
- [70] S. D. Mangan, G. K. Oral, I. Sozen, and I. E. Kocagil, 'Evaluation of settlement textures in terms of building energy , economic performance , and outdoor thermal comfort', *Sustain Cities Soc*, vol. 56, no. October 2019, p. 102110, 2020, doi: 10.1016/j.scs.2020.102110.
- [71] A. Gonzalez-Caceres, A. Bobadilla, and J. Karlshøj, 'Implementing post-occupancy evaluation in social housing complemented with BIM: A case study in Chile', *Build Environ*, vol. 158, no. May, pp. 260–280, 2019, doi: 10.1016/j.buildenv.2019.05.019.
- [72] W. Mucha, A. Mainka, and E. Brągoszewska, 'Impact of ventilation system retrofitting on indoor air quality in a single-family building', *Build Environ*, vol. 262, Aug. 2024, doi: 10.1016/j.buildenv.2024.111830.
- [73] World Green Building Council, 'About Green Building'. Accessed: Jul. 07, 2022. [Online]. Available: <https://www.worldgbc.org/what-green-building>
- [74] O. Dartevelle, G. van Moeseke, E. Mlecnik, and S. Altomonte, 'Long-term evaluation of residential summer thermal comfort: Measured vs. perceived thermal conditions in nZEB houses in Wallonia', *Build Environ*, vol. 190, no. December 2020, p. 107531, 2021, doi: 10.1016/j.buildenv.2020.107531.
- [75] D. O. Sant'Anna, P. H. Dos Santos, N. S. Vianna, and M. A. Romero, 'Indoor environmental quality perception and users' satisfaction of conventional and green buildings in Brazil', *Sustain Cities Soc*, vol. 43, no. May, pp. 95–110, 2018, doi: 10.1016/j.scs.2018.08.027.
- [76] H. Rasheed and T. K. Jayasree, 'The multifaceted role of indoor plants: A comprehensive review of their impact on air quality, health, and perception', *Energy Build*, vol. 330, Mar. 2025, doi: 10.1016/j.enbuild.2025.115312.
- [77] L. Pastore and M. Andersen, 'Building energy certification versus user satisfaction with the indoor environment: Findings from a multi-site post-occupancy evaluation (POE) in Switzerland', *Build Environ*, vol. 150, no. January, pp. 60–74, 2019, doi: 10.1016/j.buildenv.2019.01.001.
- [78] R. F. Rupp, J. Kim, R. de Dear, and E. Ghisi, 'Associations of occupant demographics, thermal history and obesity variables with their thermal comfort in air-conditioned and mixed-mode ventilation office buildings', *Build Environ*, vol. 135, no. January, pp. 1–9, 2018, doi: 10.1016/j.buildenv.2018.02.049.

- [79] J. Kim, S. Schiavon, and G. Brager, 'Personal comfort models – A new paradigm in thermal comfort for occupant-centric environmental control', *Build Environ*, vol. 132, no. November 2017, pp. 114–124, 2018, doi: 10.1016/j.buildenv.2018.01.023.
- [80] M. Rebelo, S. Almeida, L. Matos, and C. Santos, 'Conforto térmico em ambientes interiores', *Lnec*, 2009.
- [81] R. J. de Dear and G. S. Brager, 'Developing an adaptive model of thermal comfort and preference', *ASHRAE Trans*, vol. 104, pp. 1–18, 1998.
- [82] A. M. Raimundo and A. V. M. Oliveira, 'Analyzing thermal comfort and related costs in buildings under Portuguese temperate climate', *Build Environ*, vol. 219, no. February, 2022, doi: 10.1016/j.buildenv.2022.109238.
- [83] O. Fanger, *Thermal Comfort: Analysis and Applications in Environmental Engineering*. New York: McGraw Hill, 1970.
- [84] R. Macpherson, 'The assessment of the thermal environment. A review', *Br.J.Ind.Med.*, pp. 151–164, 1962.
- [85] ISO 7730, *Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*, vol. 3. 2005.
- [86] ASHRAE, 'ANSI/ASHRAE Standard 55-2017 Thermal Environmental Conditions for Human Occupancy', 2017.
- [87] EN 15251, 'Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics', 2007, *CEN, Bruxelles*.
- [88] J. F. Nicol and M. A. Humphreys, 'Adaptive thermal comfort and sustainable thermal standards for buildings', *Energy Build*, vol. 34, no. 6, pp. 563–572, 2002, doi: 10.1016/S0378-7788(02)00006-3.
- [89] H. B. Rijal, M. A. Humphreys, and J. F. Nicol, 'Adaptive model and the adaptive mechanisms for thermal comfort in Japanese dwellings', *Energy Build*, vol. 202, no. August, p. 109371, 2019, doi: 10.1016/j.enbuild.2019.109371.
- [90] L. Lan, Z. Lian, W. Liu, and Y. Liu, 'Investigation of gender difference in thermal comfort for Chinese people', *Eur J Appl Physiol*, vol. 102, no. 4, pp. 471–480, 2008.
- [91] M. T. Baquero and N. Forcada, 'Thermal comfort of older people during summer in the continental Mediterranean climate', *Journal of Building Engineering*, vol. 54, no. March, p. 104680, 2022, doi: 10.1016/j.job.2022.104680.
- [92] Z. Zhang, Y. Zhang, and A. Khan, 'Thermal comfort of people from two types of air-conditioned buildings - Evidences from chamber experiments', *Build Environ*, vol. 162, no. April, p. 106287, 2019, doi: 10.1016/j.buildenv.2019.106287.
- [93] M. Pazhoohesh and C. Zhang, 'A satisfaction-range approach for achieving thermal comfort level in a shared office', *Build Environ*, vol. 142, no. June, pp. 312–326, 2018, doi: 10.1016/j.buildenv.2018.06.008.
- [94] L. Matias, 'Desenvolvimento de um modelo adaptativo para definição das condições de conforto térmico em Portugal', Universidade Técnica de Lisboa - Instituto Superior Técnico, 2010.

- [95] J. C. P. Putra, 'A Study of Thermal Comfort and Occupant Satisfaction in Office Room', *Procedia Eng*, vol. 170, pp. 240–247, 2017, doi: 10.1016/j.proeng.2017.03.057.
- [96] L. Shtrepi *et al.*, 'Ten questions concerning Architectural Acoustics', *Build Environ*, vol. 265, Nov. 2024, doi: 10.1016/j.buildenv.2024.112012.
- [97] M. Anjos, 'Caracterização do Conforto Acústico em Edifícios de Habitação Caracterização do Conforto Acústico em Edifícios de Habitação', 2013.
- [98] J. A. E. Paris-Newton, E. Prokofieva, and N. Henry, 'Improvement of thermal insulation of residential buildings' facades via acoustic insulation', in *Energy Procedia*, Elsevier Ltd, Nov. 2015, pp. 3446–3451. doi: 10.1016/j.egypro.2015.11.134.
- [99] Jorge Patrício, *Método LNEC para avaliação e classificação da qualidade acústica de edifícios habitacionais*, 1st ed. 2013.
- [100] F. López Plazas and C. Sáenz de Tejada, 'Natural ventilation to improve indoor air quality (IAQ) in existing homes: The development of health-based and context-specific user guidelines', *Energy Build*, vol. 314, Jul. 2024, doi: 10.1016/j.enbuild.2024.114248.
- [101] United States Environmental Protection Agency, 'Indoor Air Quality'. Accessed: Jul. 10, 2024. [Online]. Available: <https://www.epa.gov/report-environment/indoor-air-quality>
- [102] M. de Jode, 'Long term monitoring of CO2 levels and ventilation rates in a naturally ventilated residential apartment', *Indoor Environments*, vol. 1, no. 3, p. 100030, Oct. 2024, doi: 10.1016/j.indenv.2024.100030.
- [103] E. O. Rasheed and H. Byrd, 'Can a naturally ventilated office outperform a mixed mode office? Pilot study on occupants' comfort', *Build Environ*, vol. 137, no. April, pp. 34–40, 2018, doi: 10.1016/j.buildenv.2018.04.004.
- [104] R. Elnaklah, I. Walker, and S. Natarajan, 'Moving to a green building: Indoor environment quality, thermal comfort and health', *Build Environ*, vol. 191, no. January, p. 107592, 2021, doi: 10.1016/j.buildenv.2021.107592.
- [105] J. Park, V. Loftness, A. Aziz, and T. H. Wang, 'Strategies to achieve optimum visual quality for maximum occupant satisfaction: Field study findings in office buildings', *Build Environ*, vol. 195, no. August 2020, p. 107458, 2021, doi: 10.1016/j.buildenv.2020.107458.
- [106] T. Hwang and T. K. Jeong, 'Effects of indoor lighting on occupants' visual comfort and eye health in a green building', in *Indoor and Built Environment*, Feb. 2011, pp. 75–90. doi: 10.1177/1420326X10392017.
- [107] K. M. Gerhardsson, T. Laike, and M. Johansson, 'Leaving lights on – A conscious choice or wasted light? Use of indoor lighting in Swedish homes', *Indoor and Built Environment*, vol. 30, no. 6, pp. 745–762, 2020, doi: 10.1177/1420326X20908644.
- [108] A. Boodi, K. Beddiar, M. Benamour, Y. Amirat, and M. Benbouzid, 'Intelligent systems for building energy and occupant comfort optimization: A state of the art review and recommendations', *Energies (Basel)*, vol. 11, no. 10, 2018, doi: 10.3390/en11102604.
- [109] E. Hoxha, C. Liardet, and T. Jusselme, 'Office densification effects on comfort, energy, and carbon lifecycle performance: An integrated and exploratory study', *Sustain Cities Soc*, vol. 55, no. January, 2020, doi: 10.1016/j.scs.2020.102032.

- [110] T. Hong, D. Yan, S. D'Oca, and C. fei Chen, 'Ten questions concerning occupant behavior in buildings: The big picture', *Build Environ*, vol. 114, pp. 518–530, 2017, doi: 10.1016/j.buildenv.2016.12.006.
- [111] H. Elsharkawy and S. Zahiri, 'The significance of occupancy profiles in determining post retrofit indoor thermal comfort, overheating risk and building energy performance', *Build Environ*, vol. 172, no. October 2019, p. 106676, 2020, doi: 10.1016/j.buildenv.2020.106676.
- [112] S. Moeller and A. Bauer, 'Energy (in)efficient comfort practices: How building retrofits influence energy behaviours in multi-apartment buildings', *Energy Policy*, vol. 168, no. June 2021, p. 113123, 2022, doi: 10.1016/j.enpol.2022.113123.
- [113] S. Salimi and A. Hammad, 'Optimizing energy consumption and occupants comfort in open-plan offices using local control based on occupancy dynamic data', *Build Environ*, vol. 176, no. February, p. 106818, 2020, doi: 10.1016/j.buildenv.2020.106818.
- [114] A. Steren, O. D. Rubin, and S. Rosenzweig, 'Energy-efficiency policies targeting consumers may not save energy in the long run: A rebound effect that cannot be ignored', *Energy Res Soc Sci*, vol. 90, no. 7, p. 102600, 2022, doi: 10.1016/j.erss.2022.102600.
- [115] M. Mashhadi Rajabi, 'Dilemmas of energy efficiency: A systematic review of the rebound effect and attempts to curb energy consumption', *Energy Res Soc Sci*, vol. 89, no. November 2021, p. 102661, 2022, doi: 10.1016/j.erss.2022.102661.
- [116] A. Berner, S. Bruns, A. Moneta, and D. I. Stern, 'Do energy efficiency improvements reduce energy use? Empirical evidence on the economy-wide rebound effect in Europe and the United States', *Energy Econ*, vol. 110, no. May 2021, p. 105939, 2022, doi: 10.1016/j.eneco.2022.105939.
- [117] D. L. 80/2006 Regulation of the Thermal Performance of Buildings RCCTE, 'Regulation of the Thermal Performance of Buildings RCCTE', p. Série I-A, 2468-2513, 1990.
- [118] D. L. 80/2006 Regulation of the Thermal Performance of Buildings RCCTE, 'Regulation of the Thermal Performance of Buildings RCCTE', p. Série I-A, 2468-2513, 2006.
- [119] Decreto-Lei n.º 79 (RSECE), 'Regulamento dos Sistemas Energéticos de Climatização em Edifícios (RSECE)', *LISBOA. Diário da República - I SÉRIE-A*, no. 4 de Abril, pp. 53 (2416-2468), 2006.
- [120] DL 101-D, 'Decreto-Lei n.º 101-D/2020 de 7 de dezembro', *Diário da República - I Série*, no. 2, pp. 3179–3182, 2020.
- [121] Direção-Geral de Energia e Geologia, *Despacho n.º 6476-H/2021 - Aprova o Manual do Sistema de Certificação Energética dos Edifícios (SCE)*. 2021, pp. 330–66.
- [122] Direção-Geral de Energia e Geologia and ADENE, 'Manual SCE - Manual Técnico para a Avaliação do Desempenho Energético dos Edifícios'.
- [123] Energy in Buildings and Communities Programme, 'About EBC'. Accessed: Oct. 30, 2021. [Online]. Available: <https://www.iea-ebc.org/ebc/about>
- [124] A. Wagner and L. O'Brien, 'IEA EBC Annex 79 - Occupant-Centric Building Design and Operation', no. March 2019, 2021.
- [125] ISO 17772-1:2017, *Energy performance of buildings - Indoor environmental quality - Part 1: Indoor environmental input parameters for the design and assessment of energy performance of buildings*. 2017, p. 60.

- [126] Technical Committee CEN/TC 169 ‘Light and Lighting’, ‘Light and lighting - Lighting of work places - Part 1: Indoor work’, *European Standard 12464*, vol. 3, pp. 1–43, 2002, doi: <http://www.din.de>.
- [127] EN 12193:2007, *Light and lighting - Sports lighting*. 2007, p. 40.
- [128] ISO 10140-1:2021, *Acoustics — Laboratory measurement of sound insulation of building elements*. 2021, p. 54.
- [129] ISO 717-1:2020, *Acoustics — Rating of sound insulation in buildings and of building elements*. 2020, p. 26.
- [130] ISO 12354-1:2017, *Building acoustics — Estimation of acoustic performance of buildings from the performance of elements*. 2017, p. 94.
- [131] EN 16798-3:2025, *Energy performance of buildings - Ventilation for buildings - Part 3: For non-residential buildings - Performance requirements for ventilation and room-conditioning systems (Modules M5-1, M5-4)*. 2025.
- [132] ANSI/ASHRAE Standard 62.1-2022, *Ventilation and Acceptable Indoor Air Quality*. 2022, p. 86.
- [133] ANSI/ASHRAE Standard 62.2-2022, *Ventilation and Acceptable Indoor Air Quality in Residential Buildings*. 2022, p. 54.
- [134] CEN - CR 1752, *Ventilation for buildings - Design criteria for the indoor environment*. 1998, p. 76.
- [135] Diário da República, *Decreto-Lei n.º 243/86 - Aprova o Regulamento Geral de Higiene e Segurança do Trabalho nos Estabelecimentos Comerciais, de Escritório e Serviços*. 1986.
- [136] Diário da República, *Portaria n.º 138-G/2021 - Estabelece os requisitos para a avaliação da qualidade do ar interior nos edifícios de comércio e serviços, incluindo os limiares de proteção, condições de referência e critérios de conformidade, e a respetiva metodologia para a medição dos poluentes e para a fiscalização do cumprimento das normas aprovadas*. 2021, p. 5.
- [137] Diário da República, *Portaria n.º 138-I/2021- Regulamenta os requisitos mínimos de desempenho energético relativos à envolvente dos edifícios e aos sistemas técnicos e a respetiva aplicação em função do tipo de utilização e específicas características técnicas*. 2021, pp. 12–53.
- [138] P. Li, T. M. Froese, and G. Brager, ‘Post-occupancy evaluation: State-of-the-art analysis and state-of-the-practice review’, *Build Environ*, vol. 133, no. February, pp. 187–202, 2018, doi: 10.1016/j.buildenv.2018.02.024.
- [139] Z. Ozturk, Y. Arayici, and P. Coates, ‘Post Occupancy Evaluation (POE) in Residential Buildings Utilizing BIM and Sensing Devices: Salford Energy House Example’.
- [140] R. V. Jones, S. Goodhew, and P. De Wilde, ‘Measured indoor temperatures, thermal comfort and overheating risk: Post-occupancy evaluation of low energy houses in the UK’, *Energy Procedia*, vol. 88, pp. 714–720, 2016, doi: 10.1016/j.egypro.2016.06.049.
- [141] P. Watson and S. Watson, ‘Warm house, Cold house: A review of measures of thermal comfort used in Get Bill Smart’s energy efficiency assessments’, *Energy Procedia*, vol. 121, pp. 190–197, 2017, doi: 10.1016/j.egypro.2017.08.017.

- [142] L. Zagreus, C. Huizenga, and E. Arens, 'A web-based POE tool for measuring indoor environmental quality', *UC Berkeley Indoor Environmental Quality*, p. 18, 2004.
- [143] SurveyMonkey, 'Survey vs questionnaire: Key differences and use cases'. Accessed: Dec. 08, 2022. [Online]. Available: <https://www.surveymonkey.com/learn/survey-best-practices/survey-vs-questionnaire/>
- [144] R. Bunn and L. Marjanovic-Halburd, 'Comfort signatures: How long-term studies of occupant satisfaction in office buildings reveal on-going performance', *Building Services Engineering Research and Technology*, vol. 38, no. 6, pp. 663–690, 2017, doi: 10.1177/0143624417707668.
- [145] H. Stopps and M. F. Touchie, 'Managing thermal comfort in contemporary high-rise residential buildings: Using smart thermostats and surveys to identify energy efficiency and comfort opportunities', *Build Environ*, vol. 173, no. November 2019, p. 106748, 2020, doi: 10.1016/j.buildenv.2020.106748.
- [146] International Well Building Institute, 'Post-Occupancy Surveys'. Accessed: Oct. 12, 2022. [Online]. Available: <https://standard.wellcertified.com/mind/post-occupancy-surveys>
- [147] L. Zagreus, C. Huizenga, E. Arens, and D. Lehrer, 'Listening to the occupants: A Web-based indoor environmental quality survey', *Center for the Built Environment*, vol. 14, no. 8, pp. 65–74, 2004, doi: 10.1111/j.1600-0668.2004.00301.x.
- [148] L. t. Graham, T. parkinson, and S. schiavon, 'Lessons learned from 20 years of CBE's occupant surveys', *Buildings and Cities*, vol. 2, no. 1, pp. 166–184, 2021, doi: 10.5334/bc.76.
- [149] 'SurveyMonkey: The World's Most Popular Survey Platform'. Accessed: Feb. 04, 2023. [Online]. Available: <http://pt.surveymonkey.com>
- [150] 'Qualtrics XM: The Leading Experience Management Software'. Accessed: Feb. 04, 2023. [Online]. Available: <https://www.qualtrics.com/pt-br/>
- [151] International Organization for Standardization, 'ISO 10551:2019 Ergonomics of the physical environment — Subjective judgement scales for assessing physical environments', 2019.
- [152] MSc. Leslie Riopel, 'What is the Positive and Negative Affect Schedule? (PANAS)', Assessed: February 2023 in <https://positivepsychology.com/positive-and-negative-affect-schedule-panas/#questionnaire>.
- [153] K. M. Gerhardsson and T. Laike, 'User acceptance of a personalised home lighting system based on wearable technology', *Appl Ergon*, vol. 96, no. October 2019, 2021, doi: 10.1016/j.apergo.2021.103480.
- [154] R. V. Jones, S. Goodhew, and P. De Wilde, 'Measured indoor temperatures, thermal comfort and overheating risk: Post-occupancy evaluation of low energy houses in the UK', *Energy Procedia*, vol. 88, pp. 714–720, 2016, doi: 10.1016/j.egypro.2016.06.049.
- [155] A. Muroi, I. Gaetani, P. J. Hoes, and J. L. M. Hensen, 'Occupant behavior in identical residential buildings: A case study for occupancy profiles extraction and application to building performance simulation', *Build Simul*, vol. 12, no. 6, pp. 1047–1061, 2019, doi: 10.1007/s12273-019-0573-x.
- [156] 'Edifícios «inteligentes» — indicador de aptidão para tecnologias inteligentes (modalidades de implantação do regime)'. Accessed: Feb. 01, 2021. [Online]. Available: <https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12365-Implementation-modalities-of-the-smart-readiness-indicator-for-buildings>

- [157] Y. Li, S. Kubicki, A. Guerriero, and Y. Rezgui, ‘Review of building energy performance certification schemes towards future improvement’, *Renewable and Sustainable Energy Reviews*, vol. 113, no. June, 2019, doi: 10.1016/j.rser.2019.109244.
- [158] T. Märzinger and D. Österreicher, ‘Supporting the smart readiness indicator-A methodology to integrate a quantitative assessment of the load shifting potential of smart buildings’, *Energies (Basel)*, vol. 12, no. 10, 2019, doi: 10.3390/en12101955.
- [159] European Commission, ‘Discussion document – definition and calculation methodology of the smart readiness indicator’, no. October, pp. 1–15, 2019.
- [160] M. R. Neto, ‘Eficiência energética e caracterização do comportamento adaptativo dos ocupantes’, *Mestrado Integrado em Engenharia da Energia e do Ambiente*, 2018.
- [161] E-REDES, ‘Balcão Digital’. Accessed: Aug. 15, 2024. [Online]. Available: <https://balcaodigital.e-redes.pt/home>
- [162] Jornal Oficial da União Europeia, *Regulamento (UE) N.º 1253/2014 da Comissão de 7 de julho de 2014 que aplica a Diretiva 2009/125/CE do Parlamento Europeu e do Conselho no que diz respeito aos requisitos de conceção ecológica das unidades de ventilação*. 2014.
- [163] American Society of Heating Refrigerating and Air-Conditioning Engineers, ‘ASHRAE Guideline 14-2002: Measurement of Energy and Demand Savings’, 2002.
- [164] Efficiency Valuation Organisation (EVO), ‘International Performance Measurement & Verification Protocol’, 2002.
- [165] U.S. Department of Energy, ‘M&V Guidelines : Measurement and Verification for Performance-Based Contracts (Version 4.0)’, 2015.
- [166] W. H. Ko, S. Schiavon, G. Brager, and B. Levitt, ‘Ventilation, thermal and luminous autonomy metrics for an integrated design process’, *Build Environ*, vol. 145, pp. 153–165, 2018, doi: 10.1016/j.buildenv.2018.08.038.
- [167] L. Matias and C. Santos, ‘Conforto térmico adaptativo no setor residencial em portugal’, *Congresso Internacional da Habitação no Espaço Lusófono*, no. November, pp. 1–12, 2013, doi: 10.13140/2.1.4471.4881.

APPENDIX

APPENDIX A – Summary of the literature review

Table A.1 - Variables and parameters of comfort and well-being of the consulted literature studies

Ref	Document, publication year, origin journal and country	Study application country, type and building characteristics	Study objective	Parameters to measure/study	Measurement method and data collection	Main conclusions
[12]	- Scientific paper 2016 - Building and Environment - Qatar, UK	- NA - Office	Review the existing literature to understand the relationship between indoor environmental quality and occupant productivity in an office.	- Indoor air quality and ventilation: Ventilation rate, indoor pollutant level, outdoor air monitoring (pollutant level) - Thermal comfort: Radiant temperature, Relative humidity, air (temperature and movement), Clothing insulation - Lighting and daylighting: Luminance level (ambient and desk), daylight and artificial light ratio, glare index - Noise and Acoustics: Indoor and outdoor sound level - Layout: Office layout and work process analysis, open plan, cellular plan or hybrid plan layout - Biophilia and views: Views of nature, biophilia features (plants, water features, others) - Look and feel: Colour schemes, spatial features, and textures. - Location and amenities: convenient office location with transport accessibility and proximity to various amenities such as healthcare, childcare, sports and entertainment facilities	<u>Literature review suggests:</u> - Indoor air quality and ventilation: Building Management System, Sensor, Occupant survey - Thermal comfort: Sensor, Calculation, Occupant survey - Lighting and daylighting: Sensor, Calculation, Occupant survey - Noise and Acoustics: Decibel Sensor, Occupant survey - Layout: Occupant survey - Biophilia and views: Occupant survey - Look and feel: Occupant survey - Location and amenities: Occupant survey	- Healthy indoor environment: financial and health benefits - Significant impact of physical and behavioural environment on occupant comfort and productivity - Thermal comfort, Indoor air quality and ventilation, office layout, noise and acoustics highly affect occupant productivity. - Interaction and correlation between daylighting and thermal comfort, 'look and feel' and views, thermal comfort and IAQ, office layout and acoustic properties.
[77]	- Scientific paper 2019 - Building and Environment - Switzerland	- Switzerland 4 offices energy-certified (Minergie label) - Comparable in dimension, construction age, occupation, function and furniture - HVAC systems - Buildings with different window types and different permissions to operate them - Different shadings and controls (automatic/manually)	Report the results of a post-occupancy evaluation conducted on Swiss-certified green buildings to analyse their ability to provide comfort to occupants	- Air quality: CO₂ level - Thermal comfort: temperature and relative humidity - Lighting: spatial and temporal variability of the visual environment - Acoustic: noise - Layout: view to the outside, privacy, personal control of the environment and self-rated productivity	- Two-week continuous indoor environmental quality monitoring campaign (winter and summer); - Point-in-time indoor environmental quality measurements and point-in-time surveys for comfort opinions (simultaneously); - Online extensive surveys (one in winter and one in summer) - Air quality: CO₂ sensor - Thermal comfort: temperature and relative humidity data loggers, survey - Lighting: HDR camera, spot luminance meter and illuminance sensors, survey	- Study factors were mostly complying with the norm prescriptions but were never attaining the commonly used 80% satisfaction threshold by the users (temperature and air quality were the most critical) - Design factors related to the personal control of the indoor environment were a way to achieve comfort (façade operation, individual thermal preferences using thermostats, possible mismatches between passive and mechanical systems) - Occupants' feedback could help design and operational process and move to more effective green building certification systems and regulations

[92]	- Scientific paper 2019 - Building and Environment - China	- South China - Central air-conditioning system (CAC) buildings: office buildings; subjects are office staff; controlled by building managers, operate continuously, and adaptative opportunities are very limited - Split air-conditioner (SAC) buildings: teaching and dormitory in a college; subjects are college students; many control opportunities - Identical experiment conditions	Conduct a comparative study on occupant thermal comfort from the CAC and SAC buildings in South China in a climate chamber to investigate their differences in physiological and psychological responses under identical environments and to specify the neutral and acceptable temperatures for the air-conditioned buildings.	Thermal comfort: indoor temperature, skin temperature, skin wittedness and heart rate	Thermal comfort: iButton thermometer, Calculation, Omron HEM – 7011 and occupant survey (winter and summer)	90% thermally acceptable SET ranges were 24.8-27.4°C for CAC buildings and 24.4-30.1°C for SAC buildings. - Subjects from CAC and SAC buildings reported the same thermal sensations. - Thermal history perceived control and thermal expectation are indicated for understanding human thermal comfort (quantitatively study them)
[16]	- Scientific paper 2018 - Building and Environment - UK, China	- NA - Shared Office in a university - One external wall with double glazing windows facing south (main influencing part to heat gains)	Approach to provide a reasonable temperature range to mitigate occupants' dissatisfaction considering their individual thermal preferences.	Thermal comfort: indoor temperature	- Thermal comfort: occupant survey (winter and summer), computational fluid dynamic CFD, sensor to measure air temperature 14-day period in winter, room temperature is manually changed. Afterwards, the survey is conducted, and the fuzzy-based pattern is compared with this survey.	- Seasonal modelling analyses room comfort/discomfort areas in different scenarios. The result identifies the thermal zones and, based on that, what occupants are considered in each zone. - Simulation cannot provide accurate data for real-time thermal comfort levels in the room. Fuzzy-based thermal preference profile finds the best temperature range and adjusts the HVAC set-points.

[59]	• Scientific paper • 2020 • Building and Environment • Berkeley, USA	• Berkeley • 4-story mixed-use building • HVAC System includes a thermally activated building (TABS) radiant system for the primary heating and cooling in the office spaces • TABS radiant uses the extreme thermal conditions from the previous day to adjust the slab setpoint for the next day.	• Development of an online survey platform that uses real-time feedback to send targeted occupant surveys (TOS) at specific indoor environmental conditions and stops sending survey requests when collected responses reach the maximum surveys required.	• Thermal comfort: indoor dry-bulb temperature, relative humidity, operative temperature, and surface (infrared) temperature • Well-being: the ability to concentrate, level of sleepiness, and perceived productivity	• Thermal comfort: TOS, Right-now survey and Sensor • Well-being: TOS and Right-now survey • TOS platform defines when and to whom to send the survey (platform written in Python) • Right-now surveys characterize whole-body thermal comfort and self-reported well-being at specific indoor environmental conditions. • Surveys on weekdays in labour time (max 3 surveys/day at least 2h apart) during almost 2 months. • 3 surveys: - Built environment general description, occupant characteristics, long-term satisfaction and comfort. - Personal characteristics, use of personal comfort devices, temperature sensitivity, method of commute, work desk location, and email - Right-now survey (11 questions – 1 min) in conjunction with the TOS program.	• TOS minimize redundancy in the collected data and minimize disruptions to participants • The advantages of the TOS platform allow building stakeholders to quickly and effectively collect data to answer research questions and evaluate indoor environmental quality.
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[23]	- Scientific paper 2020 - Building and Environment - Berkeley, USA	- Berkeley - Office-like test room - Two different conditions: with and without a window - Sample: graduate and undergraduate students from the University of California	Explore the influence of having a window with a view to the outdoors on thermal and emotional responses and cognitive performance	- Thermal comfort: air temperature, airspeed, relative humidity, radiant temperature, light level, and CO2 level - Emotions - Cognitive performance	- Outdoor conditions: solar radiation and air temperature obtained from the weather station - Thermal comfort: skin temperature sensor (iButton), other sensors, Surveys - Emotions: Circumplex model, survey - Cognitive performance: Four Modules of Cambridge Brain Sciences - Two sessions of experiment: one with a window and the other without	- Visual connection to the outdoors: statistically significant, but practically small, improvements in thermal perceptions, emotion, and cognitive performance; supports working memory and concentration. - Windows, with a view, did not affect short-term memory, planning, or divergent thinking. - People close to a window may be more forgiving of small thermal comfort deviations, which can result in energy savings through setpoint adjustments; - Window in a workplace: essential for occupants' comfort, well-being, and productivity; enhances psychological well-being (enhance positive and reduce negative emotion); - A positive effect on thermal perceptions may be at play when windows are present and could provide an effective design solution that enhances the comfort of the occupants while saving energy in the built environment, especially for cooling-dominated climates.
[140]	- Scientific paper 2016 - Energy Procedia - UK	- Two low-energy homes (CfSH level 5 - a home that is twice as thermally efficient as currently required by building legislation) - One identical mid-terrace house built to current building regulations	Discusses thermal comfort and overheating risk in identical low-energy homes in the UK Southwest (houses built to low energy standards)	Thermal comfort: air temperature	- Thermal comfort: Post-Occupancy Evaluation (POE), HWM Ecosense temperature loggers (indoor: living rooms and main bedrooms; and outdoor air temperatures) during almost 2 summer months. Logging every 5 minutes - Loggers were located away from heat sources and direct sunlight	- Houses constructed to align with higher thermal performance standards are already at risk of overheating during the summer. - Static overheating criteria analysis (CIBSE Guide A) suggested that living rooms were generally warmer than the occupants would consider acceptable. - Occupants' behaviour may be important in reducing/increasing home temperatures.

[166]	- Scientific paper 2018 - Building and Environment - Berkeley, USA	Medium Office model of the Commercial Reference Buildings	Development of ventilation autonomy and a new method of visualizing the hourly comfort data. An integrated workflow that simultaneously uses ventilation, thermal, and luminous autonomy for the assessment of passive design strategies	- Thermal comfort: thermal autonomy - Lighting: luminous autonomy - Ventilation: ventilation autonomy	- Thermal comfort: Software - Grasshopper's Honeybee to simulate spatial thermal autonomy, EnergyPlus (v8.4) as the simulation engine - Lighting: Software - DIVA 4.0 and DAYSIM's annual climate-based calculations, Radiance as the simulation engine - Ventilation: Software - EnergyPlus and Grasshopper's Honeybee as the interface. EnergyPlus' passive scalar transport method calculates CO₂ concentrations as an alternative air quality indicator.	- Considering the three metrics together, designers may have to contradict design directions if trying to both mitigate solar radiation and utilize natural ventilation. - In two climates, conventional building analysis workflow might inhibit the use of passive solar heating in higher latitude locations because luminous or thermal autonomy metrics are considered separately. - Potential of having small partial openings outside of standard window-operation hours to achieve ventilation autonomy while having a minimal impact on thermal autonomy.
[95]	- Scientific paper 2017 - Procedia Engineering - Indonesia	- Malaysia University Office - Mechanically ventilated	Investigation regarding the effect of indoor thermal to mechanically ventilated building's occupant satisfaction	Thermal comfort: air velocity, air temperature	Thermal comfort: simulation - COMSOL Multiphysics to visualize indoor environmental quality, survey, anemometer, Yes Plus LGA Meter (8h of measurements during weekday)	- The geometry model affects air circulation and maintains indoor temperature distribution. - The condition of the temperature inside the office room and the unauthorized adjustment of temperature and air velocity of the air-conditioning system contribute to the dissatisfaction of occupants. - The relationship between indoor environmental quality and occupant satisfaction must be assessed comprehensively. - When assessing occupant satisfaction, it is impossible to advance the relationship between ventilation systems, occupant behaviour, and building energy in tropical climates.

[78]	• Scientific paper • 2018 • Building and Environment • Brazil, Australia	• One centrally air-conditioned (HVAC) and three mixed-mode (MM) office buildings • Public Buildings • Florianópolis, Brazil (humid subtropical climate) • MM building occupants operate HVAC and windows to suit their preferences	• Investigate the relationship between various factors and the perception of thermal comfort in workplaces by examining the gap between the current thermal comfort criteria and the actual requirements observed for different occupants' groups	• Thermal comfort: indoor globe temperature, air temperature, relative humidity and air velocity • Personal aspects: weight, height, gender, age, clothing, activity and reliance on air-conditioning system outside of the workspace	• Thermal comfort: Survey in different seasons, microclimate data loggers (recorded according to ASHRAE 55) • “Right-here-right-now” type of survey: simultaneous measurements of physical environmental parameters and questionnaire • Two years of monitoring • Outdoor conditions: obtained from the meteorological station near the building	• Males, overweight occupants, and those more frequently exposed to air-conditioning are more likely to express thermal discomfort due to feeling ‘warm’ than females, non-overweight occupants, and those exposed to air-conditioning less regularly. • Females, non-overweight occupants, air-conditioning light users, and centralised HVAC building occupants were likelier to declare ‘cold’ discomfort. • Different occupant groups require different comfort zones. Group differences should be taken into count when designing/operating spaces.
[103]	• Scientific paper • 2018 • Building and Environment • New Zealand, UK	• New Zealand (warm summers and not-so-cold winters) • Buildings with the same location to compare them • Office buildings • Building A - Naturally ventilated building, no HVAC and openable windows • Building B - Mixed-mode ventilated building, HVAC and low E laminated double glazing	• Investigate if a naturally ventilated building can outperform a mixed-mode building in providing comfort for occupants	• Thermal comfort: temperature satisfaction, personal control • Air Quality: air quality satisfaction, personal control • Noise: noise, personal control • Lighting: natural and artificial lighting, light satisfaction, personal control • Health: perception of people's health in building	• Questionnaires administered by hand • BUS questionnaire • Buildings were surveyed during the winter (1 month apart), but the results were processed at different times (5 months apart)	• Both buildings were satisfactory and comfortable to the occupants and performed above the NZ BUS benchmark. • Occupants of building A were slightly more satisfied and comfortable than in building B. • If well-designed, naturally ventilated office spaces can provide more comfort than mixed-mode office spaces.

[50]	• PhD Thesis • 2011 • Technical University of Denmark • Denmark	• Danish Residential buildings • Office buildings	• Examine occupants' perception of comfort and self-estimated job performance in homes and offices. Particularly how building occupants understand comfort and which parameters influence the perception of comfort (not necessarily the ones related to the indoor environment)	• Thermal comfort: satisfaction, temperature, others • Acoustic: satisfaction, noise level, sound privacy, others • Visual environment: satisfaction, privacy, amount of light, others • Air quality: satisfaction, • Preferences about controlling the indoor environment (artificial light, window, solar shading, temperature) • Cleanliness and maintenance of the building • Office layout and furniture	• Questionnaire • CBE occupant satisfaction survey for office buildings	• In residential buildings, the overall indoor environment acceptability is approximately averaging the acceptability of individual parameters. This contradicts literature that indicates that thermal comfort, in most cases, has slightly higher importance for reaching overall comfort than acoustic and visual comfort and satisfaction with air quality. • Residential buildings that allow people to control the indoor environment benefit the comfort perception. A peaceful atmosphere, nature contact and the view contribute to occupants' comfort (not only indoor environmental parameters). • In office buildings, personal workspace satisfaction was influenced by the satisfaction with indoor environmental parameters, workspace and building features. For overall satisfaction, the most important parameters with personal workspace were satisfaction with space for work and storage, noise level and visual privacy.
[104]	• Scientific paper • 2021 • Building and Environment • UK, Jordan	• Employees of a single organization transit from four conventional office buildings to the first Green Building designed by the local Jordanian Green Building Guide • Conventional Building (CB): Mixed-mode ventilation system, fluorescent lamps, wall split air conditioner, operable windows, control temperature and lighting • Green Building (GB): Energy recovery ventilators, LED, VRF, air-conditioned through air handling units with a fixed set point, occupancy sensor systems for lighting	• Examine if Green Building Codes improve building performance, occupant satisfaction and health compared to conventional buildings	• IAQ • Temperature • Lighting • Acoustics • Secondary metrics: privacy, biophilia, odour, and view.	• 5 minutes survey (six months pre-moving in CB and six and twelve months after the transition to GB) • Indoor air temperature and relative humidity sensors for thermal conditions and indoor concentration level for IAQ (CO₂) • Sensors are distributed according to the majority of the typical floor area. • Monitoring during summer 2017 (Jul–Nov) in CB, summer 2018 (Jul–Nov) and winter 2019 (Dec–Feb) in GB • Questionnaire from World Green Building Council for Health, Well-Being, and Productivity in offices • Occupant environment attitude (tendency to be green) is assessed using the Environmental Attitude Inventory (EAI)	• Thermal conditions present statistically significant differences, positively biased towards the GB across the move, enhancing occupant thermal comfort. • After moving to the GB, a significant improvement in occupant perception of air quality and visual and acoustic comfort wasn't detected. At the same time, odour, mental concentration, and glare were perceived to be poor in the GB and associated with increased Sick Building Syndrome symptoms. • Green buildings may create unintended consequences regarding occupant comfort and health to pursue a better thermal environment and energy efficiency.

[75]	- Scientific paper 2018 - Sustainable Cities and Society - Brazil	- Three conventional buildings and three certified - Buildings activity - bank branches - São Paulo Metropolitan - Building's certification - LEED NC	Compare users' perceptions about indoor environmental quality and corporate satisfaction in green and conventional buildings	- Ecofriendly attitude/company alignment - Thermal Comfort - Light - Acoustics - Ergonomics - Clean - Air quality - Building features (indoor, outdoor, economy, neighbourhood) - Corporate satisfaction (work satisfaction level, interactive behaviour, communication, welfare and morale at work, community sense)	Different questionnaires to employees and customers	- Employees perceive green building spaces as better than conventional ones. Still, customers of both buildings cannot tell the differences between them. - An eco-friendly attitude was more often observed among green building employees than conventional employees. - Green building employees considered IEQ better and are more satisfied overall with the company, building features and even more propense to sustainable attitudes. Customers do not perceive the difference between buildings in any aspect.
[105]	- Scientific paper 2020 - Building and Environment - Republic of Korea, USA, UK	64 office buildings (33 federal and 31 private sector offices in finance, sales, and marketing). - Small- and medium-sized offices with less than 500 m2.	Investigate critical correlations between user satisfaction, workstation lighting conditions, and work area physical attributes	Light: Illuminance, luminance, spectrum, discomfort glare, flicker, personal control	- Light: - Konica Minolta T-10A light meter to measure illuminance levels on the work surface, computer monitors and keyboards with the task light on and off. - Luminance and glare levels were collected with a Nikon Coolpix 5400 camera with a fisheye lens. - Luminance analysis with Konica Minolta Luminance Meter LS-100 for spot measurements and a Photolux 2.1 for luminance and visual comfort analysis. - Cost-effective Open-Plan Environment (COPE) questionnaire, developed by the National Research Council Canada, added some extra questions.	- Satisfaction levels increase when occupants view the outside in their seated workstations. - Visual satisfaction increases by improving the ceiling light fixture with an indirect lens type. - Workstations that had an indirect lens type had higher satisfaction. In contrast, a prismatic ceiling lens type showed the lowest user satisfaction. - The combination of indirect light fixtures with task lights increases user satisfaction. - Using window shading devices revealed greater satisfaction with glare management. - Occupants with internal and external shading devices in their work areas showed the highest satisfaction with their overall lighting. - The work surface's illuminance level of 406 lux achieves maximum satisfaction in contemporary office environments.

[167]	• Conference Paper • 2013 • Congresso Internacional da Habitação no Espaço Lusófono • Portugal	• 100 residential buildings in various regions of the country with construction dates from 1957 to 2009	• Deepen the knowledge and characterisation of thermal comfort requirements in residential environments to validate an adaptive model for assessing thermal comfort conditions in buildings in Portugal	• Thermal comfort: air velocity, temperature and relative humidity	• Experimental measurement campaigns (summer and winter) • Air temperature, average radiant temperature, relative humidity, air speed: measured minute by minute over one hour • PMV and PPD determination (based on measurements of environmental parameters and estimation of individual parameters) • Questionnaire after the measurement period	• Average indoor temperatures between 12 °C and 21 °C in winter and between 23 °C and 34 °C in summer • Satisfied users when temperature measurements ranged from 14 °C to 26 °C. Satisfaction with such low values may be due to cultural adaptation to existing conditions, inhibition to express discomfort in their own homes and/or economic reasons.
[145]	• Scientific paper • 2020 • Building and Environment • Canada	• Two contemporary high-rise condominium buildings (59 suites) • Toronto, Canada. • Buildings constructed after 2012 • Highly-glazed envelopes • Occupants have control of their in-suite temperature set point	• Characterize the relationship between occupant comfort, behaviours, and HVAC operation in contemporary residential buildings to reveal improved comfort and energy efficiency opportunities	• Thermal comfort: relative humidity and air temperature	• Surveys before, during and after the monitoring period: - Initial survey to collect perceptions and understand the occupant behaviour - Two interim surveys during the heating and cooling seasons. Occupants report the perceived thermal comfort over the previous 24 hours. - Final survey to understand occupant interventions to mitigate thermal discomfort • Ecobee3 connected thermostats in the suite (collect relative humidity and air temperature data in 5-min intervals) • Roof-top weather station (wind speed and solar radiation) • Thermostats are most often installed in the living area, set back from the façade and around 1.4 m above the floor • Thermostat data collected for 14 months	• Prevalent occupant discomfort in both buildings • Prevalent suite over-conditioning, 35% and 23% of the time above and below the temperature setpoint during the heating and cooling season, respectively • Over-conditioning didn't operate as expected (based on previous research). • Reduce building energy use and improve occupant comfort: - Reduce setpoint temperature - Solar control on the east and west-facing glazed surfaces - Improve air leakage control on the windward side of the buildings • Improved in-suite HVAC control has a low impact on reducing building energy use, given the prevalence of over-conditioning and low-suite HVAC runtime during the heating season.

[71]	• Scientific paper • 2019 • Building and Environment • Denmark, Chile, Norway	• Social housing complex (400 apartments) • Construction year: 2013 • Chile (climate: high humidity and moderately low temperatures) • Individual apartments of 57m² each: open area including a dining room, kitchen, and living room, and an independent laundry space (semi-open), three bedrooms, and a bathroom as independent zones.	• Promoting the use of POE as a technique for improving decision-making in social housing with moisture and mould problems	• Moisture and mould	• POE procedure and data exchange detailed using BIM standards • BIM is an effective complement to POE by exporting data into formats that other software required • Collect information about the building: architectural and technical drawings, envelope thermal properties, local climate, damage and construction modification • Evaluation of orientation impact, shadow projection analysis, sun path and daylight hours, and the wind direction and velocity associated with rain penetration. • Surveys and questionnaires used to gain insight into how the users behaved and used the installations. • Indoor monitoring: air temperature, humidity, and CO₂ levels. • In-situ measurements: blower door tests, exterior walls thermal transmittance, and driving rain penetration of the façade. • Laboratory tests: airtightness of windows, thermal conductivity, and vapour permeability of materials.	• Factors involved in the moisture damage: overcrowded spaces, inadequate thermal regulation for the local climate, poor apartment and complex design, and flaws and inconsistencies in the quality of construction. • Measurements and post-analysis of the data collected indicated that the interior apartment problems were mainly because of the complex's low-quality construction and design. In some cases, occupants' behaviour contributed to the high humidity levels in the apartments.
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[91]	• Scientific paper • 2022 • Journal of Building Engineering • Spain	• 5 nursing homes in Madrid (Spain)	• Evaluate the thermal comfort of the elderly by identifying their neutral temperature and thermal comfort zone in the continental Mediterranean climate in the cooling season. Another objective is to compare the thermal comfort of elderly people (residents of nursing homes) with adults (non-residents) and elderly people from other climates	• Thermal comfort: globe temperature, air temperature, relative humidity, air velocity	• Measurements: - Three days during June, July and August. - Recorded every 15 s between 15 and 60 min (depending on activity and number of people). - Between 10 a.m. and 6 p.m. - According to ASHRAE 55, ISO 7730 and ISO 7726. - Globe temperature, air velocity, air temperature, relative humidity. - Equipment located at a central point in each room, 1.5m above the floor. • Environmental measurements and surveys were performed simultaneously in the living, therapy, dining and gym-physiotherapy rooms. • Customized right-here-right-now survey: collect subjective comfort evaluations from building occupants during 3 months in common zones. • Thermal perception was assessed through a questionnaire survey of older people (residents) and the staff (nurses, assistants, and others).	• Adults (staff): environment was warmer than older people, and they were less tolerant. • Older people are less sensitive to thermal changes and have a wider comfort zone than adults. • Comparison with similar studies from other climatic zones: the neutral temperature for the elderly is similar, but thermal comfort zones are different. • Older people: less sensitive to temperature changes than the predicted mean vote (PMV) model predicted. • This model would not be suitable for older people in Mediterranean continental climate cooling conditions.
[74]	• Scientific paper • 2021 • Building and Environment • Belgium, Netherlands	• Twenty-three nZEB houses (the majority were single-family houses with children). • Wallonia – Belgium • Houses occupied for a minimum of 3 years before this study • nZEB houses requirements rely on the definition in the European Directive 2010/31/EU on the energy performance of buildings • Houses: equipped with heating system and mechanically ventilated	• Overview of measured and perceived summer thermal conditions providing evidence of the extent of overheating situations that can be encountered in nZEB houses in a temperate climate	• Thermal comfort: indoor air temperature, outdoor temperature (to calculate a local running mean temperature)	• Face-to-face semi-structured interviews: conducted on the basis of a questionnaire • Questionnaire: perception of indoor environmental quality, conceived to capture occupant satisfaction and the main parameters that could influence evaluations (socioeconomic profiles, habits, others). • ASHRAE thermal sensation scale and other scales were used • Measurements: living rooms and bedrooms. • Air temperatures: recorded every 10 min in the living rooms and in the main bedrooms of each house during an entire year. • Sensors: placed on top of furniture, minimal height of 80 cm, away from windows (to avoid direct solar radiation) and internal heat sources.	• Summer thermal discomfort is frequent in nZEB houses in Wallonia. • Living rooms: a long-term appraisal of thermal conditions related to the frequency of extreme temperatures. • Bedrooms: occupants' thermal perception is more affected by smaller temperature deviations. • It is important to better integrate environmental controls, even in temperate climates, to properly mitigate overheating risks in nZEB houses.

[66]	- Scientific paper 2022 - Building and Environment - Chile, UK	- Residential spaces - Participants were presented with 25 randomly assigned images of interior housing living spaces in either control or treatment conditions.	Study the relationship between natural lighting in the home and the emotional subjective well-being of its inhabitants	- Emotional wellbeing - Natural lighting	- Image-based Randomised Controlled Trial methodology: using computer-generated photo simulations of a standard social housing unit in Santiago de Chile under control conditions (with no intervention) and with treatments (with interventions) - specifically, different conditions of natural lighting design visible throughout the same house. - Adaptation of the Watson and Clark PANAS-X questionnaire: participants rated how happy or sad they felt in the image of the interior space.	- Natural lighting conditions of housing significantly impact people's perceptions of happiness and sadness, with settings that have an increased amount of daylight entering the home leading to the greatest impacts. - Residential buildings must incorporate windows oriented towards the equator as much as possible to maximise emotional well-being.
[61]	- Scientific paper 2022 - Energy and Building - Netherlands, Belgium	- Low-energy houses (LEH), passive houses (PH) and zero energy houses (ZEH) - Newly built single-family dwellings (single detached houses, terraces, townhouses and apartment buildings). - Netherlands	Detect barriers and opportunities for promoting nearly zero-energy dwellings based on end-user experiences by studying end-user satisfaction in current LEHs, PHs and ZEHs	- Thermal comfort - Air quality - Noise - Information provision and control parameters	- Occupants living in houses for at least 1 year - Questionnaire: sociodemographic characteristics, house satisfaction; awareness and experiences regarding energy saving installations; building services and energy, indoor climate, design issues and information issues	- Summer comfort design and quality of heating and ventilation systems are critical factors in improving user satisfaction in nearly zero-energy dwellings. - Energy costs encourage potential residents to choose a nearly zero-energy dwelling, alongside other factors (size, location, neighbourhood and purchase price) - End users living in highly energy-efficient houses are quite satisfied and indicate a high comfort level. - End users relate perceived comfort levels directly to heating and ventilation systems. - Detailed information provision (initial instructions and written manuals) sometimes eliminates the perception of poor levels of control, dry air in winter, and noise or odour problems. - Specific need to provide quality assurance and improve information transfer to the end users of nearly zero-energy houses.

[89]	- Scientific paper 2019 - Energy and Building - Japan, UK	120 dwellings - Dwellings generally had an air conditioning unit in each room for heating and cooling, stand fans, and local heaters. - Kanto, Japan	- Quantify the seasonal differences in the comfort temperature - Develop a domestic adaptive model for Japanese dwellings - Explore how occupants achieve thermal comfort (open/close windows, use fans and turn on/off heating and/or cooling)	Thermal Comfort	- Data collected during 4 years in living rooms and bedrooms - Long-term survey six times a day in the living rooms and twice in the bedroom 5 survey periods were used - Outdoor measurements obtained from the closest meteorological station (air temperature and relative humidity) - Indoor thermal measurements in bedrooms and living rooms using a data logger.	- Residents satisfied with their dwelling's thermal environment - Occupants are well-adapted to their dwellings' thermal condition - Comfort temperature has high seasonal differences in free running mode
[107]	- Scientific paper 2020 - Indoor and Built Environment - Sweden	- Diversified sample (age, gender and household size) to have a wide experience range - Residents living in a multi-dwelling building - Sweden	- Provide a picture of residents' experiences and uses of their home lighting. - Discover the reasons for occupants leaving lights turned on in unoccupied rooms	Lighting: artificial light	- Interviews: open-ended and photo album - Questions about the residents' lighting experiences and their luminaire choices	- Perceived character of indoor home lighting can be described with three attributes: pragmatic, hedonic and social. - Wasted light in people's homes (lights left on in unoccupied rooms) can serve a purpose for the residents: avoid visual or aesthetic discomfort, make the home inviting, benefit people outside and provide safety knowing that people are inside.
[106]	- Scientific paper 2010 - Indoor and Built Environment - Republic of Korea	- Office building certified with the highest ranking by Korea's Green Building Council - Seoul	- Determine the indoor lighting environment factors that affect occupants' visual comfort and eye health - Contribute to the office building management and maintenance	Lighting	- Measurements of illuminance and luminance of the window - Questionnaire divided into sections for personal information and the respondent's satisfaction level with the indoor lighting environment - Measurements and survey conducted five times	- Significant correlation between occupants' visual comfort and satisfaction with lighting conditions and luminance distribution of the windows - After betterment on practical use of building the visual annoyance ratio decreased tremendously - Feedback from the questionnaire showed little differences after making changes to the building operation in relation to the self-reported health symptoms

Table A.2 - Parameters and methods of evaluating the energy performance of the consulted literature studies

Ref	Document, publication year, origin journal and country	Study application country, type and building characteristics	Parameters to measure/study	Measurement method and data collection	Main conclusions
[70]	- Scientific paper 2020 - Sustainable Cities and Society - Istanbul	- Istanbul - Residential Buildings - Two different types of plans: square and rectangular building floor plans and different building heights	- Layout: settlement and building design parameters (spaces between buildings in settlement texture, building and settlement texture orientation, and building and settlement form) - Building characteristics: thermal properties of the exterior, wall component of the building envelope, and trees' effect on streets on outdoor thermal comfort - Energy and economic performance - Outdoor thermal comfort conditions	- Final energy consumption was calculated using the DesignBuilder simulation programme (graphical interface of the EnergyPlus) - Tier 2 method (Intergovernmental Panel on Climate Change Guideline) to calculate CO₂ emissions based on the final energy consumption of each residential reference building in each settlement texture - LCC analysis – energy savings rates - ENVI-met v4 microclimate simulation model for outdoor thermal comfort analyses	- Design parameters used to create urban areas (settlement texture, building envelope and form, and landscape planning) impact the urban climate and, consequently, the building energy performance and the use of urban open spaces. - The relationship between settlement texture and building energy consumption is a complex balance that comprises climate parameters, urban canyons, and buildings. - The trees' shading effect significantly improved the outdoor thermal comfort level. - The height-width ratio of settlement textures on heating, cooling, and lighting energy consumption is the most important parameter affecting outdoor thermal comfort conditions. The ratio of 2.00 provides in summer the best thermal comfort conditions.
[109]	- Scientific paper 2020 - Sustainable Cities and Society - Switzerland	- Switzerland - Two offices and two meeting rooms in an academic building - Modular construction systems - Triple-glazed windows - Quiet room: concentration tasks without noisy activities and sources of distraction. - Interactive room: collaboration and communication tasks with spaces for sharing documents and equipment to remote collaboration.	- Occupancy density: employee's location and presence duration - Energy Consumption of electrical appliances and lights	- Individual Z-Wave energy meters to measure the energy consumption of electrical appliances and lights (when no data is available, Design-Builder v. 5 dynamic simulation software) - Pre-densification phase: 3 weeks - Post-densification phase: 4 weeks	- Possibility of densification of working areas while limiting impacts on employee comfort. Separate the academic office building into calm and interactive shared spaces might enable the densification of spaces by almost doubling the number of employees. - Relevance of using user-based units to have a better benchmark of building performances in use instead of surface-based functional units (surfaces cannot demonstrate/support a densification strategy improving the building performance)
[111]	- Scientific paper 2020 - Building and Environment - London	22-storey council housing tower block built in 1966 and located in East London - Tower block: in-situ reinforced concrete frame with concrete floor slabs spanning between shear walls and precast concrete panels as external walls. The exterior building envelope was refurbished in 2005 with asbestos cement over-cladding panels and double-glazed windows with UPVC frames and trickle vents - Heating provided by natural gas	- Energy use - Occupancy profiles	- The building simulation model was created using experimental data, including monitoring thermal comfort surveys and structured interviews to validate the model by implementing outdoor weather data from the Met Office in Energy Plus format, as well as actual occupancy and energy-use patterns. - DesignBuilder to create the building geometry - Occupancy profiles and energy use patterns extracted from the survey questionnaire, TM59 and SAP 2012	- Occupants' socio-demographic backgrounds and occupancy profiles significantly influenced energy use. - Improving the U-value of the external walls reduces the heating energy use during the winter season in future climate scenarios. - Occupancy profiles vary significantly for households that have different ages, numbers of occupants, and associated lifestyles. - Consider real, dominant occupancy patterns when evaluating overheating risks in different buildings. This will improve occupants' thermal comfort and buildings' energy efficiency and reduce the gap between predicted and actual buildings' performance.

					• Significance of occupancy patterns in predicting building energy performance, and hence overheating risks and heating energy demand
[141]	• Scientific paper • 2017 • Energy Procedia • Australia	• Thermal comfort and energy data were collected from 51 households, a subset of the 510 households.	• Thermal comfort • Energy Consumption • Energy efficiency	• Temperature/humidity loggers (recorded at 30-minute intervals); • Plug-in electricity sensors (on every heating device) • Current clamp sensor (on each circuit in the electrical meter board) • House observations of physical features • Structured survey and semi-structured interview • Specific measures to know the relation between thermal comfort, energy use and energy efficiency in homes: - Difference between inside and outside temperatures; - Household heating efficiency; - Time spent in comfort zone; - Comfort zone efficiency	• There is potential for individual measures used in Get Bill Smart (GBS) to be further developed and refined for other applications. It could be used in different climates and applied to new houses. • Close relationship between heating energy consumption and time spent in the comfort zone (not a linear relationship). • Houses with more efficient heaters (heat pumps) spent more time in the comfort zone during peak winter. • Energy efficiency did not necessarily lead to comfort • For low-income households, the relationship between energy use, thermal comfort and energy efficiency outcomes is dynamic
[155]	• Scientific paper • 2019 • Building Simulation • Netherlands, Italy, UK	• 12 identical prefabricated, all-electric dwellings in Holten, Netherlands	• Electricity consumption	• OB profiles were extracted through a simplified Knowledge Discovery in Database (KDD) • Occupancy, equipment and light-use profiles • OB profiles integrated into a building simulation model developed in TRNSYS v17	• KDD is a suitable technique for extracting OB profiles from a stream of raw data for implementation in building performance simulations. • It is important to appropriate OB modelling for analysing the energy use of dwellings. • For the considered dwellings, using standard OB modelling results in an underestimation of the energy use intensity (EUI) by 5.9% to 42.5%, depending on the case. • The results corroborate that the 1.6x discrepancy observed in the buildings' energy use intensity could be ascribed to OB.
[113]	• Scientific paper • 2020 • Building and Environment • Canada	• Open-plan office	• Energy consumption • Thermal comfort	• Survey • Real-time locating systems • The simulation model is created in EnergyPlus (space energy consumption, discomfort hours, and other parameters) • Bluetooth Low Energy to collect the real occupancy (one-year data)	• Applying HVAC and lighting local control strategies improves the thermal condition by 50%, along with 2% savings in energy consumption. • Optimal control strategies provide demand-driven control solutions and optimize building energy performance. • The proposed method assists decision-makers in evaluating optimized occupancy-centred building operations.
[112]	• Scientific paper • 2022 • Energy Policy • Germany	• Two multi-apartment social housing buildings with 88 apartments in total • A small city near Leipzig • Buildings constructed in 1960 on an east-west and north-south orientation	• Energy consumption - Household energy consumption - Household energy demand - Energy performance gap • Thermal comfort - Temperature - TRV setting	• Survey during three separate visits over two months • Interviews were conducted during on-site visits, using a standardised questionnaire ranging topics like residents' satisfaction with the housing situation and heating and ventilation patterns.	• In highly insulated buildings, it is more difficult for occupants to quickly regulate the indoor environment since these buildings tend to produce thermal monotony and increase inertia. • Highly insulated buildings can lead the occupants to increase open windows to regulate temperatures and to reduce their clothing or establish other psychological/habitual adaptations to achieve comfort.

		• Buildings supplied by district heat for warmth and hot water. Radiators with Thermostatic Radiator Valves (TRVs) installed in each room with a 6-point scale • Naturally ventilated apartments (windows can be tilted or completely opened)	- Ventilation duration - Window opening mode - Door status - Habits of frequency or change of TRV setting - Strategies if feeling too warm	• To know the heating energy consumption, the apartment-related heating energy demand was calculated based on building properties (apartment layouts, u-values and surfaces of exterior walls, and others) and weather data (global radiation and outdoor temperature from the weather station closer). • Comparing the apartment-related heating demand with the actual measured but weather-corrected heating energy consumption, it is possible to derive apartment-related energy performance gaps as a benchmark. • To analyse the distribution of household energy consumption, energy demand, energy performance gaps and different aspects of comfort practices, qualitative interpretations of interactions were based on box plots, frequency tables and comparisons of mean values using the statistical program Stata.	• Energy efficiency improvements can result in undesirable adaptive behaviours, leading to energy performance gaps. • Building insulation is an effective strategy to reduce energy demand and carbon emissions. The energy performance gaps and their causes require a detailed assessment of the fit between building technologies and comfort practices to develop policies for successful and appropriate occupant behaviour in buildings.
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APPENDIX B – Extensive survey (summer)

Conforto e bem-estar

Questionário

Está a ser desenvolvido um estudo para o qual necessitamos da sua colaboração.

Neste estudo pretende-se avaliar o conforto, o bem-estar e a eficiência energética nas habitações de forma a permitir uma abordagem e ferramenta inovadora destinada a melhorar a sustentabilidade das habitações.

O questionário é composto por perguntas sobre a ocupação da casa, conforto, bem-estar, equipamentos e alguns hábitos. Pede-se que responda a todas as questões considerando o período de verão e a sua habitação de um modo geral.

Se prosseguir, declara que aceita participar neste estudo sem quaisquer contrapartidas.

Pode sempre utilizar o botão ANTER. se pretender recuar no questionário, seja para corrigir algo, seja para confirmar uma resposta dada.

Obrigado por esta importante colaboração.

Conforto e bem-estar

Ambiente térmico

* 1. Qual é, normalmente, a sua sensação térmica no interior da sua casa durante o verão (caso pretenda responder "confortável" tem de mover o cursor e reposicioná-lo):

Muito Frio
Confortável
Muito Quente

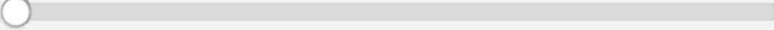
☐

Conforto e bem-estar

Ambiente térmico

* 2. Gostaria que a temperatura no interior da sua casa durante o verão fosse (caso pretenda responder "sem alteração" tem de mover o cursor e reposicioná-lo):

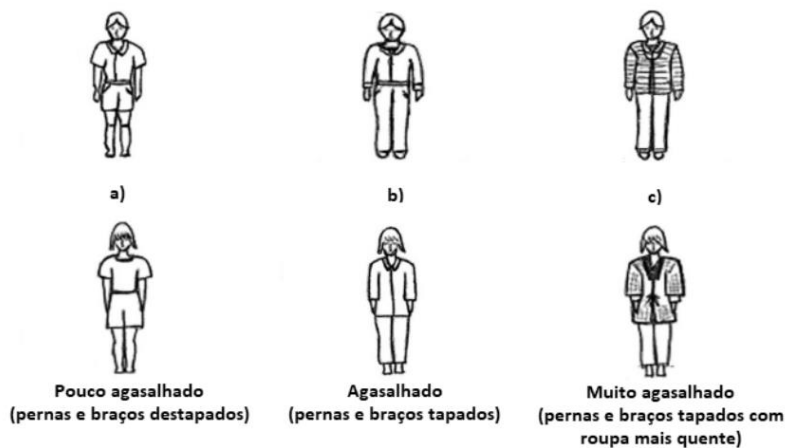
Mais Fria Sem alteração (como normalmente se encontra) Mais Quente



Conforto e bem-estar

Ambiente térmico

* 3. O nível de vestuário, afeta o isolamento térmico e a sensação de conforto térmico. As imagens apresentadas representam diferentes peças de vestuário. Indique o vestuário que normalmente utiliza no verão quando está em sua casa (deve selecionar as opções ou opção mais parecida com aquela que costuma utilizar):



- ☐ a)
☐ b)
☐ c)

Conforto e bem-estar

Ambiente térmico

* 4. Indique com que frequência utiliza equipamentos de "arrefecimento" (ventoinha, ar-condicionado) no interior da sua casa no verão (não tem de ser em contínuo, basta utilizar uma fração do dia):

- | | |
|--|--|
| ☐ Sempre/Quase sempre (5 a 7 dias/semana) | ☐ Nunca/Quase nunca (meio dia/semana ou menos) |
| ☐ Com frequência (3 a 4 dias/semana) | ☐ Não existem equipamentos de arrefecimento |
| ☐ Com pouca frequência (1 a 2 dias/semana) | ☐ Existem mas encontram-se avariados |



Conforto e bem-estar

Ambiente térmico

* 5. Indique o seu grau de satisfação quanto ao conforto térmico no interior da sua casa no verão (caso pretenda responder "neutro" tem de mover o cursor e reposicioná-lo):

Muito Insatisfeito	Neutro	Muito Satisfeito



Conforto e bem-estar

Ventilação

* 6. Indique com que frequência abre as janelas da sua casa no verão:

- ☐ Sempre/Quase sempre (5 a 7 dias/semana)
- ☐ Com frequência (3 a 4 dias/semana)
- ☐ Com pouca frequência (1 a 2 dias/semana)
- ☐ Nunca/Quase nunca (meio dia/semana ou menos)



Conforto e bem-estar

Ventilação

* 7. De uma maneira geral, no verão abre as janelas da sua casa tanto quanto gostaria?

- ☐ Sim
- ☐ Talvez
- ☐ Não



Conforto e bem-estar

Ventilação

* 8. Indique os principais motivos para não abrir as janelas na sua casa no verão (pode indicar mais do que uma opção):

- ☐ Para manter a temperatura da casa
- ☐ Ruído do exterior incomodativo
- ☐ Para não entrarem na habitação insetos/mosquitos
- ☐ Para não entrarem poeiras
- ☐ Outro (especifique)



Conforto e bem-estar

Ventilação

* 9. Indique em que compartimentos da sua casa existem manchas escuras e/ou bolores no verão no teto e/ou nas paredes e qual o nível de incomodidade que isto lhe provoca:

	Muito incómodo	Incómodo	Pouco incómodo	Não existe bolor nem manchas de humidade	Não tenho esse compartimento
Quarto principal	☐	☐	☐	☐	☐
Quarto(s) secundário(s)	☐	☐	☐	☐	☐
Sala	☐	☐	☐	☐	☐
Cozinha	☐	☐	☐	☐	☐
Casa de banho	☐	☐	☐	☐	☐
Corredor	☐	☐	☐	☐	☐
Marquise	☐	☐	☐	☐	☐



Conforto e bem-estar

Qualidade do ar interior

* 10. Indique a sua satisfação quanto à qualidade do ar interior (poluentes, poeiras, outros) da sua casa no verão (caso pretenda responder "neutro" tem de mover o cursor e reposicioná-lo):

Muito Insatisfeito	Neutro	Muito Satisfeito
☐		



Conforto e bem-estar

Qualidade do ar interior

* 11. Indique a intensidade dos odores (cheiros mais ou menos frequentes) na sua casa no verão:

- | | |
|--|--|
| ☐ Sem odor | ☐ Odor moderado |
| ☐ Odor muito fraco | ☐ Odor forte |
| ☐ Odor fraco | ☐ Odor muito forte |

Conforto e bem-estar

Qualidade do ar interior

* 12. Indique se esses odores são:

- ☐ Agradáveis
☐ Neutros
☐ Desagradáveis

Conforto e bem-estar

Qualidade do ar interior

* 13. Indique se esses odores são:

- ☐ Persistentes e recorrentes (ao longo de todo o verão e existem sempre)
☐ Casuais (não duram todo o verão e nem sempre existem)

Conforto e bem-estar

Iluminação

* 14. Classifique o nível de iluminação natural que normalmente existe na sua casa no verão (caso pretenda responder "Confortável" tem de mover o cursor e reposicioná-lo):

Muito Claro Confortável Muito Escuro

Conforto e bem-estar

Iluminação

* 15. Para melhorar o seu conforto visual, indique a partir de que horas liga a luz artificial na sua casa no verão:

- ☐ Ligo a luz praticamente todo o dia
- ☐ Ligo muitas vezes durante o dia, sobretudo em dias mais escuros
- ☐ Ligo quase somente a partir do momento em que escurece (em vários compartimentos da casa)
- ☐ Ligo quase somente a partir do momento em que escurece (unicamente nos compartimentos da casa onde se encontram pessoas)



Conforto e bem-estar

Iluminação

* 16. Indique com que frequência utiliza o sombreamento solar durante o dia na sua casa no verão (fechar persianas, estores, portadas, cortinados, outros):

- ☐ Sempre/Quase sempre (5 a 7 dias/semana)
- ☐ Com frequência (3 a 4 dias/semana)
- ☐ Com pouca frequência (1 a 2 dias/semana)
- ☐ Nunca/Quase nunca (meio dia/semana ou menos)
- ☐ Não existe na habitação
- ☐ Existe mas encontra-se avariado



Conforto e bem-estar

Iluminação

* 17. Indique a sua satisfação quanto à iluminação natural e artificial da sua casa no verão (encadeamento, reflexões, sombreamentos, outros) (caso pretenda responder "neutro" tem de mover o cursor e reposicioná-lo):

Muito Insatisfeito	Neutro	Muito Satisfeito
<input type="range"/>		



Conforto e bem-estar

Acústica/ruído

* 18. Relativamente ao ruído percepcionado dentro da sua casa, classifique o nível de incomodidade de cada um dos seguintes fatores:

	Muito incómodo	Incómodo	Pouco incómodo	Sem incómodo	Não se aplica
Ruído das pessoas dentro de casa	☐	☐	☐	☐	☐
Ruído de equipamentos dentro de casa (telemóvel, lâmpadas, eletrodomésticos, outros)	☐	☐	☐	☐	☐
Ruído de instalações de escoamento e abastecimento de água (canalizações, uso do autoclismo, chuveiro)	☐	☐	☐	☐	☐
Ruído de instalações climáticas, aquecedores, ar-condicionado, ventilação	☐	☐	☐	☐	☐
Ruído proveniente do exterior da casa (tráfego rodoviário, restauração, pessoas, outros)	☐	☐	☐	☐	☐
Ruído proveniente da casa de vizinhos	☐	☐	☐	☐	☐
Ruído proveniente de espaços comuns do edifício (elevadores, bombas, outros equipamentos, pessoas, outros)	☐	☐	☐	☐	☐

Conforto e bem-estar

Acústica/ruído

* 19. Indique a sua satisfação quanto ao ruído e isolamento acústico da sua casa no verão (caso pretenda responder "neutro" tem de mover o cursor e reposicioná-lo):

Muito Insatisfeito	Neutro	Muito Satisfeito
<input type="range"/>		



Conforto e bem-estar

Outras características da habitação

* 20. Como caracteriza a vista para o exterior da sua casa (caso pretenda responder "neutro" tem de mover o cursor e reposicioná-lo)?

Muito Desinteressante	Neutro	Muito Interessante
<input type="range"/>		



Conforto e bem-estar

Outras características da habitação

* 21. Indique o grau de importância da vista para o exterior ser uma paisagem com elementos agradáveis (jardins, floresta, rio, mar, monumentos, pontes, vista desafogada, outros) (caso pretenda responder "neutro" tem de mover o cursor e reposicioná-lo):

Sem nenhuma importância	Neutro	Muito Importante
<input type="range"/>		



Conforto e bem-estar

Outras características da habitação

* 22. Indique a sua satisfação quanto à privacidade relativamente ao exterior e envolvente da sua casa (caso pretenda responder "neutro" tem de mover o cursor e reposicioná-lo):

Muito Insatisfeito	Neutro	Muito Satisfeito
<input type="range"/>		



Conforto e bem-estar

Outras características da habitação

* 23. Indique a sua satisfação quanto à manutenção da sua casa, isto é, funcionamento de equipamentos, sombreamentos, estado da pintura, cobertura, entre outros (caso pretenda responder "neutro" tem de mover o cursor e reposicioná-lo):

Muito Insatisfeito	Neutro	Muito Satisfeito
<input type="range"/>		



Conforto e bem-estar

Outras características da habitação

24. Caso tenha indicado que está insatisfeito ou neutro relativamente à manutenção da sua casa, indique o motivo:



Conforto e bem-estar

Mobiliário, acabamentos e materiais

* 25. Indique o grau de importância da presença de plantas, elementos de água, luz, animais, materiais naturais, outros no interior da sua casa (caso pretenda responder "neutro" tem de mover o cursor e reposicioná-lo):

Sem nenhuma importância	Neutro	Muito Importante
☐		



Conforto e bem-estar

Mobiliário, acabamentos e materiais

* 26. Indique a sua satisfação quanto ao conforto do recheio da sua casa (mobiliário, tapetes, outros), combinando ergonomia com estética (caso pretenda responder "neutro" tem de mover o cursor e reposicioná-lo):

Muito Insatisfeito	Neutro	Muito Satisfeito
☐		



Conforto e bem-estar

Considerações finais

* 27. Indique a importância que tem dado aos seguintes aspetos:

	Muito importante	Importante	Pouco importante	Nada importante
Utilizar/adquirir equipamentos energeticamente eficientes	☐	☐	☐	☐
Utilizar/adquirir sistemas passivos (sistemas que não utilizam energia para climatizar a casa por exemplo)	☐	☐	☐	☐
Optar por materiais que incorporem outros reciclados, com baixos consumos energéticos na sua produção e menos poluição para o meio ambiente	☐	☐	☐	☐

Conforto e bem-estar

Considerações finais

* 28. Indique a sua preferência relativamente ao funcionamento dos sistemas que podem estar presentes na sua casa (automáticos ou manuais):

	Automático	Manual	Automático e Manual
Aquecimento/Arrefecimento (ligar/desligar, setpoint, outros)	☐	☐	☐
Ventilação mecânica (ligar/desligar)	☐	☐	☐
Iluminação artificial (ligar/desligar)	☐	☐	☐
Sombreamento (abrir/fechar, inclinação, outros)	☐	☐	☐

Conforto e bem-estar

Considerações finais

* 29. Indique a importância que cada grupo de parâmetros de conforto e o bem-estar tem para si na sua casa:

	Muito importante	Importante	Pouco importante	Nada importante
Ambiente térmico	☐	☐	☐	☐
Ar interior	☐	☐	☐	☐
Ventilação	☐	☐	☐	☐
Iluminação	☐	☐	☐	☐
Acústica/ruído	☐	☐	☐	☐
Outras características (vista, privacidade, manutenção)	☐	☐	☐	☐
Mobiliário, acabamentos e materiais	☐	☐	☐	☐

Conforto e bem-estar

Considerações finais

* 30. Indique 3 pontos que mais importância têm para si e que considera serem positivos na sua casa (pode indicar pontos que não tenham sido abordados neste questionário):

Conforto e bem-estar

Considerações finais

* 31. Indique 3 pontos que mais importância têm para si e que considera serem negativos na sua casa (pode indicar pontos que não tenham sido abordados neste questionário):

Conforto e bem-estar

Considerações finais

* 32. Indique a sua satisfação global com a sua casa considerando todos os parâmetros (caso pretenda responder "neutro" tem de mover o cursor e reposicioná-lo):

Muito Insatisfeito
Neutro
Muito Satisfeito

Conforto e bem-estar

Considerações finais

* 33. Indique a prioridade para a sua casa das medidas de melhoria de eficiência energética apresentadas na primeira coluna:

	Muito prioritário	Prioritário	Pouco prioritário	Nada prioritário	Já concretizei
Instalação e/ou substituição de equipamentos de aquecimento por outros mais eficientes	☐	☐	☐	☐	☐
Instalação e/ou substituição de equipamentos de arrefecimento por outros mais eficientes	☐	☐	☐	☐	☐
Instalação e/ou substituição de equipamentos de ventilação por outros mais eficientes	☐	☐	☐	☐	☐
Instalação e/ou substituição do isolamento térmico na cobertura e paredes	☐	☐	☐	☐	☐
Instalação e/ou substituição de janelas por outras mais eficientes	☐	☐	☐	☐	☐
Instalação e/ou substituição de proteções solares por outras mais eficientes	☐	☐	☐	☐	☐
Substituição de lâmpadas por outras mais eficientes	☐	☐	☐	☐	☐
Substituição de equipamentos (frigorífico, máquinas de lavar, outros) por outros mais eficientes	☐	☐	☐	☐	☐
Instalação de painéis solares	☐	☐	☐	☐	☐

Conforto e bem-estar

Caracterização do respondente

* 34. Acrónimo:

* 35. Sexo:

- ☐ Feminino
☐ Masculino



Conforto e bem-estar

Caracterização do respondente

* 36. Idade:

- ☐ ≤ 25 anos
☐ 26-35 anos
☐ 36-45 anos
☐ 46-55 anos
☐ ≥ 56 anos



Conforto e bem-estar

Caracterização do respondente

* 37. Rendimento mensal líquido do agregado doméstico:

- ☐ ≤ 676,40 (salário mínimo nacional líquido)
☐ 676,40 - 1352,80 (líquido)
☐ 1352,81 - 2029,20 (líquido)
☐ 2029,21 - 2705,60 (líquido)
☐ ≥ 2705,60 (líquido)



Conforto e bem-estar

Caracterização do respondente

* 38. Nos últimos 3 anos teve alguma doença ou problema de saúde relacionada com o ambiente interior e/ou a qualidade da sua casa? Pode indicar mais do que uma opção e/ou especificar na caixa de texto.

- ☐ Ambiente térmico
- ☐ Iluminação
- ☐ Qualidade do ar interior
- ☐ Ruído
- ☐ Nenhuma

Outro (especifique)

APPENDIX C – Extensive survey (winter)

Conforto e bem-estar

Questionário

Está a ser desenvolvido um estudo para o qual necessitamos da sua colaboração. Neste estudo pretende-se avaliar o conforto, o bem-estar e a eficiência energética nas habitações de forma a permitir uma abordagem e ferramenta inovadora destinada a melhorar a sustentabilidade das habitações.

O questionário é composto por perguntas sobre a ocupação da casa, conforto, bem-estar, equipamentos e alguns hábitos. Pede-se que responda a todas as questões considerando o período de inverno e a sua habitação de um modo geral.

Se prosseguir, declara que aceita participar neste estudo sem quaisquer contrapartidas.

Pode sempre utilizar o botão ANTER, se pretender recuar no questionário, seja para corrigir algo, seja para confirmar uma resposta dada.

Obrigado por esta importante colaboração.

Conforto e bem-estar

Ambiente térmico

* 1. Qual é, normalmente, a sua sensação térmica no interior da sua casa durante o inverno (caso pretenda responder "confortável" tem de mover o cursor e reposicioná-lo):

Muito Frio	Confortável	Muito Quente
<input type="range"/>		

Conforto e bem-estar

Ambiente térmico

* 2. Gostaria que a temperatura no interior da sua casa durante o inverno fosse (caso pretenda responder "sem alteração" tem de mover o cursor e reposicioná-lo):

Mais Fria Sem alteração (como normalmente se encontra) Mais Quente

☐

Conforto e bem-estar

Ambiente térmico

* 3. O nível de vestuário, afeta o isolamento térmico e a sensação de conforto térmico. As imagens apresentadas representam diferentes peças de vestuário. Indique o vestuário que normalmente utiliza no inverno quando está em sua casa (deve selecionar as opções ou opção mais parecida com aquela que costuma utilizar):

		
a)	b)	c)
		
Pouco agasalhado (pernas e braços destapados)	Agasalhado (pernas e braços tapados)	Muito agasalhado (pernas e braços tapados com roupa mais quente)

- ☐ a)
☐ b)
☐ c)

Conforto e bem-estar

Ambiente térmico

* 4. Indique com que frequência utiliza equipamentos de aquecimento no interior da sua casa no inverno (não tem de ser em contínuo, basta utilizar uma fração do dia):

- ☐ Sempre/Quase sempre (5 a 7 dias/semana) ☐ Nunca/Quase nunca (meio dia/semana ou menos)
- ☐ Com frequência (3 a 4 dias/semana) ☐ Não existem equipamentos de aquecimento
- ☐ Com pouca frequência (1 a 2 dias/semana) ☐ Existem mas encontram-se avariados



Conforto e bem-estar

Ambiente térmico

* 5. Indique o seu grau de satisfação quanto ao conforto térmico no interior da sua casa no inverno (caso pretenda responder "neutro" tem de mover o cursor e reposicioná-lo):

Muito Insatisfeito	Neutro	Muito Satisfeito
☐		



Conforto e bem-estar

Ventilação

* 6. Indique com que frequência abre as janelas da sua casa no inverno:

- ☐ Sempre/Quase sempre (5 a 7 dias/semana)
- ☐ Com frequência (3 a 4 dias/semana)
- ☐ Com pouca frequência (1 a 2 dias/semana)
- ☐ Nunca/Quase nunca (meio dia/semana ou menos)



Conforto e bem-estar

Ventilação

* 7. De uma maneira geral, no inverno abre as janelas da sua casa tanto quanto gostaria?

- ☐ Sim
- ☐ Talvez
- ☐ Não

Conforto e bem-estar

Ventilação

* 8. Indique os principais motivos para não abrir as janelas na sua casa no inverno (pode indicar mais do que uma opção):

- ☐ Para manter a temperatura da casa
- ☐ Ruído do exterior incomodativo
- ☐ Para não entrarem na habitação insetos/mosquitos
- ☐ Para não entrarem poeiras
- ☐ Outro (especifique)

Conforto e bem-estar

Ventilação

* 9. Indique em que compartimentos da sua casa existem manchas escuras e/ou bolores no inverno no teto e/ou nas paredes e qual o nível de incomodidade que isto lhe provoca:

	Muito incómodo	Incómodo	Pouco incómodo	Não existe bolor nem manchas de humidade	Não tenho esse compartimento
Quarto principal	☐	☐	☐	☐	☐
Quarto(s) secundário(s)	☐	☐	☐	☐	☐
Sala	☐	☐	☐	☐	☐
Cozinha	☐	☐	☐	☐	☐
Casa de banho	☐	☐	☐	☐	☐
Corredor	☐	☐	☐	☐	☐
Marquise	☐	☐	☐	☐	☐

Conforto e bem-estar

Qualidade do ar interior

* 10. Indique a sua satisfação quanto à qualidade do ar interior (poluentes, poeiras, outros) da sua casa no inverno (caso pretenda responder "neutro" tem de mover o cursor e reposicioná-lo):

☐ Muito Insatisfeito
 ☐ Neutro
 ☐ Muito Satisfeito

Conforto e bem-estar

Qualidade do ar interior

* 11. Indique a intensidade dos odores (cheiros mais ou menos frequentes) na sua casa no inverno:

- | | |
|--|--|
| ☐ Sem odor | ☐ Odor moderado |
| ☐ Odor muito fraco | ☐ Odor forte |
| ☐ Odor fraco | ☐ Odor muito forte |

Conforto e bem-estar

Qualidade do ar interior

* 12. Indique se esses odores são:

- ☐ Agradáveis
☐ Neutros
☐ Desagradáveis

Conforto e bem-estar

Qualidade do ar interior

* 13. Indique se esses odores são:

- ☐ Persistentes e recorrentes (ao longo de todo o inverno e existem sempre)
- ☐ Casuais (não duram todo o inverno e nem sempre existem)



Conforto e bem-estar

Iluminação

* 14. Classifique o nível de iluminação natural que normalmente existe na sua casa no inverno (caso pretenda responder "Confortável" tem de mover o cursor e reposicioná-lo):

Muito Claro	Confortável	Muito Escuro
☐		



Conforto e bem-estar

Iluminação

* 15. Para melhorar o seu conforto visual, indique a partir de que horas liga a luz artificial na sua casa no inverno:

- ☐ Ligo a luz praticamente todo o dia
- ☐ Ligo muitas vezes durante o dia, sobretudo em dias mais escuros
- ☐ Ligo quase somente a partir do momento em que escurece (em vários compartimentos da casa)
- ☐ Ligo quase somente a partir do momento em que escurece (unicamente nos compartimentos da casa onde se encontram pessoas)



Conforto e bem-estar

Iluminação

* 16. Indique com que frequência utiliza o sombreamento solar durante o dia na sua casa no inverno (fechar persianas, estores, portadas, cortinados, outros):

- | | |
|--|--|
| ☐ Sempre/Quase sempre (5 a 7 dias/semana) | ☐ Nunca/Quase nunca (meio dia/semana ou menos) |
| ☐ Com frequência (3 a 4 dias/semana) | ☐ Não existe na habitação |
| ☐ Com pouca frequência (1 a 2 dias/semana) | ☐ Existe mas encontra-se avariado |



Conforto e bem-estar

Iluminação

* 17. Indique a sua satisfação quanto à iluminação natural e artificial da sua casa no inverno (encadeamento, reflexões, sombreamentos, outros) (caso pretenda responder "neutro" tem de mover o cursor e reposicioná-lo):

Muito Insatisfeito	Neutro	Muito Satisfeito
<input type="range"/>		



Conforto e bem-estar

Acústica/ruído

* 18. Relativamente ao ruído percebido dentro da sua casa, classifique o nível de incomodidade de cada um dos seguintes fatores:

	Muito incómodo	Incómodo	Pouco incómodo	Sem incómodo	Não se aplica
Ruído das pessoas dentro de casa	☐	☐	☐	☐	☐
Ruído de equipamentos dentro de casa (telemóvel, lâmpadas, eletrodomésticos, outros)	☐	☐	☐	☐	☐
Ruído de instalações de escoamento e abastecimento de água (canalizações, uso do autoclismo, chuveiro)	☐	☐	☐	☐	☐
Ruído de instalações climáticas, aquecedores, ar-condicionado, ventilação	☐	☐	☐	☐	☐
Ruído proveniente do exterior da casa (tráfego rodoviário, restauração, pessoas, outros)	☐	☐	☐	☐	☐
Ruído proveniente da casa de vizinhos	☐	☐	☐	☐	☐
Ruído proveniente de espaços comuns do edifício (elevadores, bombas, outros equipamentos, pessoas, outros)	☐	☐	☐	☐	☐

Conforto e bem-estar

Acústica/ruído

* 19. Indique a sua satisfação quanto ao ruído e isolamento acústico da sua casa no inverno (caso pretenda responder "neutro" tem de mover o cursor e reposicioná-lo):

Muito Insatisfeito	Neutro	Muito Satisfeito
<input type="range"/>		

Conforto e bem-estar

Caracterização do respondente

* 20. Acrónimo:

APPENDIX D – Right-now survey (winter)

Conforto e bem-estar

Questionário diário

Este questionário visa conhecer comportamentos e sensações dos ocupantes da sua habitação durante duas semanas no inverno. Ele contém perguntas dirigidas ao quarto principal e à sala.

São os ocupantes permanentes da habitação quem o deverá preencher. O quarto principal foi previamente escolhido quando se colocaram os sensores.

Obrigado por estar a colaborar neste estudo.

* 1. Acrónimo:

* 2. Número de pessoas que estão em casa:

* 3. Como considera que esteve o dia? Pode indicar mais do que uma opção.

- ☐ Bom tempo
- ☐ Assim assim
- ☐ Mau tempo
- ☐ Frio
- ☐ Ameno
- ☐ Quente

Conforto e bem-estar

Relativamente ao **quarto**:

Nesta página é pedido que indique a resposta que melhor caracteriza a situação "neste momento" para o quarto principal. Caso não esteja neste compartimento pede-se que se dirija para o mesmo para que possa responder o mais próximo da realidade.

* 4. Selecione as opções que melhor definem o estado do quarto neste momento. Pode indicar mais do que uma opção.

- ☐ Janela(s)/porta(s) para o exterior fechada(s)
- ☐ Janela(s)/porta(s) para o exterior aberta(s)
- ☐ Persiana(s) / portada(s) fechada(s)
- ☐ Persiana(s) / portada(s) aberta(s)
- ☐ Aquecimento desligado
- ☐ Aquecimento ligado

* 5. Sensação relativamente ao conforto térmico no quarto neste momento:

- ☐ Muito frio
- ☐ Frio
- ☐ Ligeiramente frio
- ☐ Neutro (confortável)
- ☐ Ligeiramente quente
- ☐ Quente
- ☐ Muito quente

* 6. Sente algum tipo de desconforto no quarto neste momento? Este pode acontecer devido à temperatura, ar interior (odor, ar "pesado"), iluminação (excesso/escassez de luz, encadeamento), acústica (ruído proveniente de dentro de casa, rua, vizinhos, outros) ou outro.

- ☐ Sim
- ☐ Não

* 7. A que se deve o desconforto sentido no quarto? Pode indicar mais do que um parâmetro.

- ☐ Temperatura
- ☐ Ar interior (odor, ar "pesado", outros)
- ☐ Iluminação (excesso/escassez de luz, encadeamento, outros)
- ☐ Acústica (ruído proveniente de dentro de casa, vizinhos, rua, outros)

>

- ☐ Outro (especifique)

* 8. Que medida(s) poderá tomar para contrariar o desconforto no quarto? Pode indicar mais do que uma opção.

- ☐ Nenhuma
- ☐ Abrir janelas/portas para o exterior
- ☐ Fechar janelas/portas para o exterior
- ☐ Abrir janelas/portas interiores
- ☐ Fechar janelas/portas interiores
- ☐ Ligar aquecimento
- ☐ Desligar aquecimento
- ☐ Ligar desumidificador
- ☐ Desligar desumidificador
- ☐ Abrir persianas ou outro sombreamento exterior
- ☐ Fechar persianas ou outro sombreamento exterior
- ☐ Abrir sombreamento interior (portadas, cortinas, estores interiores, outros)
- ☐ Fechar sombreamento interior (portadas, cortinas, estores interiores, outros)
- ☐ Agasalhar-se (vestir mais roupa ou roupa mais quente)

>

- ☐ Se fez algo, especifique:



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Conforto e bem-estar

Relativamente ao **quarto**:

VAMOS AGORA CONSIDERAR A SITUAÇÃO DO **QUARTO DURANTE O DIA DE HOJE**

* 9. Selecione as opções que melhor definem o estado do quarto durante o dia de hoje. Pode indicar mais do que uma opção.

- ☐ Janela(s)/porta(s) para o exterior sempre fechada(s)
- ☐ Janela(s)/porta(s) para o exterior aberta(s) menos de uma hora
- ☐ Janela(s)/porta(s) para o exterior aberta(s) mais de uma hora
- ☐ Persiana(s) / portada(s) sempre fechada(s)
- ☐ Persianas(s) / portada(s) aberta(s) menos de uma hora
- ☐ Persianas(s) / portada(s) aberta(s) mais de uma hora
- ☐ Aquecimento sempre desligado
- ☐ Aquecimento ligado menos de uma hora
- ☐ Aquecimento ligado mais de uma hora



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Conforto e bem-estar

Relativamente à **sala**:

Nesta página é pedido que indique a resposta que melhor caracteriza a situação "neste momento" para a sala. Caso não esteja neste compartimento pede-se que se dirija para o mesmo para que possa responder o mais próximo da realidade.

* 10. Selecione as opções que melhor definem o estado da sala neste momento. Pode indicar mais do que uma opção.

- ☐ Janela(s)/porta(s) para o exterior fechada(s)
- ☐ Janela(s)/porta(s) para o exterior aberta(s)
- ☐ Persiana(s) / portada(s) fechada(s)
- ☐ Persiana(s) / portada(s) aberta(s)
- ☐ Aquecimento desligado
- ☐ Aquecimento ligado

* 11. Sensação relativamente ao conforto térmico na sala neste momento:

- ☐ Muito frio
- ☐ Frio
- ☐ Ligeiramente frio
- ☐ Neutro (confortável)
- ☐ Ligeiramente quente
- ☐ Quente
- ☐ Muito quente

* 12. Sente algum tipo de desconforto na sala neste momento? Este pode acontecer devido à temperatura, ar interior (odor, ar "pesado"), iluminação (excesso/escassez de luz, encadeamento), acústica (ruído proveniente de dentro de casa, rua, vizinhos, outros) ou outro.

☐ Sim

☐ Não



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Conforto e bem-estar

* 13. A que se deve o desconforto sentido na sala? Pode indicar mais do que um parâmetro.

☐ Temperatura

☐ Ar interior (odor, ar "pesado", outros)

☐ Iluminação (excesso/escassez de luz, encadeamento, outros)

☐ Acústica (ruído proveniente de dentro de casa, vizinhos, rua, outros)

>

☐ Outro (especifique)

* 14. Que medida(s) poderá tomar para contrariar o desconforto na sala? Pode indicar mais do que uma opção.

- ☐ Nenhuma
- ☐ Abrir janelas/portas para o exterior
- ☐ Fechar janelas/portas para o exterior
- ☐ Abrir janelas/portas interiores
- ☐ Fechar janelas/portas interiores
- ☐ Ligar aquecimento
- ☐ Desligar aquecimento
- ☐ Ligar desumidificador
- ☐ Desligar desumidificador
- ☐ Abrir persianas ou outro sombreamento exterior
- ☐ Fechar persianas ou outro sombreamento exterior
- ☐ Abrir sombreamento interior (portadas, cortinas, estores interiores, outros)
- ☐ Fechar sombreamento interior (portadas, cortinas, estores interiores, outros)
- ☐ Agasalhar-se (vestir mais roupa ou roupa mais quente)

>

- ☐ Se fez algo, especifique:



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Conforto e bem-estar

Relativamente à sala:

VAMOS AGORA CONSIDERAR A SITUAÇÃO DA SALA DURANTE O DIA DE HOJE

* 15. Selecione as opções que melhor definem o estado da sala durante o dia de hoje. Pode indicar mais do que uma opção.

- ☐ Janela(s)/porta(s) para o exterior sempre fechada(s)
- ☐ Janela(s)/porta(s) para o exterior aberta(s) menos de uma hora
- ☐ Janela(s)/porta(s) para o exterior aberta(s) mais de uma hora
- ☐ Persiana(s) / portada(s) sempre fechada(s)
- ☐ Persianas(s) / portada(s) aberta(s) menos de uma hora
- ☐ Persianas(s) / portada(s) aberta(s) mais de uma hora
- ☐ Aquecimento sempre desligado
- ☐ Aquecimento ligado menos de uma hora
- ☐ Aquecimento ligado mais de uma hora

APPENDIX E – Right-now survey (summer)

Conforto e bem-estar

Questionário diário

Este questionário visa conhecer comportamentos e sensações dos ocupantes da sua habitação durante duas semanas no verão. Ele contém perguntas dirigidas ao quarto principal e à sala.

São os ocupantes permanentes da habitação quem o deverá preencher. O quarto principal foi previamente escolhido quando se colocaram os sensores.

Obrigado por estar a colaborar neste estudo.

* 1. Acrónimo:

* 2. Número de pessoas que estão em casa:

* 3. Como considera que esteve o dia? Pode indicar mais do que uma opção.

- ☐ Bom tempo
- ☐ Assim assim
- ☐ Mau tempo
- ☐ Frio
- ☐ Ameno
- ☐ Quente

Conforto e bem-estar

Relativamente ao **quarto**:

Nesta página é pedido que indique a resposta que melhor caracteriza a situação "neste momento" para o quarto principal. Caso não esteja neste compartimento pede-se que se dirija para o mesmo para que possa responder o mais próximo da realidade.

* 4. Selecione as opções que melhor definem o estado do quarto neste momento. Pode indicar mais do que uma opção.

- ☐ Janela(s)/porta(s) para o exterior fechada(s)
- ☐ Janela(s)/porta(s) para o exterior aberta(s)
- ☐ Persiana(s) / portada(s) fechada(s)
- ☐ Persiana(s) / portada(s) aberta(s)
- ☐ Equipamento de arrefecimento desligado (ventoinha, ar-condicionado)
- ☐ Equipamento de arrefecimento ligado (ventoinha, ar-condicionado)

* 5. Sensação relativamente ao conforto térmico no quarto neste momento:

- ☐ Muito frio
- ☐ Frio
- ☐ Ligeiramente frio
- ☐ Neutro (confortável)
- ☐ Ligeiramente quente
- ☐ Quente
- ☐ Muito quente

* 6. Sente algum tipo de desconforto no quarto neste momento? Este pode acontecer devido à temperatura, ar interior (odor, ar "pesado"), iluminação (excesso/escassez de luz, encadeamento), acústica (ruído proveniente de dentro de casa, rua, vizinhos, outros) ou outro.

- ☐ Sim
- ☐ Não

* 7. A que se deve o desconforto sentido no quarto? Pode indicar mais do que um parâmetro.

- ☐ Temperatura
- ☐ Ar interior (odor, ar "pesado", outros)
- ☐ Iluminação (excesso/escassez de luz, encadeamento, outros)
- ☐ Acústica (ruído proveniente de dentro de casa, vizinhos, rua, outros)
- ☐ Outro (especifique)

* 8. Que medida(s) poderá tomar para contrariar o desconforto no quarto? Pode indicar mais do que uma opção.

- ☐ Nenhuma
- ☐ Abrir janelas/portas para o exterior
- ☐ Fechar janelas/portas para o exterior
- ☐ Abrir janelas/portas interiores
- ☐ Fechar janelas/portas interiores
- ☐ Ligar equipamento de arrefecimento (ventoinha, ar-condicionado)
- ☐ Desligar equipamento de arrefecimento (ventoinha, ar-condicionado)
- ☐ Ligar desumidificador
- ☐ Desligar desumidificador
- ☐ Abrir persianas ou outro sombreamento exterior
- ☐ Fechar persianas ou outro sombreamento exterior
- ☐ Abrir sombreamento interior (portadas, cortinas, estores interiores, outros)
- ☐ Fechar sombreamento interior (portadas, cortinas, estores interiores, outros)
- ☐ Tirar roupa
- ☐ Se fez algo, especifique:



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Conforto e bem-estar

Relativamente ao **quarto**:

VAMOS AGORA CONSIDERAR A SITUAÇÃO DO **QUARTO DURANTE O DIA DE HOJE**

* 9. Selecione as opções que melhor definem o estado do quarto durante o dia de hoje. Pode indicar mais do que uma opção.

- ☐ Janela(s)/porta(s) para o exterior sempre fechada(s)
- ☐ Janela(s)/porta(s) para o exterior aberta(s) menos de uma hora
- ☐ Janela(s)/porta(s) para o exterior aberta(s) mais de uma hora
- ☐ Persiana(s) / portada(s) sempre fechada(s)
- ☐ Persianas(s) / portada(s) aberta(s) menos de uma hora
- ☐ Persianas(s) / portada(s) aberta(s) mais de uma hora
- ☐ Equipamento de arrefecimento sempre desligado (ventoinha, ar-condicionado)
- ☐ Equipamento de arrefecimento ligado menos de uma hora (ventoinha, ar-condicionado)
- ☐ Equipamento de arrefecimento ligado mais de uma hora (ventoinha, ar-condicionado)



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Relativamente à **sala**:

Nesta página é pedido que indique a resposta que melhor caracteriza a situação "neste momento" para a sala. Caso não esteja neste compartimento pede-se que se dirija para o mesmo para que possa responder o mais próximo da realidade.

* 10. Selecione as opções que melhor definem o estado da sala neste momento. Pode indicar mais do que uma opção.

- ☐ Janela(s)/porta(s) para o exterior fechada(s)
- ☐ Janela(s)/porta(s) para o exterior aberta(s)
- ☐ Persiana(s) / portada(s) fechada(s)
- ☐ Persiana(s) / portada(s) aberta(s)
- ☐ Equipamento de arrefecimento desligado (ventoinha, ar-condicionado)
- ☐ Equipamento de arrefecimento ligado (ventoinha, ar-condicionado)

* 11. Sensação relativamente ao conforto térmico na sala neste momento:

- ☐ Muito frio
- ☐ Frio
- ☐ Ligeiramente frio
- ☐ Neutro (confortável)
- ☐ Ligeiramente quente
- ☐ Quente
- ☐ Muito quente

* 12. Sente algum tipo de desconforto na sala neste momento? Este pode acontecer devido à temperatura, ar interior (odor, ar "pesado"), iluminação (excesso/escassez de luz, encadeamento), acústica (ruído proveniente de dentro de casa, rua, vizinhos, outros) ou outro.

☐ Sim

☐ Não



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Conforto e bem-estar

* 13. A que se deve o desconforto sentido na sala? Pode indicar mais do que um parâmetro.

☐ Temperatura

☐ Ar interior (odor, ar "pesado", outros)

☐ Iluminação (excesso/escassez de luz, encadeamento, outros)

☐ Acústica (ruído proveniente de dentro de casa, vizinhos, rua, outros)

☐ Outro (especifique)

* 14. Que medida(s) poderá tomar para contrariar o desconforto na sala? Pode indicar mais do que uma opção.

- ☐ Nenhuma
- ☐ Abrir janelas/portas para o exterior
- ☐ Fechar janelas/portas para o exterior
- ☐ Abrir janelas/portas interiores
- ☐ Fechar janelas/portas interiores
- ☐ Ligar equipamento de arrefecimento (ventoinha, ar-condicionado)
- ☐ Desligar equipamento de arrefecimento (ventoinha, ar-condicionado)
- ☐ Ligar desumidificador
- ☐ Desligar desumidificador
- ☐ Abrir persianas ou outro sombreamento exterior
- ☐ Fechar persianas ou outro sombreamento exterior
- ☐ Abrir sombreamento interior (portadas, cortinas, estores interiores, outros)
- ☐ Fechar sombreamento interior (portadas, cortinas, estores interiores, outros)
- ☐ Tirar roupa
- ☐ Se fez algo, especifique:



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Conforto e bem-estar

Relativamente à **sala**:

VAMOS AGORA CONSIDERAR A SITUAÇÃO DA **SALA DURANTE O DIA DE HOJE**

* 15. Selecione as opções que melhor definem o estado da sala durante o dia de hoje. Pode indicar mais do que uma opção.

- ☐ Janela(s)/porta(s) para o exterior sempre fechada(s)
- ☐ Janela(s)/porta(s) para o exterior aberta(s) menos de uma hora
- ☐ Janela(s)/porta(s) para o exterior aberta(s) mais de uma hora
- ☐ Persiana(s) / portada(s) sempre fechada(s)
- ☐ Persianas(s) / portada(s) aberta(s) menos de uma hora
- ☐ Persianas(s) / portada(s) aberta(s) mais de uma hora
- ☐ Equipamento de arrefecimento sempre desligado (ventoinha, ar-condicionado)
- ☐ Equipamento de arrefecimento ligado menos de uma hora (ventoinha, ar-condicionado)
- ☐ Equipamento de arrefecimento ligado mais de uma hora (ventoinha, ar-condicionado)

APPENDIX F – Systematize information from each case study (feedback and measurements)

Table F.1 - Case study 1 summary: comfort and well-being parameters

	Satisfaction parameters			
	Thermal comfort	Air quality	Lighting	Acoustic
Class	2	2	2	2
Extensive survey	• <u>Temperature preference</u>: In summer slightly cooler, and in winter slightly warmer • <u>Thermal sensation</u>: Comfortable in summer and winter • <u>Use of air-conditioning</u>: often in winter and always/almost always in summer • <u>Heating/Cooling system preference</u>: Automatic	• <u>Window opening</u>: often in winter and always/almost always in summer • In summer and winter, open the windows as often as want • <u>Humidity</u>: doesn't exist • <u>Odour</u>: doesn't exist • <u>Ventilation system preference</u>: Automatic	• <u>Natural lighting</u>: bright in summer and comfortable in winter • <u>Use of artificial lighting</u>: Switches on only when it gets dark and in rooms where people are present • <u>Use of solar shading</u>: in summer, always/almost always, and in winter, never/almost never • <u>Shading system preference</u>: Manual • <u>Lighting system preference</u>: Manual	• <u>Noise sources that cause discomfort</u>: outside slightly disturbing in summer and winter. Neighbours slightly disturbing in winter
Right-now survey	• <u>Thermal sensation</u>: Comfortable in summer and mostly slightly cool in winter (sometimes indicates comfortable) • <u>Use of air-conditioning</u>: off in winter and in summer	• <u>Window opening</u>: in winter, during the day, are closed. In summer, during the day, are mostly open more than 1 hour	• <u>Use of solar shading</u>: In winter and in summer, during the day, the blinds are open more than 1 hour	-
Measurements	<u>Annual</u> • Winter (T, RH): 17.5°C, 45.1% • Summer (T, RH): 25.1°C, 54.8% <u>14-days</u> • Winter (T, RH): 16.9°C, 50.9% • Summer (T, RH): 24.7°C, 53.5%	<u>14-days</u> • Winter (CO₂): 501 ppm • Summer (CO₂): 463 ppm	-	-
Importance of some aspects	• <u>Energy efficient equipment</u>: Important • <u>Passive systems</u>: Important • <u>Materials with other recycled materials, low energy consumption and less pollution</u>: Not important • <u>View</u>: Very important and very interesting • <u>Biophilia</u>: Important			
Improvement measures priority	• <u>Priority</u>: cooling equipment and solar panel • <u>Already realized</u>: Did not identify any of the options			

Table F.2 - Case study 1 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)

	Satisfaction parameters			
	Privacy	Maintenance	Furniture and others	Global
Class	-	-	-	-
Extensive survey	-	-	-	• <u>Positive points</u>: Comfort, view, sun exposure • <u>Negative points</u>: Degradation of materials, broken appliances, condominium

Table F.3 - Case study 2 summary: comfort and well-being parameters

	Satisfaction parameters			
	Thermal comfort	Air quality	Lighting	Acoustic
Class	1	1	3	3
Extensive survey	• <u>Temperature preference</u>: In summer slightly cooler and in winter slightly warmer • <u>Thermal sensation</u>: slightly cool in winter and slightly warm in summer • <u>Use of air-conditioning</u>: never/almost never in winter and often in summer • <u>Heating/Cooling system preference</u>: Automatic and Manual	• <u>Window opening</u>: always/almost always in winter and summer • In summer and winter open the windows as often as want • <u>Humidity</u>: bathroom, main bedroom and secondary bedroom. The secondary bedroom is the most disturbing. • <u>Odour</u>: doesn't exist • <u>Ventilation system preference</u>: Manual	• <u>Natural lighting</u>: Comfortable in summer and winter • <u>Use of artificial lighting</u>: Switches on only when it gets dark and in rooms where people are present • <u>Use of solar shading</u>: in summer always/almost always and in winter infrequently • <u>Shading system preference</u>: Manual • <u>Lighting system preference</u>: Manual	• <u>Noise sources that cause discomfort</u>: Common areas slightly disturbing in summer and winter. Outside, HVAC equipment and water drainage slightly disturbing in winter. People indoors slightly disturbing in summer
Right-now survey	• <u>Thermal sensation</u>: Mostly comfortable in summer and in winter (sometimes indicates slightly warm and slightly cool) • <u>Use of air-conditioning</u>: off in winter and in summer	• <u>Window opening</u>: in winter and in summer, during the day, are open more than 1 hour	• <u>Use of solar shading</u>: In winter and in summer, during the day, the blinds are open more than 1 hour	-
Measurements	<u>Annual</u> • Winter (T, RH): 19.0°C, 70.2% • Summer (T, RH): 26.7°C, 49.2% <u>14-days</u> • Winter (T, RH): 19.0°C, 67.8% • Summer (T, RH): 25.2°C, 61.5%	<u>14-days</u> • Winter (CO₂): 945 ppm • Summer (CO₂): 490 ppm	-	-
Importance of some aspects	• <u>Energy efficient equipment</u>: Very important • <u>Passive systems</u>: Important • <u>Materials with other recycled materials, low energy consumption and less pollution</u>: Not important • <u>View</u>: Important and uninteresting • <u>Biophilia</u>: Very important			
Improvement measures priority	• <u>Priority</u>: heating equipment • <u>Very high priority</u>: solar panel • <u>Already realised</u>: thermal insulation of roof and walls, windows, sunshades, light bulbs			

Table F.4 - Case study 2 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)

	Satisfaction parameters			
	Privacy	Maintenance	Furniture and others	Global
Class	2	-	-	-
Extensive survey	-	-	-	• <u>Positive points</u>: Furniture, acoustic, lighting • <u>Negative points</u>: View, winter thermal comfort, humidity

Table F.5 - Case study 3 summary: comfort and well-being parameters

	Satisfaction parameters			
	Thermal comfort	Air quality	Lighting	Acoustic
Class	1	-	-	-
Extensive survey	• <u>Temperature preference</u>: in summer slightly cooler, and in winter much hotter • <u>Thermal sensation</u>: cool in winter and slightly warm in summer. • <u>Use of air-conditioning</u>: wood heating in winter and always/almost always cooling in summer • <u>Heating/Cooling system preference</u>: Automatic and Manual	• <u>Window opening</u>: always/almost always in winter and summer • In summer and winter, maybe open the windows as often as want. In summer is to maintain the temperature and to prevent insects/mosquitoes from entering. In winter it's due to the absence of the house. • <u>Humidity</u>: main bedroom and is slightly disturbing • <u>Odour</u>: doesn't exist in summer. In winter is very weak and they are neutral and casual. • <u>Ventilation system preference</u>: Automatic and Manual	• <u>Natural lighting</u>: Comfortable in summer and winter • <u>Use of artificial lighting</u>: Switches on only when it gets dark and in rooms where people are present • <u>Use of solar shading</u>: always/almost always in winter and summer • <u>Shading system preference</u>: Automatic and Manual • <u>Lighting system preference</u>: Manual	• <u>Noise sources that cause discomfort</u>: outside and neighbours slightly disturbing in summer and winter. Slightly disturbing in summer from the water drainage system. Slightly disturbing in winter with people inside the house.
Right-now survey	• <u>Thermal sensation</u>: Mostly comfortable in summer and in winter (sometimes indicates slightly warm and slightly cool) • <u>Use of air-conditioning</u>: off in winter and in summer	• <u>Window opening</u>: in winter, during the day, are mostly closed. In summer, during the day, are open less than 1 hour	• <u>Use of solar shading</u>: In winter and in summer, during the day, the blinds are open more than 1 hour	-
Measurements	<u>Annual</u> • Winter (T, RH): 16.9°C, 63.5% • Summer (T, RH): 23.5°C, 71.8% <u>14-days</u> • Winter (T, RH): 17.0°C, 59.7% • Summer (T, RH): 23.2°C, 70.5%	<u>14-days</u> • Winter (CO₂): 793 ppm • Summer (CO₂): 676 ppm	-	-
Importance of some aspects	• <u>Energy efficient equipment</u>: Very important • <u>Passive systems</u>: Very important • <u>Materials with other recycled materials, low energy consumption and less pollution</u>: Very important • <u>View</u>: Important and interesting • <u>Biophilia</u>: Very important			
Improvement measures priority	• <u>Priority</u>: house equipment and solar panel • <u>Very priority</u>: heating equipment and windows • <u>Already realised</u>: thermal insulation of roof and walls, sunshades, light bulbs			

Table F.6 - Case study 3 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)

	Satisfaction parameters			
	Privacy	Maintenance	Furniture and others	Global
Class	-	-	-	-
Extensive survey	-	-	-	• <u>Positive points</u>: Location (far from the city centre), privacy, central vacuum, pre-installation for ac and central heating • <u>Negative points</u>: Wood-burning fireplace, aluminium tilt windows

Table F.7 - Case study 4 summary: comfort and well-being parameters

	Satisfaction parameters			
	Thermal comfort	Air quality	Lighting	Acoustic
Class	1	-	-	1
Extensive survey	• <u>Temperature preference</u>: much colder in summer and much hotter in winter • <u>Thermal sensation</u>: cold in winter and hot in summer • <u>Use of air-conditioning</u>: infrequently in winter and summer. • <u>Heating/Cooling system preference</u>: Manual	• <u>Window opening</u>: infrequently in winter and always/almost always in summer • In summer and winter doesn't open the windows as often as want. In summer is to prevent insects/mosquitoes from entering. In winter is to maintain the temperature and to prevent insects/mosquitoes from entering • <u>Humidity</u>: bathroom, main bedroom, living room and sunroom. The bathroom is the most disturbing, followed by the sunroom and slightly disturbing the living room and bedroom • <u>Odour</u>: very weak in winter and moderate in summer. Unpleasant in summer and winter. Casual in winter and persistent in summer. • <u>Ventilation system preference</u>: Manual	• <u>Natural lighting</u>: bright in summer and slightly bright in winter • <u>Use of artificial lighting</u>: in summer switches on when it gets dark and in several compartments, and in winter switches on practically all day long • <u>Use of solar shading</u>: always/almost always in summer and often in winter • <u>Shading system preference</u>: Manual • <u>Lighting system preference</u>: Manual	• <u>Noise sources that cause discomfort</u>: In summer slightly disturbing from the water drainage system and outside. neighbours disturbing in summer. In winter slightly disturbing from equipment inside home, water drainage system and HVAC equipment. In winter disturbing from outside and very disturbing from the neighbours
Right-now survey	• <u>Thermal sensation</u>: Mostly slightly cool in winter and slightly warm in summer (sometimes indicates comfortable and warm) • <u>Use of air-conditioning</u>: in winter, during the day, is off. In summer, during the day, is on more than 1 hour	• <u>Window opening</u>: in winter and in summer, during the day, are closed	• <u>Use of solar shading</u>: In winter and in summer, during the day, the blinds are open more than 1 hour	-
Measurements	<u>Annual</u> • Winter (T, RH): 16.1 °C, 70.3% • Summer (T, RH): 27.5 °C, 49.6% <u>14-days</u> • Winter (T, RH): 16.1 °C, 66.9% • Summer (T, RH): 26.3 °C, 53.6%	<u>14-days</u> • Winter (CO₂): 668 ppm • Summer (CO₂): 586 ppm	-	-
Importance of some aspects	• <u>Energy efficient equipment</u>: Important • <u>Passive systems</u>: Important • <u>Materials with other recycled materials, low energy consumption and less pollution</u>: Important • <u>View</u>: Very important and very uninteresting • <u>Biophilia</u>: Important			
Improvement measures priority	• <u>Priority</u>: heating and cooling equipment, thermal insulation of roof and walls, windows, sunshades, light bulbs • <u>Already realized</u>: Did not identify any of the options			

Table F.8 - Case study 4 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)

	Satisfaction parameters			
	Privacy	Maintenance	Furniture and others	Global
Class	-	-	-	-
Extensive survey	-	-	-	• Positive points: Location, interior furnishings and well-oriented • Negative points: Humidity/Mould, old floors, plumbing odours

Table F.9 - Case study 5 summary: comfort and well-being parameters

	Satisfaction parameters			
	Thermal comfort	Air quality	Lighting	Acoustic
Class	1	-	-	-
Extensive survey	• Temperature preference: In summer slightly cooler, and in winter warmer • Thermal sensation: Cool in winter and slightly warm in summer • Use of air-conditioning: infrequently in winter and always/almost always in summer • Heating/Cooling system preference: Automatic	• Window opening: often in winter and always/almost always in summer • In summer, open the windows as often as want. In winter no, to maintain the temperature • Humidity: bathroom, main bedroom and secondary bedroom. All disturbing. • Odour: doesn't exist in summer. In winter is very weak, and they are neutral and casual • Ventilation system preference: Automatic	• Natural lighting: Comfortable in summer and winter • Use of artificial lighting: Switches on only when it gets dark and in rooms where people are present • Use of solar shading: always/almost always in summer and in winter • Shading system preference: Automatic • Lighting system preference: Manual	• Noise sources that cause discomfort: outside slightly disturbing in winter. In summer disturbing from outside and neighbours and very disturbing from people inside the house
Right-now survey	• Thermal sensation: Comfortable in winter and mostly in summer (sometimes indicates slightly warm) • Use of air-conditioning: off in winter and in summer	• Window opening: In winter and in summer, during the day, are open more than 1 hour	• Use of solar shading: In winter and in summer, during the day, the blinds are open more than 1 hour	-
Measurements	<u>Annual</u> • Winter (T, RH): 15.8 °C, 76.1% • Summer (T, RH): 23.7 °C, 69.5% <u>14-days</u> • Winter (T, RH): 16.3 °C, 73.7% • Summer (T, RH): 24.5 °C, 67.8%	<u>14-days</u> • Winter (CO₂): 736 ppm • Summer (CO₂): 638 ppm	-	-
Importance of some aspects	• Energy efficient equipment: Very important • Passive systems: Very important • Materials with other recycled materials, low energy consumption and less pollution: Very important • View: Very important and neutral • Biophilia: Very important			
Improvement measures priority	• Priority: thermal insulation of roof and walls • Very high priority: solar panel • Already realised: light bulbs, equipment			

Table F.10 - Case study 5 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)

	Satisfaction parameters			
	Privacy	Maintenance	Furniture and others	Global
Class	-	-	-	-
Extensive survey	-	-	-	• Positive points: Small areas, garden, location • Negative points: Old, not connected to basic sanitation

Table F.11 - Case study 6 summary: comfort and well-being parameters

	Satisfaction parameters			
	Thermal comfort	Air quality	Lighting	Acoustic
Class	1	1	1	2
Extensive survey	• Temperature preference: In summer cooler and in winter, slightly warmer for P1. For P2 unchanged in summer and warmer in winter • Thermal sensation: In winter slightly cool, and in summer warm • Use of air-conditioning: P2 often and P1 always/almost always in winter. In summer, always/almost always both occupants. • Heating/Cooling system preference: P1 Automatic and Manual and P2 Manual	• Window opening: P2 often in winter and P1 always/almost always. In summer, always/almost always, both occupants. • In summer, P1 open the windows as often as want and P2 maybe to prevent insects/mosquitoes and dust from entering. In winter, P1 open the windows as often as want and P2 no, to maintain the temperature. • Humidity: bathroom, main bedroom and kitchen. The bedroom is the most disturbing, followed by the bathroom and then kitchen • Odour: for P1 doesn't exist in summer and winter. For P2, there is a very weak odour in summer and winter, neutral and casual • Ventilation system preference: P1 Automatic and Manual and P2 Manual	• Natural lighting: slightly dark in summer and winter • Use of artificial lighting: switch on regularly during the day, especially on dark days in summer and in winter, switch on practically all day long • Use of solar shading: always/almost always in summer and in winter • Shading system preference: P1 Automatic and Manual and P2 Manual • Lighting system preference: P1 Automatic and Manual and P2 Manual	• Noise sources that cause discomfort: P1 in summer is disturbed by the outside, neighbours and building common areas. In summer, P2 is disturbed by the outside, common areas of the building, neighbours, hvac equipment and water drainage. In winter, P2 is disturbed by neighbours, water drainage, building common areas, hvac equipment, equipment inside the house and people inside the house
Right-now survey	• Thermal sensation: Mostly comfortable and slightly cool in winter and mostly comfortable and slightly warm in summer (sometimes indicates warm, hot and cool) • Use of air-conditioning: Mostly on (no pattern related to the hours)	• Window opening: In winter, during the day, are open (no pattern related to the hours). In summer, during the day, are open more than 1 hour	• Use of solar shading: In winter, during the day, the blinds are open less than 1 hour or closed (no pattern). In summer, during the day, the blinds are open more than 1 hour	-
Measurements	<u>Annual</u> • Winter (T, RH): 19.2 °C, 64.2% • Summer (T, RH): 27.4 °C, 59.5% <u>14-days</u> • Winter (T, RH): 19.3 °C, 59.0% • Summer (T, RH): 27.2 °C, 57.6%	<u>14-days</u> • Winter (CO₂): 975 ppm • Summer (CO₂): 905 ppm	-	-
Importance of some aspects	• Energy efficient equipment: Very important • Passive systems: Very important • Materials with other recycled materials, low energy consumption and less pollution: Very important • View: Important. For P1 is uninteresting and for P2 very uninteresting • Biophilia: Important			
Improvement measures priority	• Priority: heating and cooling equipment • Very high priority: solar panel • Already realised: windows, sunshades, light bulbs, equipment			

Table F.12 - Case study 6 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)

	Satisfaction parameters			
	Privacy	Maintenance	Furniture and others	Global
Class	2	-	-	-
Extensive survey	-	-	-	• Positive points: Location, indoor finishes, recently renovated; small (easy to maintain); rental value • Negative points: Small areas, interior living room, rear orientation; layout of rooms

Table F.13 - Case study 7 summary: comfort and well-being parameters

	Satisfaction parameters			
	Thermal comfort	Air quality	Lighting	Acoustic
Class	1	1	1	2
Extensive survey	• Temperature preference: In summer much colder. In winter, P1 unchanged and P2 warmer • Thermal sensation: in winter P1 comfortable and P2 cool. In summer hot for both occupants • Use of air-conditioning: P2 always/almost always and P1 never/almost never in winter. In summer P2 always/almost always and P1 often • Heating/Cooling system preference: Manual	• Window opening: infrequently in winter. In summer P1 often and P2 always/almost always • In summer P2 maybe open the windows as often as want and P1 no to maintain the temperature. In winter doesn't open the windows as often as want to maintain the temperature and P2 adds that is to prevent entering insects/mosquitoes. • Humidity: bathroom, main and secondary bedroom, kitchen, living room and corridor. The bedrooms are the most disturbing, followed by the bathroom, kitchen and living room, and corridor • Odour: doesn't exist in summer and winter • Ventilation system preference: Manual	• Natural lighting: in summer P1 says bright and P2 comfortable. In winter P1 says slightly bright and P2 dark • Use of artificial lighting: In summer switches on only when it gets dark and in rooms where people are present. In winter P1 switches on only when it gets dark and in rooms where people are present and P2 switches on regularly during the day, especially on darker days • Use of solar shading: always/almost always in summer. In winter P2 always/almost always and P1 never/almost never • Shading system preference: Manual • Lighting system preference: Manual	• Noise sources that cause discomfort: P1 in summer is disturbed by the outside. P2 is disturbed by the outside, equipment inside the house and very disturbed with neighbours. In winter, P2 is disturbed by the building common areas, neighbours and very disturbed with equipment inside the house
Right-now survey	• Thermal sensation: Mostly comfortable in winter and mostly comfortable and warm in summer (sometimes indicates slightly cool) • Use of air-conditioning: off in winter and mostly more than 1 hour in summer	• Window opening: In winter and in summer, during the day, are closed	• Use of solar shading: In winter, during the day, the blinds are open more than 1 hour. In summer, during the day, the blinds are closed	-
Measurements	<u>Annual</u> • Winter (T, RH): 17.9 °C, 72.6% • Summer (T, RH): 27.6 °C, 42.6% <u>14-days</u> • Winter (T, RH): 19.1 °C, 75.3% • Summer (T, RH): 27.4 °C, 45.3%	<u>14-days</u> • Winter (CO₂): 1050 ppm • Summer (CO₂): 681ppm	-	-
Importance of some aspects	• Energy efficient equipment: Very important • Passive systems: Important • Materials with other recycled materials, low energy consumption and less pollution: Important • View: For P1 is important and interesting. For P2 is very important and very interesting • Biophilia: Important for P1 and not important for P2			
Improvement measures priority	• Priority: ventilation equipment, windows and thermal insulation of roof and walls • Already realised: heating and cooling equipment, light bulbs, house equipment			

Table F.14 - Case study 7 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)

	Satisfaction parameters			
	Privacy	Maintenance	Furniture and others	Global
Class	2	1	-	-
Extensive survey	-	-	-	• Positive points: Natural light, view, typology T3, areas, laundry • Negative points: High temperatures in summer, no lift, lack of building exterior painting and roof waterproofing (building top floor), interior bathrooms and corridor without natural light and ventilation

Table F.15 - Case study 8 summary: comfort and well-being parameters

	Satisfaction parameters			
	Thermal comfort	Air quality	Lighting	Acoustic
Class	-	1	-	1
Extensive survey	• Temperature preference: in summer slightly cooler, and in winter unchanged • Thermal sensation: in summer P1 warm and P2 comfortable. In winter slightly warm for both occupants • Use of air-conditioning: often in winter and summer • Heating/Cooling system preference: P1 Automatic and P2 Automatic and Manual	• Window opening: always/almost always in summer. In winter P1 often and P2 infrequently • In summer P1 open the windows as often as want, and P2 no to maintain the temperature to prevent insects/mosquitoes and dust from entering. In winter, P2 open the windows as often as want and P1 maybe as often as want, to prevent dust from entering • Humidity: secondary bedroom is slightly disturbing • Odour: doesn't exist in summer and winter for P2. For P1 there is a very weak odour in summer and winter, unpleasant and casual • Ventilation system preference: P1 Automatic and P2 Automatic and Manual	• Natural lighting: slightly bright in summer and in winter • Use of artificial lighting: In summer P1 switches on only when it starts to get dark in various rooms of the house, while P2 only switches on in rooms with people. In winter P2 switches on only when it starts to get dark in various rooms, while P1 only switches on in rooms with people • Use of solar shading: in summer always/almost always. In winter P1 often and P2 never/almost never • Shading system preference: P1 Manual and P2 Automatic and Manual • Lighting system preference: P1 Automatic and P2 Automatic and Manual	• Noise sources that cause discomfort: outside disturbing in summer and neighbours very disturbing. P2 also disturbed with HVAC equipments. In winter disturbing with outsider and people inside house. P1 also very disturbed with neighbours and P2 disturbed with equipment inside the house
Right-now survey	• Thermal sensation: Mostly comfortable in winter and mostly comfortable and slightly warm in summer (sometimes slightly cool) • Use of air-conditioning: Off in winter and in summer	• Window opening: In winter, during the day, are closed. In summer, during the day, are open more than 1 hour	• Use of solar shading: In winter and in summer, during the day, the blinds are open more than 1 hour	-
Measurements	Annual • Winter (T, RH): 18.5 °C, 66.1% • Summer (T, RH): 26.6 °C, 47.5% 14-days • Winter (T, RH): 19.7 °C, 65.9% • Summer (T, RH): 25.0 °C, 56.6%	14-days • Winter (CO₂): 951 ppm • Summer (CO₂): 503 ppm	-	-
Importance of some aspects	• Energy efficient equipment: Important • Passive systems: Not important • Materials with other recycled materials, low energy consumption and less pollution: Not important • Vista: Very important. For P1 is neutral and for P2 is interesting • Biophilia: Important for P1 and very important for P2			

	Satisfaction parameters			
	Thermal comfort	Air quality	Lighting	Acoustic
Improvement measures priority	• <u>Priority</u>: light bulbs, sunshades, cooling equipment and ventilation equipment • <u>Very high priority</u>: heating equipment • <u>Already realised</u>: windows			

Table F.16 - Case study 8 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)

	Satisfaction parameters			
	Privacy	Maintenance	Furniture and others	Global
Class	1	-	-	-
Extensive survey	-	-	-	• <u>Positive points</u>: Light; quality of materials; state of conservation; outdoor deck, duplex; only one unit with neighbours; riverside location • <u>Negative points</u>: Lack of storage room, airshaft that reverberates the noise caused by the neighbour's dogs; no storage room/garage

Table F.17 - Case study 9 summary: comfort and well-being parameters

	Satisfaction parameters			
	Thermal comfort	Air quality	Lighting	Acoustic
Class	1	-	-	-
Extensive survey	• <u>Temperature preference</u>: in summer slightly cooler, and in winter P1 warmer and P2 slightly warmer • <u>Thermal sensation</u>: slightly warm in summer and slightly cool in winter • <u>Use of air-conditioning</u>: in winter always/almost always, and often in summer • <u>Heating/Cooling system preference</u>: P1 Manual and P2 Automatic and Manual	• <u>Window opening</u>: always/almost always in summer and in winter. In summer open the windows as often as want but in winter no, to maintain the temperature. • <u>Humidity</u>: bathroom. Very disturbing for P1 and slightly disturbing for P2 • <u>Odour</u>: Moderate in winter. The odour is casual and unpleasant for P1 and persistent and neutral for P2. The odour in summer for P1 is moderate, and for P2 weak. The odour is casual and unpleasant for P1 and casual and neutral for P2 • <u>Ventilation system preference</u>: Manual	• <u>Natural lighting</u>: in summer bright for P1 and comfortable for P2. In winter bright for P1 and slightly bright for P2 • <u>Use of artificial lighting</u>: In summer switch on only when it gets dark and in rooms where people are present. In winter, P1 switches on practically all day, and P2 switches on only when it gets dark and in rooms where people are present • <u>Use of solar shading</u>: always/almost always in summer and in winter • <u>Shading system preference</u>: Manual • <u>Lighting system preference</u>: Manual	• <u>Noise sources that cause discomfort</u>: In summer disturbed with water drainage and people inside the house. P1 also disturbed with equipment inside the house. In winter P1 disturbed with water drainage and people inside the house
Right-now survey	• <u>Thermal sensation</u>: Mostly comfortable in winter and in summer (sometimes indicates slightly cool, slightly warm and warm) • <u>Use of air-conditioning</u>: mostly on more than 1 hour in winter and off in summer	• <u>Window opening</u>: In winter and in summer, during the day, are open more than 1 hour	• <u>Use of solar shading</u>: In winter and in summer, during the day, the blinds are open more than 1 hour	-
Measurements	<u>Annual</u> • Winter (T, RH): 15.6 °C, 56.9% • Summer (T, RH): 24.0 °C, 53.8% <u>14-days</u> • Winter (T, RH): 14.7 °C, 54.2% • Summer (T, RH): 25.5 °C, 46.4%	<u>14-days</u> • Winter (CO₂): 703 ppm • Summer (CO₂): 432 ppm	-	-
Importance of some aspects	• <u>Energy efficient equipment</u>: Very important • <u>Passive systems</u>: Very important			

	Satisfaction parameters			
	Thermal comfort	Air quality	Lighting	Acoustic
	• <u>Materials with other recycled materials, low energy consumption and less pollution</u>: Very important • <u>View</u>: For P1 is important and neutral. For P2 is very important and neutral • <u>Biophilia</u>: Important for P1 and very important for P2			
Improvement measures priority	• <u>Priority</u>: heating, cooling and ventilation equipment • <u>Very high priority</u>: thermal insulation of roof and walls • <u>Already realised</u>: windows, sunshades, light bulbs, equipment, solar panel			

Table F.18 - Case study 9 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)

	Satisfaction parameters			
	Privacy	Maintenance	Furniture and others	Global
Class	-	1	2	-
Extensive survey	-	-	-	• <u>Positive points</u>: Rooms dimensions, garden • <u>Negative points</u>: Lots of stairs, interior rooms (living room and bathroom)

Table F.19 - Case study 10 summary: comfort and well-being parameters

	Satisfaction parameters			
	Thermal comfort	Air quality	Lighting	Acoustic
Class	1	2	2	-
Extensive survey	• <u>Temperature preference</u>: in summer slightly cooler and in winter slightly warmer • <u>Thermal sensation</u>: in summer P1 slightly warm and P2 warm. In winter both are comfortable • <u>Use of air-conditioning</u>: wood heating in winter and infrequently cooling in summer • <u>Heating/Cooling system preference</u>: Automatic and Manual	• <u>Window opening</u>: in summer always/almost always and infrequently in winter • In summer open the windows as often as want. In winter P2 open the windows as often as want but P1 no, due to winter time. • <u>Humidity</u>: bathroom. For P1 is slightly disturbing and for P2 is disturbing • <u>Odour</u>: doesn't exist in summer and winter • <u>Ventilation system preference</u>: Automatic and Manual	• <u>Natural lighting</u>: P1 comfortable and bright for P2 in summer. In winter, P1 comfortable and slightly dark for P2 • <u>Use of artificial lighting</u>: In summer switch on only when it gets dark and in rooms where people are present. In winter switch on regularly during the day, especially on darker days • <u>Use of solar shading</u>: always/almost always in summer and in winter • <u>Shading system preference</u>: Automatic and Manual • <u>Lighting system preference</u>: Automatic and Manual	• <u>Noise sources that cause discomfort</u>: Disturbing with equipment inside the house, water drainage, building common areas, neighbours and outside. P2 also disturbed with HVAC equipment. In winter, disturbed with water drainage, HVAC equipment, and outside. P1 also disturbed with equipment inside the house, and P2 with building common areas and neighbours
Right-now survey	• <u>Thermal sensation</u>: Mostly comfortable in winter and in summer (sometimes indicates slightly cool and slightly warm) • <u>Use of air-conditioning</u>: off in winter and in summer	• <u>Window opening</u>: In winter and in summer, during the day, are closed	• <u>Use of solar shading</u>: In winter and in summer, during the day, the blinds are open more than 1 hour	-
Measurements	<u>Annual</u> • Winter (T, RH): 18.4 °C, 67.1% • Summer (T, RH): 25.6 °C, 42.2% <u>14-days</u> • Winter (T, RH): 18.6 °C, 65.5% • Summer (T, RH): 25.2 °C, 60.5%	<u>14-days</u> • Winter (CO₂): 673 ppm • Summer (CO₂): 616 ppm	-	-
Importance of some aspects	• <u>Energy efficient equipment</u>: Very important • <u>Passive systems</u>: Very important • <u>Materials with other recycled materials, low energy consumption and less pollution</u>: Important • <u>View</u>: Very important and interesting			

	Satisfaction parameters			
	Thermal comfort	Air quality	Lighting	Acoustic
	• <u>Biophilia</u> : Very important for P1 and neutral for P2			
Improvement measures	• <u>Priority</u> : solar panel, house equipment and heating equipment			
priority	• <u>Very high priority</u> : cooling equipment			
	• <u>Already realised</u> : windows, sunshades, light bulbs			

Table F.20 - Case study 10 summary: comfort and well-being parameters (privacy, maintenance, furniture and others and global)

	Satisfaction parameters			
	Privacy	Maintenance	Furniture and others	Global
Class	1	-	-	-
Extensive survey	-	-	-	• <u>Positive points</u>: House layout, solar orientation, absence of noise, view, acoustics and thermals quality <u>Negative points</u>: Lack of cooling system, constructive quality of the walls, inefficient boiler, no AC, privacy, more balconies