TESE DE DOUTORAMENTO

ANALYSIS OF TECHNIQUES FOR SUSTAINABLE AND COMFORTABLE BUILDINGS: A CONTRIBUTION FROM CIRCULAR TO REGENERATIVE ECONOMY

ANDRÉS VILABOA DÍAZ

ESCOLA DE DOUTORAMENTO INTERNACIONAL DA UNIVERSIDADE DE SANTIAGO DE COMPOSTELA
PROGRAMA DE DOCTORADO EN ENERGÍAS RENOVABLES Y SOSTENIBILIDAD ENERGÉTICA

SANTIAGO DE COMPOSTELA
2021

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

DECLARACIÓN DO AUTOR DA TESE

Analysis of techniques for sustainable and comfortable buildings: a contribution from circular to regenerative economy

D. Andrés Vilaboa Díaz

Presento a miña tese, seguindo o procedemento axeitado ao Regulamento, e declaro que:

1) A tese abarca os resultados da elaboración do meu traballo.
2) De ser o caso, na tese faise referencia ás colaboracións que tivo este traballo.
3) Confirmo que a tese non incorre en ningún tipo de plaxio doutros autores nin de traballos presentados por min para a obtención doutros títulos.
4) A tese é a versión definitiva presentada para a súa defensa e coincide a versión impresa coa presentada en formato electrónico

E comprométome a presentar o Compromiso Documental de Supervisión no caso de que o orixinal non estea na Escola.

En Santiago de Compostela, 7 de Outubro de 2021

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

AUTORIZACIÓN DA DIRECTORA E TITORA DA TESE

Analysis of techniques for sustainable and comfortable buildings: a contribution from circular to regenerative economy

Profa. Dra. Dª. Pastora María Bello Bugallo

INFORMA:

Que a presente tese, correspóndese co traballo realizado por D. Andrés Vilaboa Díaz, baixo a miña dirección/titorización, e autorizo a súa presentación, considerando que reúne os requisitos esixidos no Regulamento de Estudos de Doutoramento da USC, e que como directora desta non incorre nas causas de abstención establecidas na Lei 40/2015.

De acordo co indicado no Regulamento de Estudos de Doutoramento, declara tamén que a presente tese de doutoramento é idónea para ser defendida en base á modalidade de Monográfica con reproducción de publicaciones, nos que a participación do doutorando foi decisiva para a súa elaboración e as publicacións se axustan ao Plan de Investigación.

En Santiago de Compostela, 7 de Outubro de 2021

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

TABLE OF CONTENTS

INDEX OF FIGURES VII

INDEX OF TABLES XI

INDEX OF ACRONYMS XIII

INDEX OF NOMENCLATURES XVII

SUMMARY 1

RESUMEN 3

RESUMO 7

CHAPTER 1. INTRODUCTION 17

1.1. OVERVIEW OF CONSTRUCTION SECTOR 17
1.2. ENERGY POLICIES 24
1.3. ENERGY POLICIES IN BUILDINGS 29
1.4. SUSTAINABLE BUILDINGS 31
1.5. TOWARDS TO REGENERATIVE ECONOMY 38

CHAPTER 2. OBJECTIVES 43

CHAPTER 3. METHODOLOGY 47

CHAPTER 4. STUDY OF THE EFFECTS OF MASS AND THERMAL INERTIA IN BUILDINGS AND THEIR IMPLICATIONS IN THE INDOOR TEMPERATURE 51

SUMMARY 53
4.1. INTRODUCTION 55
4.2. THEORETICAL CONCEPTS 61
4.3. OBJECTIVES 63
4.4. CASE STUDY 64
4.5. METHODOLOGY 64
4.6. DEVELOPMENT AND PRESENTATION OF RESULTS 66
4.6.1. Mathematical model to describe the behaviour of a single-layer wall 66

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

4.6.1.1. Analysis of a single-layer wall ... 71
4.6.1.2. Analysis of the system behaviour to different disturbances ... 75
4.6.1.3. Analysis in the frequency domain ... 78
4.6.1.4. Relationship between the number of nodes and the accurate of the mathematical model ... 80
4.6.2. Study of the thermal inertia of materials ... 82
4.6.3. Study on the placement of isolation ... 86
4.6.3.1. Analysis of heat flow ... 90
4.6.4. Study of the temperature inside a building ... 91
4.6.4.1. Simulation of the temperature inside a building ... 97
4.7. DISCUSSION ... 100
4.8. CONCLUSIONS ... 104

CHAPTER 5. ENERGY EFFICIENCY IN BUILDINGS THE RELEVANCE OF SOLAR INPUTS AND THERMAL INERTIA 107

SUMMARY ... 109
5.1. INTRODUCTION ... 111
5.2. THEORETICAL CONCEPTS ... 114
5.2.1. Solar radiation ... 114
5.2.1.1. Obtaining of the coefficients A, B and C of Stephenson and Threlked model. 118
5.2.1.2. Sol-air temperature ... 120
5.3. OBJECTIVES ... 121
5.4. CASE STUDY ... 122
5.5. METHODOLOGY ... 123
5.6. DEVELOPMENT AND PRESENTATION OF RESULTS ... 124
5.6.1. Study of the influence of solar radiation through walls ... 126
5.6.2. Study of the influence of solar radiation through windows . 131
5.7. DISCUSSION ... 134
5.8. CONCLUSIONS ... 135

CHAPTER 6. ANALYSIS OF ECO-MATERIALS IN THE CONSTRUCTION SECTOR: EVALUATION OF THERMAL BEHAVIOUR AND LIFE CYCLE ASSESSMENT ... 137

SUMMARY ... 139
6.1. INTRODUCTION ... 141
6.2. OBJECTIVES ... 144
6.3. CASE STUDY ... 145
6.4. METHODOLOGY ... 147
6.5. DEVELOPMENT AND PRESENTATION OF RESULTS ... 148
6.5.1. Analysis of eco-materials from waste ... 148

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

6.5.1.1. Eco-materials from agricultural wastes 148
6.5.1.2. Eco-materials from industry waste 150
6.5.1.3. Eco-materials from sludge of water treatment plant (SWTP)..... 151
6.5.1.4. Eco-materials from plastic waste 152
6.5.1.5. Eco-materials from construction waste..... 153
6.5.1.6. Eco-materials from mining and quarrying waste 154
6.5.2. Selection of eco-materials to study..... 155
6.5.2.1. Hemp Concrete 155
6.5.2.2. Isotex 156
6.5.2.3. Olive Core Flour (OCF) 156
6.5.2.4. Wheat Straw (WS) 157
6.5.2.5. Summary of selected eco-materials 157
6.5.3. Analysis of the thermal behaviour of the eco-materials 159
6.5.4. Analysis of energy demand for different case studies..... 161
6.5.5. Environmental impact analysis 169
6.6. DISCUSSION 172
6.7. CONCLUSIONS 175

CHAPTER 7. STUDY OF THE INFLUENCE OF SOLAR SHADOW DEVICES IN THE SOLAR INPUTS OF BUILDINGS179

SUMMARY 181
7.1. INTRODUCTION 183
7.2. THEORETICAL CONCEPTS 186
7.3. OBJECTIVE 187
7.4. CASE STUDY 187
7.5. METHODOLOGY 188
7.6. DEVELOPMENT AND PRESENTATION OF RESULTS 189
7.6.1. Summary of the solar control device for buildings 189
7.6.2. Study of the influence of the windows properties in solar contributions 196
7.6.3. Study of the influence of fixed solar shading device in solar contributions 198
7.6.3.1. Study of the overhang length 202
7.6.3.2. Study of the overhang length and g-value of window 206
7.6.4. Study of the influence of dynamic solar shading device in solar contributions 208
7.6.4.1. Study of the fixed angle awning 210
7.6.4.2. Study of the optimal angle awning 211
7.6.5. Analysis of current legislation..... 213
7.7. CONCLUSIONS 216

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

CHAPTER 8. REVIEW OF INDOOR AIR QUALITY AND VENTILATION SYSTEMS.....219

SUMMARY 221
8.1. INTRODUCTION 223
8.2. METHODOLOGY 225
8.3. DEVELOPMENT 226
8.4. RESULTS 227
8.4.1. Indoor Air Quality 229
8.4.2. Location of the case study 236
8.4.2.1. Residential buildings 237
8.4.2.2. Educational buildings 239
8.4.2.3. Offices buildings 241
8.4.3. Ventilation 243
8.5. STUDY OF THE INFLUENCE OF VENTILATION IN BUILDINGS 248
8.6. COVID-19 AND INDOOR AIR QUALITY 255
8.7. DISCUSSION 259
8.8. CONCLUSIONS 267

CHAPTER 9. INFLUENCE OF BUILDING DESIGN ON THERMAL COMFORT: ANALYSIS OF THERMAL INERTIA271

SUMMARY 273
9.1. INTRODUCTION 275
9.2. OBJECTIVE 277
9.3. METHODOLOGY 277
9.4. THERMAL COMFORT 278
9.4.1. Heat balance method 278
9.4.2. Adaptive method 283
9.5. ANALYSIS OF THERMAL COMFORT DEPENDING ON THE THERMAL ENVELOPE 286
9.5.1. Case Study 286
9.5.1.1. Definition of outdoor conditions 287
9.5.1.2. Definition of building model 287
9.5.2. Results 288
9.6. DISCUSSION 292
9.7. CONCLUSIONS 294

CHAPTER 10. BEST AVAILABLE TECHNIQUES FOR SUSTAINABLE AND COMFORTABLE BUILDINGS.....297

SUMMARY 297
10.1. INTRODUCTION 299

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

10.2. OBJECTIVE 302
10.3. METHODOLOGY 302
10.4. RESULTS 303
10.5. CONCLUSIONS 312

CHAPTER 11. CONCLUSIONS 313

REFERENCES 321

DIFFUSION OF RESULTS 355

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

INDEX OF FIGURES

FIGURE 1.1: INTEGRATED STRATEGIC ENERGY TECHNOLOGY (SET) PLAN 18
FIGURE 1.2: FINAL ENERGY CONSUMPTION IN EU BY SECTOR IN 2017 [DATA SOURCE: EUROPEAN ENVIRONMENT AGENCY, 2021] 19
FIGURE 1.3: FINAL ENERGY CONSUMPTION IN HOUSEHOLDS IN SPAIN IN 2017 [DATA SOURCE: EUROSTAT, 2020] 20
FIGURE 1.4: ENERGY SOURCE FOR HEATING AND COOLING IN THE SPANISH IN 2017 [DATA SOURCE: EUROSTAT, 2020] 20
FIGURE 1.5: EVOLUTION OF FINAL ENERGY CONSUMPTION IN HOUSEHOLD OF SPAIN [DATA SOURCE: IDAE, 2020] 21
FIGURE 1.6: DISTRIBUTION OF FINAL ENERGY CONSUMPTION IN SPAIN ACCORDING TO THE CLIMATIC ZONE [DATA SOURCE: IDAE] 22
FIGURE 1.7: EUROPEAN CLIMATE AND ENERGY TARGETS 27
FIGURE 1.8: SUMMARY OF THE MAIN ENERGY CERTIFICATIONS IN BUILDINGS 35
FIGURE 1.9: CIRCULAR ECONOMY INDICATORS [ADAPTED FROM COM(2018)29] 39
FIGURE 2.1: SUMMARY OF THE OBJECTIVES 45
FIGURE 3.1: SUMMARY OF THE STEPS FOLLOWED FOR THE DEVELOPMENT 48
FIGURE 4.1: VARIABLES INCLUDED IN THE MODEL THAT AFFECT THE INDOOR TEMPERATURE 60
FIGURE 4.2: GRAPHICAL REPRESENTATION OF DECREMENT FACTOR AND TIME LAG . 61
FIGURE 4.3: REPRESENTATION OF A MONOLAYER WALL AS AN ELECTRIC CIRCUIT WITH ONE NODE (A), WITH TWO NODES (B) AND WITH THREE NODES (C) 67
FIGURE 4.4: BLOCK DIAGRAM OF THE CONCRETE WALL RESOLUTION BY ELECTRIC ANALOGY FOR 3 NODES 74
FIGURE 4.5: VARIATION OF THE INNER SURFACE TEMPERATURE TO A UNIT STEP PERTURBATION DISTURBED CONSIDERING 3 NODES 76
FIGURE 4.6: VARIATION OF INNER SURFACE TEMPERATURE TO A SINUSOIDAL DISTURBANCE CONSIDERING A NUMBER OF NODES N=3 78
FIGURE 4.7: RESPONSE OF A 20 CM THICK CONCRETE WALL TO A SINUSOIDAL DISTURBANCE 80
FIGURE 4.8 VARIATION OF THE INTERIOR SURFACE TEMPERATURE AND THE OFFSET OF A CONCRETE WALL (20 CM THICK) AS A FUNCTION OF THE NUMBER OF NODES 81
FIGURE 4.9: REPRESENTATION THE RESPONSE IN THE INNER SURFACE OF DIFFERENT MATERIALS WITH A 20 CM THICKNESS WHEN THE SYSTEM IS PERTURBED FROM A SINE WAVE 83
FIGURE 4.10: REPRESENTATION OF DECREMENT FACTOR AND TIME LAG ACCORDING TO CONCRETE THICKNESS WALL 85

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

FIGURE 4.11: MULTI-LAYER WALL REPRESENTATION WITH 5 NODES PER MESH 86
FIGURE 4.12: VARIATION OF INNER SURFACE TEMPERATURE IN A WALL WITH OUTDOOR AND INDOOR THERMAL MASS..... 88
FIGURE 4.13: GRAPHICAL REPRESENTATION OF THE CUSHIONING EFFECT OF THE THERMAL WAVE WHICH PRODUCES EACH FACADE 88
FIGURE 4.14: SYSTEM RESPONSE WHEN IT IS SUBJECTED TO A UNITARY STEP DISTURBANCE (TOP: WITH INSIDE ISOLATION, BOTTOM: WITH OUTSIDE ISOLATION)..... 89
FIGURE 4.15: HEAT FLOW IN SUMMER CONDITIONS WHEN THE THERMAL MASS IS OUTSIDE AND INSIDE 90
FIGURE 4.16: BLOCK DIAGRAM FOR CALCULATING THE INDOOR TEMPERATURE 96
FIGURE 4.17: INNER TEMPERATURE VARIATION WHEN THE FACADES IN CONTACT WITH THE OUTSIDE HAVE INDOOR ISOLATION..... 99
FIGURE 4.18: INNER TEMPERATURE VARIATIONS WHEN THE FACADES ARE IN CONTACT WITH THE OUTSIDE HAVE OUTDOOR ISOLATION 100
FIGURE 4.19: REPRESENTATION OF THE EVOLUTION OF TEMPERATURE WITH TIME: A) INSIDE INSULATION AND OUTSIDE THERMAL MASS; B) OUTSIDE INSULATION AND INSIDE THERMAL MASS..... 103
FIGURE 5.1: ADJUSTMENT USING A POLYNOMIAL FUNCTIONS OF THE VARIATION OF A PARAMETER WITH THE DAYS OF THE YEAR..... 119
FIGURE 5.2: ADJUSTMENT USING A POLYNOMIAL FUNCTION OF THE VARIATION OF B PARAMETER WITH THE DAYS OF THE YEAR..... 119
FIGURE 5.3: ADJUSTMENT USING A POLYNOMIAL FUNCTION OF THE VARIATION OF C PARAMETER WITH THE DAYS OF THE YEAR..... 120
FIGURE 5.4: GRAPHICAL REPRESENTATION OF THE OUTDOOR TEMPERATURE AND THE SOL-AIR TEMPERATURE ON A HORIZONTAL SURFACE..... 126
FIGURE 5.5: ESTIMATION OF THE INDOOR TEMPERATURE WHEN THE BUILDING HAS INSIDE INSULATION CONSIDERING SOLAR RADIATION..... 127
FIGURE 5.6: VARIATION OF THE INDOOR TEMPERATURE FOR WALLS WITH INSIDE INSULATION AND TAKING INTO ACCOUNT THE SOLAR RADIATION..... 128
FIGURE 5.7: VARIATION OF THE INDOOR TEMPERATURE FOR WALLS WITH OUTSIDE INSULATION AND TAKING INTO ACCOUNT THE SOLAR RADIATION..... 129
FIGURE 5.8: VARIATION OF THE INDOOR TEMPERATURE FOR WALLS WITH INSIDE INSULATION AND TAKING INTO ACCOUNT THE SOLAR RADIATION IN A SUMMER DAY..... 130
FIGURE 5.9: VARIATION OF THE INDOOR TEMPERATURE FOR WALLS WITH OUTSIDE INSULATION AND TAKING INTO ACCOUNT THE SOLAR RADIATION IN A SUMMER DAY..... 131
FIGURE 5.10: VARIATION OF THE INDOOR TEMPERATURE FOR WALLS WITH INSIDE AND OUTSIDE INSULATION AND TAKING INTO ACCOUNT THE SOLAR RADIATION THROUGH THE WINDOW DURING A WINTER DAY..... 133

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

FIGURE 5.11: VARIATION OF THE INDOOR TEMPERATURE FOR WALLS WITH INSIDE AND OUTSIDE INSULATION AND TAKING INTO ACCOUNT THE SOLAR RADIATION THROUGH THE WINDOW DURING A SUMMER DAY 134
FIGURE 6.1: TOTAL AMOUNT OF WASTE GENERATED IN EUROPEAN UNION [DATA SURCE: EUROSTAT, 2020] 142
FIGURE 6.2: DRAWING OF THE BUILDING TO STUDY 145
FIGURE 6.3: REPRESENTATION THE RESPONSE IN THE INNER SURFACE OF DIFFERENT ECO-MATERIALS WITH A 20 CM THICKNESS WHEN THE SYSTEM IS PERTURBED FROM A SINE WAVE 160
FIGURE 6.4: DECREMENT FACTOR AND TIME LAG FOR ECO-MATERIALS WITH 20 CM THICKNESS 161
FIGURE 6.5: SANKEY DIAGRAM FOR ORIGINAL SCENARIO 0 (BASE CASE) 162
FIGURE 6.6: SANKEY DIAGRAM SCENARIO 1 (HEMP CONCRETE) 163
FIGURE 6.7: SANKEY DIAGRAM FOR SCENARIO 2 (ISOTEX) 164
FIGURE 6.8: SANKEY DIAGRAM FOR SCENARIO 3 (4% OCF) 165
FIGURE 6.9: SANKEY DIAGRAM FOR SCENARIO 4 (8% OCF) 165
FIGURE 6.10: SANKEY DIAGRAM FOR SCENARIO 5 (3% WS) 166
FIGURE 6.11: SANKEY DIAGRAM FOR SCENARIO 6 (7% WS) 167
FIGURE 6.12: NRE, CED AND GWP OF MATERIALS 171
FIGURE 7.1: SUMMARY OF THE VARIABLES TO TAKE INTO ACCOUNT FOR SOLAR CONTROL IN BUILDINGS 186
FIGURE 7.2: GLOBAL TRANSMISSION OF ENERGY THROUGH GLASS 197
FIGURE 7.3: SOLAR HEIGHT VARIATION OVER THE YEAR. OURENSE (ON TOP) AND MURCIA (ON BOTTOM) 199
FIGURE 7.4: SOLAR ANGLES WITH RESPECT TO A TILT SURFACE (ADAPTED FROM ASHRAE 2011) 200
FIGURE 7.5: SOLAR PROJECTION ON A WINDOW WITH AN OVERHANG 201
FIGURE 7.6: SOLAR RADIATION ON WINDOW WITH SOUTH ORIENTATION AND G-VALUE OF 1. LOCATION IN OURENSE. REFERENCE DAY 20/06 (ON TOP) AND 21/12 (ON BOTTOM 203
FIGURE 7.7: SOLAR RADIATION ON WINDOW WITH SOUTH ORIENTATION AND G-VALUE OF 1. LOCATION IN MURCIA. REFERENCE DAY 20/06 (ON TOP) AND 21/12 (ON BOTTOM) 204
FIGURE 7.8: REDUCTION OF SOLAR RADIATION DEPENDING ON THE LENGTH OF THE OVERHANG FOR A WINDOW WITH A HEIGHT OF 1,5 METERS 206
FIGURE 7.9: SOLAR RADIATION INPUT DURING THE DAY 20/06 IN OURENSE AND MURCIA FOR THE 12 CASES 207
FIGURE 7.10: SOLAR RADIATION INPUT DURING THE DAY 21/12 IN OURENSE AND MURCIA FOR THE 12 CASES 207
FIGURE 7.11: SOLAR PROJECTION ON A WINDOW WITH A DYNAMIC AWNING 209

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

FIGURE 7.12: SOLAR ENERGY INPUT FOR A 1,5 M WINDOW VARYING THE ANGLE OF THE AWNING DEPENDING ON THE SOLAR HEIGHT (OURENSE, REFERENCE DAY 20/06) 212
FIGURE 7.13: SOLAR ENERGY INPUT ACCUMULATED IN THE MONTH OF JULY 214
FIGURE 7.14: REDUCTION OF GLOBAL SOLAR RADIATION FOR EACH CASE 215
FIGURE 8.1: HAZARDS IDENTIFICATION IN INDOOR AIR QUALITY [DATA SOURCE: SCHER, 2007] 223
FIGURE 8.2: NUMBER OF PUBLICATIONS ACCORDING TO WEB OF SCIENCE (1900 TO 2020)..... 227
FIGURE 8.3: PERCENTAGE OF PUBLICATIONS BASED ON CASE STUDY (UP TO LEFT) TYPE OF VENTILATION (UP TO RIGHT) AND TYPE OF HAZARD. 228
FIGURE 8.4: CHORD DIAGRAM OF THE NUMBER OF PUBLICATIONS REVIEWED DEPENDING ON THE TOPIC 229
FIGURE 8.5 SUMMARY OF HAZARD SOURCES..... 235
FIGURE 8.6: EVOLUTION OF THE OUTDOOR AND INDOOR TEMPERATURE FOR DIFFERENT AIR CHANGE RATES (0,67 AND 2,2H^{-1}) FOR ENCLOSURES WITH OUTSIDE THERMAL MASS..... 250
FIGURE 8.7: EVOLUTION OF THE OUTDOOR AND INDOOR TEMPERATURE FOR DIFFERENT AIR CHANGE RATES (0,67 AND 2,2H^{-1}) FOR ENCLOSURES WITH INSIDE THERMAL MASS..... 251
FIGURE 8.8: EVOLUTION OF THE OUTDOOR AND INDOOR TEMPERATURE FOR AN AIR CHANGE RATES OF 0,67 H^{-1} DURING THE DAY AND 2,2H^{-1} DURING THE NIGHT FOR ENCLOSURES WITH INSIDE THERMAL MASS 253
FIGURE 8.9: EVOLUTION OF THE OUTDOOR AND INDOOR TEMPERATURE FOR AN AIR CHANGE RATES OF 0,67 H^{-1} AND 2,2H^{-1} DURING THE WINTER FOR ENCLOSURES WITH OUTSIDE THERMAL MASS..... 254
FIGURE 8.10: EVOLUTION OF CO_2 CONCENTRATION AS A FUNCTION OF THE NUMBER OF PEOPLE CONSIDERING AN ACH = 0,67 H^{-1} 258
FIGURE 8.11: EVOLUTION OF CO_2 CONCENTRATION AS A FUNCTION OF THE NUMBER OF PEOPLE CONSIDERING AN ACH = 2,20 H^{-1} 259
FIGURE 9.1: PREDICTED PERCENTAGE OF DISSATISFIED (PPD) VS PREDICTED MEAN VOTE (PMV) 281
FIGURE 9.2: AVERAGE TEMPERATURES OF THE LAST 7 DAYS PRIOR TO 18TH JULY 2020..... 289
FIGURE 9.3: EVOLUTION OF THE INDOOR TEMPERATURE WITH THE THERMAL MASS OUTSIDE AND WITH THE THERMAL MASS INSIDE..... 290
FIGURE 9.4: EVALUATION OF THERMAL COMFORT BASED ON THE POSITION OF THE THERMAL MASS. ON THE LEFT WITH AN AIR SPEED OF 0,3M/S. ON THE RIGHT WITH AN AIR SPEED OF 0.9 M / S [ADAPTED FROM TAYLOR ET AL, 2020]..... 292
FIGURE 10.1: TABLE OF THE AREAS OF THE BEST AVAILABLE TECHNIQUES 303

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

INDEX OF TABLES

TABLE 1.1: AVERAGE CONSUMPTION OF BUILDINGS IN SPAIN VS NZEB REFERENCE VALUES [DATA SOURCE: EU/2016/1318; IDAE, 2011] 23
TABLE 1.2: BENCHMARKS FOR THE ENERGY PERFORMANCE OF NZEB IN FUNCTION OF EU CLIMATIC ZONES [DATA SOURCE: EU/2016/1318] 32
TABLE 4.1: MATLAB CODE FOR A STEP DISTURBANCE 75
TABLE 4.2: MATLAB CODE FOR A SINE WAVE DISTURBANCE 77
TABLE 4.3: DATA OBTAINED FOR THE CONCRETE WALL BASED ON THE NUMBER OF NODES 81
TABLE 4.4: THERMAL PROPERTIES OF MATERIALS USED IN THE SIMULATION [IETCC, 2010] 82
TABLE 4.5: SUMMARY OF THE RESULTS OBTAINED IN THE SIMULATION FOR DIFFERENT MATERIALS WITH A 20 CM THICKNESS 84
TABLE 4.6: SUMMARY OF RESULTS DEPENDING ON THE WALL THICKNESS 85
TABLE 4.7: SUMMARY OF LAYER PROPERTIES OF THE WALL 87
TABLE 4.8: SUMMARY OF THE RESULTS OBTAINED THROUGH THE SIMULATION OF THE TWO WALLS 87
TABLE 4.9: COMPARISON OF MAXIMUM AND MINIMUM HEAT FLUX PER UNIT AREA .. 91
TABLE 4.10: SUMMARY OF THE TYPE OF DISTURBANCE AND VALUE OF THE COEFFICIENTS OF THE DIFFERENT TERMS OF THE TRANSFER FUNCTION 95
TABLE 4.11: SUMMARY OF THE BUILDING CHARACTERISTICS 97
TABLE 4.12: VALUE OF THE COEFFICIENTS OF THE TRANSFER FUNCTION FOR THE CALCULATION OF THE INDOOR TEMPERATURE 98
TABLE 4.13: COMPARATIVE DATA FOR MODEL VALIDATION 101
TABLE 5.1: DAY OF THE YEAR, DECLINATION AND TIME EQUATION FOR THE 21ST DAY OF EACH MONTH AND THE PARAMETERS A, B AND C USED TO CALCULATE THE DIRECT SOLAR RADIATION [ASHRAE, 2011] 117
TABLE 5.2: SUMMARY OF LAYER PROPERTIES OF THE WALL 122
TABLE 5.3: SUMMARY OF THE RESULTS OBTAINED THROUGH THE SIMULATION OF THE TWO WALLS 123
TABLE 5.4: SUMMARY OF THE BUILDING CHARACTERISTICS 123
TABLE 5.5: DESCRIPTION OF SINUSOIDAL WAVES THAT DISTURB THE SYSTEM WHEN THE SOLAR RADIATION IS CONSIDERED 127
TABLE 6.1: ORIGINAL BUILDING MATERIALS DESCRIPTION 146
TABLE 6.2: SUMMARY OF ECO-MATERIAL PROPERTIES 157
TABLE 6.3: SUMMARY OF SCENARIOS TO STUDY TO BE ANALYSED USING LESOSAI 158
TABLE 6.4: SUMMARY OF SIMULATIONS PERFORMED WITH LESOSAI SOFTWARE 167

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

TABLE 6.5: INDICATORS OF LIFE CYCLE ASSESSMENTS OF MATERIAL MATERIALS . 170
TABLE 7.1: SUMMARY OF CHARACTERISTICS OF THE SELECTED LOCATIONS 188
TABLE 7.2. SUMMARY OF THE SOLAR CONTROL DEVICE FOR BUILDINGS [BASED ON KUHN, 2017] 190
TABLE 7.3: TYPE OF GLASSES USED FOR SIMULATIONS [EXTRACTED FROM CLIMALIT] 196
TABLE 7.4. SUMMARY OF THE SOLAR RADIATION TRANSMITTED DEPENDING ON THE TYPE OF GLASS..... 197
TABLE 7.5: SUMMARY OF THE SOLAR ENERGY TRANSMITTED INWARDS THE BUILDING IN FUNCTION OF THE LENGTH OF THE OVERHANG (G-VALUE OF 1) 205
TABLE 7.6: SOLAR ENERGY INPUT FOR A 1.5 M WINDOW DEPENDING ON THE AWNING ANGLE 210
TABLE 7.7: SOLAR RADIATION INPUT DEPENDING ON THE LENGTH AND VARYING THE ANGLE OF THE AWNING DEPENDING ON THE SOLAR HEIGHT (REFERENCE DAY 20/06) 212
TABLE 7.8: SUMMARY OF THE ACCUMULATED SOLAR ENERGY IN JULY 214
TABLE 8.1: SUMMARY OF THE EVOLUTION OF TEMPERATURE WITH THE AIR CHANGE RATE..... 252
TABLE 8.2: SUMMARY OF INDOOR AIR QUALITY PARAMETERS, SOURCES AND CONTROL VENTILATION..... 263
TABLE 9.1: TEMPERATURE VALUES IN THE CITY OF OURENSE [METEOGALICIA, 2020]..... 287
TABLE 9.2: DESCRIPTION OF THE THERMAL ENVELOPE..... 288
TABLE 9.3: OPERATING TEMPERATURES FOR DIFFERENT DEGREE OF ACCEPTABILITY OF OCCUPANTS AND AIR SPEED [EXTRACTED FROM TAYLOR ET AL, 2020].... 291
TABLE 10.1: BEST AVAILABLE TECHNIQUES REGARDING THERMAL ENVELOPE 306
TABLE 10.2: BEST AVAILABLE TECHNIQUES REGARDING SUSTAINABLE MATERIALS 308
TABLE 10.3: BEST AVAILABLE TECHNIQUES REGARDING SOLAR RADIATION 309
TABLE 10.4: BEST AVAILABLE TECHNIQUES REGARDING SOLAR SHADOW DEVICES 310
TABLE 10.5: BEST AVAILABLE TECHNIQUES REGARDING VENTILATION 311

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

INDEX OF ACRONYMS

BAT	Best Available Techniques
BIPV	Transparent Building-Integrated PV-elements
BIST	Transparent building-integrated solar thermal
BREEAM	British Building Research Establishment Environmental Assessment Method
CC	Chilled Ceiling
CDW	Concrete and Demolition Waste
CED	Cumulative Energy Demand
CEAP	Circular Economy Action Plan
CFD	Computational Fluid Dynamics
COP21	21st Conference of the Parties
CWD	Ceramic Waste Powders
DIS	Dynamic Insulation System
DV	Displacement ventilation
EC	European Commission
EPS	Expanded Polystyrene
EU	European Union
FRCA	Fine Recycled Concrete Aggregates
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEPA	High Efficiency Particulate Air filters
HVAC	Heat, Ventilation and Air Conditioning
IPCC	Intergovernmental Panel on Climate Change

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

LEED	Leadership in Energy and Environmental Design
LCA	Life Cycle Assessment
NRE	Non-Renewable Energy
nZEB	nearly Zero-Energy Buildings
OCF	Olive Core Flour
OF	Olive Fibres
OPC	Ordinary Portland Cement
OSB	Oriented strand board
PCM	Phase Change Materials
PEB	Positive Energy Buildings
PER	Renewable Primary Energy
PHPP	Passive House Planning Package
PM	Particulate Matter
PMV	Predicted Mean Vote
POFA	Palm Oil Fuel Ash
PPD	Predicted Percent Dissatisfied
PV	Personalized Ventilation
RHA	Rice Husk Ash
SCBA	Sugar Cane Bagasse Ash
SCHER	Scientific Committee on Health and Environmental Risks
SF	Straw Fibres
SW	Smart Windows
SWTP	Sludge of Water Treatment Plant
TFEU	Treaty on the Functioning of the European Union
UFAD	Under-Floor Air Distribution
UVGI	Ultraviolet Germicidal Irradiation
USGBC	U.S. Green Building Council

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

VOC	Volatile Organic Compounds
WBGT	Wet Bulb Globe Temperature
WHO	World Health Organization
WMP	Waste Metallized Plastic
WOS	Web Of Science
WS	Wheat Straw
WWR	Window-to-Wall Ratio
XPS	Extruded polystyrene

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

INDEX OF NOMENCLATURES

A	Apparent extraterrestrial irradiance $[W/m^2]$
$A_{0,i}$	Surface against zones with constant temperature $[m^2]$
Ai	Surface against outdoor zones $[m^2]$
Amp	Temperature wave amplitude $[°C]$
B	Atmospheric extinction coefficient
C	Proportion of diffuse radiation on the horizontal surface
$C(t)$	CO_2 concentration [ppm]
C_0	Initial CO_2 concentration [ppm]
C_{ext}	Outdoor CO_2 concentration [ppm]
C_P	Heat Capacity [$J/m^2 \cdot K$]
$C_{p,air}$	Heat Capacity of the air [J/K]
d	Days of the year
e	Thickness of a wall [m]
ET	Mean outdoor effective temperature [^oC]
f_{Cl}	Clothing surface area factor
F_{N-1}	Angle factor between a person and the surface
G	Solar radiation or horizontal surface [W/m^2]
$G_{b,t}$	Direct radiation [W/m^2]
$G_{d,H}$	Diffuse radiation on a horizontal surface [W/m^2]
$G_{d,t}$	Diffuse radiation [W/m^2]
G_{in}	Indoor CO_2 generation
$G_{r,t}$	Shortwave radiation reflected in the Earth surface [W/m^2]
G_T	Solar radiation [W/m^2]
$g\text{-}value$	Solar factor of the window
h_c	Convective heat transfer coefficient [$W/(m^2 \cdot K)$]
h_{in}	Convective coefficient air inside a building [$W/(m^2 \cdot K)$]
H_{shadow}	Projection of the sun rays on the window [m]
hs,y	Projection of solar radiation on the surface of the glass [m]
i	Intensity through circuit [A]
i_c	Intensity through capacitor [A]

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

I_{Cl}	Clothing insulation [$m^2 \cdot K/W$]
i_r	Intensity through resistance [A]
L	Length of the overhang [m]
Ly	Projection of the awning on the surface of the glass [m]
M	Metabolic rate [W/m^2]
M_T	Thermal mass [$J/(K \cdot m^3)$]
n	Air renovations [h^{-1}].
p_a	Water vapour partial pressure [Pa]
Q_{in}	Internal loads [W/m^2]
R	Electrical resistance [Ω] or Thermal resistance [$m^2 \cdot K/W$]
t	Time [s].
T_0	Average monthly outside temperature [$°C$]
$T_{0,i}$	Temperature of zones at constant temperature [$°C$]
t_a	Air temperature [^oC]
T_{avg}	Average wave temperature [$°C$]
t_c	Comfort temperature [$°C$]
t_{Cl}	Clothing surface temperature [$°C$]
T_{ext}	Outdoor temperature [$°C$]
$T_{ext,max}$	Outdoor maximum temperature [$°C$]
$T_{ext,min}$	Outdoor minimum temperature [$°C$]
$T_{in,max}$	Indoor maximum temperature [$°C$]
$T_{in,min}$	Indoor minimum temperature [$°C$]
t_n	Neutral indoor temperature [$°C$]
t_N	Temperature of each surface [$°C$]
t_{pr}	Mean radiant temperature based on the surface temperature [$°C$]
$\overline{t_r}$	Mean radiant temperature [$°C$]
$T_{sur,in}$	Temperature on the inner surface of the wall [$°C$]
U-value	Thermal transmittance [$W/(m^2 \cdot K)$]
V	Volume of the building [m^3]
V_0	Voltage power supply [V]
v_{air}	Relative air velocity [m/s]
V_C	Voltage on the capacitor [V]
W	Effective mechanical power [W/m^2]
α	Thermal diffusivity [m^2/s]
αs	Solar height [^{o}]

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

β	Tilt surface [^{o}]
γ	Orientation [^{o}]
γs	Solar Azimuth [^{o}]
δ	Declination angle [^{o}]
ϑ_s	Zenith angle [^{o}]
λ	Latitude [^{o}] or thermal conductivity [$W/(m \cdot K)$]
μ	Decrement factor
ρ	Density [kg/m^3] or albedo
τ	Hour angle [^{o}]
φ_0	Constant phase of the thermal wave [rad]
ω	angular speed [rad/s]

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

SUMMARY

Construction is one of the strategic sectors for the European Union to achieve a low-carbon economy. Buildings are responsible for 40% of primary energy consumption and represents for 36% of CO_2 emissions [COM/2020/662]. In 2011, it was estimated that buildings could reduce their consumption by 41% [COM/2011/0885], since 75% of current buildings are inefficient [COM/2016/765]. In the construction of buildings, more than 50% of the raw materials extracted are consumed [COM/2020/788] and 37% of the total waste in the European Union is generated [Eurostat, 2020]. To achieve one of the objectives established in the Paris Agreement and achieve the decarbonisation of the sector, there must be a transformation towards nearly zero energy building. For this, the renovation and construction of new buildings not only must improve the thermal envelope, but also incorporate passive technologies that allow reducing energy consumption [EU/2018/844]. However, the sector is faced the opportunity to advance towards a regenerative economy and collaborate towards the achievement of the objectives established in the proposed Environment Action Programme to 2030 (8th Environment Action Programme) [COM/2020/652]. The regenerative economy must be resilient, protect the well-being of future generations and that economic growth is not associated with the use of resources and environmental degradation.

This Doctoral Thesis evaluates techniques for a circular and regenerative economy (Best Available Techniques) that allows the construction sector to achieve sustainable and comfortable buildings, guaranteeing adequate indoor air quality and thermal comfort. Furthermore, a model is developed to evaluate the thermal behaviour of the building through the consecutive implementation of factors such as thermal inertia, solar radiation and ventilation. The obtained model allows the analysis of techniques to improve sustainability and comfort in buildings.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

First, from the point of view of energy consumption, the influence of thermal inertia and solar radiation on the indoor temperature of buildings are evaluated. A model is developed that allows obtaining the indoor temperature of a building based on the materials used and solar radiation, showing the importance of the placement of the thermal mass. Since solar contributions can produce conditions of thermal discomfort, solar shadow devices and the efficiency of the most representative ones are evaluated.

Due to the high consumption of raw materials and generation of waste in the construction phase of buildings, the sustainable materials that are currently being used in the sector are analysed. Also, these materials must guarantee low energy consumption of buildings, so the thermal behaviour of sustainable materials with mixtures of agricultural waste is analysed.

Buildings must guarantee healthy indoor conditions, which allow maintaining adequate indoor air quality and thermal comfort. Regarding indoor air quality, a systhematic review is carried out, identifying which are the main pollutants present in indoor air and which are the techniques to minimize their concentration. In addition, the thermal comfort of the occupants must be guaranteed, so the main theories are described and how the design of the enclosure affects thermal comfort.

Finally, the main techniques analysed are framed from the point of view of indoor air quality and thermal comfort, as circular economy techniques towards a regenerative economy (Best Available Techniques). Candidate techniques for BAT are focused on the thermal envelope, the control of solar radiation, the use of sustainable materials and ventilation. These techniques contribute to the construction of sustainable buildings and to improve the thermal performance of buildings and comfort. The techniques analysed allow progress towards the decarbonization of the sector and reducing consumption of natural resources.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

RESUMEN

La construcción es uno de los sectores estratégicos de la Unión Europea para alcanzar una economía baja en carbono. Los edificios son actualmente responsables del 40% de consumo de energía primaria y del 36% de las emisiones de CO_2 de la Union Europea [COM/2020/662]. En el año 2011, se estimaba que los edificios podrían reducir su consumo en un 41% [COM/2011/0885], ya que un 75% de los edificios eran ineficientes [COM/2016/765]. En la construcción de los edificios se consume más del 50% de las materias primas extraídas [COM/2020/788] y se genera el 37% de los residuos totales de la Unión Europea [Eurostat, 2020]. Para lograr uno de los objetivos establecidos en el Acuerdo de París y alcanzar la descarbonización del sector, se deben de transformar en edificios de consumo de energía casi nulo. Para ello, la renovación y la construcción de nuevos edificios no debe solo mejorar la envolvente térmica, sino que además debe incorporar tecnologías pasivas que permitan reducir el consumo energético [EU/2018/844]. No obstante, el sector se encuentra ante la oportunidad de avanzar hacia una economía regenerativa y colaborar hacia la consecución de los objetivos establecidos en la propuesta del programa de acción en materia de medioambiente hasta 2030 (VIII Programa de Acción en materia de Medio Ambiente) [COM2020/652]. La economía regenerativa debe ser resiliente, proteger el bienestar de las generaciones futuras y que el crecimiento económico no esté asociado con el uso de recursos y la degradación ambiental.

Esta Tesis Doctoral evalua técnicas para una economía circular y regenerativa (Mejores Técnicas Disponibles) que permitan al sector de la construcción la consecución de edificios sostenibles y confortables, garantizando una adecuada calidad del aire interior y confort térmico. Además, se desarrolla un modelo que permite evaluar el comportamiento térmico del edificio implementando de forma consecutiva factores como la inercia térmica, la radiación solar y la

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

ventilación. El modelo obtenido, permite analizar las técnicas hacia la mejora de la sostenibilidad y el confort en los edificios.

En primer lugar, desde el punto de vista del consumo energético, se evalúa la influencia de la inercia térmica y la radiación solar en la temperatura interior de los edificios. Para ello, se desarrolla un modelo que permita obtener la temperatura interior en función de los materiales utilizados y la radiación solar, mostrando la importancia de la colocación de la masa térmica. Con motivo de que los aportes solares pueden producir condiciones fuera del confort térmico, se evalúa los sistemas de protección solar y la eficacia de los más representativos.

Debido al alto consumo de materias primas y generación de residuos en la fase de construcción de los edificios, se analizarán los materiales sostenibles que actualmente se están utilizando en el sector. Además, estos materiales deben permitir un bajo consumo energético de los edificios, por lo que se analiza el comportamiento térmico de materiales sostenibles con mezclas de residuos agrícolas.

En los edificios se debe de asegurar condiciones interiores saludables, que permitan mantener una adecuada calidad del aire y confort térmico. Respecto a la calidad del aire interior, se realiza una revisión bibliográfica, identificando cuales son los principales contaminantes presentes en el aire interior y cuales son las técnicas que permitan minimizar su concentración. Por otro lado, en todo momento se debe garantizar el confort térmico de sus ocupantes, por lo que se describe las principales teorías y como el diseño de la envolvente afecta al confort térmico.

Finalmente, las principales técnicas analizadas, se enmarcan desde el punto de vista de la calidad del aire interior y del confort térmico, como técnicas de economía circular hacia una economía regenerativa (Mejores Técnicas Disponibles). Las técnicas candidatas a Mejores Técnicas Disponibles estan enfocadas en la envolvente térmica, el control de la radiación solar, la utilización de los materiales sostenibles y la ventilación. Las técnicas contribuyen a la construcción de edificaciones sostenibles y a mejorar el rendimiento térmico de los edificios y el confort. Estas técnicas permiten avanzar hacia la

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

descarbonización del sector y la reducción del consumo de recursos naturales.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

RESUMO

Resumo con extension mínima de 3.000 palabras en galego de acordo ó artigo 35 do Regulamento de estudos de doutoramento do 2020 da Universidade de Santiago de Compostela.

A construción é un dos sectores estratéxicos da Unión Europea para alcanzar unha economía baixa en carbono. Os edificios son actualmente responsables do 40% do consumo de enerxía primaria e do 36% das emisións de CO_2 [COM/2020/662]. No ano 2011, estimábase que os edificios podían reducir o seu consumo enerxético nun 41% [COM/2011/0885], xa que un 75% dos edificios eran ineficientes [COM/2016/765]. Na construción dos edificios consúmese máis do 50% das materias primas extraídas [COM/2020/788] e xérase o 37% dos residuos totais da Unión Europea [Eurostat, 2020]. Para lograr un dos obxectivos establecidos no Acordo de París e alcanzar a descarbonización do sector, débese transformar en edificios de consumo de enerxía case nulo. Para iso, a renovación e a construción de novos edificios non só debe mellorar a envolvente térmica senón que tamén debe incorporar tecnoloxías pasivas que permitan reducir o seu consumo enerxético [EU/2018/844]. O sector enfróntase á oportunidade de avanzar cara a unha economía rexenerativa e colaborar para a consecución dos obxectivos establecidos na proposta do programa de acción en materia medioambiental ata 2030 (VIII Programa de Acción Ambiental) [COM/2020/652]. A economía rexenerativa debe ser resiliente, protexer o benestar das xeracións futuras e que o crecemento económico non estea asociado ao uso de recursos e á degradación ambiental.

Esta Tese Doutoral avalía técnicas para unha economía circular e rexenerativa (Mellores Técnicas Dispoñibles) que permitan ó sector da construción a consecución de edificios sostibles e confortables, garantindo unha adecuada calidade do aire interior e confort térmico.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Ademais, desenvólvese un modelo que permite obter o comportamento térmico dun edificio implementando de forma consecutiva variables como a inercia térmica, a radiación solar e a ventilación. O modelo obtido permitirá analizar as técnicas cara a mellora da sostibilidade e do confort nos edificios.

No capítulo 4, avalíase o comportamento térmico dos edificios tendo en conta a inercia térmica, o que permitirá o deseño e construción de edificios máis eficientes e confortables. Para a realización deste estudo, desenvólvese un modelo matemático capaz de predicir a temperatura interior dun edificio en función de variables como a temperatura exterior, a radiación solar, a renovación do aire e as cargas internas do edificio. Ca finalidade de simular condicións reais, a temperatura exterior asimílase a unha onda tipo senoidal. O modelo matemático está baseado na analoxía entre o campo eléctrico e térmico, e ten en conta a capacidade de acumulación de enerxía térmica do edificio. As ecuacións comezan a elaborarse partindo dun muro monocapa representado por unha resistencia eléctrica e un condensador, análogo á resistencia térmica e á capacidade térmica do muro. A resposta obtida polo sistema, permite obter o comportamento térmico do muro, mediante a obtención do factor de decrecemento e o desfase de onda. Ademais, o modelo obtido non só permite avaliar o comportamento dun muro monocapa, senón que é extrapolable a muros multicapa. Tras a obtención do modelo, comézase simulando o comportamento térmico dun muro monocapa de 20 cm de espesor de diferentes materias (formigón, granito, madeira, ladrillos e material illante). Os resultados obtidos mostran que os materiais con mellor resposta térmica, son aqueles que teñen una alta densidade e capacidade calorífica e unha baixa condutividade térmica, xerando unha onda de temperatura interior con menor factor de decrecemento e maior desfase. A madeira é o material que presenta un mellor comportamento térmico, xerando unha temperatura máis estable no interior e producindo un factor de decrecemento de 0,0932 e un desfase de 11,47 horas. En segundo lugar sitúase o ladrillo cun factor de decrecemento de 0,2952 e un desfase de onda de 7,35 horas. Posteriormente, o illante térmico, obtivo un desfase de onda de 5,47 horas e un factor de decrecemento de 0,4927. Respecto ao granito e ao

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

formigón, son os materiais que peor resultado amosaron e debido a que teñen propiedades semellantes, obtense en ambos casos unha resposta similar, con valores de factor de decrecemento de 0,6172 e 0,6303 e un desfase de onda de 4,51 e 4,41 horas. Este tipo de materiais, a pesar de non ter a mellor resposta térmica, son materiais moi utilizados en edificios antigos e históricos. Neste tipo de construcións, estes materiais presentan grandes espesores aumentando a súa masa térmica, o xera unha temperatura interior cunha redución da amplitude de onda próxima ao 100% para muros con espesores de 1 metro, o que permite manter temperaturas estables durante todo o ano. Para avaliar o impacto da inercia térmica nos edificios, estúdase a influencia da colocación de illamento térmico (8 cm) nun muro de formigón (20 cm). Os resultados mostran que, pese a analizar un cerramento coa mesta transmitancia térmica, a resposta que xera é diferente. A colocación do illamento no exterior xera temperaturas máis estables, cun factor de decrecemento de 0,0105 e un desfase de onda de 8,01 horas, mentres que ao colocar o illamento no interior, obtense un factor de decrecemento de 0,3199 e un desfase de onda de 7,46 horas. Polo tanto, a colocación do illamento polo exterior e a masa térmica polo interior permite obter temperaturas máis estables que ao colocar o illamento polo interior e a masa térmica polo exterior do edificio. Ademais, ao analizar unha variación da temperatura exterior durante un período de tempo máis longo, a colocación do illamento no exterior e a masa térmica polo interior permite obter un sistema máis estable aos cambios de temperatura. O uso de illamento no interior das paredes elimina a capacidade térmica de acumulación de calor, xerando unha maior flutuación de temperatura.

Coa finalidade de que o modelo considere a radiación solar na evolución da temperatura interior, no capitulo 5, o sistema complétase engadindo o efecto desta variable. A radiación solar é unha fonte enerxética renovable que vai influír na evolución da temperatura interior dos edificios. Durante o inverno, as entradas solares axudan a diminuír a demanda de enerxía. Non obstante, unha mala xestión da radiación solar pode provocar un aumento do consumo enerxético para o arrefriamento no verán e causar condicions interiores fóra do confort térmico. Para a análise da influencia da radiación solar nos

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

edificios considérase o fluxo de calor a través de cerramentos opacos e a través de superficies vidradas. O obxectivo é completar o modelo matemático que permite predicir a temperatura no interior dun edificio tendo en conta as entradas solares e a inercia térmica do edificio. O efecto da radiación solar analízase introducindo a temperatura sol-aire, a cal ten en conta a radiación solar directa, difusa e a radiación solar de onda corta reflectida nas superficies. O modelo completado coa radiación solar, permite avaliar os picos de temperatura xerados polo quecemento da radiación solar nas paredes e os picos xerados polas achegas solares a través das fiestras. A radiación solar a través dos cerramentos, non xera grandes flutuacións, sen embargo, a colocación da masa térmica polo interior, contribúe a reducir as oscilacións térmicas. A principal entrada de enerxía da radiación solar prodúcese a través das fiestras. As achegas solares dependen do tamaño, orientación e propiedades do vidro. De feito, a colocación da masa térmica polo interior, produce temperaturas máis altas no inverno en comparación ca colocación da masa térmica polo exterior, sen embargo no verán o efecto é o contrario. Isto é debido ao diferente desfase de onda que xera cada cerramento. Tendo en conta a inercia térmica do edificio, as achegas solares deben controlarse no verán para evitar temperaturas interiores fóra da zona de confort e un maior gasto enerxético en refrixeración.

Debido ó alto consumo de materias primas e a xeración de residuos na fase de construción dos edificios, analízase, no capitulo 6, o comportamento térmico dos materiais procedentes de residuos que actualmente se están a empregar no sector. Ademais, estes materiais deben garantir un baixo consumo enerxético do edificio, polo que se analiza o comportamento térmico de materiais con mesturas de residuos agrícolas ou biomasa. Entre os materiais analizados encóntrase formigón de cáñamo, bloques de madeira-cemento (isotex) e ladrillos con mesturas de palla (3 e 7%) e fariña de oso de oliva (4 e 8%). A resposta térmica dos materiais é analizada utilizando como referencia un muro de monocapa de 20 cm de espesor, mediante a aplicación do modelo matemático desenvolto previamente. Os resultados mostraron que a utilización de residuos mellora as propiedades térmicas dos materias convencionais, reducindo o factor

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

de decrecemento e aumentando o desfase de onda. Os materiais con mellor comportamento térmico son o formigón de cáñamo e o isotex, co que se obtivo un factor de decrecemento de 0,0655 e 0,0313 e un desfase de onda de 9,12 e 9,99 horas respectivamente. Respecto aos ladrillos, o incremento da cantidade de residuos, xera unha onda con menor factor de decrecemento e maior desfase de onda con respecto ó ladrillo convencional. No caso dos ladrillos compostos con mesturas de palla do 3 e 7 %, obtense un factor de decrecemento de 0,1615 e 0,1348 e un desfase de onda de 7,62 e 7,96 horas. Respecto aos ladrillos formados por un 4 e 8% de fariña de oso de oliva, obtéñense valores de 0,1713 e 0,1389 para o factor de decrecemento e de 7,5 e 7,9 horas para o desfase de onda. A introdución de residuos, mellora notablemente as propiedades térmicas con respecto ao material convencional. Ca finalidade de avaliar a aplicación dos materias na construción dun edificio, analízase o consumo enerxético mediante o software de simulación Lesosai. Pártese dun caso base (escenario 0), o cal emprega materiais convencionais cunha demanda enerxética de 10,7 kWh/m^2. Analízanse 6 escenarios diferentes, un para cada material seleccionado. Os resultados mostran, que a utilización de formigón de cáñamo (escenario 1) e bloques de madeira – cemento (escenario 2), permiten obter edificios cun consumo enerxético similar ao caso base (escenario 0), con demandas enerxéticas de 11,8 e 10,9 kWh/m^2. Sen embargo, o emprego de ladrillos con mesturas de residuos, mostran consumos enerxéticos elevados, con valores de 25,4 e 24,3 kWh/m^2 que empregan ladrillos con mesturas de palla ao 3 e 7% (escenarios 5 e 6) e con valores de 25,7 e 24,5 kWh/m^2 para o edificio construído con ladrillos con mesturas de fariña de oso de oliva de 4 e 8% (escenario 3 e 4). Unha das grandes vantaxes do uso destes materiais, radica no seu menor impacto ambiental en comparación cos materiais convencionais utilizados na construción dos edificios.

Unha das técnicas analizadas para a construción de edificios eficientes son os sistemas de protección solar, que posibilitan o control da radiación cara o interior do edificio (capítulo 7). Os aportes solares permiten reducir o demanda enerxética para calefacción dos edificios no inverno; sen embargo, poden producir condicións fóra do confort térmico durante o verán. Polo tanto, avalíanse os sistemas de

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

protección solar e a eficacia dos máis representativos co fin de reducir o consumo enerxético en refrixeración. En primeiro lugar, realízase unha revisión sistemática das principais técnicas existentes para o control dos aportes solares nos edificios, co fin de identificar cales son os sistemas fixos e móbiles que permiten mellorar o sostibilidade e o confort nos edificios. Para o control dos aportes solares nos edificios avalíanse as propiedades das ventás, o beiril como sistema de protección solar fixo e o toldo como sistema de protección solar móbil, onde se analiza a lonxitude e o ángulo. A selección do valor do factor solar da ventá e a lonxitude do beiril nas fases de deseño do edificio son esenciais para realizar un control adecuado da radiación solar. A maior lonxitude do beiril reduce en maior medida a entrada da radiación solar no verán ca no inverno. No caso das propiedades da ventá, valores baixos do factor solar evitarán a entrada de radiación solar que beneficia a redución do arrefriamento no verán, pero aumenta as necesidades de calefacción no inverno. Os dispositivos fixos de protección solar, son capaces de evitar a entrada de radiación solar directa pero permitindo o paso da radiación solar difusa, de xeito que manterán as condicións de iluminación no interior dos edificios. Os dispositivos de control solar dinámico teñen a versatilidade que non ten o sistema fixo. No caso analizado, os toldos poden ser un sistema eficiente e de baixo custo para reducir a entrada de radiación solar no verán. Estes sistemas, poden chegar a reducir ata un 29% a entrada de enerxía no verán para unha mesma lonxitude.

Ademais da construción de edificios eficientes e sostibles, débense garantir condicións interiores saudables, que permitan manter unha adecuada calidade do aire. A ventilación e a calidade do aire interior é un aspecto importante que se debe garantir en todos os edificios e que se fíxo relevante debido á pandemia mundial provocada pola COVID-19. Por iso, no capítulo 8, elabórase unha revisión dos principais perigos ambientais (químicos, biolóxicos e físicos) que están presentes no interior dos edificios. Estes contaminantes clasifícanse en función do tipo de edificio e revísase a información sobre o seu control e eliminación. Finalmente, avalíase a influencia da ventilación na temperatura interior mediante o modelo desenvolto nos capitulos anteriores. Entre os perigos químicos destaca

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

a concentración de CO_2 producida principalmente pola respiración humana. O control deste parámetro utilizase para controlar a dispersión do SARS-CoV-2, porque é un parámetro medible e controlable a partir da concentración de CO_2. A concentración de CO_2 no aire interior dos edificios, pode ser controlada mediante o emprego de sistemas de ventilación mecánica. Non obstante, tamén é posible a través da ventilación natural pero, nestes casos, a renovación do aire interior para manter os niveis de CO_2 en valores saudables, está condicionada pola temperatura e pola calidade do aire exterior. O control da concentración de CO_2 mediante a ventilación natural nas estacións frías provoca condicións de confort térmico indesexables, polo que se perxudica a ventilación interior para salvagardar a temperatura interior. Outro dos perigos químicos presentes no interior dos edificios sé o material particulado (PM2,5 e PM10). Entre as principais fontes de concentración de material particulado atópase a actividade humana e a proximidade a ambientes industriais ou con elevada contaminación atmosférica. A redución do PM mediante ventilación natural pode non ser eficaz xa que depende da calidade do aire exterior, xa que aumenta a concentración de PM no interior. Polo tanto, para controlar as PM é preciso o uso de filtros adecuados nos sistemas de ventilación. Os tipos de materiais utilizados no interior dos edificios tamén son unha fonte de contaminación do aire interior debido á presenza de compostos orgánicos volátiles (COV). Estes compostos aumentan a concentración do aire interior co aumento da temperatura, o control deste parámetro baséase nunha ventilación e temperatura adecuada e na utilización de materiais adecuados. Outros contaminantes presentes no aire interior dependen da zona de construción do edificio, como o gas radon, unha fonte de radiación ionizada que pode provocar cancro de pulmón. O emprego de técnicas de ventilación natural para o control da calidade do aire nos edificios, causa variación na temperatura interior do edificio. Polo tanto, mediante a utilización do modelo desenvolvido, avalíase a variación de temperatura provocada pola renovación do aire interior. En edificios coa masa térmica polo interior e o illamento polo exterior, prodúcese unha temperatura interior máis estable. Neste caso, ó aplicar a ventilación natural mediante a apertura das fiestras, a

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

temperatura interior experimenta unha maior oscilación e a onda resultante ten a mesma fase que a onda de temperatura exterior. Nos edificios con inercia térmica exterior, pola súa configuración, o rango de temperatura interior ao longo do día é maior que nos edificios con masa térmica interior, polo que, durante o proceso da ventilación natural, a temperatura interior ten unha menor variación.

Finalmente, no capítulo 9, estúdase o confort térmico nos edificios, comezando por unha revisión e análise dos diferentes métodos de cálculo do confort térmico. Tendo en conta que a envolvente térmica ten un papel fundamental, avalíase o confort térmico xerado por unha envolvente con diferentes localizacións de illamento e masa térmica. Deste xeito, preténdese demostrar que ca colocación da masa térmica no interior, acádase un maior grao de confort térmico e tamén diminue a demanda enerxética en refrixeración. Os estudos de Fanger en cámaras frigoríficas permitiron estudar a porcentaxe de satisfacción das persoas en ambientes controlados e na actualidade utilízase para avaliar o confort en edificios con sistemas de climatización. Co motivo de que Fanger non tivo en conta a "adaptación" das persoas, Dear e Brager desenvolveron o modelo de confort tendo en conta a capacidade de adaptación das persoas. Este enfoque adaptativo, utilízase actualmente en edificios con sistemas de ventilación natural. Debido á influencia do deseño da envolvente no confort térmico, analízase o impacto da localización da masa térmica e o illamento térmico. Neste caso, emprégase o modelo adaptativo acordo a norma ASHRAE 55-2020 a cal permite establecer cales serían as condicións térmicas aceptables para os ocupantes. A análise da evolución do confort realízase en condicións climáticas de verán, xa que os aportes de calor poden xerar temperaturas interiores máximas fóra da zona de confort. No caso analizado, a inercia térmica no interior do edificio produce unha oscilación de temperatura interior máis estable (oscilación de temperatura de 0,8 ºC) con respecto á envolvente con inercia térmica no exterior (oscilación de temperatura de 7,5 ºC). Debido a estas flutuacións de temperatura, as condicións de confort no interior do edificio varían ao longo do día. Cando a masa térmica é colocada no interior, a temperatura interior obtida é máis estable, o que permite manter o confort cun grao de

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

aceptabilidade superior ao 80%. Sen embargo, coa colocación da masa térmica no exterior, ao producirse unha maior flutuación de temperatura, chéganse a alcanzar temperaturas interiores máximas por encima do rango de confort, cun nivel de aceptabilidade por debaixo do 80%. Polo tanto, é necesario a utilización de equipos de ventilación mecánica para garantir o confort de polo menos o 80% dos ocupantes. Neste caso, a velocidade do aire debe aumentarse para obter un grao de aceptabilidade do 80%.

Ao longo da Tese Doutoral, analízanse técnicas para a construción de edificios sostibles e confortables. Polo que se realiza un inventario de técnicas candidatas ás mellores técnicas dispoñibles (MTD) que permitan ao sector da construción avanzar cara unha economía circular e rexenerativa. Os inventarios obtéñense en forma de bases de datos, tendo en conta aspectos relacionados coa sostibilidade e o confort en cada técnica.

As técnicas candidatas a Mellores Técnicas Dispoñibles están enfocadas na envolvente térmica, ó control da radiación solar, ó emprego de materiais sostibles e á ventilación. As técnicas contribúen á construción de edificios sostibles e a mellorar o rendemento térmico e o confort nos edificios. Estas técnicas permiten avanzar cara a descarbonización do sector e a redución do consumo de recursos naturais.

.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

CHAPTER 1. INTRODUCTION

1.1. OVERVIEW OF CONSTRUCTION SECTOR

Energy is a valuable and indispensable resource for social development. Fossil energy resources are finite and the world reserves decrease, so the energy is becoming a most precious asset for the sustainable development of human activity. In the European Union, energy imports are increasing, so if renewable energies are not encouraged to produce electrical energy, the energetic imports could reach the 70% of European Union needs compared to 53% of energy imported in 2014 [EU, 2014]. Therefore, EU must reduce energy dependence on fossil fuels, not only from the point of view of future security supply, but also in order to not aggravate the climate change effects.

Nowadays, human activity is responsible for global warming. The continuous emissions of Greenhouse Gases (GHG) cause a greater warming and increase the probability of serious, widespread and irreversible impacts on people and the ecosystems. According to IPCC (Intergovernmental Panel on Climate Change), If no action is taken against climate change, the Earth's average temperature is likely to rise by 4,8^{o}C by 2100 [IPCC, 2014]. To try to mitigate climate change, the European Union established a set of binding legislation to achieve the targets in the year 2050. The long-term objective established seeks to keep the average temperature of the planet below 2^{o}C and to make efforts to keep it below 1,5^{o}C.

The GHG emissions depend on different factors: population size, economic activity, lifestyle, energy use, soil use, technology and climate policy [IPCC, 2014]. The reduction of GHG emissions must be to allow the economic development of the member states. Thus, during the period between 1990 and 2018, GHG emissions have been reduced by 23%, allowing the economy to grow by 61% [EU, 2019]

One of the most important points for European Union is the use of energy. There are programs to improve the energy efficiency in

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

different areas like industry, transport or buildings. Working about the use of energy, the energy consumption and GHG emissions can be reduced, contributing to reduce the energy imports and to ensure the sustainable development for future generations.

All sectors need to contribute to the low-carbon transition (power generation, industry, transport, buildings, construction and agriculture) depending on their saving potential. The European Commission indicate that the emissions in this field could be reduced between 88 and 91% until 2050. The energy efficiency projects contribute to sustainable development, with the advantages that involves from the point of view of the environment, climate change and the quality of the atmosphere, as well as socio-economic benefits such as new companies, jobs and local revenues.

The energy system has to evolve in all sectors, so the European Union in 2015 established ten priority actions to accelerate the transformation of the energy system and create jobs (Figure 1.1).

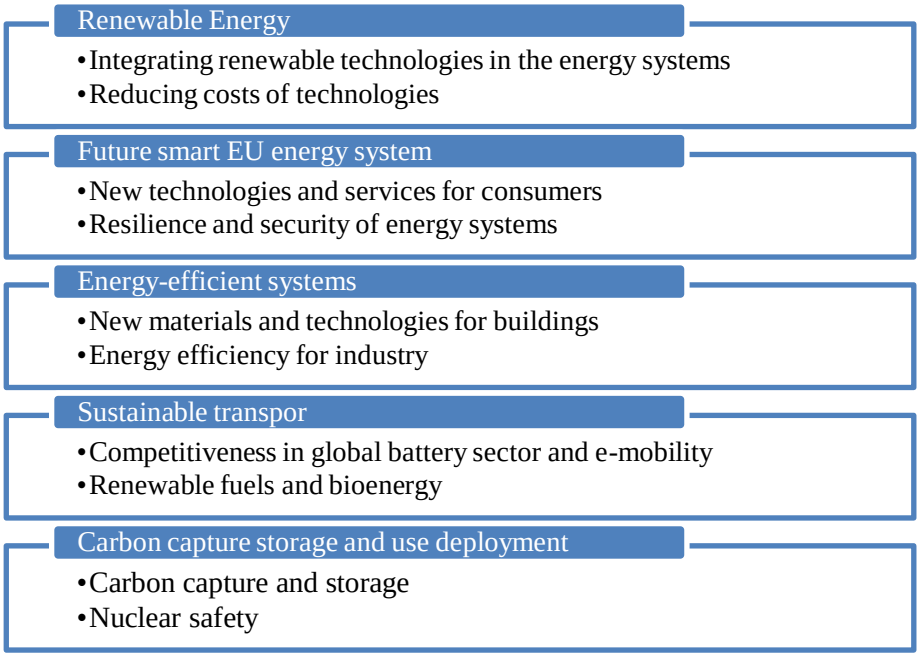

Figure 1.1: Integrated Strategic Energy Technology (SET) Plan

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Integrated Strategic Energy Technology (SET) Plan identifies the strategic priorities and actions required to accelerate the transformation of the energy system in a cost-effective manner. Buildings are within the SET Plan, to strengthen energy efficient systems, through the development of new materials and the large-scale promotion nearly Zero-Energy Buildings. In addition, buildings can contribute to the technological development of a smarter energy system, through the control of the thermal inertia of buildings, and the promotion of renewable energies for self-consumption.

Buildings are one of the major consumers of final energy in European Union, as they are responsible for 40% of European Union final energy consumption (including household, commercial and public services) (see Figure 1.2) and 36% of the total emissions of CO_2. The promotion of passive solutions (urban vegetation, green roofs, thermal insulation, shadows on buildings ...) contribute to reducing cooling and heating energy consumption in a sustainable way [EU, 2018]

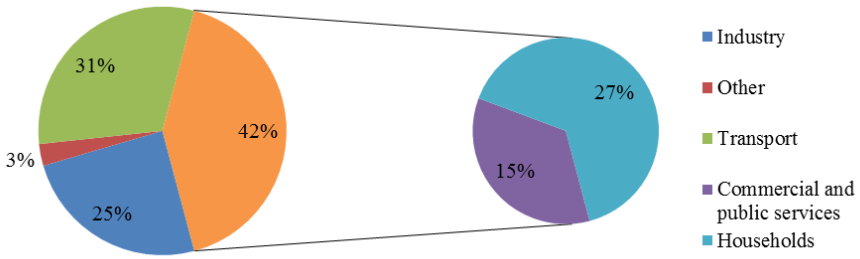

Figure 1.2: Final energy consumption in EU by sector in 2017 [Data source: European Environment Agency, 2021]

In Spain, most of the energy consumption in buildings is destined for heating (Figure 1.3). According to Eurostat, in 2017 the final energy consumption for heating accounted for 43% of the total compared to 1% for cooling.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

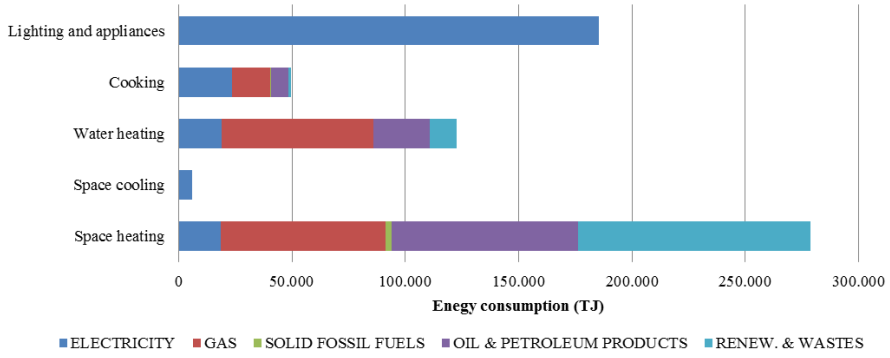

Figure 1.3: Final energy consumption in households in Spain in 2017 [Data source: Eurostat, 2020]

Non-renewable fossil fuels (gas, solid fuels and petroleum products) are the main energy source for heating and cooling buildings in Spain, reaching up to 55% of the total energy allocated to this use. Meanwhile, renewable energy accounts for 36% of the energy destined for air conditioning, where only 0,3% of the energy comes from solar thermal energy compared to 35,7% that comes from biofuels (see Figure 1.4)

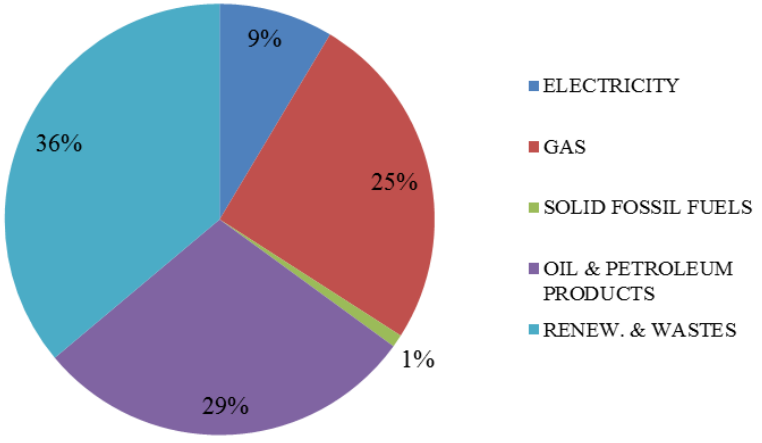

Figure 1.4: Energy source for heating and cooling in the Spanish in 2017 [Data source: Eurostat, 2020]

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Final energy consumption of households in Spain has evolved over time. Figure 1.5 shows the trend of final energy consumption. Before the start of the 2008 economic crisis, energy consumption in buildings was progressively increasing. Furthermore, in the last 10 years, there has been a reduction in the energy consumption of fossil fuels (coal and petroleum products) and an increase in the consumption of electrical and renewable energy.

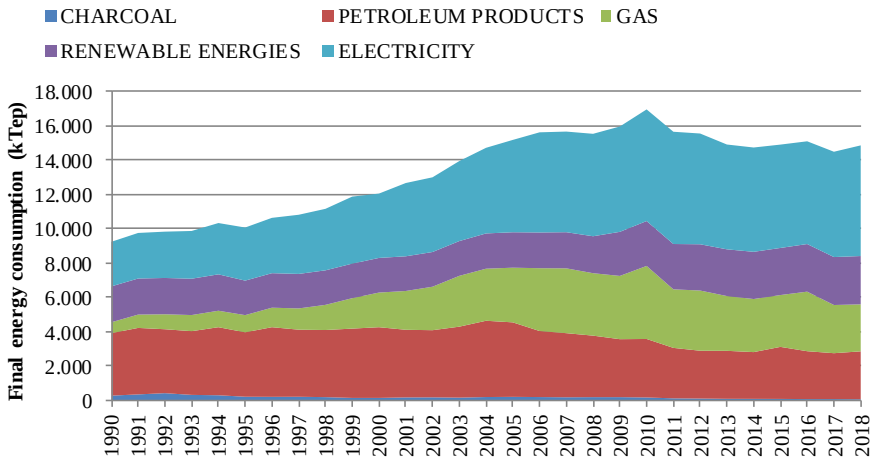

Figure 1.5: Evolution of final energy consumption in household of Spain [Data source: IDAE, 2020]

Average consumption of buildings in Spain varies depending on the climatic situation. The SPAHOUSEC project report for 2011 establishes that the average consumption in Spanish households located in the continental zone is 13.141 *kWh/year*, in the Mediterranean zone is 8.959 *kWh/year* and in the North Atlantic zone is 10.331 *kWh/year*. Average energy consumption in Spain is 10.521 *kWh/year* [IDAE, 2011]

Figure 1.6 shows the distribution of energy consumption as a function of the different areas. Continental area has the highest energy consumption, mainly for air conditioning (55,3% for heating and 0,7% for cooling), caused by differences in temperature between summer and winter. In the Mediterranean and North Atlantic areas, consumption for air conditioning is below the Spanish average. Due to

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

the milder temperatures during the year, the Mediterranean area allocates 40,9% of energy consumption to heating, compared to 40,1% in the Atlantic area. However, between both areas there is a higher energy consumption in refrigeration for the Mediterranean area (1,1%) compared to the North Atlantic area (0,1%), caused by the higher temperatures during the summer.

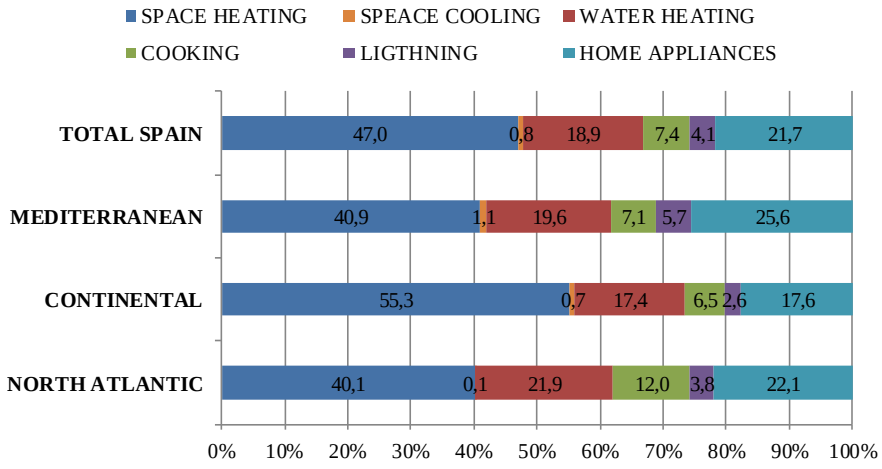

Figure 1.6: Distribution of final energy consumption in Spain according to the climatic zone [Data source: IDAE]

For the reduction of final energy consumption in buildings, sustainable design plays a crucial role. The construction of sustainable buildings that allow energy losses to be minimized, solar contributions to be optimized and ventilation systems to be adapted, allow pleasant comfort conditions to be achieved with minimum energy consumption.

Comparing the consumption data of buildings in Spain with the European Union reference values for the NZEB, they are currently well above the reference values. Table 1.1 summarizes the average energy consumption of primary energy in heating, cooling, ventilation, hot water and lighting based on the data obtained from the SPAHOUSEC project classified by climatic zone. This comparison shows the current high energy consumption of buildings in Spain and the wide margin for improvement that exists in existing buildings

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

compared to NZEBs. Currently, the energy consumption of the housing stock is between 2,6 and 4,8 times higher than the energy consumption of a highly efficient building.

Table 1.1: Average consumption of buildings in Spain vs NZEB reference values [Data source: EU/2016/1318; IDAE, 2011]

Climatic zones	Energy Building Consumption [kWh/y]	Average surface [m^2]	Energy consumption per surface [kWh/(m^2·y)]	Net Primary energy consumption [kWh/(m^2·y)]	Net primary energy for NZEB [kWh/(m^2·y)]
Mediterranean	8.959	103,8	86,3	64,2	0 - 15
Continental	13.141	103,5	127,0	104,7	20 - 40
Oceanic	10.331	93,7	110,3	85,9	15 - 30

*Net primary energy consumption in heating, cooling ventilation, hot water and lighting calculated from the data of the SPAHOUSEC project, eliminating consumption in household appliances.

In Spain, the 51,3% of residential buildings in Spain are prior to the year 1980 [Ministerio de Fomento, 2011]. Therefore, the buildings are prior to RD 2429/1979, where the basic building standard is approved with the first thermal conditions of the buildings (NBE-CT), which established the first measures aimed at saving energy in the buildings. However, in 1969, the first requirement regarding thermal insulation is collected, where maximum limits were established between 1,20 and *1,60 kcal/h·m^2·ºC* (1,40 and 1,86 *W/m^2·ºC*). However, despite this requirement, it was enough to put an air chamber to achieve this transmittance [Ministerio de Fomento, 2014]

Due to the age of the building stock and the low thermal requirement of the buildings, the rehabilitation of the current building stock in Spain plays an important role in achieving the objectives set by the European Union. According to European Union data, for every 1% increase in energy efficiency improvement, gas imports could be reduced by 2,6%, so the renovation of the current building stock is a priority [EU, 2018]

Currently in Spain, the requirements in the thermal envelope of buildings have become more stringent, increasing the quality of the thermal envelope after the modification of RD 2016/314 through RD 2019/732. This modification of the legislation seeks to adapt the content to the provisions of Directive 2010/31. In this way, thermal

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

transmittance values are established for walls in contact with the outside between 0,37 and 0,70 $W/m^2 \cdot K$. Likewise, a radon protection section established in Directive 2013/59 is incorporated.

There are more alternatives to reduce CO_2 emissions in the construction sector as the selection of low environmental impact construction materials. The construction sector is responsible for 37% of the waste generated [Eurostat, 2020] and also consumes 50% of the extracted raw material [COM/2020/98]

The construction sector has to actively contribute to the achievement of the objectives set by the European Union towards a low-carbon economy. Currently, the sector has the potential not only to reduce its energy consumption during the useful life of the building, but also in the construction phase. The use of sustainable materials in which waste is valued must contribute greatly to the reduction of greenhouse gas emissions.

1.2. ENERGY POLICIES

The world is facing an energy and environmental challenge. The economic development and improvement of the quality of life of the inhabitants produces greater energy consumption.

Energy becomes a necessary and essential asset for the socio-economic development of countries. In this area, the European Union has been updating its energy policies seeking to preserve and improve the environment. On the Treaty on the Functioning of the European Union (TFEU) [EU, 2012], article 194 includes the objectives of the energy policies of the European Union: ensure the functioning of the energy market; ensure security of energy supply; promote energy efficiency and energy saving and the development of new and renewable forms of energy; and promote the interconnection of energy networks.

Among the main objectives set by the TFEU, the development of renewable energies and energy efficiency play a key role in ensuring a secure energy supply and reducing dependence on imports of fossil fuels. The entire energy transition is marked by a reduction in greenhouse gas emissions. In 2007, the European Council established as key objectives the reduction of 20% of GHG emissions and a

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

renewable energy quota of 20%, where the reduction of 20% of energy consumption could mean a saving of 100,000 million euros and a reduction of 800 million tonnes per year [COM/2008/30]

In 2009, Directive 2009/28/CE on the promotion of the use of energy from renewable sources was published. The Directive establishes a 20% share of energy from renewable sources and also a 10% share of energy from renewable sources in the consumption of transportation fuels [EU, 2009]. The Decision 406/2009/CE is also published, which establishes the minimum contribution of each state to the reduction of GHG emissions by 2020, and establishes the minimum objective of 20% for the entire community [EU, 2009]. In order to achieve the quota set by the EU in terms of both renewable energies and the reduction of GHG emissions, improving energy efficiency and saving energy is a priority.

The current framework on energy efficiency is made up of a series of directives. Directive 2012/27/EU on energy efficiency is the main European standard for achieving the objectives of reducing energy consumption assumed by the EU. The objectives set by the regulations are global objectives to be met by the member states, thus establishing a common framework and ensuring an energy efficiency objective of 20% by 2020 and thus prepare the way for the coming years. In addition, the regulations include a long-term strategy for renovating buildings as an objective. As a starting point, public administrations must renew the air conditioning and cooling systems of public buildings at a rate of 3% of the surface per year [EU, 2012]. This regulation already shows that buildings are going to be a fundamental sector for the achievement of the objectives in terms of energy efficiency and therefore the reduction of greenhouse gases.

In 2012, there had already been a 12% reduction in GHG (compared to 1990 levels) and the share of renewable energy was at 13%, also promoting the employment of 4,2 million people despite the economic crisis. In 2014, the strategic framework on climate and energy for the period 2020-2030 was published. The European Commission proposes to set as objectives for the period 2020-2030, a reduction in GHG emissions of 40% (compared to 1990 emissions), a

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

share of renewable energies of 27% and an improvement in energy efficiency of 27 % [COM/2014/15]

In 2015, the Paris Agreement was adopted, which is an international treaty on climate change, in which 191 parties have participated (COP21), and which is also legally binding [United Nations, 2015]. The Paris Agreement establishes a long-term objective to limit global warming to a maximum of 2*ºC* above pre-industrial levels and also to establish as a more ambitious objective, a maximum temperature increase of 1,5*ºC*. At this point, the European Union commits to reducing GHG emissions by 40% by 2030 [COM/2016/0110]

In order to take the first steps towards achieving the objectives of the "Paris Agreement", the European Union needs to open the way for cleaner energy. The European Commission in the package "Clean Energy For All Europeans" establishes regulatory proposals and measures to accelerate a sustainable transition that will bring economic growth and new job opportunities [COM/2016/0860]. The legislative proposals aim to put energy efficiency first, make the EU a leader in renewable energy and also strengthen the treatment of consumers.

Regarding energy efficiency, the European Commission proposes the revision of the previously set objectives in terms of energy efficiency and raising them to 30% by 2030. This measure will cause an increase in GDP by 70.000 million euros and the creation of more than 400.000 jobs. In terms of energy efficiency, buildings are presented as one of the sectors with the greatest savings potential. The renewal rate was at 1% per year, the European Commission considers it essential to support and accelerate the renovation of the building stock [COM/2016/0860]

The target relative to the share of renewable energies, established at 27%, the European Council and the European Parliament encourage the revision of the target and raise it to 30%. In the Proposal for a Directive, COM/2016/767, it was indicated that the target set for 2030 would not be met and it was estimated that a 24,3% share of renewable energies would be reached. Therefore, the joint objectives set in the Paris Agreement would be breached and the joint objectives

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

set by the EU would not be achieved. This scenario would also harm the energy security provided by renewable energies. To guarantee the minimum share of renewable energy of 27% by 2030, the Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources is presented. The main objective is to reduce investor insecurity, eliminate administrative obstacles and highlight the need to update the political framework [COM/2016/0767]

In 2018, a common framework and binding targets are established for the year 2030. The targets for renewable energy and energy efficiency become more ambitious. Directive 2018/2001 establishes a renewable energy quota of 32% of final energy consumption in the EU and Directive 2018/2002 establishes an increase in the energy efficiency of the Union of at least 32,5% by 2030.

All the objectives set by the EU until 2030 and the efforts made to achieve them, seek to establish the path to achieve the long-term objectives. The EU is responsible for 10% of GHG emissions; however it wants to be the world leaders towards a transition of net zero emissions by 2050. An economic and sustainable development is possible. During 1990 and 2016, GDP increased by 54%, however energy was reduced by 2% and GHG emissions by 22% [EU, 2018]

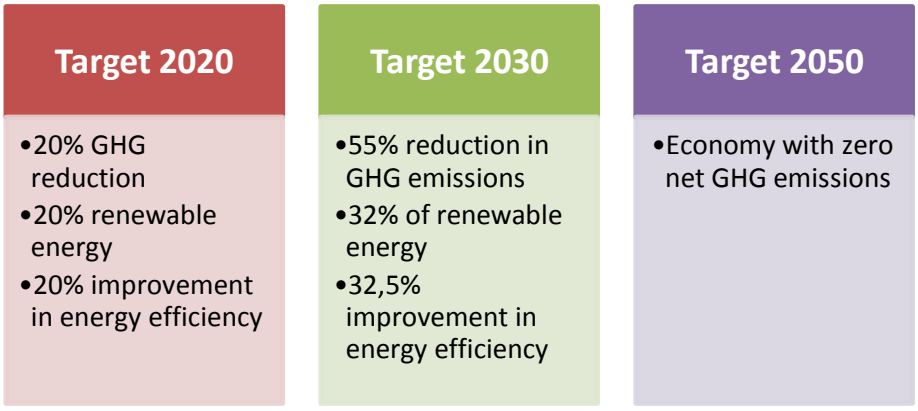

Figure 1.7: European climate and energy targets

To lead this transition towards an economy with zero net GHG emissions, 7 strategic pillars were established in 2018 [COM/2018/773]:

- Maximize the benefits of energy efficiency, prioritizing zero-emission buildings
- Maximize the deployment of renewable energy and the use of electricity to decarbonize the energy supply
- Establish clean, safe and connected mobility
- A competitive industry and the circular economy to reduce greenhouse gas emissions.
- Develop an adequate infrastructure of smart grids and interconnections
- Take advantage of all the benefits of the bioeconomy and create carbon sinks
- Combat the rest of CO_2 emissions with carbon capture and storage

In 2020, the European Commission publishes a legislative proposal to achieve climate neutrality. In addition, Regulation (EU) 2018/1999 ("European Climate Law") is modified through document COM/2020/80 final and its subsequent revision through document COM/2020/563 final. The main objective of the proposals is to achieve zero net emissions by 2050. For this, EU proposes to establish as a binding objective, a reduction of GHG emissions of 55% with respect to 1990 levels by 2030 and establishes that at the latest, in June 2021.

The European Climate Law (Regulation EU/2021/1119) establishes the goal of reaching neutrality by 2050, thereby increasing greenhouse gas reductions to 55% by 2030 compared to 1990 levels. To meet this goal by 2030, establish a plan where all sectors play a fundamental role. By 2030, electricity production from renewable energy sources is estimated to double from 32 to 65%. This renewable electricity production will allow the decarbonization of heating and cooling in buildings and industry. There are other actions in buildings that will increase this decarbonization, such as increasing the rate of renewal, digitization and integration of renewable energies. Buildings

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

and electricity generation can achieve reductions of up to 60% compared to 2015 [COM/2020/562]

1.3. ENERGY POLICIES IN BUILDINGS

The buildings are in the spotlight and are postulated as one of the strategic sectors. The European Climate Pact also supports the need for green buildings, providing information on the benefits of energy efficiency and the use of sustainable materials. The construction sector consumes more than 50% of the extracted raw materials; therefore it is necessary to introduce materials with low carbon emissions [COM/2020/788]. At this point, the use of recycled materials and recovery of materials in construction are included within the Circular Economy Action Plan of the European Union [COM/2020/98]

The buildings have more and more prominence and have been for years as the main sector in the fulfilment of European objectives. The specific regulations of this sector have been evolving, increasing their requirements in order to have a decarbonized building stock that allows reducing energy poverty and improving energy security.

The "Energy Roadmap for 2050" published in 2011 included buildings as one of the sectors to achieve high energy efficiency and they continue to be the strategic point for the achievement of long-term strategic objectives. In 2011, it was already estimated that energy demand in buildings could be reduced by 41% in 2050 (compared to 2005 and 2006) if the minimum requirements for new appliances and buildings were increased and the renovation rate increased [COM/2011/885]. Due to the aging of the current building stock and the fact that the current buildings, which are being built, will be present in 2050, the construction sector is accentuated as one of the driving sectors for the achievement of long-term objectives.

The directive 2002/91/EC relative to the energy efficiency of buildings, was created to respond to the objectives established by the Kyoto Protocol. The directive aims to promote the energy efficiency of buildings taking into account factors such as climatic conditions. The regulations establish a methodology for calculating energy efficiency and its minimum requirements. In addition, the obligation to have an energy certificate in new buildings, for sale or for rent and

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

the need to pass periodic inspections in the boilers is also implemented [2002/91/EC]

Due to the great savings potential of buildings and that it was still not promoted, Directive 2002/91/EC was modified by Directive 2010/31/EU. In Directive 2010/31/EU, it is still a priority to establish a methodology for calculating energy efficiency and its minimum requirements, as well as the need to carry out energy certifications and reviews of air conditioning systems. Furthermore, Directive 2010/31/EU already incorporate the need for nearly zero-energy buildings (nZEB). In this sense, the directive establishes that by 31 December 2020, all new buildings are nearly zero-energy buildings while for public buildings this date is brought forward to 31 December 2018 [2010/31/EU]. To establish the methodological framework that member states must apply to calculate the optimal levels of profitability of the minimum energy efficiency requirements of new and existing buildings and their elements, Commission Delegated Regulation No 244/2012 is published as a complement to directive Directive 2010/31/EU.

In 2016, a proposal on the energy efficiency of buildings is published [COM/2016/765]. It was estimated that 75% of the buildings in the building stock would be inefficient and the renovation rate of the buildings was between 0,4 and 1,2% per year, so the proposal aims to accelerate the renovation rate of the buildings. Among the objectives, it stands out to set a roadmap with target milestones for 2030 that allows decarbonizing the building stock by 2050. This renovation strategy will reduce energy poverty. In addition, this same year the recommendations to promote buildings with zero energy consumption are published and a recommendation of the reference values applicable to energy efficiency according to the climate zone is published [2016/1318/EU]

The 2015 Paris Agreement established to promote efforts to have a decarbonized building stock between now and 2050, so it is necessary to guarantee building renovation strategies in order to transform them into buildings with zero-energy buildings. Therefore, Directive 2018/844/EU modifies Directive 2010/31/EU in order to review the European objectives and establish a roadmap that includes

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

milestones for 2030, 2040 and 2050. Moreover, buildings should not only focus on improving the thermal envelope, but must have passive elements that allow reducing energy consumption and improving comfort.

Finally, in 2020, the European Commission publishes document COM(2020)662, a document whose main objective is to double the energy renovation rate of buildings. The consideration of increasing the renovation rate of buildings is not only evaluated from the energy point of view, but is also born as a stimulus to improve the economy, which has been diminished by the pandemic caused by COVID-19. This boost could generate 160,000 green jobs by 2030, improving energy efficiency and reducing energy poverty.

1.4. SUSTAINABLE BUILDINGS

According to the Directive 2010/31/EU related to energy performance of buildings, a nearly Zero-Energy Buildings is defined as: "Building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby".

In the European Union, from the year 2021, all new buildings are nZEB [EU, 2010]. This implies that buildings, in addition to having low energy consumption, must produce part of their energy from renewable sources. In order to achieve this type of construction and in order to comply with European regulations, it is established that newly constructed buildings (NZEB), primary energy consumption must be 85% less than the building stock of 2006 [EU, 2013]

The European Union establishes the guidelines to promote NZEBs, establishing a primary energy indicator in $kWh/(m^2 \cdot year)$, establishing scales according to the reference area, which is summarized in Table 1.2. The requirements of "Net primary energy" and "Primary energy" are established. Net primary energy corresponds to the energy destined for heating, cooling, ventilation, hot water and lighting [EU, 2016] and primary energy is defined by the directive 2010/31 as energy from renewable and non-renewable

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

sources which has not undergone any conversion or transformation process [EU, 2010]

Table 1.2: Benchmarks for the energy performance of NZEB in function of EU climatic zones [Data source: EU/2016/1318]

EU climatic zones	NZEB	Net primary energy [kWh/(m^2·y)]	Primary energy use covered [kWh/(m^2·y)]	Primary energy covered by renewable sources [kWh/(m^2·y)]
Mediterranean	Offices	20 - 30	80 -90	60
	New single family house	0 - 15	50 - 65	50
Oceanic	Offices	40 - 55	85 -100	45
	New single family house	15 - 30	50 - 65	35
Continental	Offices	40 - 55	85 - 100	45
	New single family house	20 - 40	50 - 70	30
Nordic	Offices	55 - 70	85 - 100	30
	New single family house	40 - 65	65 - 90	25

Mediterranean: Catania (others: Athens, Larnaca, Luga, Seville, Palermo).
Oceanic: Paris (others: Amsterdam, Berlin, Brussels, Copenhagen, Dublin, London, Macon, Nancy, Prague, and Warszawa.
Continental: Budapest (others: Bratislava, Ljubljana, Milan, and Vienna).
Nordic: Stockholm (Helsinki, Riga, Stockholm, Gdansk, Tovarene).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Thus, for example, in the case of residential buildings located in the Mediterranean area, the net energy consumption is established between *0-15 kWh/m^2·year*, allowing primary energy consumption between *50-65 kWh/m^2·year* and from renewable energy sources 50 kWh/m^2·year. In the case of the most adverse climatic zone, these reference values are more permissive. Thus, in the Nordic area, a net energy consumption of 40-65 *kWh/m^2·year* is established, equivalent to a primary energy use of 65-90 *kWh/m^2*·year of which must be covered with renewable energies 25 *kWh/m^2·year* [2016/1318/EU]

The member countries of the European Union must adapt their state regulations to facilitate the conversion of the building stock. Central-western European countries (Germany, Denmark, Ireland, the United Kingdom, and Belgium) have achieved greater implementation of national legislation for the promotion of nZEB [Topriska et al, 2018]. Southern European countries are the least prepared for the transition and the least in updating existing buildings. Among the main barriers are: geography and climate (they must be able to adapt to hot and cold temperatures), methodological (lack of laboratory or field measurements to analyse real performance) and legislative (lack of local strategy and infrastructure human) [Attia et al, 2017]. In general, the training of professionals in nZEB is necessary to accelerate the transition to nZEB.

Currently, there are certifications and standards in the market to achieve nZEB. In Figure 1.8, the types of certifications most used in the current market are shown, including their main characteristics.

The Passive House label is a certification developed by the Passive House Institute based on energy efficiency, thermal comfort and air quality. Currently, there are three types of classes depending on the renewable primary energy (PER) used to replace the demanded energy. Based on this criterion, the Passive House Classic (PER <60 *kWh/m^2·year*), Passive House Plus (PER <45 *kWh/m^2·year*) and Passive House Premium (PER <30 *kWh/m^2·year*) certification are distinguished [PHI]. Moreover, the Passive House certification not only applies to new homes, but is also applicable to home refurbishments through the EnerPHit certificate. The construction of the Passive House has the following main characteristics:

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

- High thermal insulation (U_{max} = 0,15 $W/m^2 \cdot K$).
- High energy efficiency windows (U_{value} <= 0,80 $W/m^2 \cdot K$ and *g-value* = 0,5).
- Ventilation and heat recovery (75% heat recovery).
- Airtightness of the building (Airtightness <0,6 air changes per hour at 50 Pascals pressure.
- Absence of thermal bridges.

There are numerous studies on the high efficiency of Passive House. The first building certified with the Passive House standard in England was evaluated using the Passive House Planning Package (PHPP) and monitored obtaining results within the standard. The space heating demand monitored was 12,1 kWh/m^2 (below the standard of 15 kWh/m^2), but total primary energy target was 125 kWh/m^2 (>120 kWh/m^2). However, problems are identified that could reduce the value to 113 kWh/m^2 [Ridley et al, 2013]. Truong et al also monitored the behaviour of a house during a period of one year, but in this case, the building is located in Autralia. The results showed a 64% energy saving compared to similar buildings. In addition, with respect to the predictions made with the Passive House Planning Package (PHPP) tool, the data obtained turned out to be better, obtaining lower energy consumption and primary energy demanded [Truong et al, 2017]

Passive House certification allows guaranteeing a stable comfort temperature. According to the case analysed by Liang et al in a house in England, the passive house managed to maintain a temperature of 22^{o}C with a primary energy demand of 64.11 $kWh/m^2 \cdot year$, while in a conventional house the primary energy demand had a value of 147 $kWh/m^2 \cdot$year, but with an average indoor temperature of 16^{o}C [Liang et al, 2017]. However, despite guaranteeing adequate thermal comfort, they are more susceptible to increases in temperature due to human activity (cooking or activities that generate heat) and the high degree of thermal insulation and hermeticity [Rohdin et al. 2014]. This problem was also obtained by Ridley et al (2013), where in the simulation in PHPP, internal loads of 3,65 W/m^2 were considered and after the measurements the internal gains had increased by 43%. In order to avoid overheating in summer, it is essential to use solar

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

protections [Rohdin et al 2014], however, sometimes a combination between adequate air renewal and shading systems (preferably mobile and outdoor) is necessary to achieve an adequate indoor temperature [Figueroa-Lopez et al, 2021]

Figure 1.8: Summary of the main energy certifications in buildings

MINERGIE is another of the standards based on efficiency and comfort. This Swiss certification and has a similar philosophy to Passive House. The energy consumption of MINERGIE building is around 60% less than conventional Swiss building. [Beleyer et al 2009]. This certification also distinguishes different types of certifications: MINERGIE, MINERGIE-P, MINERGIE-A, with an energy needs for new buildings of 55, 50 and 35 $kWh/m^2 \cdot a$ respectively.

The MINERGIE-A certificate is the most demanding of the three categories and requires a zero balance of primary energy (including space heating, domestic hot water, ventilation and auxiliary electricity). The MINERGIE-A buildings are well insulated and have a heat pump and photovoltaic energy [Hall et al, 2014]. According to the study carried out by Yang et al, where they compare MINERGIE buildings with renovated buildings, it was shown that the indoor air quality was higher in the MINERGIE building. The concentrations of pollutants such as radon, volatile organic compounds and formaldehyde and fungi were lower in MINERGIE buildings [Yang et al, 2020]

The LEED (Leadership in Energy and Environmental Design) certification was developed by the U.S. Green Building Council (USGBC). LEED is a green certificate that already encompasses other parameters within the certification such as indoor air quality and the building's environmental impact. LEED certifications prioritize health and wellness without sacrificing environmental considerations [Worden et al, 2019] in addition to obtaining a higher category by using sustainable materials [Alqahtani et al, 2021]. Among the objectives of the evaluation of the LEED label is focused on the energy costs of the building [Schwartz et al 2013]. Regarding the score, LEED prioritizes indoor air quality while energy performance of buildings has less weight [Awadh, 2017]. Different LEED certifications can be obtained depending on the credits achieved in the different categories, from LEED Certified (between 40 and 49 points) to LEED Platinum (more than 80 points), between both labels are LEED Silver (50 to 59 points) and LEED Gold (60 and 79 points). According to the review carried out by Leskinen et al 2019, LEED

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

certification allows to increase rental income and reduce operating expenses and risks of a property [Leskinen et al, 2019]

The reduction in operating costs of LEED buildings in the design phase, in a case study in Bogota, can lead to reductions in water consumption of 42,7% and a reduction in electricity consumption of the 31,2% with a payback of less than 10 years [Ribero et al, 2016]

Like the LEED certificate, the BREEAM (British Building Research Establishment Environmental Assessment Method) is based on the score of a series of categories. It is applicable both in new buildings and renovations. One of the mains objectives of BREEAM is the reduction of CO_2 emissions due to energy consumption of buildings [Schwartz et al 2013]. One of the categories with more weight in the score in the BREEAM certificate is energy. In fact, achieving a high energy performance and therefore a higher score in this field is much more rigorous in BREEAM certifications [Awadh, 2017]

The different certifications establish the way for the decarbonization of the construction sector and the creation of sustainable buildings throughout their life cycle, from construction to maintenance. Moreover, a meticulous design of buildings could allow a step towards Positive Energy Buildings (PEB), that is, buildings that produce more energy than they consume. An example is observed in the case study shown by Magrini et al, in which it shows a building that consumes 37% of the energy that it produces [Magrini et al, 2020]

In addition to the newly constructed buildings, the renovation of buildings will play a fundamental role in the decarbonization process of the housing stock. The retrofit of buildings using a standard such as Passive House can reduce CO_2 emissions during the building's operation stage between 50 and 80%, a reduction between 61 and 76% in primary energy consumption [Piccardo et, 2020]. Improving the thermal insulation, tightness and quality of windows, not only it is possible to reduce energy consumption, but also a more stable indoor temperature is obtained [Lee, 2020]

This sector will also be important for the introduction of sustainable materials from waste and that will promote the circular economy. As an example, the study carried out by Rosso et al shows

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

the potential for energy savings due to the use of km0 materials that use agricultural residues such as straw or hemp. In this case, the energy consumption of buildings was reduced by 33,6% by introducing 12 *cm* of hemp insulation on the outside, increasing to 36,1% by changing the windows [Rosso et al, 2020]

Buildings have a potential that is still undeveloped. All variables must be taken into account for efficient and sustainable construction. The optimal selection of materials, taking into account their thermal properties and their sustainability, will reduce the environmental impact of the building during its operation and construction or renovation. Taking into account the solar contributions will avoid undesirable conditions of discomfort and minimize the energy consumption of HVAC systems. Therefore, the optimization of solar shadow devices will be essential. Finally, guaranteeing adequate comfort, both thermal and air quality, will be essential to guarantee the health and well-being of the inhabitants. The optimization of all these variables will allow obtaining a sustainable, efficient and decarbonized real estate park.

1.5. TOWARDS TO REGENERATIVE ECONOMY

The first action plan of the European Union for a circular economy dates from 2015 (COM/2015/0614), where it includes a package with 54 measures towards the transition from a circular economy. In it, specific measures were already included for the construction and demolition sector:

- Evaluation prior to demolition.
- Voluntary recycling of construction and demolition waste materials.
- Establish environmental indicators during the life cycle of a building and incentives for their application.

The values of products, materials and resources must be maintained in the economy for as long as possible, minimizing the generation of waste [EU, 2015]. The circular economy should cover the entire production process: obtaining the raw material, the production stage, consumption, waste generation and recovery as raw

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

material. This closed cycle of processes will allow the EU to be more competitive, increasing resources and reducing price volatility.

In order to have a monitoring framework for the circular economy action plan, the indicators that collect the main elements of the circular economy are presented in 2018 (COM/2018/29). To do this, they establish ten indicators grouped into four groups:

- Production and consumption.
- Waste management.
- Secondary raw materials.
- Competitiveness and innovation.

Figure 1.9 shows a summary of the indicators of the circular economy monitoring framework [COM/2018/29]

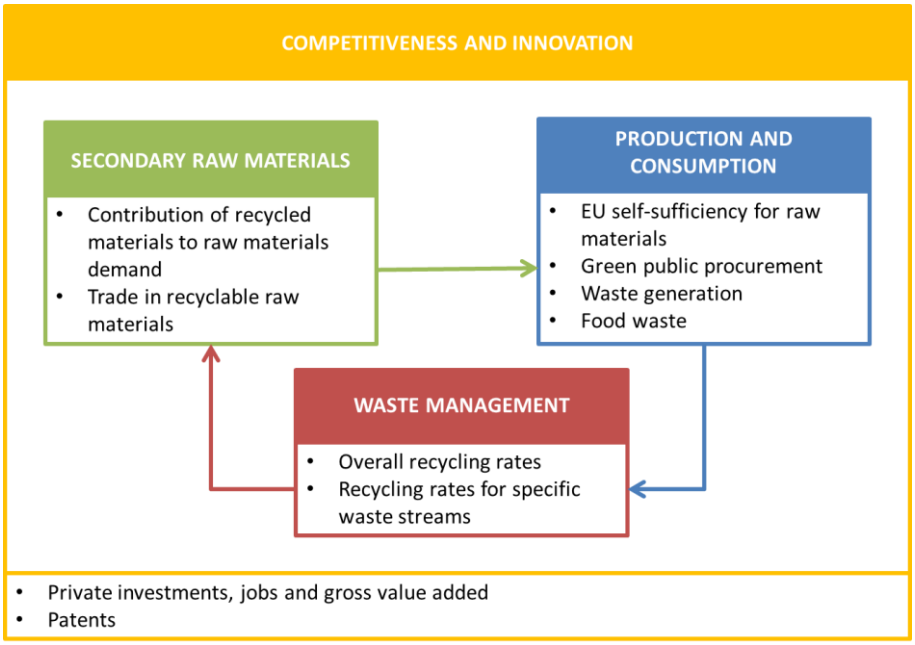

Figure 1.9: Circular economy indicators [Adapted from COM(2018)29]

Following the European Green Deal, the new Circular Economy Action Plan (CEAP) was adopted in March 2020. To achieve climate neutrality in 2050, it is necessary to move towards the circularity of

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

the economy and decouple economic growth from the consumption of resources. Therefore, the European Union must move towards a regenerative model, in such a way that it returns more resources to the planet than it takes from [EU, 2020]

Regarding buildings, COM/2020/98 already highlights its potential, where the extraction of materials, the manufacture of construction products, and construction and renovation, represents between 5 and 12% of GHG emissions and is estimated a reduction of up to 80%. To promote the circularity of the sector, the European Union will establish requirements on recycled content for certain construction products, integrate life cycle assessment in public procurement, review material recovery targets set in EU legislation and promote initiatives to reduce soil sealing, rehabilitate abandoned or contaminated sites and promote the safe, sustainable and circular use of excavated soils.

The objective of the circular economy should be to provide materials, composites and systems with a second life, in such a way that they can be reused once the useful life of the building ends. Buildings must have a low energy and water footprint, in such a way that they have local and renewable energy sources and rainwater reuse systems [Rahla et al, 2021]. According to the analysis carried out by Minunno et al, the Life Cycle Assessment (LCA), taking into account the criteria of circular economy, can reuse 62% of the mass of the building (belonging to steel) and reduce GHG emissions by 88% due to the reuse of materials in the construction stage [Minunno et al, 2020]

Different sectors must evolve towards a climate neutral economy in order to achieve environmental objectives. However, the economy must not remain only in circularity, but must adapt to contribute to the objectives of the 8th Environment Action Program and move towards a regenerative economy. An economy that returns more resources to the planet than it takes from it, that nothing is wasted, and there are no net greenhouse gas emissions.

The regenerative economy must be resilient, protect the well-being of future generations and that economic growth is not associated with the use of resources and environmental degradation. For this, the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

8th Environment Action Program establishes 6 objectives (COM/2020/652):

1. Irreversible and progressive reduction of greenhouse gas emissions and increase of removals by natural or other sinks in the Union
2. Strengthening resilience and reducing vulnerability to climate change
3. Evolution towards a regenerative growth model
4. Zero pollution targets for a toxic-free environment
5. The protection, conservation and recovery of biodiversity, and the improvement of natural capital
6. The promotion of environmental sustainability and the reduction of the main climatic and environmental pressures associated with production and consumption

The regenerative economy must allow the evolution of current systems without generating environmental degradation. Buildings must contribute to the evolution towards a regenerative economy with intelligent systems for managing water, energy and where waste becomes an asset.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

CHAPTER 2. OBJECTIVES

The main objective of this Doctoral Thesis is to evaluate techniques that contribute to the construction of sustainable and comfortable buildings through circular and regenerative economy techniques. Circular economy techniques (Best Available Techniques) must evolve into long-term regenerative techniques. A regenerative growth with the objective of zero emissions and that allows protecting ecosystems by reducing the environmental pressures associated with production and consumption.

The main techniques analyzed are framed from the point of view of sustainability and comfort. The techniques must allow the construction sector to evolve towards a low-carbon model, which allow the construction of buildings with low energy consumption. On the one hand, the sector must progress towards a model that reduces the use of natural resources (energy and materials) and therefore economic growth is separated from the use of resources and environmental degradation. On the other hand, the techniques must improve the well-being of the occupants, guaranteeing adequate thermal comfort and healthy indoor air quality and having an environment free of dangers.

Knowing the thermal behaviour of buildings is essential for the construction of efficient buildings. First, a model is developed to predict the indoor temperature of a building. This model allows evaluating the indoor temperature based on the outdoor temperature, solar radiation, the air renovation and the internal loads of the building. The disturbance of the system is assimilated to real conditions, so the outdoor temperature must be taken as a sine wave.

Once the model has been developed, it must also be analysed which materials are those that allow maintaining a more stable indoor temperature. An important point to analyse is the influence of the thermal inertia and the insulation placement of a building in the evolution of the indoor temperature.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Currently the construction sector is one of the sectors that generate the most waste. The use of sustainable materials in the sector helps to reduce the amount of waste. For this, a review of the main construction materials that are used in mixtures with waste is carried out. Finally, the thermal behaviour is analysed in order to compare them with conventional materials.

Another important point with energy implications for buildings is solar radiation. Solar radiation makes it possible to reduce energy consumption in winter, but nevertheless, in summer it can cause high indoor temperatures. For this, the solar shading devices are analysed and subsequently the influence of the fixed and mobile solar protections.

After analysing the influence of outdoor temperature and solar radiation on indoor temperature, another variable that affects indoor temperature is ventilation. Ventilation and indoor air quality is an important aspect that must be guaranteed in all buildings and has been more relevant due to the global pandemic caused by COVID-19. Therefore, a review of the main environmental hazards (chemical, biological and physical) that are present inside buildings is prepared. These pollutants are categorized based on the type of building and information about their control and disposal are reviewed. Finally, the influence of ventilation on indoor temperature is evaluated using the model developed.

Finally, thermal comfort is analysed. First, the different methods for calculating thermal comfort in buildings are reviewed and analysed. Secondly, different studies associated with the different theories are reviewed. Subsequently, how the placement of thermal insulation in buildings affects thermal comfort is analysed.

All the techniques discussed have the final purpose of achieving comfortable and sustainable buildings. Therefore, the candidates Best Available Techniques developed in each chapter are analyzed from the point of view of sustainability and comfortability. The techniques contribute to the decarbonization of the sector as techniques for the circulating and regenerative economy in order to optimize the design of buildings. Buildings must guarantee the well-being of their occupants, so the techniques are also analyzed from the point of view

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

of comfort, including the hazards present in the indoor air (chemical, biological and thermal). In this way, the results obtained in the first chapters are analyzed taking into account thermal comfort and sustainability.

The analyzed techniques aim to guarantee sustainability and thermal comfort in buildings (see Figure 2.1). The studies carried out are based on the development of a model that allows predicting the interior temperature of buildings considering the thermal envelope and solar radiation, as the main variables. Both factors are essential to guarantee adequate thermal comfort. In addition, an adequate control of solar contributions allows optimizing the energy management of buildings and also avoids situations of thermal discomfort.

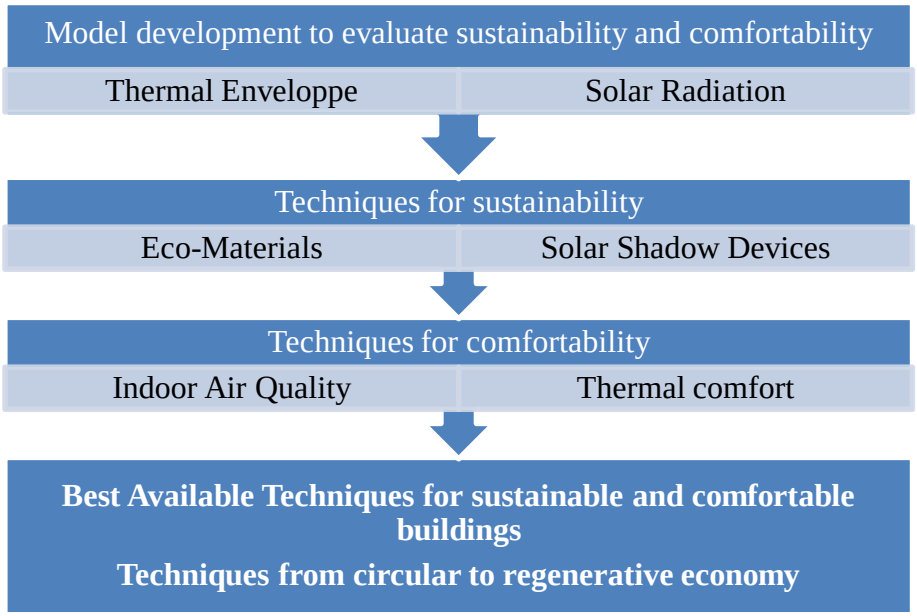

Figure 2.1: Summary of the objectives

Therefore, the final objective is to establish the Best Available Techniques from the point of view of indoor air quality and thermal comfort, as circular economy techniques towards a regenerative economy.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

CHAPTER 3. METHODOLOGY

For achieving the objectives described in the previous section, the Doctoral Thesis is developed in different chapters. Each chapter is developed independently, including a systematic review of the background and the state of the art, objectives, methodology, development, discussion of results and conclusions.

In CHAPTER 1, an introduction is made where the work is contextualized and justified. The main objectives of this study (CHAPTER 2) and the methodology (CHAPTER 3) to be followed for the development of this document are exposed. The process followed is summarized in Figure 3.1.

In CHAPTER 4 the tool used as the basis for the development of this study is created and that serves as a starting point to evaluate the most important variables that influence the thermal comfort and energy efficiency of the building. A model is implemented that allows establishing the indoor temperature of a building based on external variables such as temperature, solar radiation, ventilation and internal loads. After developing the model, the thermal behavior of different materials and thermal inertia of the building and its effect on the indoor temperature are evaluated

In CHAPTER 5 solar radiation is introduced into the model. To develop the equation of solar radiation and have the need to evaluate the influence of solar radiation on a building a separate chapter is dedicated. After including solar radiation in the model, the influence of solar radiation through walls and solar contributions through windows are analyzed.

Once the tool is obtained, the variables that make it possible to improve the sustainability of buildings are analyzed. In CHAPTER 6, the different sustainable materials that reduce the amount of waste generated by the construction sector are evaluated from a thermal point of view. Subsequently, different case studies are carried out on a model building, with the aim of comparing the energy demand of a

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

building built with eco-materials and with conventional materials. Finally, an environmental impact assessment of the materials under study is carried out using Lfe Cycle Assessment (LCA) indicators such as Non-renewable Energy (NRE), Cumulative Energy Demand (CED) and Global Warming Potential (GWP)

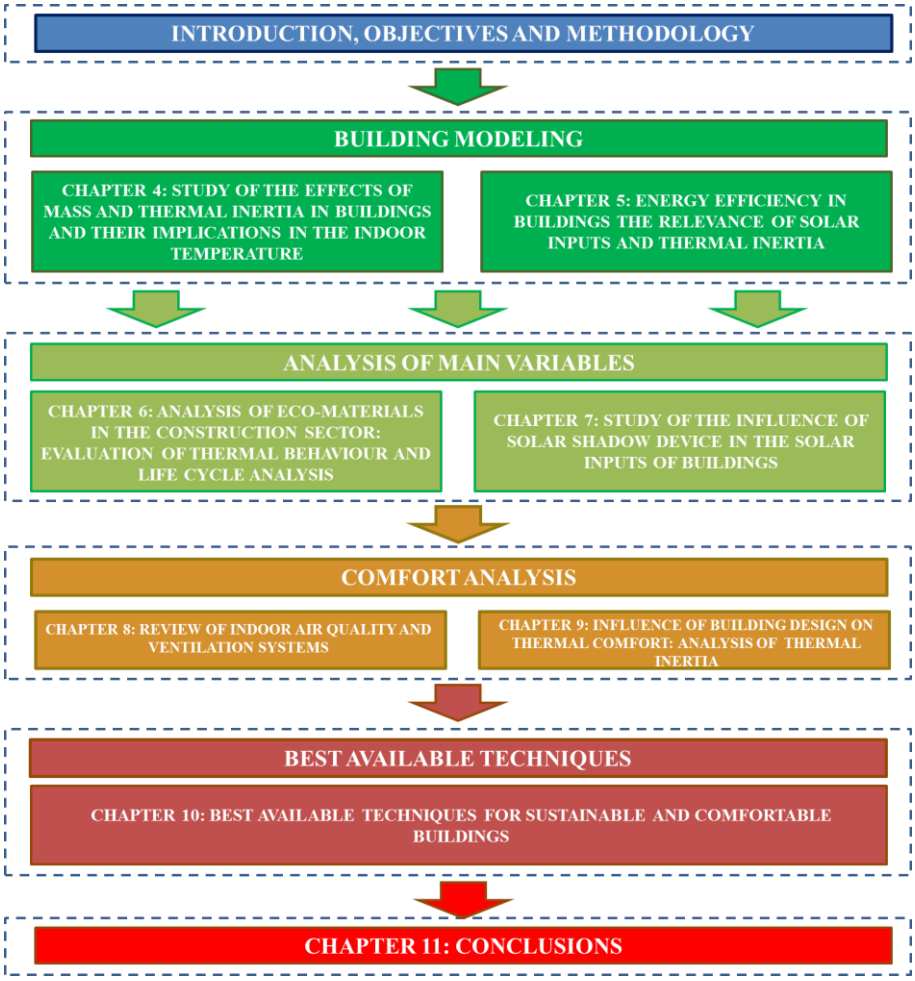

Figure 3.1: Summary of the steps followed for the development

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Due to the problems in thermal comfort and energy consumption generated by an excess of solar radiation, solar shadow devices are analysed in CHAPTER 7. Solar shadow devices are analysed from the point of view of the energy consumption of buildings. The influence of solar shadow devices are introduced in the model developed in CHAPTER 5. With the developed model, the influence of window characteristics on the thermal performance of buildings, the efficiency of fixed solar shading devices and dynamic solar shading devices are analyzed.

Another variable that affects comfort and energy consumption is ventilation. CHAPTER 8 analyses the main hazards present in the air and the criteria to be met to ensure adequate indoor air quality. First, a systematic review of the main hazards affecting indoor air quality is carried out. The systemic review is performed based on: indoor air quality, location of the case study (residential buildings, educational buildings and office buildings) and type of ventilation. Subsequently, an evaluation of the indoor temperature and air quality in buildings based on natural ventilation is carried.

The development of the model and the analysis of the main variables that affect the indoor temperature are aimed to guaranteeing thermal comfort. In CHAPTER 9, thermal comfort is analysed, so a review of the theories about thermal comfort is carried out. To analyze the importance of building design on comfort, the influence on thermal comfort as a function of the thermal envelope is analyzed.

The most representative techniques analyzed throughout the document are compiled in CHAPTER 10 as Best Available Techniques. These compilations of techniques allow the construction sector to evolve from a circular economy to a regenerative economy.

Finally, a chapter of conclusions is made (CHAPTER 11), where the main conclusions obtained are presented.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

CHAPTER 4. STUDY OF THE EFFECTS OF MASS AND THERMAL INERTIA IN BUILDINGS AND THEIR IMPLICATIONS IN THE INDOOR TEMPERATURE

This chapter is a reproduction of the following publication derived from the research carried out by the doctoral student during the training stage:

- Title: Development and application of a thermal comfort model in buildings
- Authors: Vilaboa Díaz, A; Bello Bugallo, P.M.
- Publisher: EDP Sciences
- Journal: Renewable Energy and Environmental Sustainability.
- eISSN: 2493-9439
- Impact Factor: Indexed in DOAJ - Directory of Open Access Journals
- DOI: https://doi.org/10.1051/rees/2021038
- Year of publication: 2022
- Contribution of the doctoral student: contribution to development of the research and writing the paper.
- Authorization of the journal/publisher for the use of the publication in the doctoral thesis. URL: https://www.rees-journal.org/about-the-journal/copyright-and-license-agreement
  Copyright and license agreement indicates that the author of a publication has permission to use it without restrictions. This URL is exactly transcribed below:
  - Copyright on any article in the Renewable Energy and Environmental Sustainability is retained by the author (s) under the Creative Commons license, which permits unrestricted use, distribution, and reproduction provided the original work is properly cited.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

SUMMARY

Buildings are responsible for 40% of final energy consumption in the European Union [EEA, 2021], of which 37% of energy is destined for heating [Eurostat, 2020]. The high energy consumption for heating is the result of the inefficiency of the sector. One of the main techniques for reducing energy consumption is to improve the thermal envelope.

Improving the building envelope significantly reduces energy demand. Therefore, in order to evaluate the techniques that allow reducing energy consumption and moving towards a circular and regenerative economy, a mathematical model able to predict the system response to outdoor temperature variations is developed

The model is developed using the analogy between the electric and thermal field. The implanted model allows analyzing the time lag and the decrement factor of different materials and types of envelope.

First, the influence of the thermal properties of the materials (conductivity, density and heat capacity) in the response when they are disturbed by a sine wave is analyzed.

Subsequently, the placement of the thermal insulation in the building envelope is analyzed. The placement of the insulation has an influence on the evolution of the indoor temperature of the building, which affects thermal comfort and energy consumption. Therefore, a case study is analyzed, where the thermal behavior of a building is evaluated taking into account the thermal envelope, ventilation and internal loads.

The optimal placement of the mass and thermal inertia, the properties of the materials and the thickness have a direct impact on the indoor temperature. Placing the thermal insulation on the outside and the thermal mass on the inside, allows obtaining more stable indoor temperatures, improving thermal comfort. For two elements with the same U-value, the energy flow is reduced by up to 13% by placing the insulation on the outside.

This chapter discusses techniques related to the thermal envelope in order to achieve nearly Zero-Energy Buildings and move towards a circular and regenerative economy.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

4.1. INTRODUCTION

For the construction of sustainable buildings with low energy consumption, it is necessary to carry out an optimal design in the previous stage of its construction. The energy consumption of buildings depends on various factors such as the design of the thermal envelope, which is one of the main design points to guarantee low energy consumption and the decarbonization of the sector. The achievement of sustainable buildings contributes towards a circular and regenerative economy and to construct buildings that use less resources and energy.

To achieve this aim, energy losses must be avoided by designing a good thermal envelope, which provides lower energy consumption. For increasing energy efficiency in buildings, this study analyses thermal inertia and its implications in the indoor temperature. A good design of the building envelope, taking into account the thermal inertia of its materials allows us to obtain a more stable temperature inside the buildings and therefore comfort is increased.

The facade properties (*U-value*, thermal inertia …) affect the energy demand [Ihara et al, 2015], so that it is important a good design of the thermal envelope and to know the influence of the energy accumulation of materials in indoor temperature. Thermal conductivity is the most important property to establish an adequate comfort temperature, obtaining better results when the value is lower [Avendaño-Vera et al, 2020]. The thermal inertia and the insulation placement are very important parameters to analyse. A correct design of the envelope taking into account these two parameters help to reduce the energy consumption for both heating and cooling [Ihara et al., 2015; Stazi et al, 2012; Fang et al, 2014]

S. Ferrari (2007) defined the thermal inertia of the building as the heat storage capacity in its structure and its performance to slow down heat transmission. The heat accumulation capacity of the building envelope has an impact on the final energy consumption. If two building elements with the same thermal transmittance but different energy accumulation capacity are compared, those elements having the greatest heat capacity produce energy savings in heating and cooling [Ihara et al, 2015; Ferrari, 2017; Kosssekaa et al, 2013]. If the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

thermal inertia are combined with other types of energy saving systems (such as solar shadow device), the energy saving in cooling improves notably. Energy savings in cooling in a building with solar shadow device can be 19% lower when using walls with high thermal inertia [Aste et al, 2009]

The energy storage capacity not only depends on its heat capacity, but it also affects its density and its thermal conductivity. By increasing density, a heavier structure is obtained and, as a result, the energy storage capacity increases. This structure delays the heat transfer by increasing the gap of the thermal wave. Furthermore, this increased density produces a greater stability of the indoor temperature. In addition, the optimal density of the material must be selected according to the type of climate varying between 1.800 and 2.500 kg/m^3 [Avendaño-Vera et al, 2020]. Finally, the thermal conductivity of the material also influences thermal inertia, since highly conductive materials allow greater heat flow, which facilitates the loss of the energy accumulated in materials. Then, materials with high conductivity cause a minor gap and greater temperature oscillation [Kontoleon et al, 2013]

There are different experimental studies about the influence of the thermal inertia in the indoor thermal environment [Stephen et al, 2014; Martin et al, 2010; Orosa et al, 2012]. One of this studies [Martin et al, 2010] analyses the thermal behaviour of different existing constructive solutions in Spain, showing that, traditional houses, built with materials with high thermal inertia, have an indoor environment more stable than modern houses built with lightweight materials. Specially, in summer and winter, when the outside temperature variation has a value of 25,4^oC and 23,6^oC, respectively, the decrement factor in buildings with heavier materials has a value about 0,20. The savings achieved in refrigeration reach between 67 and 75% with respect to the use of light materials [Kuczynski et al, 2020]. This behaviour is also observed in historical buildings. The stone used in this type of building has a high thermal inertia, which allows maintaining the interior temperature at stable values. In addition, ventilation systems at night, allow eliminating the heat accumulated by the walls [Evola et al, 2017]

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The walls with heavier materials have better behaviour during shorts periods of cold weather. During these periods, the constructions with higher thermal inertia do not need heating whereas the buildings constructed with lightweight materials, the heat must be supplied, due to the low heat stored in their structure [Orosa et al, 2012]

The influence of the thermal properties of materials may generate to greater indoor temperature variations and therefore, greater energy consumption. So, it is important to use the suitable material in order to improve the energy efficient of the buildings [Martin et al, 2010; Orosa et al, 2012]. Therefore, knowing the influence of the thermal inertia in the indoor temperature evolution helps to improve climate systems. Thus, the control of this property when designing envelope elements improves building energy efficiency. However, in spite of having a low heat capacity, the use of thermal insulation also has special importance. In fact, the placement of thermal insulation on the outside offers better results than placing it on the inside [Sami et al, 2012]. Also, the insulation helps to decrease the decrement factor and the increase the lag [Stephan et al, 2014]

Temperature is an important parameter to be controlled to obtain thermal comfort, so studying thermal inertia is very important. The use of materials with high thermal inertia, allow maintaining the indoor temperature within the comfort range. According to the study carried out by Kuczynski et al (2020), they obtained that the indoor temperature in a building made with light materials, exceeded the maximum comfort temperature ($26^{o}C$) by 1,6 times more than in a building with heavy materials. This study should be made not only at residential level, but also for industrial use. For example, Mazarrón and Canas (2008) developed a mathematical model to calculate temperature inside wine caves, taking into account a sinusoidal variation of the external temperature, soil type and depth. This model facilitates their design and knows the indoor temperature.

To study the energy efficiency of buildings, it is important to analyse the wall composition to improve the thermal insulation. There are different methods to analyse the thermal behaviour of a wall, allowing the analysis of different scenarios without the need for experimental data collection. Among the different models are

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

analytical models, which allow exact solutions but applied to simplified cases. Resolution by electrical network analogy is also widely used in scientific literature, which establishes the analogy between the electric and thermal field. Currently, numerical simulation models are already widely used; they allow evaluating the performance of buildings through the use of commercial software or creation of their own code. This type of simulation software allows evaluating a wide range of physical phenomena [Verbeke et al, 2018]

Ozel et al (2007) analyse the behaviour of a multilayer wall establishing the heat flow equations and solving it using finite differences. For the resolution of the model, they start from a periodic exposure to solar radiation, to the variation of outdoor temperature and to a constant indoor temperature. The set of finite difference equations is solved using matrix functions in *Matlab*. Using the model developed as a basis, Ozel et al (2014) analysed, for the optimal insulation thickness, the influence of placing the insulation outside, in the middle or inside. In the case analysed, it is obtained that placing the exterior insulation produces a lower temperature fluctuation and a better thermal performance is obtained.

Other authors solve the heat transfer equation by performing a numerical analysis of finite differences. Asan (2000) solved the one-dimensional heat transfer equations using the Crank-Nicolson scheme, analysing the decrement factor and the time lag for different insulation locations. Among the results obtained, it stands out that in the case of using a single insulation block; the best option is to place it outside. However, to guarantee the minimum decrement factor and maximum time lag, the optimal option is to distribute the insulation in the outer layer and in the middle the multilayer wall.

The resolution of the heat transfer equation was also solved using the analogy between electric field and thermal field, where the systems transfer function was established using the impedance and voltage of the equivalent electrical circuit. Danielle et al (2013), analyse the behaviour of multilayer walls, in the event of an outdoor temperature disturbance, obtaining the temperature on the interior surface without taking into account the transfer of heat by convection to the interior. In this way, it analyses the decrement factor and time

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

lag for different walls. The configuration with the best performance was obtained for walls whose insulation was located on the outside and inside and the thermal mass in the centre. Using this analogy, Kontoleon (2013) analysed the influence of density and conductivity of concrete through the dynamic heat transfer model.

The electrical analogy was also used by Raefat et al (2017) to analyse the behaviour of a multilayer wall for bricks with different materials and numbers of cavities, taking into account the heat transfer by radiation and convection in the brick cavities. Raefat et al solved the equations using Mathematica Software. The equations were based on the development carried out by Bouchair (2008), where he uses the analogy of thermal resistance and electrical resistance. Bouchair (2008), includes in the parameters to be evaluated the size and number of holes in the brick, the material used as filling and the emissivity.

Laaouatni et al (2019) used the electrical analogy to evaluate the effect of phase change materials (PCM). In this study, it takes into account the variation of the properties of materials with temperature. The results are validated by an experimental test and compared with a result using a finite element model. The developed RC model allows evaluating the optimal amount of PCM material and the dimension of the elements.

Hichem et al (2013) solved the heat transfer model using commercial *Fluent* software, solving Computational Fluid Dynamics (CFD) models and performing an experimental analysis of the results. In this case, the use of Phase Change Materials (PCM) and the implications of incorporating it into the brick holes are analysed. The results show a reduction of up to 90% of the heat flux when introducing the PCM material in the holes in the middle and near the outer wall. Using CFD models and validated with experimental data, Dabbagh et al (2020), evaluate the performance of a prototype mechanically operated Dynamic Insulation System (DIS). The system allows the insulation to mechanically rotate within the chamber, thus varying the *R-value*. The *R-value* of the wall is reduced when the insulation begins to rotate and therefore it is placed transversally, reaching a reduction of the *R-value* greater than 50%.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

In this chapter, the mathematical model to predict indoor temperature is established using the relationship between electrical and thermal analogy. For the development of the equations, the unidirectional heat flow is assumed. The model takes into account those areas of the buildings in contact with constant temperatures, the influence of ventilation and internal loads. Furthermore, the model will allow evaluating the influence of solar radiation later chapters.

The differential equations obtained are solved using the *Laplace* transform. The model obtained not only allows evaluating the thermal behaviour of different multilayer walls, but also, it allows the dynamic behaviour of a building without the need for large computational resources. To obtain an accurate model, each layer of each wall is divided into different sections, in order to create finite sections and thus obtain a temperature profile through the wall adjusted to reality.

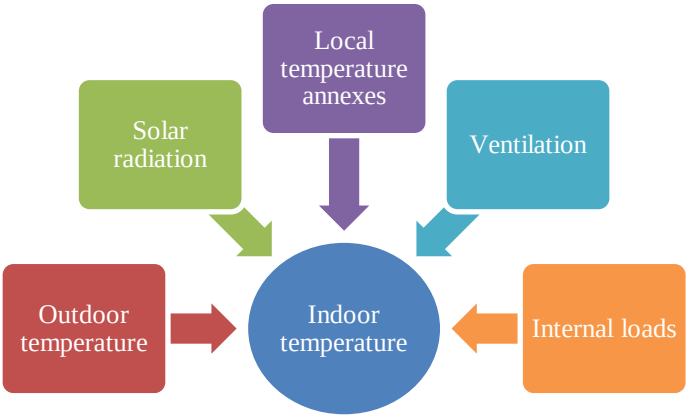

Figure 4.1: Variables included in the model that affect the indoor temperature

With the model, the influence of different materials used in buildings can be analysed and thus estimate the indoor temperature evolution, due to that each material affects the decrement factor and time lag of the wave in a different way. These variables allow analysing what type of material is appropriate in order to achieve an indoor temperature more stable and therefore, take a first step towards a model that allows estimating the indoor temperature depending on the external dynamic conditions.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Improve the thermal envelope of buildings decrease the energy consumption for heating in winter and for cooling in summer [Ihara et al, 2015] and, for that, to increase energy savings, because "the cheaper energy is that is not consumed".

Therefore, the thermal inertia is an important parameter to study. The thermal capacity of materials seems to be a relevant parameter to analyse for moderate climates and intermediate seasons, where it can work as a stabilizing factor of the thermal dynamics of the whole building system [Aste et al, 2015]

4.2. THEORETICAL CONCEPTS

The inertia is the resistance to change that opposes a body, so bodies are said to have more inertia when the difficulty of altering their state of rest or motion increases.

Thermal inertia is the ability of a system to conserve heat energy and to release it. Taking into account the accumulation capacity of materials, air conditioning needs can be reduced and more energy-efficient buildings can be built.

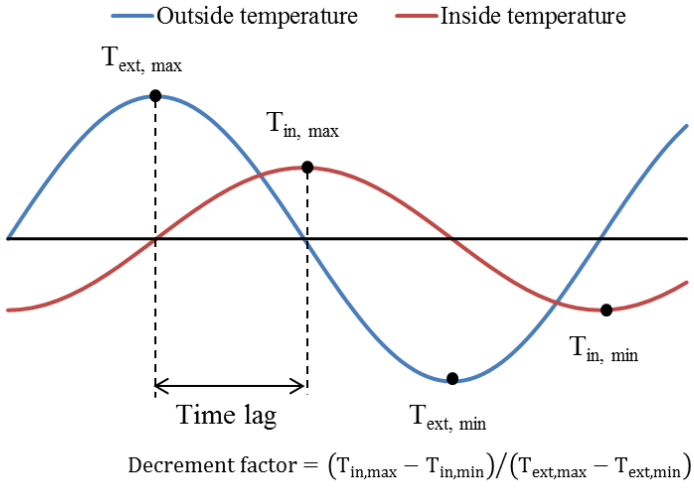

Figure 4.2: Graphical representation of decrement factor and time lag

Thermal inertia involves two phenomena, namely, the decrease in the variation of temperature and the delay between outdoor and indoor temperature (see Figure 4.2). The amplitude of a wave of outdoor temperature is buffered when passing through the enclosure. In addition, a gap between the peaks of maximum temperature emerges. This time lag is the time that the wave takes to cross the enclosure. Due to the changes in the outdoor temperature, the heat accumulated in the wall can find a more "comfortable" exit, generating a thermal wave bounce, which produces a lesser temperature oscillation.

The decrement factor (μ) can be calculated from the maximum and minimum temperatures inside (T_{in}) and outside (T_{ext}), as shown in equation [Eq.4.1] [Kontoleon et al, 2013]

$$\mu = \left(T_{in,max} - T_{in,min}\right)/\left(T_{ext,max} - T_{ext,min}\right) \qquad \text{[Eq.4.1]}$$

A large thermal inertia causes a more buffered heat wave, which shows a greater time lag. The optimal situation occurs when the time lag allows heat accumulation during higher radiation hours, when the outdoor temperature is higher, and heat transfer to the inside when it is cold outside. Moreover, thick walls can be close to 100% cushioning, maintaining constant temperature in spite of daily thermal oscillations, as it occurs in caves and cathedrals.

Thermal mass (M_T) is calculated by adding the product of the heat capacity (C_P) to the density (ρ) of each layer (i):

$$M_T = \sum_i C_{P\,i} \cdot \rho_i \quad [J/K \cdot m^3] \qquad \text{[Eq.4.2]}$$

This term indicates the amount of heat per unit volume and kelvin degree that an enclosure is able to accumulate. It can be interesting to know the storage capacity of an element of the envelope per unit of transversal flow surface of heat, so the equation above is multiplied by the thickness of the wall (e):

$$M_T = \sum_i C_{P\,i} \cdot \rho_i \cdot e_i \quad [J/K \cdot m^2] \qquad \text{[Eq.4.3]}$$

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Finally, another element to take into account is thermal diffusivity (α), which relates conductivity (λ) to heat capacity (Cp) and the density of the material (ρ) [Sami et al, 2012]

$$\alpha = \lambda/(C_p \cdot \rho) \qquad [m^2/s] \qquad \text{[Eq.4.4]}$$

Thermal diffusivity is a factor which expresses the rate of change of the system until it reaches equilibrium. This parameter gives an idea of the ability that the material has to spread the temperature to the inside. Thus, materials with high thermal diffusivity have a greater variation of temperature so they have a greater tendency to change and reach equilibrium faster. Here lies the importance of analysing this factor because, apart from taking into account the thermal mass of the material, thermal diffusivity must also be considered.

4.3. OBJECTIVES

The aim of this work is to develop a model which predicts the indoor temperature, based on the method of *Equivalent electrical network* for the calculation of the indoor surface temperature of walls in contact with the outside, and the establishment of the indoor temperature by an energy balance.

At the same time, the dynamic response of a single-layer wall is analysed. The system is subjected to a sinusoidal disturbance, and its response on the indoor surface is also analysed. Thus, the response of enclosures having different thermal properties can be compared.

This chapter tries to show the importance of designing various elements of the thermal envelope properly, in order to achieve more stable indoor conditions; as well as the advantages offered by the correct placement of the insulating material in opaque enclosures with the same thermal transmittance. The optimal design of the envelope allows reducing the energy demand of the buildings and improving the sustainability and competitiveness of the sector.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

4.4. CASE STUDY

Buildings are the objective of this study, where, based on the elements of their envelope, indoor temperature can be calculated.

The building model used in this work is a cube-shaped one, with two exterior facades, two walls having a constant temperature and its concrete slab and roof being in contact with the ground and the outside, respectively. The outside elements of the envelope are composed of a 20 *cm* concrete layer and 8 *cm* of insulation. The elements in the constant temperature area are composed of a 20 *cm* concrete layer.

To accomplish the goal of this study two versions are study: when the concrete wall has the insulation in de outside and when the concrete wall has the insulation is in the inside.

4.5. METHODOLOGY

In general, two hypotheses can be proposed to obtain a model which could determine the thermal behaviour of a building. On the one hand, steady-state conditions may be considered, that is., assuming a constant outdoor temperature, in which case, a constant indoor temperature is obtained. On the other hand, dynamic conditions may be taken into account, and so the model is closer to reality. In the development of this work, the dynamic conditions have been considered, so the system analysed is subject to outdoor temperature fluctuations.

The development of the mathematical model that allows the prediction of the indoor building temperature depending on the outdoor temperature variations is based on the method of *Equivalent electrical network*. This model uses the analogy between an electric circuit and the heat transfer through a multi-layer wall. It can be an electric circuit consisting of capacitors and resistors to simulate the heat capacity and envelope thermal resistance, respectively. One of the main advantages of the model is the intuitively understanding of the phenomenon of heat exchange in a building as well as its easy analytical solution [Marincic, 1999]

In order to facilitate the mathematical development of the problem, the approach is divided into two distinct systems. Firstly, the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

surface temperature of the different elements of the envelope is estimated using the method of Equivalent Electrical Network. To do this, each element of the envelope is divided into several sections, in such a way that the space calculation interval is diminished and, thus, the accuracy of the results increases. Secondly, once the model that allows to predict the surface temperature of the walls is created, the indoor temperature is calculated, posing a balance of energy. Thus, four different aspects are considered, namely, the variations of the surface temperature; the energy losses due to the renewal of air; possible internal loads and, finally, the influence on the temperature inside the walls which are in contact with areas at constant temperature.

This work is developed in the following stages:

- Mathematical model to describe the behaviour of a single-layer wall.

The mathematical model which allows calculating the temperature on the inner surface of a wall in contact with the outside is described. To do so, the similarity between the electric field and the heat field is used. We start from the most basic case, which is a single *RC* circuit, and then we add a second circuit in cascade with the purpose of obtaining a system of *n* equations for *n* circuits. In addition, we realize a simulation of a single-layer wall and discuss the need of a larger number of nodes implementing the equations in *Matlab*.

- Study of the thermal inertia of materials.

Due to the large amount of materials used in construction and its different thermal properties, the behaviour of different materials to a sinusoidal disturbance is analysed.

- Study on the placement of isolation.

It is important to design a thermal envelope offering a high resistance to heat flow in order to minimize energy losses and lower energy consumption. It is important the placing of the insulation and the element with greater thermal mass. So, it is analysed the difference in the response of a multi-layer wall by placing insulation inside and outside, and the impact on the heat flow through it.

- Study of the temperature inside a building.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

One of the objectives of the study is to predict the variation of the indoor temperature of a building or housing. From the response of each wall to the outdoor temperature, an energy balance from the inner surface of the walls towards the inside. Once the equations are obtained, it is implemented in *Matlab* and the solution is obtained in the time domain. Finally, the indoor building temperature is calculated comparing when its elements against the outside have their insulation on the inside or outside.

4.6. DEVELOPMENT AND PRESENTATION OF RESULTS

The influence of thermal inertia in the evolution of indoor temperature is studied using the existing parallelism between the electric field and the thermal field. This parallelism describes the mechanism of heat transfer based on electrical analogy.

4.6.1. Mathematical model to describe the behaviour of a single-layer wall

A homogeneous wall can be represented by an electrical circuit consisting of a resistor (R) and a capacitor (C), representing the thermal resistance and the heat capacity of the wall (Figure 4.3a).

The potential difference of the power (V_0) is equivalent to the outdoor temperature, and the inner surface temperature is related to the potential difference in the capacitor (V_C). The resolution of this system is trivial, and therefore, the surface temperature according to external disturbance can be calculated

The intensity flowing through the circuit (i) is the equivalent of the heat flux that flows through the wall, which, in this case, is equal to the current flowing through the capacitor (i_c). So, the intensity is equal to the potential difference in the capacitor divided by its resistance.

$$i(t) = i_c(t) = C \cdot \frac{dV_c(t)}{dt} \qquad \text{[Eq.4.5]}$$

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

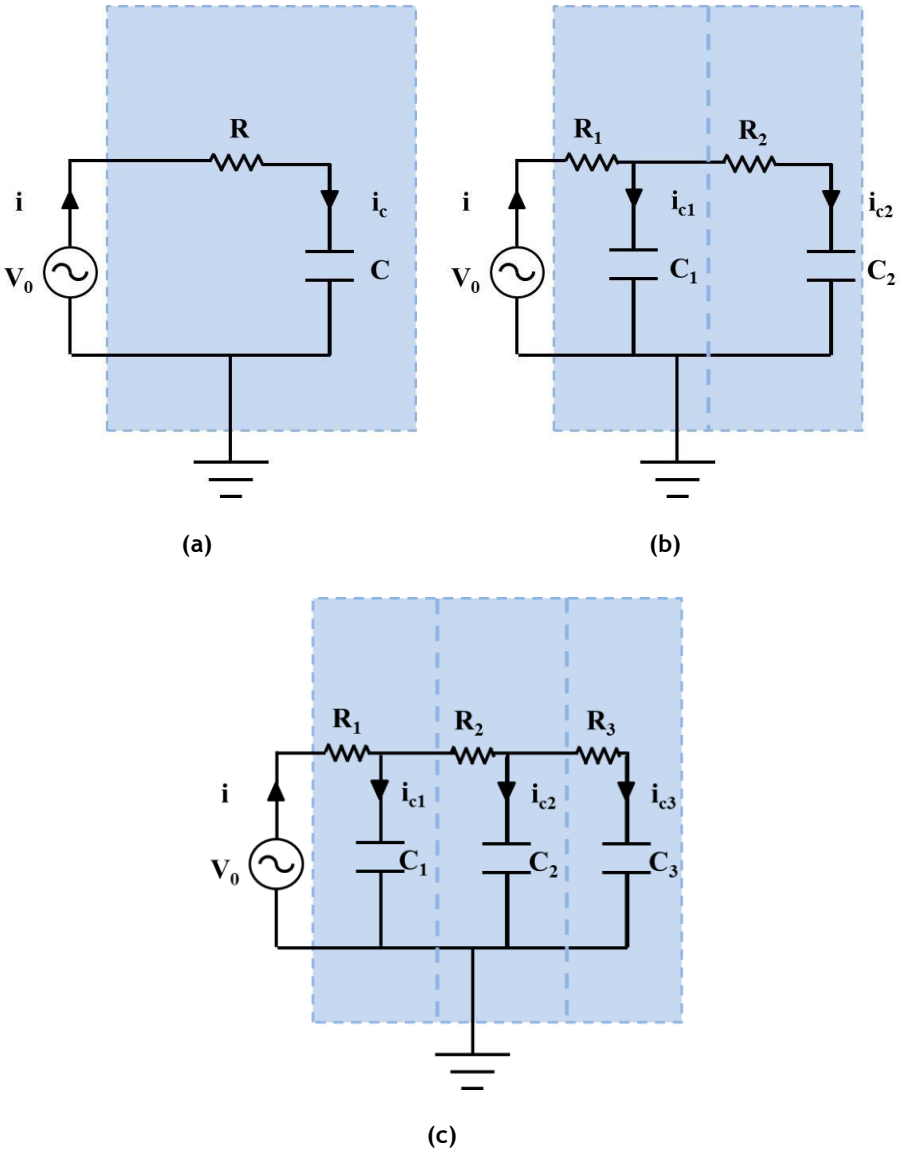

Figure 4.3: Representation of a monolayer wall as an electric circuit with one node (a), with two nodes (b) and with three nodes (c)

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The voltage on the capacitor (V_C), which depends on the time, can be calculated using *Kirchhoff's law*. So, the intensity through the condenser must be equal to the intensity that circulates through the resistance. In this way, the following linear equation is obtained:

$$V_0(t) = i_r(t) \cdot R + V_c(t) \qquad \text{[Eq.4.6]}$$

The intensity flowing through the capacitor (i_C) is equal to that flows through the resistance (i_r). So, combining equations [Eq.4.5] and [Eq.4.6], the following expression is obtained:

$$V_0(t) = i_c(t) \cdot R + V_c(t) = R \cdot C \cdot \frac{dV_c(t)}{dt} + V_c(t) \qquad \text{[Eq.4.7]}$$

By using *Laplace* transforms, this equation can be solved:

$$V_0(s) = R \cdot C \cdot V_c(s) \cdot s + V_c(s)$$

$$V_c(s)/V_0(s) = 1/(R \cdot C \cdot s + 1) \qquad \text{[Eq.4.8]}$$

Thus, the transfer function in Laplace domain is obtained from the input voltage to the output voltage on the capacitor. The response of voltage in the capacitor in time domain can be obtained from equation [Eq.4.8]

Analogously, transfer function allows us to obtain a response of the enclosure facing a perturbation of the outdoor temperature. In this case, a transfer function of order 1 is obtained. The time constant of the system obtained is $\tau = R \cdot C$.

Using the electrical analogy, the temperature on the inner surface (*Tsur,in*) and the external surface (*Text*) are related by equation [Eq.4.9]:

$$T_{sur,in}(s)/T_{ext}(s) = 1/(R \cdot C \cdot s + 1) \qquad \text{[Eq.4.9]}$$

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Where:

- *C*: is the heat capacity of the node, which is calculated from the equation [Eq.4.3] *[J/m^2·K]*
- *R*: is the thermal resistance of the node *[m^2·K/W]*

To represent a single layer wall as a *RC* circuit, the temperature of energy accumulation is equal to the inner surface temperature. This supposition can lead to imprecise results when estimating the surface temperature. If a single node is considered, the wall has a single accumulation temperature. As the energy accumulation of the wall depends on its temperature, the wall is divided into several sections, so that accumulation of the innermost layer temperature is equal to the indoor surface temperature.

Suppose the case in which the wall is represented by two resistors (R_1 and R_2) and two capacitors (C_1 and C_2). The system resolution is the same as in the previous case, except that now there are two electrical meshes (Figure 4.3b) and an equation is obtained for each electrical mesh.

In this case, the intensity generated by the power supply (i) is equal to that flowing through capacitor 1 (i_{c1}) and through capacitor 2 (i_{c2}).

$$i_{c1}(t) = C_1 \cdot \frac{dV_{c1}(t)}{dt} \quad \text{[Eq.4.10]}$$

$$i_{c2}(t) = C_2 \cdot \frac{dV_{c2}(t)}{dt} \quad \text{[Eq.4.11]}$$

$$i_1(t) = i_{c2}(t) + i_{c1}(t) \quad \text{[Eq.4.12]}$$

Where, V_{c1} and V_{c2} represent the voltage drop across capacitor 1 and 2 respectively. Applying *Kirchhoff's laws* for mesh 1 and mesh 2:

$$V_0(t) = i_1(t) \cdot R_1 + V_{c1}(t) \quad \text{[Eq.4.13]}$$

$$V_{c1}(t) = i_2(t) \cdot R_2 + V_{c2}(t) \quad \text{[Eq.4.14]}$$

Introducing equations [Eq.4.10], [Eq.4.11], [Eq.4.12] in [Eq.4.13] and [Eq.4.14] and taking into account that the current flowing through capacitor 2 is equal to that flowing through resistor 2.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

$$V_0(t) = \left(C_1 \cdot \frac{dV_{c1}}{dt} + C_2 \cdot \frac{dV_{c2}}{dt}\right) \cdot R_1 + V_{c1}(t) \quad \text{[Eq.4.15]}$$

$$V_{c1}(t) = C_2 \cdot \frac{dV_{c2}}{dt} \cdot R_2 + V_{c2}(t) \quad \text{[Eq.4.16]}$$

Applying the *Laplace* transform for the resolution and rearranging equations [Eq.4.15] and [Eq.4.16]:

$$V_0(s) = C_2 \cdot R_1 \cdot V_{c2}(s) \cdot s + (1 + C_1 \cdot R_1 \cdot s) \cdot V_{c1}(s) \quad \text{[Eq.4.17]}$$

$$V_{c1}(s) = C_2 \cdot V_{c2}(s) \cdot s \cdot R_2 + V_{c2}(s) \quad \text{[Eq.4.18]}$$

Combining equations [Eq.4.17] and [Eq.4.18]:

$$V_0(s) = C_2 \cdot R_1 \cdot V_{c2}(s) \cdot s + (C_2 \cdot V_{c2}(s) \cdot s \cdot R_2 + V_{c2}(s)) \cdot (1 + C_1 \cdot R_1 \cdot s) \quad \text{[Eq.4.19]}$$

Finally, the voltage on capacitor 2 is established as a function of the voltage at the source:

$$\frac{V_{c2}(s)}{V_0(s)} = \frac{1}{C_2 \cdot R_1 \cdot s + (C_2 \cdot R_2 \cdot s + 1) \cdot (1 + C_1 \cdot R_1 \cdot s)}$$

$$\frac{V_{c2}(s)}{V_0(s)} = \frac{1}{C_2 \cdot R_2 \cdot C_1 \cdot R_1 \cdot s^2 + C_2 \cdot R_1 \cdot s + C_2 \cdot R_2 \cdot s + C_1 \cdot R_1 \cdot s + 1} \quad \text{[Eq.4.20]}$$

If two nodes are used to describe a single-layer wall, the model obtained is more accurate, but the resolution of the equations is more complex. Considering two nodes, a transfer function of order two is obtained:

$$\frac{V_{c2}(s)}{V_0(s)} = \frac{1}{C_2 \cdot R_2 \cdot C_1 \cdot R_1 \cdot s^2 + (C_2 \cdot R_1 + C_2 \cdot R_2 + C_1 \cdot R_1) \cdot s + 1} \quad \text{[Eq.4.21]}$$

This transfer function has a higher precision than equation [Eq.4.8]. The wall is divided in two sections, so the spatial interval is smaller. Considering two nodes, a system of two equations and two unknowns is obtained. It can be represented in a matrix form through equations [Eq.4.17] and [Eq.4.18]:

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

$$\begin{pmatrix} V_0(s) \\ V_{c1}(s) \end{pmatrix} = \begin{pmatrix} 1 + C_1 \cdot R_1 \cdot s & C_2 \cdot R_1 \cdot s \\ 0 & 1 + C_2 \cdot R_2 \cdot s \end{pmatrix} \cdot \begin{pmatrix} V_{c1}(s) \\ V_{c2}(s) \end{pmatrix} \quad \text{[Eq.4.22]}$$

From the matrix obtained, n nodes can be considered to solve a homogeneous wall, obtaining a system of *n* equations with *n* unknowns.

$$\begin{pmatrix} V_0(s) \\ V_{c1}(s) \\ V_{c2}(s) \\ V_{c3}(s) \\ \vdots \\ V_{cn-1}(s) \end{pmatrix} = \begin{pmatrix} 1+C_1 \cdot R_1 \cdot s & C_2 \cdot R_1 \cdot s & C_3 \cdot R_1 \cdot s & C_4 \cdot R_1 \cdot s & \cdots & C_n \cdot R_1 \cdot s \\ 0 & 1+C_2 \cdot R_2 \cdot s & C_3 \cdot R_2 \cdot s & C_4 \cdot R_2 \cdot s & \cdots & C_n \cdot R_2 \cdot s \\ 0 & 0 & 1+C_3 \cdot R_3 \cdot s & C_4 \cdot R_3 \cdot s & \cdots & C_n \cdot R_3 \cdot s \\ 0 & 0 & 0 & 1+C_4 \cdot R_4 \cdot s & \cdots & C_n \cdot R_4 \cdot s \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 1+C_n \cdot R_n \cdot s \end{pmatrix} \cdot \begin{pmatrix} V_{c1}(s) \\ V_{c2}(s) \\ V_{c3}(s) \\ V_{c4}(s) \\ \vdots \\ V_{cn}(s) \end{pmatrix}$$

[Eq.4.23]

Using this matrix, a more accurate simulation is obtained, as increasing the number of nodes, the spatial interval is smaller, and therefore, the accumulation temperature of the innermost layer is closer to the surface temperature of the wall. Matrix The equation can be used not only for the resolution of a monolayer wall of *n* nodes, but also to solve multilayer walls, where each layer (*i*) is divided into *n/i* nodes.

4.6.1.1. Analysis of a single-layer wall

A single-layer wall is studied, particularly a concrete wall whose thickness is 20 *cm*, with a heat capacity of 1.000 *J/(kg·K)*, a conductivity of 2,5 *W/(m·K)* and a density of 2.400 *kg/m*^{3} [CTE, 2010]. A three-node mesh is used to calculate the inner surface temperature. Thus, a system of 3 equations with 3 unknowns is obtained. In this case, the single-layer wall is represented as an electrical circuit with 3 resistor and 3 capacitors (Figure 4.3c).

Using the electrical analogy, the system matrix is created by equation [Eq.4.23]:

$$\begin{pmatrix} V_0(s) \\ V_{c1}(s) \\ V_{c2}(s) \end{pmatrix} = \begin{pmatrix} 1+C_1 \cdot R_1 \cdot s & C_2 \cdot R_1 \cdot s & C_3 \cdot R_1 \cdot s \\ 0 & 1+C_2 \cdot R_2 \cdot s & C_3 \cdot R_2 \cdot s \\ 0 & 0 & 1+C_3 \cdot R_3 \cdot s \end{pmatrix} \cdot \begin{pmatrix} V_{c1}(s) \\ V_{c2}(s) \\ V_{c3}(s) \end{pmatrix} \quad \text{[Eq.4.24]}$$

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Developing the matrix [Eq.4.24] a system of 3 equations with 3 unknowns is obtained:

$$V_0(s) = (1 + C_1 \cdot R_1 \cdot s) \cdot V_{c1}(s) + C_2 \cdot R_1 \cdot s \cdot V_{c2}(s) + C_3 \cdot R_1 \cdot s \cdot V_{c3}(s) \quad \text{[Eq.4.25]}$$

$$V_{c1}(s) = (1 + C_2 \cdot R_2 \cdot s) \cdot V_{c2}(s) + C_3 \cdot R_2 \cdot s \cdot V_{c3}(s) \quad \text{[Eq.4.26]}$$

$$V_{c2}(s) = (1 + C_3 \cdot R_3 \cdot s) \cdot V_{c3}(s) \quad \text{[Eq.4.27]}$$

The three expressions can be combined, in such a way that the source voltage (V_0) is obtained as a function of the voltage in capacitor 3 (V_{c3}), which would be the response of the wall.

$$V_0(s) = (1 + C_1 \cdot R_1 \cdot s) \cdot \left(V_{c3}(s) \cdot (1 + C_2 \cdot R_2 \cdot s) \cdot (1 + C_3 \cdot R_3 \cdot s) + C_3 \cdot R_2 \cdot s \cdot V_{c3}(s)\right) + C_3 \cdot R_1 \cdot s \cdot V_{c3}(s) + C_2 \cdot R_1 \cdot s \cdot V_{c3}(s) \cdot (1 + C_3 \cdot R_3 \cdot s) \quad \text{[Eq.4.28]}$$

Finally, the voltage in capacitor 3 is related as a function of the source voltage and it is simplified.

$$V_{c3}(s)/V_0(s) = 1/(C_1 \cdot C_2 \cdot C_3 \cdot R_1 \cdot R_2 \cdot R_3 \cdot s^3 + (C_1 \cdot C_2 \cdot R_1 \cdot R_2 + C_1 \cdot C_3 \cdot R_1 \cdot R_2 + C_1 \cdot C_3 \cdot R_1 \cdot R_3 + C_2 \cdot C_3 \cdot R_1 \cdot R_3 + C_2 \cdot C_3 \cdot R_2 \cdot R_3) \cdot s^2 + (C_1 \cdot R_1 + C_2 \cdot R_1 + C_2 \cdot R_2 + C_3 \cdot R_1 + C_3 \cdot R_2 + C_3 \cdot R_3) \cdot s + 1) \quad \text{[Eq.4.29]}$$

The wall has a thermal resistance of 0,08 $m^2 \cdot K/W$ and its thermal mass is 480.000 $J/(m^2 \cdot K)$. Its transfer function is obtained by developing the matrix and introducing its thermal properties. As the wall is divided into three parts, its thermal resistance and thermal mass per node must be introduced in the matrix [Eq.4.24], that is, the total value divided by three. Thus, the relationship between the input voltage and the voltage in the capacitor 3 is obtained by equation [Eq.4.30]

$$V_{c3}(s)/V_0(s) = 1/(77.672.296.296 \cdot s^3 + 91.022.222 \cdot s^2 + 25.600 \cdot s + 1) \quad \text{[Eq.4.30]}$$

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

As the transfer function uses 3 nodes to obtain the inner surface temperature, the system's block diagram can be posed (see Figure 4.4). The electrical circuit, which is equivalent to the single-layer wall with three nodes, is formed by three cascaded *RC* circuits. The disturbance is source voltage (V_0), and the output signal is the voltage across capacitor 3 (V_{C3}).

The present analysis shows that, if two or more cascaded *RC* circuits are connected, the output of the first being the entry of the second, their general transfer function is not the product of their individual transfer functions (*1/(RCs+1)*). This is so because when the transfer function of an isolated circuit is obtained, it is generally assumed that its output is not charged, meaning that no power is delivered to the output. However, when the second circuit is connected to the output of the first, a certain amount of power is delivered and, therefore, the assumption that there is no load is not valid. This is why, if the transfer function of this system is obtained under the assumption that the second circuit is not loaded, this assumption is not valid [Cancelas et al, 2014; Navarro, 2012]

Leaving the electrical analogy, equation [Eq.4.30] can be expressed having into account the external temperature (T_{ext}) and the wall's inner surface temperature ($T_{sur,in}$).

$$T_{sur,in}(s)/T_{ext}(s) = 1/(77.672.296.296 \cdot s^3 + 91.022.222 \cdot s^2 + 25.600 \cdot s + 1) \quad \text{[Eq.4.31]}$$

The block diagram (Figure 4.4) shows the relationship between the output voltage (V_{C3}) and the source voltage (V_0). Dealing with thermal equivalence, the block diagram represents the operation between the output temperature ($T_{sur,in}$) and the input temperature (T_{ext}).

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

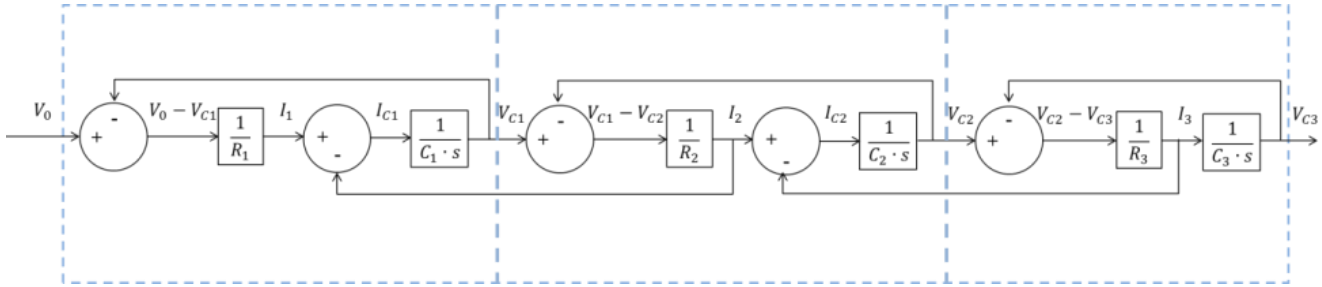

Figure 4.4: Block diagram of the concrete wall resolution by electric analogy for 3 nodes

4.6.1.2. Analysis of the system behaviour to different disturbances

Once the transfer function has been obtained, the system behaviour is analysed having into account different types of disturbances. First, the system is analysed when perturbed by a step disturbance and then by a sine wave disturbance. The results are obtained by implementing the transfer function in the Laplace domain in *Matlab*.

- Analysis for a step disturbance

The simplest case is when the perturbation is of a step type. Thus, the system is submitted to a unit step disturbance, taking place, as a result, an increase of $1^{o}C$ in the temperature comparing to initial stage:

$$T_{ext}(s) = 1/s \qquad \text{[Eq.4.32]}$$

Introducing this disturbance in equation [Eq.4.31], the evolution of inner surface temperature is obtained when the perturbation is a step.

$$T_{sur,in}(s) = \frac{1}{77.672.296.296 \cdot s^3 + 91.022.222 \cdot s^2 + 25.600 \cdot s + 1} \cdot \frac{1}{s} \qquad \text{[Eq. 4.33]}$$

This equation allows us to obtain the evolution of inner surface temperature in Laplace domain. Therefore, the variation of inner surface temperature in the time domain can be obtained. Using Matlab, the evolution of this variable is plotted in the time domain (see Figure 4.5). This plot shows that the system reaches stability. Therefore, the Matlab code used is shown in the next table.

Table 4.1: Matlab code for a step disturbance

```
num=[1]
den=[77672296296 91022222 25600 1]
step(tf(num,den))
```

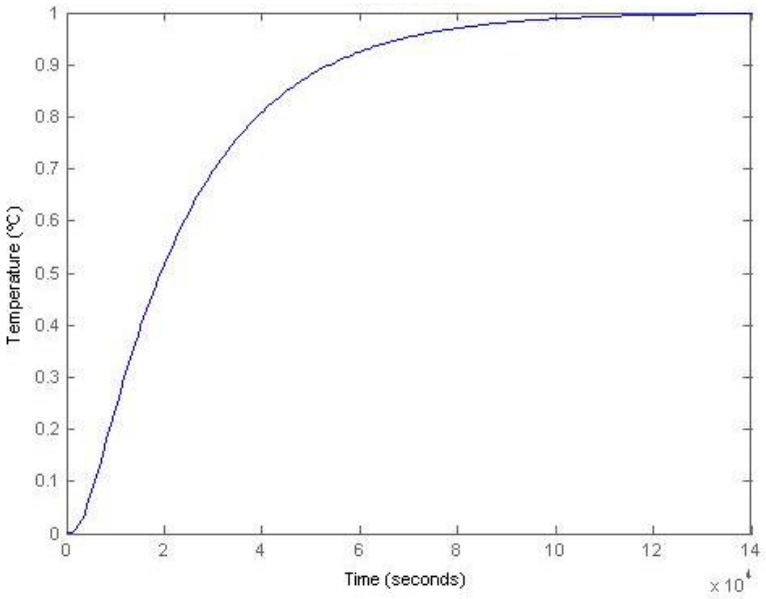

Figure 4.5: Variation of the inner surface temperature to a unit step perturbation disturbed considering 3 nodes

- Analysis for a sine wave perturbation

As the wall is subject to external temperature variation, the system is altered by a sine wave perturbation. This perturbation occurs because the external temperature oscillates during the day. This variation can be approximated as a sine wave (equation [Eq.4.34]).

$$T_{ext}(t) = T_{avg} + Amp \cdot sin(\omega \cdot t + \varphi_0) \qquad \text{[Eq.4.34]}$$

Where:

- T_{avg}: is the wave average temperature [$°C$]
- Amp: is the wave's amplitude [$°C$]
- ω: is the angular speed *[rad/s]* that is equal to $2 \cdot n/T$ (T is the period in seconds).
- t: is the time [s]
- φ_0: is a constant phase of the thermal wave [rad]

Laplace transform is used in equation [Eq.4.34]:

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

$$T_{ext}(s) = \frac{T_{avg}}{s} + \frac{Amp \cdot \left(w \cdot cos(\varphi_0) + s \cdot sin(\varphi_0) \right)}{s^2 + \omega^2} \qquad \text{[Eq.4.35]}$$

Equation [Eq.4.36] shows the evolution of the inner surface temperature in Laplace domain when the system is perturbed by a sine function.

$$T_{ext}(s) = \frac{1}{77.672.296.296 \cdot s^3 + 91.022.222 \cdot s^2 + 25.600 \cdot s + 1} \cdot \left(\frac{T_m}{s} + \frac{Amp \cdot \left(w \cdot cos(\varphi_0) + s \cdot sen(\varphi_0) \right)}{s^2 + -\omega^2} \right) \qquad \text{[Eq.4.36]}$$

As well as a step disturbance, equations are implemented in Matlab, defining the transfer function and the perturbation. The sine wave is characterized by a maximum of 40°*C* and a minimum of 20*ºC*, so its average temperature is 30°*C* and its amplitude 10°*C*, its period is 24 hours. The language used in *Matlab* is shown in Table 4.2. The program plots the temperature evolution when the system is disturbed for 10 days (see Figure 4.6).

Table 4.2: Matlab code for a sine wave disturbance

```
num=[1]
den=[77672296296 91022222 25600 1]
Tm=30
Amp=10
fi= 0
w=2*pi/(3600*24)
t= [0:1800:864000]
P=Tm+Amp*sin(w*t+fi)
[X,Y]=lsim(num,den,P,t)
plot(t,X)
[maximo,indicemax]=max(X)
t(indicemax)
```

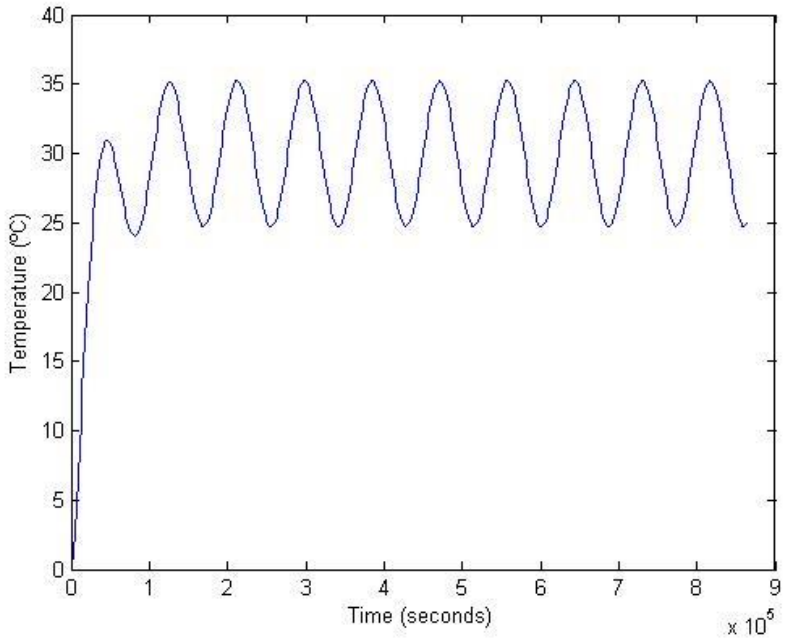

Figure 4.6: Variation of inner surface temperature to a sinusoidal disturbance considering a number of nodes n=3

The response of a linear system in stationary state to a sinusoidal input is a sine wave with the same frequency, but with a different amplitude and phase. In this case, the system reaches a maximum temperature of 35,24*ºC* and a minimum of 24,76*ºC*.

4.6.1.3. Analysis in the frequency domain

Finally, the proposed mathematical system is analysed from the frequency domain. Working in this domain the steady state response to a sinusoidal input is obtained. If a linear system with a sinusoidal input $e(t)=A\cdot sin(w\cdot t)$ is considered, it can be shown that the steady-state output is of the form $s(t)=B\cdot sin(w\cdot t+\varphi)$. The advantage of the frequency response is that the sinusoidal transfer function can be obtained in a simple way, substituting j·w for s in the transfer function. [University of Oviedo, 2014]

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

If the transfer function obtained from the frequency domain is analysed, where the angular velocity, $\omega = 2 \cdot n/T$, the next equation is obtained:

$$\frac{V_{c3}(s = j \cdot \omega)}{V_0(s = j \cdot \omega)} = \frac{1}{77.672.296.296 \cdot \left(j \cdot \frac{2 \cdot \pi}{24 \cdot 3600}\right)^3 + 91.022.222 \cdot \left(j \cdot \frac{2 \cdot \pi}{24 \cdot 3600}\right)^2 + 25.600 \cdot \left(j \cdot \frac{2 \cdot \pi}{24 \cdot 3600}\right)} \quad \text{[Eq.4.37]}$$

Operating and simplifying:

$$\frac{V_{c3}(s = j \cdot \omega)}{V_0(s = j \cdot \omega)} = 0{,}1431 - j \cdot 0{,}5054 \quad \text{[Eq.4.38]}$$

From the complex number obtained, the module (Z) and the phase or argument (φ) can be calculated from the real (Re) and imaginary (Img) part of the number.

$$Z = \sqrt{Re^2 + Img^2} \quad \text{[Eq.4.39]}$$

$$\varphi = tan^{-1}\left(\frac{Img}{Re}\right) \quad \text{[Eq.4.40]}$$

The variable Z defines what is known as the decrement factor (μ), which is the relationship between the temperature oscillation produced inside and the outdoor temperature oscillation as seen in equation [Eq.4.1]

Starting from the fact that the system is disturbed by an outdoor temperature wave as described mathematically from equation [Eq.4.34]. The response of the system is a sine wave, with amplitude proportional to the decrement factor (μ), and an increase in time lag (φ). Thus, the evolution of the outside temperature once the steady state is reached is described by equation [Eq.4.41]

$$V_{c3}(w) = T_m + Amp \cdot \mu \cdot sin(\omega \cdot t + \varphi) \quad \text{[Eq.4.41]}$$

Analysing the concrete wall for a thickness of 20 *cm* in the frequency domain, it is possible to obtain the decrement factor and the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

time lag produced by the wall. For this, the modulus and impedance of equation [Eq.4.38] are compared and using equation [Eq.4.39] and [Eq.4.40] a decrement factor of 0,5253 and a time lag of 4,95 hours are obtained.

Figure 7 shows the variation of the outdoor thermal wave, with a time lag $\varphi 0 = 0$ and the response of the monolayer wall considering 3 nodes. As it appeared graphically, a maximum temperature of 35,25^{o}C and a minimum of 24,75^{o}C is reached, confirming what was previously obtained by means of the Laplace domain.

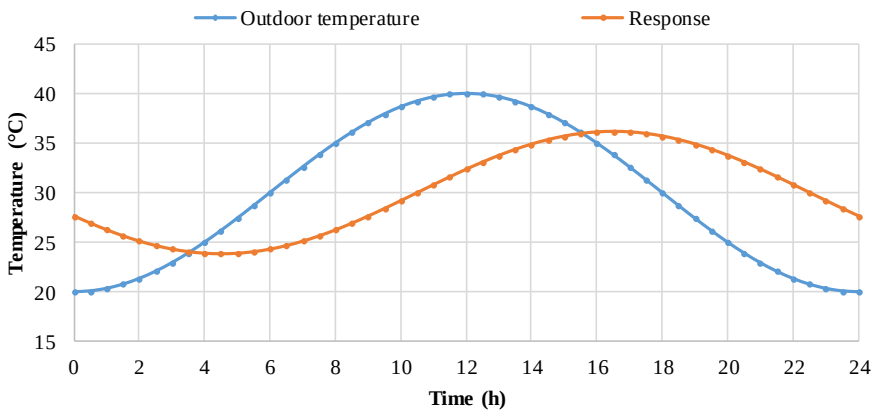

Figure 4.7: Response of a 20 cm thick concrete wall to a sinusoidal disturbance

4.6.1.4. Relationship between the number of nodes and the accurate of the mathematical model

In order to evaluate the importance of the results based on the number of nodes considered, the simulation of the 20 *cm* thick concrete wall described above is carried out. The behaviour of this wall is analysed by a sinusoidal disturbance with a maximum temperature of 40°C and a minimum of 20°C. The thermal resistance has a value of 0,08 $m^2 \cdot K/W$, and the value of the heat capacity per unit area is 480,000 $J/(m^2 \cdot K)$. The results obtained are shown in Table 4.3.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 4.3: Data obtained for the concrete wall based on the number of nodes

Number of nodes n	Δx [m]	Inner maximum temperature [°C]	Temperature difference with respect to the mesh of more nodes [%]	Time lag [h]	Time lag difference with respect to the mesh of more nodes [%]	Decrement Factor
1	0,200	33,88	6,64	4,69	5,87	0,3372
2	0,100	34,63	4,57	5,08	14,67	0,4638
3	0,067	35,24	2,89	4,95	11,74	0,5253
4	0,050	35,56	2,01	4,82	8,80	0,5578
5	0,040	35,76	1,46	4,73	6,77	0,5776
10	0,020	36,16	0,36	4,51	1,81	0,6172
15	0,013	36,29	--	4,43	--	0,6303

The simulations carried out for meshes with a greater number of nodes tend to the same value, thus, for a mesh of *n=1* an error of 6,64% is made in the estimation of the temperature with respect to a mesh with 15 nodes. For the simulation with 15 nodes, the interior surface temperature of the wall divides it into 15 parts of 1,3 *cm*. The trend of the value of the phase shift and of the surface temperature is represented in Figure 4.8.

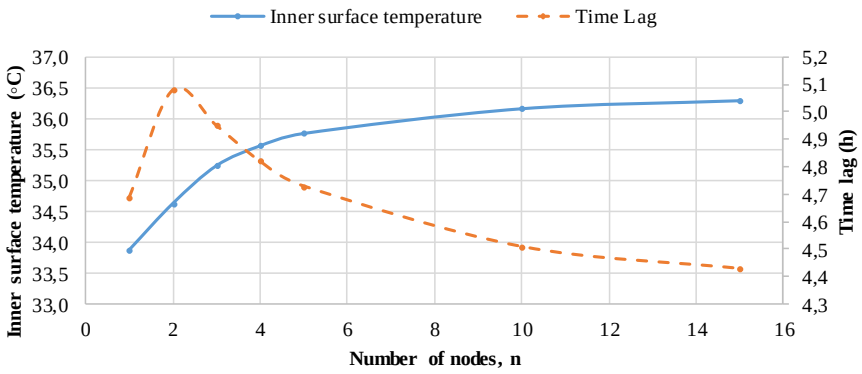

Figure 4.8 Variation of the interior surface temperature and the offset of a concrete wall (20 cm thick) as a function of the number of nodes

With the objective of obtaining accurate results, a mesh with a minimum of 5 nodes is used for the calculation of the surface temperature. In this way an error of 1,46% is made in the calculation of the temperature and 6,77 % in the calculation of the time lag.

4.6.2. Study of the thermal inertia of materials

Once the mathematical model is described, the influence of the thermal inertia of materials is known. The results obtained depend on the properties of the materials used, namely heat capacity, density and conductivity (see Table 4.4). To calculate this influence, a 20 *cm* thick wall is taken as reference and different materials are used for the simulation. In this case, a mesh with 10 nodes is used to simulate a single-layer wall. The perturbation is a sine wave with a maximum temperature of 40^{o}C and a minimum of 20^{o}C.

Table 4.4: Thermal properties of materials used in the simulation [IETCC, 2010]

Material	Heat capacity [J/kg·K]	Density [kg/m^3]	Conductivity [W/m·K]	Thermal mass [J/m^2·K]	Thermal diffusivity [cm^2/s]
Concrete	1.000	2400	2,50	480.000	0,0104
Brick	850	1630	0,60	277.100	0,0043
Granite	1.000	2600	2,80	520.000	0,0108
Wood middleweight	1.600	650	0,18	208.000	0,0017
Isolation	1.404	30	0,03	8.424	0,0076

The results show that concrete and granite are the materials with the highest heat accumulation capacity due to their high density and heat capacity. However they also show an elevated conductivity. Therefore, it is interesting to introduce a new factor, namely, thermal diffusivity, which expresses the rate of heat flow until equilibrium is reached. Thus, despite of the elevated thermal mass of concrete and granite, they are the materials with a high diffusivity, so they lose accumulated heat easier.

Insulating materials are on the opposite side. That is, they show a lower energy accumulation capacity, but their accumulated energy is

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

lost more slowly. This is so because isolations have low conductivity and, therefore, a lower value of thermal diffusivity.

The response obtained when the system is perturbed by a sine wave is shown in Figure 4.9. As expected, concrete and granite have a similar behaviour because they show similar thermal properties. These materials have a higher internal temperature oscillation and a smaller lag, showing the worst performance, in spite of their high capacity to accumulate energy. This happens because of their high conductivity, which produces a higher loss of the accumulated heat.

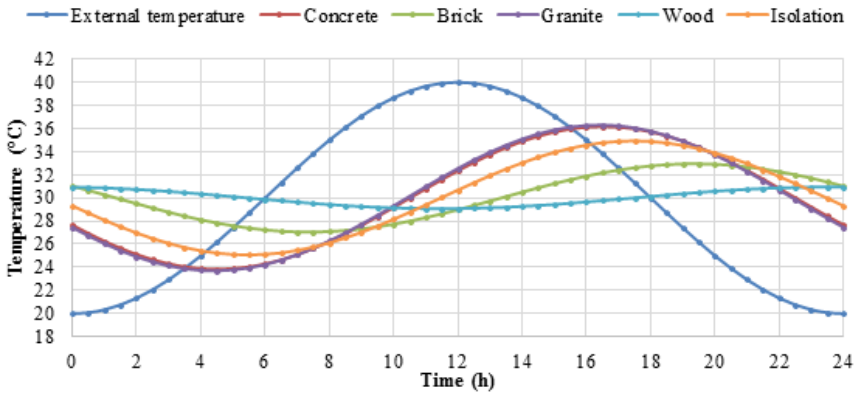

Figure 4.9: Representation the response in the inner surface of different materials with a 20 cm thickness when the system is perturbed from a sine wave

The material that shows the best performance is wood, despite its not being a material with high energy storage. However, it presents less thermal diffusivity, allowing to retain energy during more time, and therefore, more stable temperatures and a greater time lag. Specifically, the temperature oscillation generated would be 1,82^{o}C (compared to 20^{o}C external temperature), so it has a factor decrement of 0,0932 (see Table 4.5).

Brick and insulation materials are in the middle. Concerning the insulations, they present high oscillation despite their low thermal diffusivity. Their low capacity of heat accumulation is a disadvantage, so they generate a thermal oscillation of 9,89^{o}C and have a smaller lag

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

than wood. Finally, brick generates a better response than insulation. It produces waves with an oscillation of 5,88*ºC*. Bricks have a factor decrement of 0,2952 and a lag of 7,35 hours.

Table 4.5: Summary of the results obtained in the simulation for different materials with a 20 cm thickness

Material	Maximum inner surface [˚C]	Minimum inner surface [˚C]	Oscillation [˚C]	Lag [h]	Decrement factor
Concrete	36,16	23,84	12,32	4,51	0,6172
Brick	32,94	27,06	5,88	7,35	0,2952
Granite	36,29	23,71	12,58	4,41	0,6303
Wood middleweight	30,91	29,09	1,82	11,47	0,0932
Isolation	34,92	25,08	9,84	5,47	0,4927

The materials with better performance are those having a high density and a low thermal conductivity. Thus, they allow accumulating a great amount of energy, which is lost more slowly. Therefore, these materials are more stable to change.

These results were shown using different materials having the same thickness. The wall thickness is an important feature to analyse because it has an impact on the thermal mass. That is, when the wall thickness increases, the thermal mass improves. Thus, the results change when the thickness is increased. For that, the materials with the worst behaviour are analysed, especially concrete and granite. Therefore, both the lag and the decrement factor are calculated depending on thickness. The simulation is carried out using a mesh with 10 nodes. The thermal properties of the wall are described in Table 4.4.

Table 4.6 and Figure 4.10 show the results when the wall thickness is changed. We can observe that, when the thickness is less than 10 *cm*, the temperature only changes 1*ºC* and the time lag is less than 1,5 hours. Thus, increasing the wall thickness, the thermal oscillation decreases and the time lag increases, getting a decrement factor of 0,0034 when the thickness reaches 1 metre. Thus, a temperature variation of only 0,06*ºC* is obtained.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 4.6: Summary of results depending on the wall thickness

Thickness [cm]	Thermal mass [J/m^2·K]	Oscillation [°C]	Lag [h]	Decrement factor
5	120.000	19,94	0,37	0,9969
10	240.000	19,06	1,43	0,9537
15	360.000	16,28	2,95	0,8149
20	480.000	12,32	4,51	0,6172
30	720.000	6,32	7,11	0,3158
40	960.000	3,30	9,41	0,1641
60	1.440.000	0,93	13,94	0,0466
100	2.400.000	0,06	22,62	0,0034

Figure 4.10 shows that the decrement factor tends to zero, generating a cushioning near to 100%, so that, indoor temperature is constant. Furthermore, the wave lag increases linearly with the wall thickness.

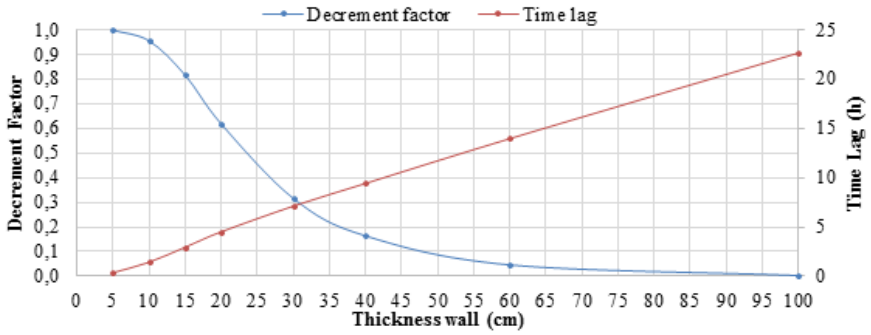

Figure 4.10: Representation of decrement factor and time lag according to concrete thickness wall

With a concrete or granite wall, a good decrement factor and time lag can be achieved when the thickness increases because the thermal mass also increases. A good example can be seen in cathedrals, which have a constant indoor temperature despite of their stone walls. This is due to their walls' thickness, which is bigger than 1 metre.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

4.6.3. Study on the placement of isolation

When designing the building's thermal envelope, it is important to consider the location of the isolation and the thermal mass. In this section, two cases are analysed. On the one hand, the temperature evolution is analysed when the isolation is in the innermost layer and, therefore, the thermal mass is placed in the outdoor layer. On the other hand, the opposite case is analysed. That is, the isolation is placed in the outdoor layer and the thermal mass is placed inside the building.

The wall reference is made by two layers. In both cases, the element with a bigger thermal mass has 20 *cm* of concrete. The isolation has a thickness of 8 *cm* thickness and a conductivity of 0,032 *W/(m·K)*. The thermal resistance of the air in the outside wall also is taken into account (details shown in Table 4.7). In this simulation a mesh with 5 nodes per layer is used, so the wall is simulated with 10 nodes (Figure 4.11).

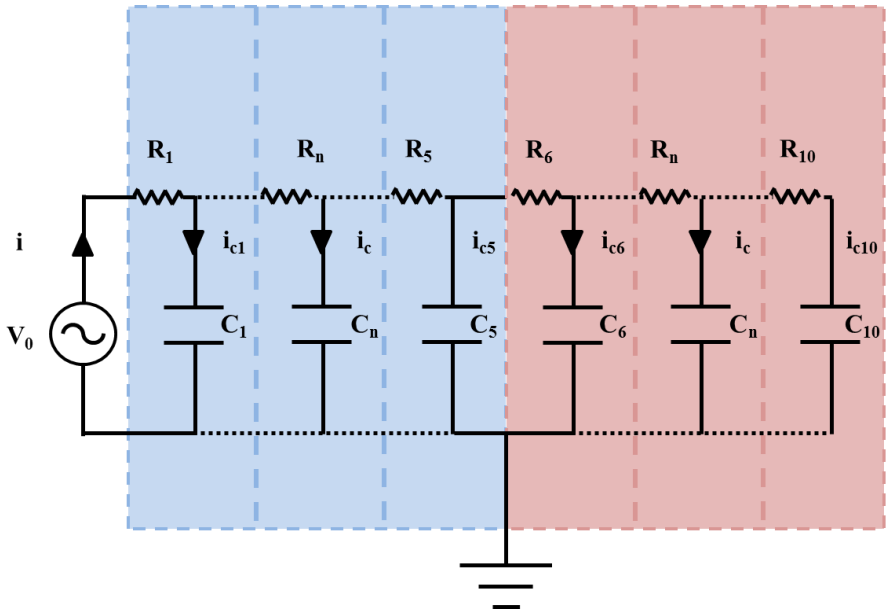

Figure 4.11: Multi-layer wall representation with 5 nodes per mesh

Table 4.7: Summary of layer properties of the wall

Layer	Thickness [m]	Heat capacity [J/(kg·K)]	Density [kg/m^3]	Conductivity [W/(m·K)]	Thermal resistance [(m^2·K)/W]
External air	-	-	-	-	0,04
Concrete	0,2	1000	2400	2,5	0,08
Isolation	0,08	1404	30	0,032	2,5

The climate conditions used correspond with a summer day in the city of Ourense (Spain), specifically on July 8th, 2007. This day the maximum temperature was 40,99^{o}C at 15:50 hours and the minimum 17,08^{o}C [Meteogalicia, 2014], producing an oscillation of 23,91^{o}C.

Independently of the statement isolation and concrete, the enclosure has the same thermal resistance (2,62 $m^2 \cdot K/W$), and its thermal transmittance has a value of 0,382 $W/(m^2 \cdot K)$. Nevertheless, the results obtained are different. The decrement factor and the time lag for each case can be obtained through a simulation in *Matlab* (results shown in Table 4.8).

Table 4.8: Summary of the results obtained through the simulation of the two walls

Type of wall	Thermal mass [J/(m^2·K)]	Oscillation [°C]	Time lag [h]	Decrement factor
Inner isolation and external thermal mass	483.369	7,64	7,46	0,3199
External isolation and inner thermal mass	483.369	0,26	8,01	0,0105

The results obtained (Figure 4.12 and Figure 4.13) show that when the isolation is placed in the inner layer, it generates a greater temperature oscillation and a smaller time lag. However, when the isolation is placed in the outdoor layer the results obtained shows less temperature oscillation and a bigger time lag. This is so because, introducing the element with greater thermal mass in the outdoor layer, energy is stored, but energy is lost more quickly due to its high thermal diffusivity. Therefore there is nothing that prevents the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

leakage of energy to the outside. Moreover, as the isolation has a low thermal diffusivity, it needs more time to accumulate energy, so in the end the energy flowing to the outside is greater than the energy flowing through the isolation.

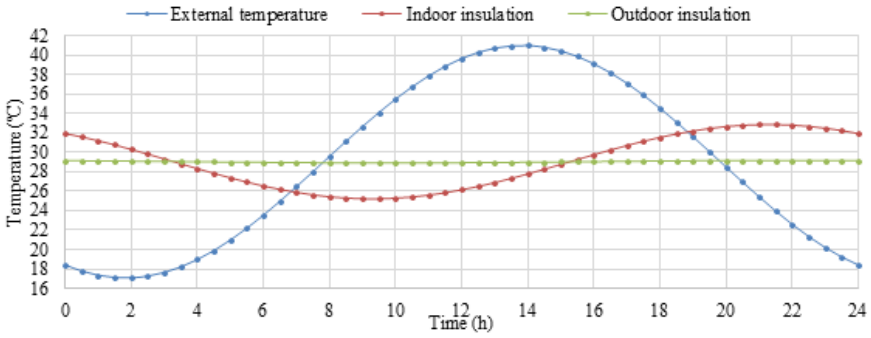

Figure 4.12: Variation of inner surface temperature in a wall with outdoor and indoor thermal mass

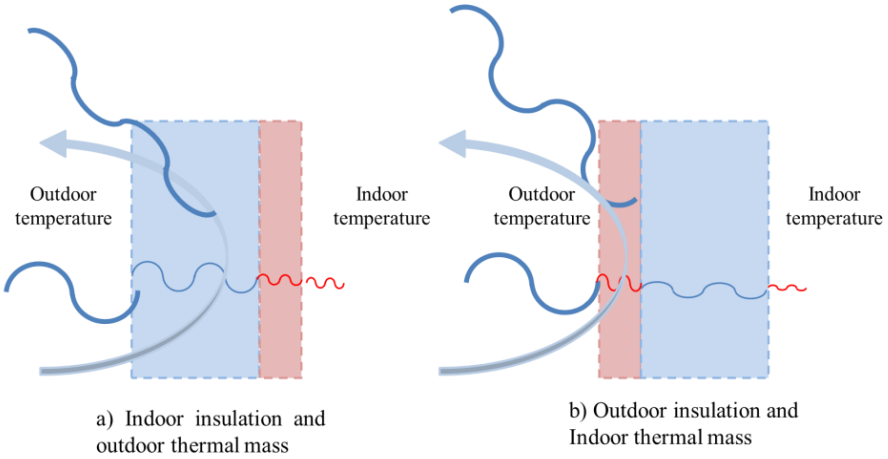

Figure 4.13: Graphical representation of the cushioning effect of the thermal wave which produces each facade

However, if insulation is placed outdoor, it keeps the inner surface temperature more stable. This stability is produced because the isolation has a lower thermal diffusivity and prevents energy from flowing outside through the concrete. In this way, the innermost wall accumulates a greater amount of energy, returning the heat inside.

Depending on the position of the isolation, great differences can be observed. If the isolation is placed in the outside layer and thus the thermal mass is inside, a constant temperature is recorded in the inner surface. Regarding the time lag, the resultant wave is delayed 0,5 hours more than when the isolation is placed inside.

It is interesting to analyse the time response of each wall, that is, the time that the system takes to stabilize itself when it is perturbed by any disturbance. For this reason, we analyse the time constant, which is the time that the system's accumulation takes to reach stability. Both systems are subjected to a unitary step disturbance and the results are obtained through a simulation in *Matlab*.

Both cases have been analysed. Figure 4.14 shows when the isolation is inside and when the isolation is placed in the outdoor layer. In the first case, the response reaches 63% the perturbation in $0{,}5 \cdot 10^5$ seconds (13,9 hours) and, in the second case in $1{,}3 \cdot 10^6$ seconds (15 days).

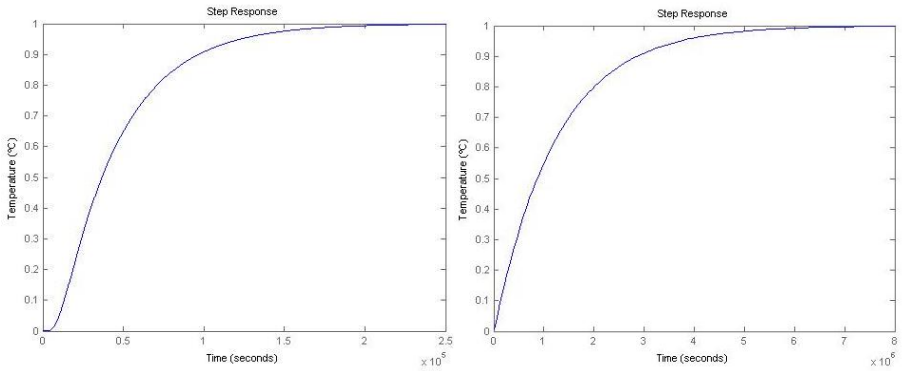

Figure 4.14: System response when it is subjected to a unitary step disturbance (top: with inside isolation, bottom: with outside isolation)

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The results obtained between both walls are different, obtaining a greater stability when the thermal mass is placed inside. The thermal mass generates little oscillations in the inner surface temperature and a greater time lag of the thermal wave.

4.6.3.1. Analysis of heat flow

As the inner surface temperature differs depending on the position of the thermal mass and the isolation, it is interesting to analyse the heat flow through the wall in both cases. The heat flow per area (Q/A) depends on the temperature gradient at each instant and the wall thermal transmittance. In both cases, the thermal resistance has the same value (2,58 $m^2 \cdot K/W$), so when the air resistance is added, the thermal transmittance (U_{wall}) has a value of 0,382 $W/(m^2 \cdot K)$.

$$Q(t)/A = U_{wall} \cdot \left(T_{ext}(t) - T_{sur,in}(t)\right) \qquad \text{[Eq.4.42]}$$

Analysing both facades in the summer conditions described in paragraph 4.6.3, we obtain the heat flow through the enclosure during a day (Figure 4.15).

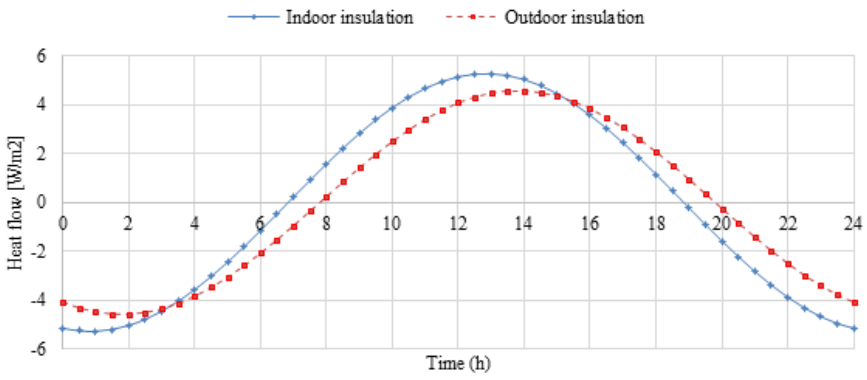

Figure 4.15: Heat flow in summer conditions when the thermal mass is outside and inside

The results show that when the thermal mass is outside, the maximum heat flow through the enclosure is 5,24 W/m^2, while, when the thermal mass is inside, the maximum heat flow is 4,55 W/m^2. This

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

produces a great advantage when the climate systems are designed because, comparing two enclosures with the same thermal transmittance, the maximum heat flow is different. So, if the thermal mass is placed inside, the reduction of heat flow is of 13,28%. If the energy lost is lower, the maximum power for heating or cooling systems is smaller. Therefore, HVAC systems are smaller and with less power, so the installation costs decrease.

Table 4.9 shows the maximum and minimum energy fluxes obtained by introducing the thermal mass from the outside and inside.

Table 4.9: Comparison of maximum and minimum heat flux per unit area

	Thermal mass by the outside	Thermal mass by the indoor
Maximum heat flow [W/m^2]	5,24	4,55
Minimum heat flow [W/m^2]	-5,24	-4,55

4.6.4. Study of the temperature inside a building

One of the main objectives of this study is the prediction of temperature inside a building. The mathematical model described is used to estimate the inner surface temperature of a wall in contact with the exterior, but it is interesting to obtain a model that allows us to calculate the temperature inside a building or dwelling.

To estimate the indoor temperature, it is necessary to obtain a new mathematical model which is a continuation of the previous model. In this case, the electric analogy is discarded and, therefore, the global energy balance of a building is used.

When the energy balance of a building is made, the know variables are the external temperature and the inner surface temperature, which is calculated previously by the method of *Equivalent electrical network*. In the energy balance we include the energy exchange of the elements of the envelope with outdoors and with zones at a constant temperature. Air renovations and heat contributions of people or electrical equipment are also included. All these heat inputs are accumulated inside a building by the air. Therefore, the energy balance is shown in equation [Eq.4.43]

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

$$\sum_{I} h_{in}\cdot A_i\cdot\left(T_{sur,in}(t)-T_{in}(t)\right)+\sum_{i} h_{in}\cdot A_{0,i}\cdot\left(T_{0,i}(t)-T_{in}(t)\right) +0{,}32\cdot n\cdot V\cdot\left(T_{ext}(t)-T_{in}(t)\right)+Q_{in}(t)=C_{p,air}\cdot\frac{dT_{in}(t)}{dt} \quad \text{[Eq.4.43]}$$

Where:

- h_{in}: is the convection coefficient of air inside [7,69 $W/(m^2\cdot K)$]
- A_i: is the area of inner surface of the envelope elements against outdoors [m^2]
- $T_{sur,in}$: is the inner surface temperature of each envelope element [°C]
- T_{in}: is the temperature inside a building [$°C$]
- $A_{0,i}$: is the area of inner surface of each envelope element against a place with constant temperature [m^2]
- $T_{0,i}$: is the temperature of each zones at constant temperature [$°C$]
- n: is the number of air renovations [h^{-1}]
- V: is the volume of the building analysed [m^3]
- T_{ext}: is the external temperature $[°C]$
- Q_{in}: is the internal loads produced by electronic equipment and by the people living in the building [W/m^2]
- $C_{p,air}$: is the heat capacity of the air [J/K]

The transfer function to estimate the temperature inside a building is obtained based on the system disturbances. For this, it is necessary to solve equation [Eq.4.43] using the *Laplace* transformation. This gives as a result equation [Eq.4.44]

$$T_{int}(s)=\sum_{i}\frac{h_{int}\cdot A_i}{h_{int}\cdot\sum\left(A_i+A_{0,i}\right)+0{,}32\cdot n\cdot V+C_{p,aire}\cdot s}\cdot T_{sup,i}(s)+ +\sum_{i}\frac{h_{int}\cdot A_0}{h_{int}\cdot\sum\left(A_i+A_{0,i}\right)+0{,}32\cdot n\cdot V+C_{p,aire}\cdot s}\cdot T_{0,i}(s) +\frac{0{,}32\cdot n\cdot V}{h_{int}\cdot\sum\left(A_i+A_{0,i}\right)+0{,}32\cdot n\cdot V+C_{p,aire}\cdot s}\cdot T_{ext}(s) +\frac{1}{h_{int}\cdot\sum\left(A_i+A_{0,i}\right)+0{,}32\cdot n\cdot V+C_{p,aire}\cdot s}\cdot Q_{in}(s) \quad \text{[Eq.4.44]}$$

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

By equation [Eq.4.44], the indoor temperature can be calculated in *Laplace* domain based on their input variables. The equation is solved by *Matlab*, which allows us to obtain the temperature evolution in the time domain.

In order to facilitate the understanding of the equation, each term of the expression is analysed separately. The first term shows the variation of the indoor temperature of the building as a function of the temperature variations on the inner surface of the elements of the envelope. This term is also influenced by the outdoor temperature and the characteristics of the envelope element. The sinusoidal disturbance is shown in equation [Eq.4.34] and expressed in the *Laplace* domain in equation [Eq.4.35].

The transfer function of the temperature in the interior as a function of the surface temperature is of order 1. Therefore, it can be summarized as a function of the coefficients *a*, *b* and *c*, in order to simplify the expression:

$$\frac{T_{int}(s)}{T_{sup,i}(s)} = \sum_i \frac{h_{int} \cdot A_i}{h_{int} \cdot \sum(A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V + C_{p,air} \cdot s} = \frac{c}{a + b \cdot s} \quad \text{[Eq.4.45]}$$

The indoor temperature in the *Laplace* domain when introducing a sinusoidal disturbance is:

$$T_{int}(s) = \frac{c}{a + b \cdot s} \cdot \left(\frac{T_m}{s} + \frac{Amp \cdot \left(w \cdot cos(\varphi_0) + s \cdot sen(\varphi_0) \right)}{s^2 + w^2} \right) \quad \text{[Eq.4.46]}$$

The inverse *Laplace* transform is performed to obtain the response in time.

$$T_{int}(t) = \quad \text{[Eq.4.47]}$$
$$\frac{Amp \cdot a \cdot c \cdot \sin(\varphi_0 + t \cdot w) - Amp \cdot b \cdot c \cdot w \cdot \cos(\varphi_0 + t \cdot w)}{a^2 + b^2 \cdot w^2} + \frac{T_m \cdot c}{a}$$
$$- \frac{c \cdot e^{-\frac{a \cdot t}{b}} \cdot \left(T_m \cdot a^2 + Amp \cdot a^2 \cdot sen(\varphi_0) + T_m \cdot b^2 \cdot w^2 - Amp \cdot a \cdot b \cdot w \cdot \cos(\varphi_0) \right)}{a \cdot (a^2 + b^2 \cdot w^2)}$$

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Where:

$$a = h_{int} \cdot \sum(A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V; \quad b = C_{p,air}; \quad c = h_{int} \cdot A_i$$

Obtaining the *Laplace* transform and the inverse transform has been carried out with the Matlab program, using symbolic calculation. In this way the transfer function in the time domain for a sinusoidal disturbance is obtained.

The second term of the transfer function relates the value of the indoor temperature as a function of the zones at constant temperature that are in contact with the building envelope.

$$\frac{T_{int}(s)}{T_{0,i}(s)} = \frac{h_{int} \cdot A_0}{h_{int} \cdot \sum(A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V + C_{p,air} \cdot s} = \frac{d}{a + b \cdot s} \qquad \text{[Eq.4.48]}$$

When considering a constant temperature (T_0), a step input is taken as a disturbance, with a step equal to T_0:

$$T_{0,i}(s) = \frac{T_0}{s} \qquad \text{[Eq.4.49]}$$

The disturbance is introduced in the transfer function obtaining:

$$T_{int}(s) = \frac{d}{a + b \cdot s} \cdot \frac{T_0}{s} \qquad \text{[Eq.4.50]}$$

Performing the inverse *Laplace* transform:

$$T_{int}(t) = \frac{T_0 \cdot d}{a} - \frac{T_0 \cdot d \cdot e^{-\frac{a \cdot t}{b}}}{a} \qquad \text{[Eq.4.51]}$$

Where:

$$a = h_{int} \cdot \sum(A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V; \quad b = C_{p,air}; \quad d = h_{int} \cdot A_0$$

The third term of the transfer function relates the variation of the indoor temperature as a function of the outdoor temperature

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

influenced by air renovations. In this case, the type of disturbance is also a sinusoidal function, so the transfer function is the same as that of the first term [Eq.4.47]

Finally, the fourth term of the equation relates the indoor temperature as a function of the internal heat inputs. This type of input is considered constant, so the type of disturbance is a step and the transfer function in the time domain is the same as in equation [Eq.4.51]

Table 4.10 shows the type of disturbance used for each case and the expression of the coefficients of the transfer function in the time domain.

Table 4.10: Summary of the type of disturbance and value of the coefficients of the different terms of the transfer function

Term of transfer function	Disturbances	Coefficients			
		a	b	c	d
$\frac{T_{int}(s)}{T_{sup,i}(s)}$	Sinusoidal	$h_{int} \cdot \sum (A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V$	$C_{p,air}$	$h_{int} \cdot A_i$	-
$\frac{T_{int}(s)}{T_{0,i}(s)}$	Step	$h_{int} \cdot \sum (A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V$	$C_{p,air}$	-	$h_{int} \cdot A_0$
$\frac{T_{int}(s)}{T_{ext}(s)}$	Sinusoidal	$h_{int} \cdot \sum (A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V$	$C_{p,air}$	$0{,}32 \cdot n \cdot V$	-
$\frac{T_{int}(s)}{Q_{in}(s)}$	Step	$h_{int} \cdot \sum (A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V$	$C_{p,air}$	-	1

The block diagram that represents the mathematical model described in equation [Eq.4.44] is shown in Figure 4.16. The Figure shows the relationship between the input variables (T_{ext} *(s)*, $T_{0,n}$*(s)* and *Q(s)*) and the output variable (T_{int}*(s)*).

The indoor temperature has as input variables: the outdoor temperature, the temperatures of the zones at constant temperature and the internal loads. Within this block diagram, the diagram described in Figure 4.4 is also included, which calculates the surface temperature of each wall as a function of the external temperature.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

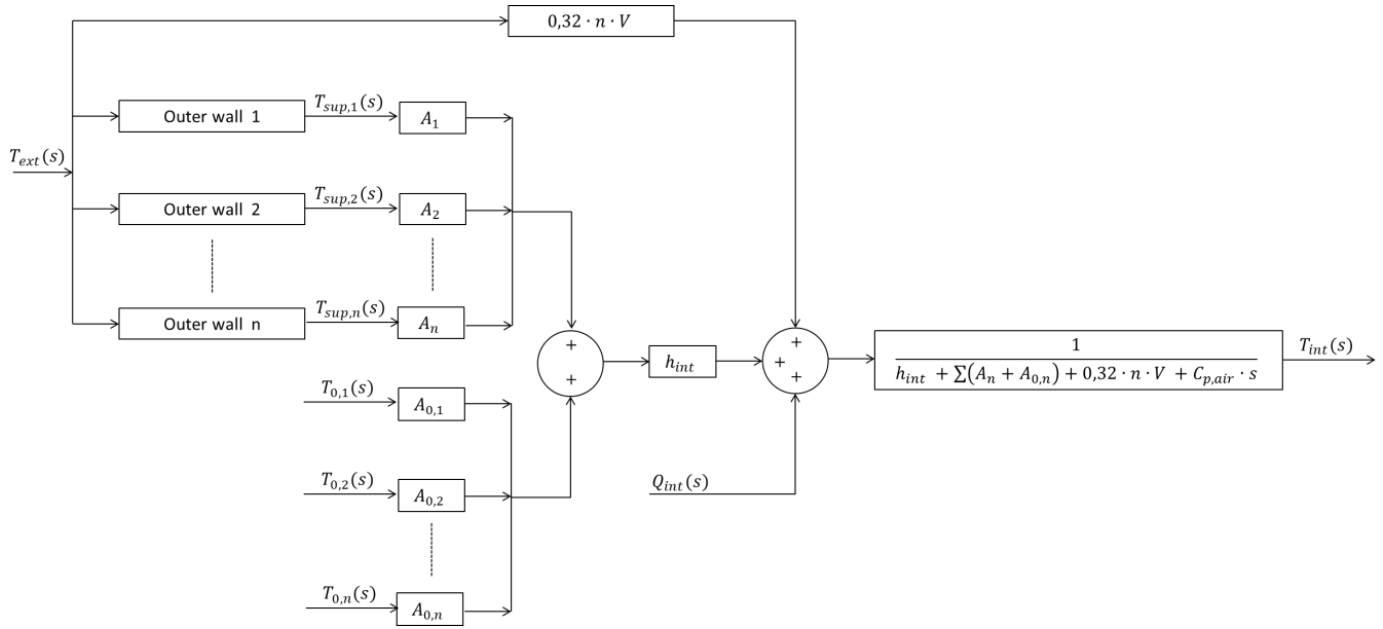

Figure 4.16: Block diagram for calculating the indoor temperature

4.6.4.1. Simulation of the temperature inside a building

With the purpose of analysing a real case, a standard building is taken as a reference. To simplify the operations, the building is considered as a block.

The dwelling has a surface of 80 m^2. Two of its facades and its roof are in contact with outdoors, while its other two walls and the concrete deck are in contact with a zone having a constant temperature. These last elements are composed of concrete with a 20 *cm* thickness.

The elements in contact with outdoors, including the flat roof, are composed of 20 *cm* of concrete and 8 *cm* of isolation. This type of elements are analysed from two points of view. Firstly, the thermal mass is placed outside and the isolation in the innermost layer. Secondly, the isolation is placed outside and, therefore, the thermal mass is inside. The thermal properties of the materials are shown in Table 4.7 and the responses of each facade are in Table 4.8. The information about the geometric characteristics of the building is in Table 4.11.

Table 4.11: Summary of the building characteristics

Surface [m^2]	Flat roof	80
	Facade 1 (South)	60
	Facade 2 (North)	60
	Concrete deck against ground	80
	Wall 1	48
	Wall 2	48
Building volume [m^3]		480
Number of time renovations [h^{-1}]		1

As a reference, the climatic conditions that have been used to the simulation correspond to one of the coldest days recorded in the city of Ourense (5th of February 2012). The maximum temperature reached was 8,89^oC and the minimum temperature was -5,85^oC [Meteogalicia, 2014]

The type of disturbance used was, on the one hand, the outdoor temperature that influences the heat flow due to time renovations, and

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

on the other hand, the response that each wall produces before a sine disturbance of external temperature. The walls in contact with zones at a constant temperature are perturbed by a step disturbance. Therefore, the reference temperature of the concrete deck that is in contact with the ground is $8^{o}C$. The constant temperature of the walls in contact with unheated zones is $10^{o}C$.

Using the geometric characteristics of the building, the thermal properties of each wall and the climatic conditions, the simulation can be realised implementing in Matlab the transfer function (Equation [Eq.4.44]). Firstly, we analyse the external facades with the thermal mass in the innermost layer and, therefore, their insulation in the outside. Table 4.12 summarizes the values of the transfer function coefficients.

Table 4.12: Value of the coefficients of the transfer function for the calculation of the indoor temperature

Coefficient of the transfer function	Façade 1 y 2	Roof	Wall 1 y 2	Floor	Air renovations
a [W/K]	3.046	3.046	3.046	3.046	3.046
b [J/K]	595.056	595.056	595.056	595.056	595.056
c [W/K]	462	615	-	-	154
d [W/K]	-	-	369	615	-

Replacing the parameters in the transfer function in the *Laplace* domain and taking into account the elements of the envelope against the outdoor, the elements against areas at constant temperature and the air renovations, it is obtained:

$$\begin{aligned} T_{int}(s) = & \frac{462}{3.046 + 595.056 \cdot s} \cdot T_{sup,1}(s) \\ & + \frac{462}{3.046 + 595.056 \cdot s} \cdot T_{sup,2}(s) + \frac{615}{3.046 + 595.056 \cdot s} \cdot T_{sup,roof}(s) \\ & + \frac{369}{3.046 + 595.056 \cdot s} \cdot T_{0,1}(s) + \frac{369}{3.046 + 595.056 \cdot s} \cdot T_{0,2}(s) \\ & + \frac{615}{3.046 + 595.056 \cdot s} \cdot T_{0,floor}(s) + \frac{154}{3.046 + 595.056 \cdot s} \cdot T_{ext}(s) \end{aligned} \quad [4.52]$$

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Figure 4.17 shows the temperature evolution inside a building when the isolation is inside, disregarding the internal loads and the solar radiation. The system response is a sine wave with less amplitude and with a different phase. Specifically, a maximum temperature of 6,0^{o}C and a minimum of 3,8^{o}C, so the average temperature is 4,90^{o}C, with a time lag of 6,5 hours. The average temperature is greater than the outdoor, as the building is in contact with zones with a constant temperature, which is higher than the outdoor average, increasing the inner average temperature.

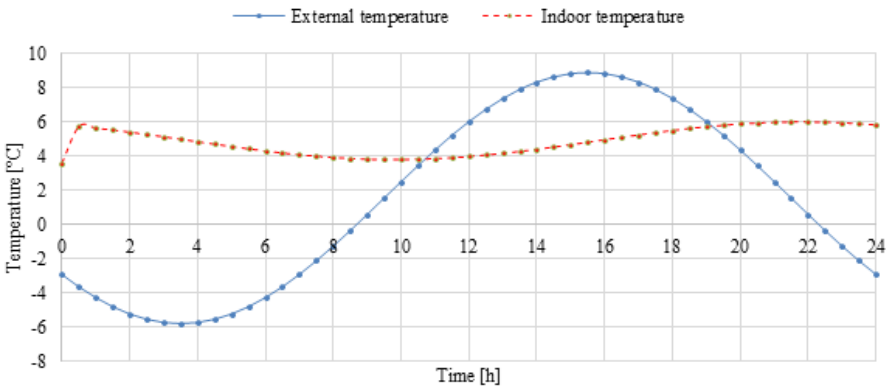

Figure 4.17: Inner temperature variation when the facades in contact with the outside have indoor isolation

Secondly, we analyse the temperature variation when the external facades have the insulation outside and, therefore, the material with more thermal mass inside. The results are shown in Figure 4.18.

When the thermal mass is in the innermost layer, the temperature variation of the building is practically constant, reaching a maximum of 5,25^{o}C and a minimum of 4,55^{o}C. As for the time lag, the resultant wave is in the same phase than the disturbance. This is due to the influence of the air renovations. As in the inner surface, the temperature is nearly constant. This parameter is influenced by the energy flow of the air renovations, which is a wave with the same phase than external temperature. This produces that the time lag of resultant wave is lost.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

In the case of introducing the insulation inside or outside, the time lag decreases regarding the time lag that the facades generate. Due to that, the air renovations are taken into account to calculate the temperature inside a building, whose phase is the same than the external temperature. Therefore, the wave of indoor temperature is the sum of the waves generated in the inner surface of each facade plus the wave produced by the air renovations.

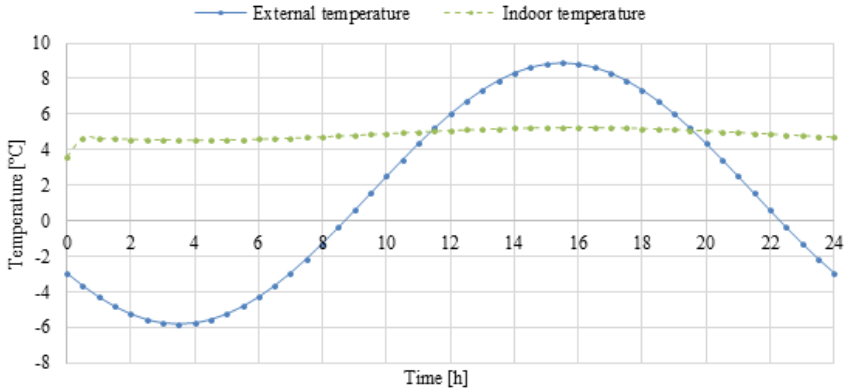

Figure 4.18: Inner temperature variations when the facades are in contact with the outside have outdoor isolation

If both results are compared, we can observe that the temperature is more stable when the thermal mass is inside and the insulation is placed outdoors. The temperature variation obtained is $0{,}70^{o}C$ versus $2{,}2^{o}C$, obtained when the thermal mass is outdoors.

This results show the importance of placing correctly, if it is possible, the components of the envelope building. Thus, it has been demonstrated that for a facade with the same thermal resistance, the results obtained are different and they depend on the placement of the insulation and the thermal mass.

4.7. DISCUSSION

The model described in this chapter using the electrical analogy, allows predicting the thermal behaviour of the enclosures in a simple way, without the need for complex simulations. The development of

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

the model in the domain of frequency allows the equations developed to be evaluated in steady state. However, although the disturbance of the system varies over time, the steady state model allows the user to quickly evaluate the evolution of the indoor temperature in buildings and make an optimal selection of materials.

The development of the model has been carried out dividing each mesh into 5 nodes. In this way, an error of 1,46% is assumed in the temperature calculation and 6,77% in the time lag calculation. The use of a greater number of nodes would improve the precision of the results obtained, however, these errors are assumed in the results.

To validate the model developed in the study, the results obtained by Maalouf et al. The authors analysed the thermal behaviour of a monolayer wall to a periodic outside temperature wave through a heat transfer model. The numerical resolution is based on the finite difference technique [Maalouf et al, 2011]. The table shows the thermal properties of the three monolayer walls analysed (normal concrete, brick and hemp concrete) and the results obtained.

Table 4.13: Comparative data for model validation

DATA				Results of Maalouf et al		Model Results	
Material	Density [kg/m^3]	Thermal Conductivity [W/m.K]	Specific heat [J/kg.K]	Indoor temp. wave amplitude [°C]	Time lag [hour]	Indoor temp. wave amplitude [°C]	Time lag [hour]
Normal concrete	2.300	1,6	850	1,43	5,5	3,7	5,7
Brick	1.630	0,6	850	0,85	6,5	1,87	7,3
Hemp concrete	413	0,1058	1.000	0,245	7	0,9	8,6

When comparing the results, differences are observed between both models. The models solved by numerical methods are more precise than the resolution by models that use the RC electrical analogy [Danielle et al, 2013]. In this case, the model was developed in *Matlab* and later it has been entered in an *Excel spreadsheet*, so the results are obtained without the need for specific software. However, despite the differences obtained in the results, the material with the

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

best performance in both models is Hemp Concrete, causing a greater reduction in temperature and a greater time lag.

The selection of the suitable materials, allows optimizing the thermal behaviour of the buildings and therefore they must be selected properly. The materials that generate a softer internal temperature and greater time lag are those with higher density and low thermal conductivity, due to the high capacity to accumulate heat.

Among the materials used, wood is the one with the best thermal behaviour, generating a more stable temperature inside and producing a time lag of 11,47 hours. Wood is a material with great potential, since its use as a substitute for conventional construction materials can reduce CO_2 emissions by 69% in the construction phase [Himes et al, 2020]. In the second place is the brick with a decrement factor of 0,2952 and a time lag of 7,35 hours. Even the thermal behaviour of the bricks can be improved using PCM, which has reduced the heat flow by 90% when filling the holes in the brick [Hichem et al, 2013]

Regard to granite and concrete, they are materials with similar properties and therefore a similar response is obtained. These types of materials, despite not having the best thermal response, are widely used materials in old buildings. In this type of construction, these materials have great thicknesses, which generate a lower temperature oscillation and a greater time lag.

According to the simulations carried out (Table 4.6) for walls with a thickness of 1 meter, a decrement factor of 0,0034 and a time lag of 22,62 *h* are obtained. This type of construction allows very stable temperatures to be maintained throughout the year. Evola et al (2019), analyse the thermal inertia of a heavyweight traditional buildings, obtaining results similar to the simulations carried out in this chapter. Among the results, it is shown that for a stone wall with a thickness of 70 cm, a decrement factor between 0,01 and 0,02 and a time lag of 8 hours is obtained (compared to the theoretical value of 18,7 hours).

The placement of thermal insulation is an important point to take into account when designing a building. In this case, a comparison was made with respect to placing the insulation inside or outside. The results show that placing the insulation on the outside generates more

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

stable temperatures, with a temperature oscillation of 0,26^{o}C compared to 7,64^{o}C when placing the insulation inside. In addition, by analysing a variation in the outside temperature over a longer period of time, placing the insulation outside allows to obtain a system that is more stable to changes. The use of insulation inside the walls eliminates the thermal capacity of heat accumulation, generating a greater fluctuation in temperature.

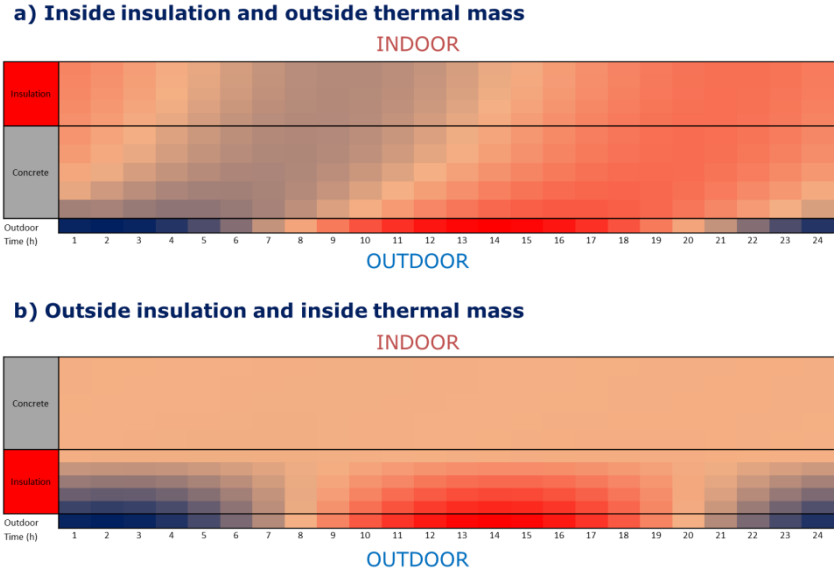

Figure 4.19: Representation of the evolution of temperature with time: a) inside insulation and outside thermal mass; b) outside insulation and inside thermal mass

In the analysis carried out by Al-saena et al (2011) for different walls, they obtained that the worst thermal behaviour was the wall with a single layer of insulation on the outside, on the basis that it generated a greater decrement factor and less time lag. However, introducing several layers of insulation in the wall (inside, in the middle and outside) generated a decrement factor 10 times less and a time lag twice as long, as well as a reduction in heating and cooling loads.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The model described has also made it possible to evaluate the indoor temperature of a building, taking into account walls against the exterior, against areas with constant temperature, the influence of ventilation and internal thermal loads. In this way, when analysing the building, it is observed again that the interior temperature is more stable when the thermal mass is outside, obtaining a variation of $0{,}7^{o}C$ with respect to $2{,}2^{o}C$ when placing the interior insulation.

There are studies that analyse the combination of enclosures with high thermal inertia with solar shadow devices. In this case, in Mediterranean climates, the optimization of solar inputs can reduce the indoor temperature by $1{,}8^{o}C$ in summer [Congedo et al, 2020]. Buildings with high thermal inertia are more susceptible to external disturbances, due to the fact that they generate more stable temperatures. Therefore, there must be greater control over solar inputs, ventilation and internal loads.

4.8. CONCLUSIONS

In this chapter, a mathematical model has been developed, which allows for obtaining the temperature variation inside a building along a day, using the analogy between electric field and thermal field and, later, an energy balance.

The equations describe the behaviour of a single-layer wall and a multilayer wall. Furthermore, it has analysed the response of each wall to a step disturbance and a sine disturbance. Also, the system has been analysed from the frequency domain, and the block diagram, where the relationship between the input variables and their output is represented, is also shown. As for the multilayer walls, the differences between the places of the insulation have been shown, observing great differences in both cases. The main conclusions obtained are:

- The higher the number of nodes used in the simulation, the higher the precision of the model, obtaining more reliable results.
- The materials with better behaviour, when are perturbed by a sine disturbance, have a high density and heat capacity and a low thermal conductivity. In this case, the factor decrement is low and the time lag increases.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

- The thickness of the wall is important to obtain more stable indoor conditions. When the thickness increases, the thermal mass also increases. Thus, when the thickness is high, the factor decrement can be nearly zero and the time lag is high.
- The thermal diffusivity is an important parameter to analyse because it shows the velocity change of the system.
- Introducing thermal mass inside and insulation outside generates more stable temperatures than placing insulation inside, in spite of the thermal transmittance having the same value in both cases.
- Placing the thermal mass inside produces a lower heat flow than when it is placed outside. This option permits designing climate systems with less power. Thus, the loss of energy when the thermal mass is inside is 13,28% lower than when it is outside.
- When the building's behaviour is simulated, the indoor temperature is more stable when the thermal mass is inside. However, the influence of the loss of energy, due to air renovations, causes that indoor temperature was practically in the same phase than external temperature.
- It is necessary to take into account the zones with constant temperature because these zones can increase or decrease the average temperature in a building. However, these zones do not affect time lag.

The importance of the study of mass and thermal inertia of materials is the key to obtain stable ambient conditions. The method of *Equivalent electrical network*, combining with the *Energy balance*, allows an approximate calculation of indoor temperature when the system is perturbed by a sine disturbance of external temperature. The design of thermal envelope is basic to achieve nearly *Zero-Energy Buildings*. However, achieving enclosures with a low thermal transmittance is not enough. The order of the wall components is also important, systems with the thermal mass inside and the insulation outside showing more advantages.

Therefore, these techniques make it possible to achieve buildings with lower energy demand, minimize the use of energy resources and reduce greenhouse gas emissions. In this way, these techniques allow

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

the sector to contribute to the development of a circular and regenerative economy.

Being able to predict the temperature inside a building is useful in the design of air conditioning control systems. An approximation of the outside temperature evolution can be obtained from the weather forecast. With the model developed, a control system which anticipates to outside temperature variations can be obtained, in order to keep the indoor temperature in comfort zone.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

CHAPTER 5. ENERGY EFFICIENCY IN BUILDINGS THE RELEVANCE OF SOLAR INPUTS AND THERMAL INERTIA

This chapter is a reproduction of the following publication derived from the research carried out by the doctoral student during the training stage:

- Title: Development and application of a thermal comfort model in buildings
- Authors: Vilaboa Díaz, A; Bello Bugallo, P.M.
- Publisher: EDP Sciences
- Journal: Renewable Energy and Environmental Sustainability.
- eISSN: 2493-9439
- Impact Factor: Indexed in DOAJ - Directory of Open Access Journals
- DOI: https://doi.org/10.1051/rees/2021038
- Year of publication: 2022
- Contribution of the doctoral student: contribution to development of the research and writing the paper.
- Authorization of the journal / publisher for the use of the publication in the doctoral thesis. URL: https://www.rees-journal.org/about-the-journal/copyright-and-license-agreement
  Copyright and license agreement indicates that the author of a publication has permission to use it without restrictions. This URL is exactly transcribed below:
  - Copyright on any article in the Renewable Energy and Environmental Sustainability is retained by the author (s) under the Creative Commons license, which permits unrestricted use, distribution, and reproduction provided the original work is properly cited.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

SUMMARY

Solar radiation is a renewable energy source that can actively contribute to the reduction of energy consumption in heating through passive design techniques. On the contrary, poor management of solar radiation can lead to unwanted comfort conditions and increase the energy consumption of cooling systems.

Buildings is one of the systems with the greatest potential for energy saving and, therefore, is one of the essential sectors to achieve the European Union's goal of achieving a net zero greenhouse gas emission by 2050 [EU, 2018]. Two types of strategies can be proposed to reduce the energy consumption of buildings. On the one hand, design an optimal thermal envelope taking into account thermal transmittance and thermal inertia. These two parameters make it possible to reduce energy losses and minimize internal temperature fluctuations. The second strategy consists of a good design of the glazed surfaces and the solar shading devices applying passive techniques. The amount of solar inputs due to glazing surfaces are determined by the size of the windows, the orientation, external obstructions, the glazing properties and the properties of solar shadow devices [EU ,2014]

The purpose of this chapter is to complete the mathematical model that allows predicting the temperature inside a building taking into account the solar inputs and the thermal inertia of the building. The model completed with solar radiation, allows evaluating the temperature peaks generated by the heating of solar radiation on the walls and the peaks generated by the solar contributions through the windows.

The impact generated by solar radiation is less than that generated through glazed surfaces. However, placing the thermal mass inside the building allows higher temperatures to be maintained in winter thanks to the solar contributions through the windows. This technique allows reducing energy consumption in heating.

The resulting model allows the analysis of type of windows and solar shadow devices suitable for each case study.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

5.1. INTRODUCTION

Energy efficiency in buildings improves dramatically by designing nearly Zero-Energy Buildings, renovating old buildings to improve the energy efficiency and replacing fossil fuels for electricity and renewable energy [EC, 2012]. To achieve a more efficient architecture, natural resources as solar energy must be take advantage. Therefore, solar energy is an important resource, which allows designing buildings with high energy efficiency. During the winter, the solar inputs can help to decrease energy demand. However, poor management of solar radiation can cause an increase in energy consumption for cooling in summer.

Among the different aspects to take into account to optimize solar inputs, the orientation, size and properties of windows and solar shadow devices are relevants. For south orientation windows, heating needs are lower since they receive a greater amount of solar radiation. Regarding windows, large sizes require a greater power of heating and cooling over the year. The use of large windows on the south side and smaller windows on the north side, allows gaining solar energy in buildings and reducing energy demand for heating. However, using a larger window area on the south side during the summer increases the need for refrigeration [Pearsson et al 2006]

Chi et al (2018) analysed the influence of natural lighting on energy consumption in cooling and heating through simulations. The authors obtained that in order to not exceed the total energy of 120 kWh/m^2; the illuminated area towards the south should not exceed 40%, while the areas towards the north, east and west should not exceed 50%. Passive solar control strategies combined with the thermal inertia of buildings, allow a significant reduction in energy consumption. Albayyaa et al (2019) evaluated the influence of passive systems on energy consumption, obtaining savings of up to 37%, reaching a reduction of 58% in the case of buildings with high thermal inertia.

Window-to-wall ratio (WWR) is a fundamental parameter that defines the luminosity and thermal environment of buildings. Xue et al (2009) optimized WWR for a building located in a low latitude region in China. They evaluated the proportion of the windows to

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

guarantee a luminosity of at least 75%, as a result a minimum WWR of 32% was obtained for all orientations. Under these conditions, according to simulations carried out with Energy Plus, the introduction of 1,8 *m* long solar protection devices (vertical and horizontal) can reduce the energy demand in cooling by 6,5%. In this case, to maintain the luminosity of 75%, the WWR value increases to 40%.

Feng et al (2017) analysed the influence of orientation and WWR in nearly-zero energy buildings located in cold regions. In this study, the authors obtained that the greatest impact generated by the WWR occurs on the east and west façade, because by increasing the WWR from 10% to 30%, the heat gained by solar radiation is 16 times higher to lost heat, thus increasing energy consumption in refrigeration. Based on the simulations carried out with Energy Plus, they obtained that the optimal WWR for east orientations is between 10-15%, for a south orientation between 10-22,5% and for north orientations reduce based on the lighting and ventilation conditions. Vanhoutteghem et al (2015) also reached an optimal WWR between 15-20% for south-facing areas for buildings in Denmark. However, in well-insulated buildings, the solar gains that can be obtained from higher WWR only compensate for the additional heat losses. Therefore it recommends U-values between 0,3-0,5 $W/(m^2 \cdot K)$ before increasing the WWR.

The properties of the windows are also an important parameter for reducing the energy demand of the home. According to the simulations carried out by Pearson et al (2006), the lowest energy consumption in buildings would occur if there were no windows on the north or south side. However, the study carried out by Grynning et al (2013) indicated that the use of windows with adequate properties could be equal to or even better than opaque walls, since there are windows with a U-value of 0,4 $W/(m^2 \cdot K)$. Furthermore, in conventional windows, reducing the U-value from 1,2 to 0,8 $W/(m^2 \cdot K)$, reduces the energy demand between 5-15%. The reference U-value of 0,4 $W/(m^2 \cdot K)$ established by Grynning et al agrees with that proposed by Vanhoutteghem et al (2015), who recommend in nearly Zero Energy Buildings facing south an U-value between 0,3-

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

0,5 $W/(m^2 \cdot K)$. Furthermore, for these U-values, optimal g-values are obtained below 0,3-0,4.

Excess solar radiation in summer can generate uncomfortable conditions of habitability, so it is necessary to have passive elements that are improve the thermal comfort of the buildings. Currently, there are emerging technologies on the market that modify the properties of glass and that allow optimizing the solar contributions received. One of these technologies is electrochromic (EC) windows, which allow the optical properties of glass to be modified. Tavares et al (2014) performed simulations for buildings located in Mediterranean climates. The authors obtained good results for cooling periods and shows that they are not very useful for heating periods. Fiorito et al (2020) studied the energy savings caused by photovoltaic (PVC) windows, this type of cell combines the ability of glass to change colour and has the ability to function as a photovoltaic cell. Among the results obtained for a building located in Australia, they obtained that in tropical and subtropical climates an energy saving of up to 20% can be achieved, while in climates dominated by periods of heating energy savings can reach 32% in the case of high WWR values and with a north orientation.

To analyse the influence of solar radiation through the walls, various authors use the parameter sol–air temperature. The use of the sol-air temperature takes into account the orientation of each façade, thus obtaining differences in the estimation of energy demand for heating and cooling. Ramin et al (2015) calculated the energy demand of the home taking this parameter into account and using static calculation methods (conventional degree-hours method). Using this method, the results show an increase in energy demand for cooling and a reduction in demand for heating. However, using dynamic calculation methods, the obtained results are lower than the values obtained using static calculation methods. Ozel et al (2007) introduce solar radiation in the finite difference equations using the sol-air temperature, so in this way, it is able to evaluate the behaviour of the walls taking into account not only the outside temperature.

He li et al (2021), analysed which were the parameters that affect the absorption of solar energy in buildings. The equations were solved

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

by the finite volume method using CFD software. Among the results obtained that the variables affecting the absorption of solar energy are: the heat accumulation coefficient, the heat-transfer coefficient, the consecutive sunny days, the radiation intensity, and the outdoor air temperature.

In order to analyse the influence of solar radiation on the indoor temperature of buildings, this variable is incorporated into the mathematical model described in the previous chapter. In this part, solar shadow devices are not taken into account and only solar radiation input through the walls and through the windows is evaluated. Solar radiation is introduced using the sol-air temperature. Thus, the variation produced by solar radiation in the indoor temperature can be theoretically analysed. The influence of the placement of the thermal inertia and the insulation cause a different disturbance in the temperature, so the object of this chapter is to evaluate the temperature oscillation produced.

5.2. THEORETICAL CONCEPTS

5.2.1. Solar radiation

To develop the mathematical model for calculating the indoor temperature in a building, we have to take into account the solar radiation. On the one hand, we must consider the incident solar radiation on the envelope and, on the other side; we must consider the direct radiation through the windows. For that, we have to know how to calculate the incident solar radiation on a tilted surface that it depends on its inclination and orientation. Quantitative knowledge of the incident radiation on a slope surface with an arbitrary orientation is important for the design of buildings and, above all, thermal comfort.

The Earth rotates around the Sun according to an elliptical orbit, with the Sun at one of the two focus, the angle which the radiation reach the Earth's surface varies with the days of the year, reaching a maximum of 23,45° and a minimum of -23,45°, which is the angle of the axis rotation. Therefore declination angle (δ) is defined as the angle between the Sun's rays and the Equator plane.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

$$\delta = 23{,}45° \cdot sen\left(360° \cdot \frac{284 + d}{365}\right) \quad \text{[Eq.5.1]}$$

Where *d* is the number of days since the start of the year

When the declination angle is positive, the solar radiation affects above the equatorial plane, while for negative declinations, the radiation affects below the equatorial plane. The maximum solar declination (23,45°), occurs in midsummer (June 20-21), reaching the Tropic of Cancer, while the minimum decline (-23,45°) occurs on the winter solstice (December 21-22), moment in which the sunlight reaches the Tropic of Capricorn.

The hour angle (τ) converts the solar time into the number of degrees which the sun moves across the sky. The sun reaches its maximum height at solar noon (t=12), in this moment the angle hour is zero.

$$\tau = (15 \cdot t - 180)° \qquad 0 \leq t \leq 24 \quad \text{[Eq.5.2]}$$

The incidence angle of the solar radiation on the Earth's surface vary with the solar time (t) and latitude (λ), so the angle between the sun and the vertical is known as zenith angle (θs), and it depends on the hour angle (τ), latitude (λ) and declination angle (δ):

$$cos\,\theta_s = cos\,\delta \cdot cos\,\lambda \cdot cos\,\tau + sin\,\delta \cdot sin\,\lambda \quad \text{[Eq.5.3]}$$

If the zenith angle is known, the solar height (αs) can be obtained, this is the angle between the sun and the horizontal plane.

$$\alpha_s = 90° - \theta_s \quad \text{[Eq.5.4]}$$

Finally, we must to describe the azimuth (γs), which is the angle between the vertical plane of the observer which contains the sun and the vertical plane of the meridian of the observer.

$$\gamma_s = \frac{\cos\delta \cdot \sin\tau}{\sin\theta_s} \quad \text{[Eq.5.5]}$$

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Once the solar radiation geometry is described, the incident angle on a surface with a determined orientation (γ) and tilt (β) can be calculated. This angle is important since it affects the direct component of the solar radiation.

The tilt (β) is the angle between the surface plane and the horizontal and it takes values between 0 and 180°. The surface orientation (γ) is the angle between the vertical projection on the ground of the normal to the surface and the South direction. With all this parameters, we can get the incident angle of the sun rays on the surface to study (ϑ).

$$cos\,\theta = sin\,\theta_s \cdot sin\,\beta \cdot cos(\gamma_s - \gamma) + cos\,\theta_s \cdot cos\,\beta \qquad \text{[Eq 5.6]}$$

The incident total solar radiation (G_T) depends on the direct radiation ($G_{b,t}$), the diffuse radiation ($G_{d,t}$) and the shortwave radiation that is reflected in the Earth's surface or by nearby surfaces ($G_{r,t}$).

$$G_T = G_b \cdot cos\,\theta + G_{d,t} + G_{r,t} \qquad \text{[Eq 5.7]}$$

If the solar radiation on a horizontal surface is not known, it must to be estimate showed that the direct solar radiation on the Earth surface can be estimated using this equation:

$$G_b = A \cdot e^{-\frac{B}{sin\,\alpha_s}} \qquad \text{[Eq 5.8]}$$

Where A is the apparent extraterrestrial irradiance and B is the atmospheric extinction coefficient. These two coefficients are functions of the day and they take into account the seasonal variation of the Earth-Sun distance and the amount of steam in the air.

The diffuse component of the radiation is the most difficult to estimate because it is not a directional component and it has wide variations. For clear days, Threlked (1963) introduced a dimensionless parameter (C), that it depends on the content of dust and moisture from the atmosphere and therefore, it varies throughout the year [Ashrae, 2011]

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 5.1: Day of the year, declination and time equation for the 21st day of each month and the parameters A, B and C used to calculate the direct solar radiation [Ashrae, 2011]

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Day of the year	21	52	80	111	141	172	202	233	264	294	325	355
Declination [º]	-19,9	-10,6	0,0	11,9	20,3	23,5	20,5	12,1	0,0	-10,7	-19,9	-23,5
Time equation [min]	-11,2	-13,9	-7,5	1,1	3,3	-1,4	-6,2	-2,4	7,5	15,4	13,8	1,6
A [W/m^2]	1230	1215	1186	1136	1104	1088	1085	1107	1152	1193	1221	1234
B	0,142	0,144	0,156	0,180	0,196	0,205	0,207	0,201	0,177	0,160	0,149	0,142
C	0,058	0,060	0,071	0,097	0,121	0,134	0,136	0,122	0,092	0,073	0,063	0,057

A= apparent extraterrestrial irradiance

B= atmospheric extinction coefficient

C= Proportion of diffuse radiation on the horizontal surface

The value of parameters *A*, *B* and *C* are shown in Table 5.1.

$$C = \frac{G_{d,H}}{G_b} \quad \text{[Eq 5.9]}$$

Where $G_{d,H}$ is the component of diffuse radiation on a horizontal surface under a sky clear. The following equation is used to estimate the amount of diffuse radiation arriving in a tilted surface ($G_{d,t}$) using diffuse radiation on a horizontal surface (G_d).

$$G_{d,t} = C \cdot G_d \cdot \left(\frac{1 + cos\,\beta}{2}\right) \quad \text{[Eq 5.10]}$$

The reflected radiation ($G_{r,t}$) falling on a surface is obtained from the global radiation on a horizontal surface (G) and the terrestrial albedo (ρ):

$$G_{r,t} = G \cdot \rho \cdot \left(\frac{1 + cos\,\beta}{2}\right) \quad \text{[Eq 5.11]}$$

The intensity of the reflected radiation that reaches any surface depends on the nature of the reflective surface and the incidence angle between the direct beam of the Sun and the reflecting surface.

5.2.1.1. Obtaining of the coefficients A, B and C of Stephenson and Threlked model.

For the calculation of direct solar radiation on a horizontal surface, Stephenson defines a series of parameters that depend on the distance between the Earth and the Sun. Therefore, it seems interesting to obtain a relation between the proposed parameters *A*, *B* and *C* and the day of the year.

The coefficient *A* shows the variation of apparent solar radiation (Figure 5.1). If this parameter is represented against the day of the year, we can observe that the trend approaches a polynomial function of degree 6. The same procedure for atmospheric extinction coefficient *B* and the proportion of diffuse radiation on the horizontal surface *C* is carried out in Figure 5.2 and Figure 5.3.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

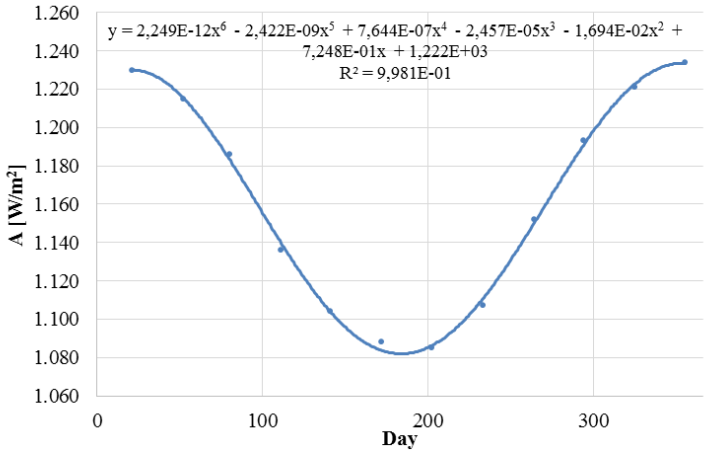

Figure 5.1: Adjustment using a polynomial functions of the variation of A parameter with the days of the year

$$A = 2{,}249 \cdot 10^{-12} \cdot d^6 - 2{,}422 \cdot 10^{-9} \cdot d^5 + 7{,}644 \cdot 10^{-7} \cdot d^4 - 2{,}457 \cdot 10^{-5} \cdot d^3 - 1{,}694 \cdot 10^{-2} \cdot d^2 + 0{,}725 \cdot d + 1.222 \quad \text{[Eq 5.12]}$$

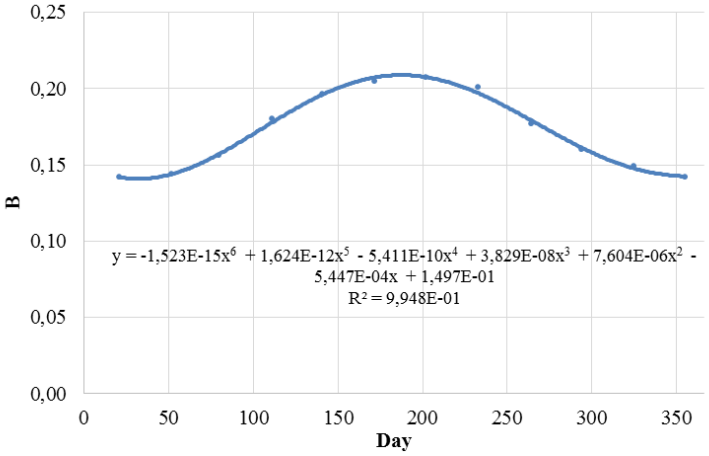

Figure 5.2: Adjustment using a polynomial function of the variation of B parameter with the days of the year

$$B = -1{,}523 \cdot 10^{-15} \cdot d^6 + 1{,}624 \cdot 10^{-12} \cdot d^5 - 5{,}411 \cdot 10^{-10} \cdot d^4 + 3{,}829 \cdot 10^{-8} \cdot d^3 + 7{,}604 \cdot 10^{-6} \cdot d^2 - 5{,}447 \cdot 10^{-4} \cdot d + 0{,}1497 \quad \text{[Eq 5.13]}$$

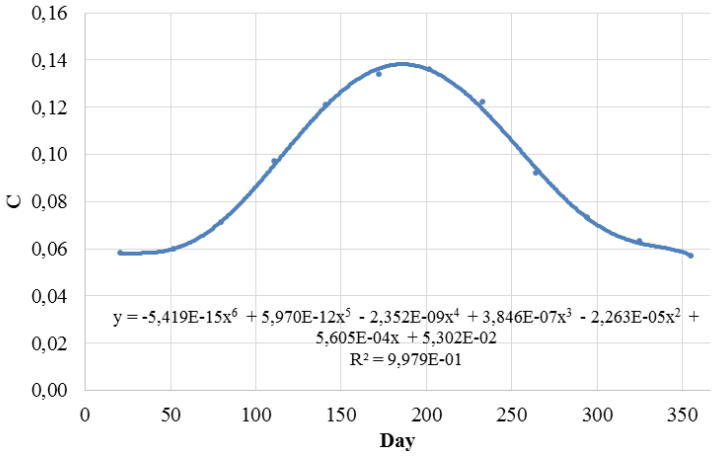

Figure 5.3: Adjustment using a polynomial function of the variation of C parameter with the days of the year

$$C = -5{,}419 \cdot 10^{-15} \cdot d^6 + 5{,}970 \cdot 10^{-12} \cdot d^5 - 2{,}352 \cdot 10^{-9} \cdot d^4 + 3{,}846 \cdot 10^{-7} \cdot d^3 - 2{,}263 \cdot 10^{-5} \cdot d^2 + 5{,}605 \cdot 10^{-4} \cdot d + 5{,}302 \cdot 10^{-2} \quad \text{[Eq 5.14]}$$

5.2.1.2. Sol-air temperature

The sol-air temperature is the outdoor temperature, which in absence of all radiation exchanges, generates the same heat flow through a wall that is equal to the combination of the solar incident radiation, the exchange of radiant energy with the sky and the exchange of heat convection with outdoor air [ASHRAE, 2009]

If an energy balance is realised on the outside of a wall, we obtain:

$$\frac{q}{A} = \alpha_0 \cdot G_t + h_0 \cdot \left(T_{ext} - T_{sup,ext}\right) - \varepsilon \cdot \Delta R \quad \text{[Eq 5.15]}$$

Where:

- α_0: absorptivity of the external face subjected to solar radiation.
- Gt: incident solar radiation on the surface, it depends on its orientation [W/m^2]
- h_0: coefficient of heat transfer by radiation and convection from the outside [W/m^2]

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

- T_{ext}: outdoor air temperature [$°C$]
- $T_{sup,ext}$: temperature on the outside surface of the wall [$°C$]
- ε: the emittance of outside surface.
- ΔR: difference between the incident long-wave radiation of the sky and its surroundings and the emitted radiation by a black body at the same temperature of the outside air [W/m^2]

The heat flow between the outside surface and equivalent sol-air temperature ($T_{sol\text{-}aire}$) can be expressed as:

$$\frac{q}{A} = h_0 \cdot \left(T_{sol-air} - T_{sup,ext}\right) \quad \text{[Eq 5.16]}$$

If equations [Eq 5.15] and [Eq 5.16] are combined:

$$T_{sol-aire} = T_{ext} + \frac{\alpha_0 \cdot G_t}{h_0} - \frac{\varepsilon \cdot \Delta R}{h_0} \quad \text{[Eq 5.17]}$$

Therefore, sol-air temperature allows knowing the amount of heat conduction through the wall from the outside including solar radiation.

Vertical surfaces receive long-wave radiation from the ground, the sky and from other vertical surfaces, so determine the value of ΔR with precision is complex. When solar radiation is high, the temperature of objects are higher than air temperature, thus, the long wave radiation compensates the low emittance of the sky. Therefore, we can assume in vertical surfaces that $\varepsilon \cdot \Delta R = 0$. On the other hand, for horizontal surfaces, the long wave radiation is only received from the sky, so the term ΔR has a value of 20 $BTU/h \cdot ft^2$ (63,09 W/m^2) [Ashrae, 2011]

The absorptivity of long wave radiation depends on the colour of the outside surface exposed to solar radiation. For example, for clear colours we use 0,60 as value, for dark tones 0,90 and for surface with medium shades we use 0,75.

5.3. OBJECTIVES

This work intends to complete the model that allows predicting the temperature inside a building. In a previous stage, we develop a model that it could predict the indoor temperature taken into account the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

thermal mass. Therefore, to complete the mathematical model, the solar radiation is added.

In the first place, we introduce the influence of solar radiation through walls and then we complete the model adding the input solar radiation through windows. With these two new terms, we can estimate the temperature inside a building and calculate the energy that the building needs to heat and refrigerate.

5.4. CASE STUDY

The object of this chapter is to complete the mathematical model described in the previous chapter; where based on the elements of their envelope and the solar radiation received, indoor temperature can be calculated. The building model used in this work is a cube-shaped one, with two exterior facades one of them with a window, two walls having a constant temperature and its concrete deck and roof being in contact with the ground and the outside, respectively. The outdoor-side elements of the envelope are composed of a 20 *cm* concrete layer and 8 *cm* of insulation. Regarding the elements against zones at constant temperature, they are composed of a 20 *cm* layer of concrete.

The dwelling has a surface of 80 m^2. Two of its facades and its roof are in contact with outdoors, while its other two walls and the concrete slab are in contact with a zone at constant temperature. These last elements are composed of concrete with a 20 cm thickness. The thermal properties of the materials are shown in Table 5.2 and the responses of each facade are in Table 5.3.

Table 5.2: Summary of layer properties of the wall

Layer	Thickness [m]	Heat capacity [J/(kg·K)]	Density [kg/m^3]	Conductivity [W/(m·K)]	Thermal resistance [(m^2·K)/W]
External air	-	-	-	-	0,04
Concrete	0,2	1000	2400	2,5	0,08
Isolation	0,08	1404	30	0,032	2,5

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 5.3: Summary of the results obtained through the simulation of the two walls

Type of wall	Thermal mass [J/(m^2·K)]	Oscillation [°C]	Time lag [h]	Decrement factor
Inner isolation and external thermal mass	483.369	7,64	7,46	0,3199
External isolation and inner thermal mass	483.369	0,26	8,01	0,0105

The elements in contact with outdoors, including the flat roof, are composed of 20 *cm* of concrete and 8 *cm* of isolation. This type of elements are analysed from two points of view. Firstly, the thermal mass is placed outside and the isolation in the innermost layer. Secondly, the isolation is placed outside and, therefore, the thermal mass is inside. The information about the geometric characteristics of the building is in Table 5.4 (extracted from the previous Chapter).

Table 5.4: Summary of the building characteristics

Surface [m^2]	Flat roof	80
	Facade 1 (South)	60
	Facade 2 (North)	60
	Concrete slab	80
	Wall 1	48
	Wall 2	48
Building volume [m^3]		480
Number of time renovations [h^{-1}]		1

5.5. METHODOLOGY

Once the geometry of the solar radiation is described and the case study is defined, we proceed to develop the model that allows calculating the indoor temperature in a building including the solar radiation. In this way, to calculate the indoor temperature we take into account the thermal mass and the solar radiation. We analyse the dynamic behaviour of the building in winter and summer weather. The study is realised in the next stages:

- Study of the influence of solar radiation through walls.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Firstly, we analysed the influence of solar radiation in the variation of indoor surface temperature. For that, we introduce the sol-air temperature in the model. This temperature oscillation is affected by thermal inertia.

- Study of the influence of solar radiation through windows.

In this case, we analyse the influence of solar inputs through windows. These contributions are the ones that most affect the interior temperature.

5.6. DEVELOPMENT AND PRESENTATION OF RESULTS

Once study the influence of the thermal inertia in the indoor temperature in buildings, it is necessary to study how the solar radiation affects to indoor temperature. With this new study the previous model is completed and therefore the equations are more accurate.

For developing the model to predict the indoor temperature in buildings, two stages were realised. First, model which allowed calculating the temperature on the inner surface of a wall in contact with the outside was developed. In this case, we used the analogy between the electric field and the heat and we achieved the next equation:

$$T_{sur,in}(s)/T_{ext}(s) = 1/(R \cdot C \cdot s + 1) \qquad \text{[Eq 5.18]}$$

Where:

- *C*: is the heat capacity of the node, which is calculated from the equation [Eq.4.3] [$J/m^2 \cdot K$]
- *R*: is the thermal resistance of the node [$m^2 \cdot K/W$]

Once the temperature on the inner surface of a wall was calculated, the second stage was developed. In this step, an energy balance was realised taking into account the temperature on the inner surface of a wall, air renovations and heat contributions of people or electrical equipment.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

$$\sum_i h_{in} \cdot A_i \cdot \left(T_{sur,in}(t) - T_{in}(t)\right) + \sum_i h_{in} \cdot A_{0,i} \cdot \left(T_{0,i}(t) - T_{in}(t)\right) + 0{,}32 \cdot n \cdot V \cdot \left(T_{ext}(t) - T_{in}(t)\right) + Q_{in}(t) = C_{p,air} \cdot \frac{dT_{in}(t)}{dt} \quad \text{[Eq 5.19]}$$

Where:

- h_{in}: is the convection coefficient of air inside [7,69 $W/(m^2 \cdot K)$]
- *Ai*: is the area of inner surface of the envelope elements against outdoors [m^2]
- $T_{sur,in}$: is the inner surface temperature of each envelope element [°*C*]
- T_{in}: is the temperature inside a building [°C]
- $A_{0,i}$: is the area of inner surface of each envelope element against a place with constant temperature [m^2]
- $T_{0,i}$: is the temperature of each zones at constant temperature [°*C*]
- *n*: is the number of air renovations [h^{-1}]
- *V*: is the volume of the building analysed [m^3]
- T_{ext}: is the external temperature [°*C*]
- Q_{in}: is the internal loads produced by electronic equipment and by the people living in the building [W/m^2]
- $C_{p,air}$: is the heat capacity of the air [*J/K*]

The transfer function was solved by using the *Laplace* transformation. This gives as a result equation [Eq.4.44]

$$T_{int}(s) = \sum_i \frac{h_{int} \cdot A_i}{h_{int} \cdot \sum\left(A_i + A_{0,i}\right) + 0{,}32 \cdot n \cdot V + C_{p,aire} \cdot s} \cdot T_{sup,i}(s) + \sum_i \frac{h_{int} \cdot A_0}{h_{int} \cdot \sum\left(A_i + A_{0,i}\right) + 0{,}32 \cdot n \cdot V + C_{p,aire} \cdot s} \cdot T_{0,i}(s) + \frac{0{,}32 \cdot n \cdot V}{h_{int} \cdot \sum\left(A_i + A_{0,i}\right) + 0{,}32 \cdot n \cdot V + C_{p,aire} \cdot s} \cdot T_{ext}(s) + \frac{1}{h_{int} \cdot \sum\left(A_i + A_{0,i}\right) + 0{,}32 \cdot n \cdot V + C_{p,aire} \cdot s} \cdot Q_{internas}(s) \quad \text{[Eq 5.20]}$$

With this equation obtained in the previous study, the influence of the solar radiation is introduced.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

5.6.1. Study of the influence of solar radiation through walls

For studying the solar radiation through a wall, two kinds of walls are considered, with the isolation by the outside and by the inside. The walls are composed by 20 *cm* of concrete and 8 *cm* of isolation.

As a reference, the climatic conditions that have been used to the simulation correspond to one of the coldest days recorded in the city of Ourense (February 5, 2012). The maximum temperature reached was 8,89^{o}C and the minimum temperature was -5,85^{o}C.

The wall has a colour of medium tonality, so the absorptivity is 0.75. Finally, a clarity index of 0,38 was added, which is the relationship between real sun hours and theoretical sun hours.

The influence of solar radiation on the outside surface of the wall makes that heat flow that occurs will be equivalent to a maximum temperature of 16,14°*C*. The sol-air temperature must be calculated for every enclosure because the value depends on its tilt and orientation. In the Figure, the sol-air temperature for a horizontal surface ($\beta=0$, $\gamma=0$) is showed:

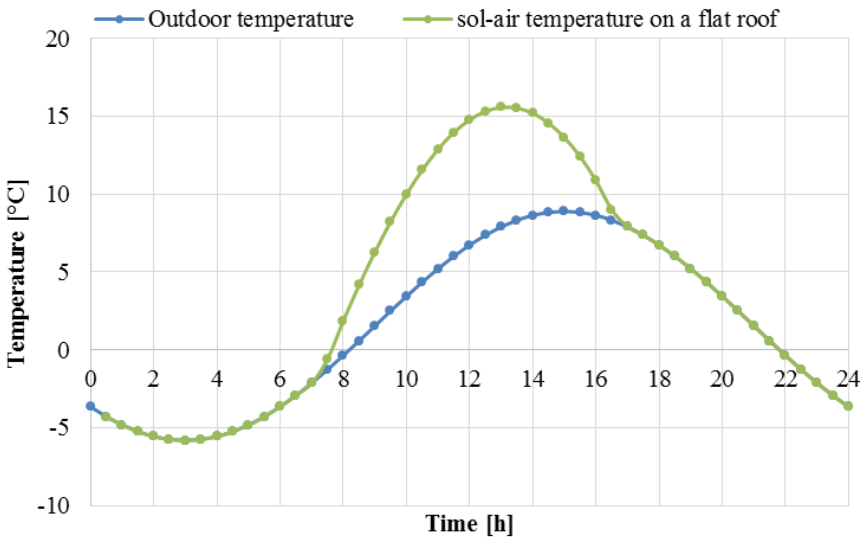

Figure 5.4: Graphical representation of the outdoor temperature and the sol-air temperature on a horizontal surface

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

As a result, a new disturbance is obtained and its effect on different walls can be analysed. This new disturbance is the combination of two waves (Figure 5.5). One of disturbance is the outdoor temperature wave without solar radiation; and the second is the wave that disturbs the system during the day taking into account the solar radiation. In this way, an only disturbance is obtained where the effect of the solar radiation is showed. Table 5.5 shows the characteristics of the two waves:

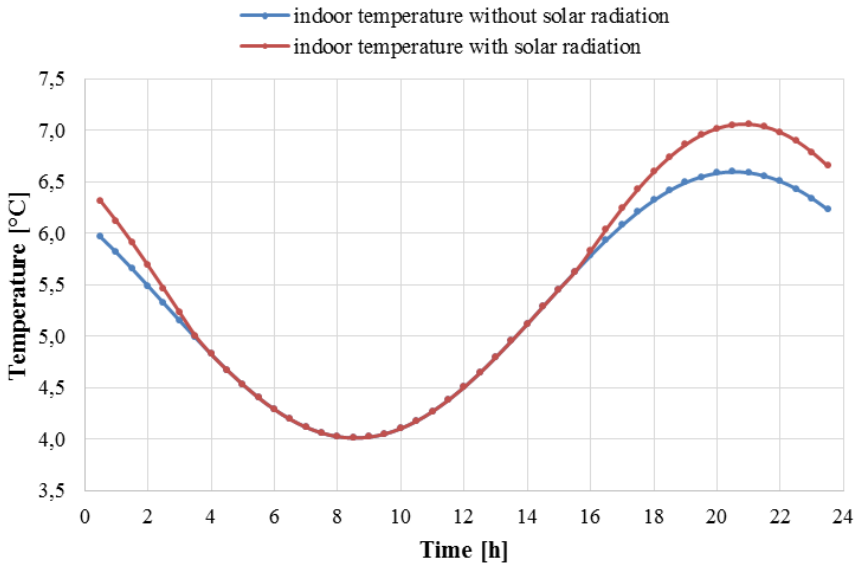

Figure 5.5: Estimation of the indoor temperature when the building has inside insulation considering solar radiation

Table 5.5: Description of sinusoidal waves that disturb the system when the solar radiation is considered

Wave characteristics	Outdoor temperature wave	Sol-air temperature wave
Maximum temperature [°C]	8,89	15,57
Minimum temperature [°C]	-5,8	-5,8
Wave amplitude [°C]	7,35	10,68
Average temperature [°C]	1,55	4,88
Oscillation [°C]	14,69	21,37

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

First, the wall with outside isolation is analysed. For that, the system perturbation for the two types of waves is obtained. Due to the time lag that causing the envelope against the outside elements, solar radiation does not affect the indoor surface temperature during the hours of sunshine; this peak of temperature is delayed. Thus, the contribution of energy that enters the building due to radiation is accumulated in the envelope and subsequently gives it to the inside.

Figure 5.6 shows the influence of solar radiations through the walls without taking into account the solar radiation through the windows. In this case, the indoor temperature increases in 0,5^{o}C, therefore, the average temperature in a building is increased and it reaches 5,5^{o}C. However, the oscillation is higher when the isolation is inside and the total oscillation reaches the 2,6^{o}C.

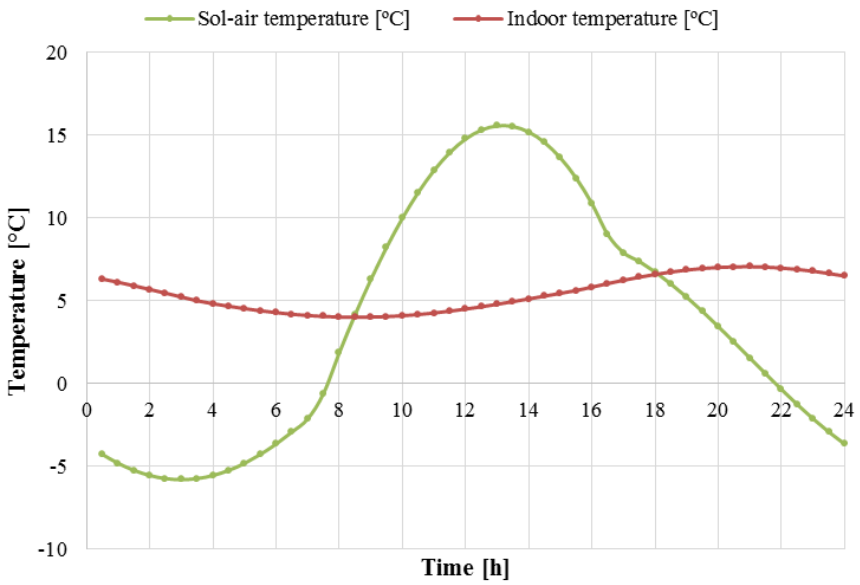

Figure 5.6: Variation of the indoor temperature for walls with inside insulation and taking into account the solar radiation

When the insulation is outside and therefore the thermal mass is inside (Figure 5.7) a constant response is produced. So when solar radiation is introduced is not appreciated an increase of temperature.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The maximum temperature reached is 5,66^{o}C and the minimum is 4,95^{o}C so the average temperature is 5,30^{o}C. The average temperature is lower than with the inside isolation because this configuration is less influenced by solar radiation. However, temperatures more stables are achieved with the outside insulation.

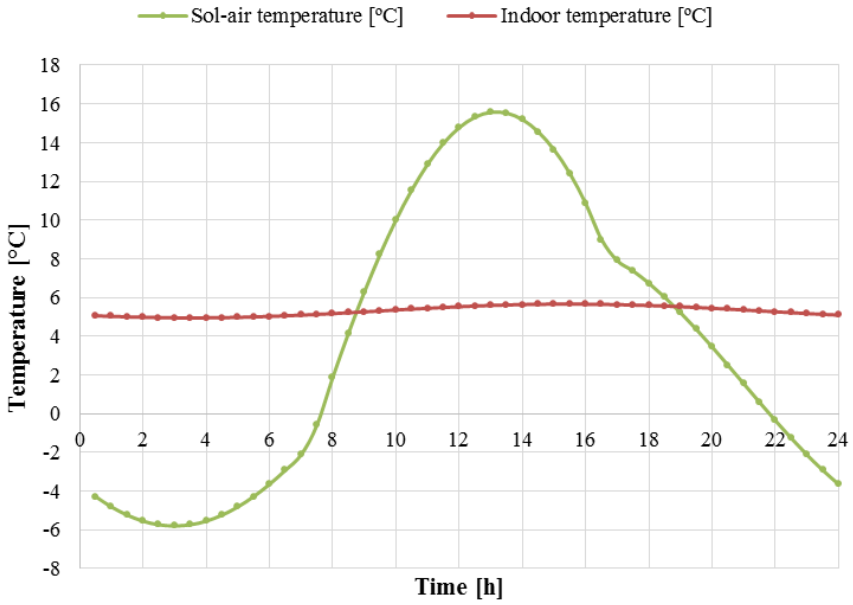

Figure 5.7: Variation of the indoor temperature for walls with outside insulation and taking into account the solar radiation

Once analysed the behaviour of each wall in winter conditions, it is interesting to study the evolution of indoor temperature in a summer day. In this case, one of the warmest day in the city of Ourense is taken into account, this day the maximum temperature reaches 40,99^{o}C and the minimum of 17,08^{o}C (June 8, 2013) [Meteogalicia, 2018]. In this month, the relationship between sunshine hours actual and theoretical are 0,53. Also, it will be suppose that the envelope against constant temperature areas found at 24^{o}C and the temperature of the ground is 22^{o}C.

Analysing the first case, where the thermal mass is outside (Figure 5.8), the results shows that the minimum temperature is

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

24,29^{o}C and the maximum is 29,23^{o}C, producing an oscillation of 4,94^{o}C. The average temperature is lower than the sol-air temperature, due to the influence of the zones at constant temperature. These temperatures are below the outdoor average temperature and therefore, they produce that the indoor temperature decreases.

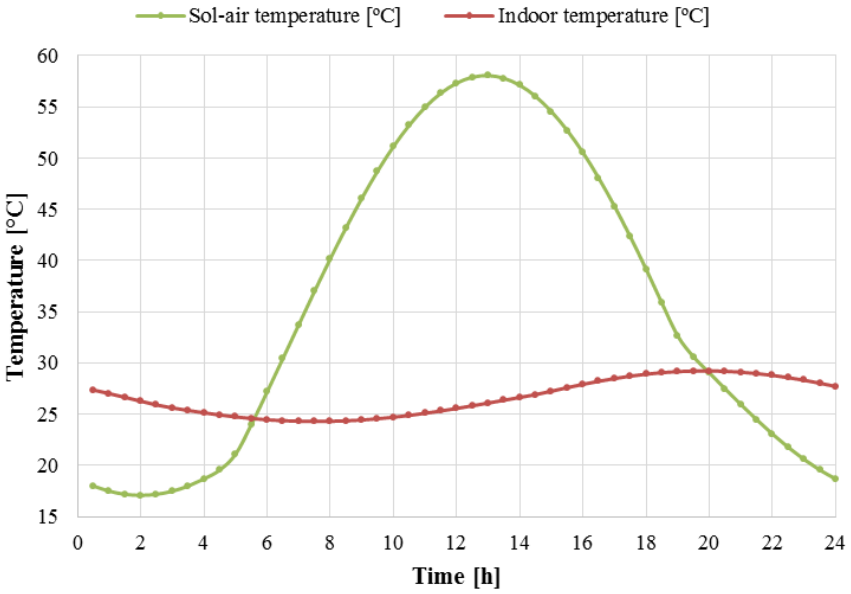

Figure 5.8: Variation of the indoor temperature for walls with inside insulation and taking into account the solar radiation in a summer day

Finally, the behaviour using an outside insulation is analysed (Figure 5.9). As it happens in cold conditions, the temperature is more stable. In this case, the maximum temperature is 26,98^{o}C and the minimum is 25,82^{o}C, setting the average in 26,40^{o}C with an oscillation of 1,16^{o}C.

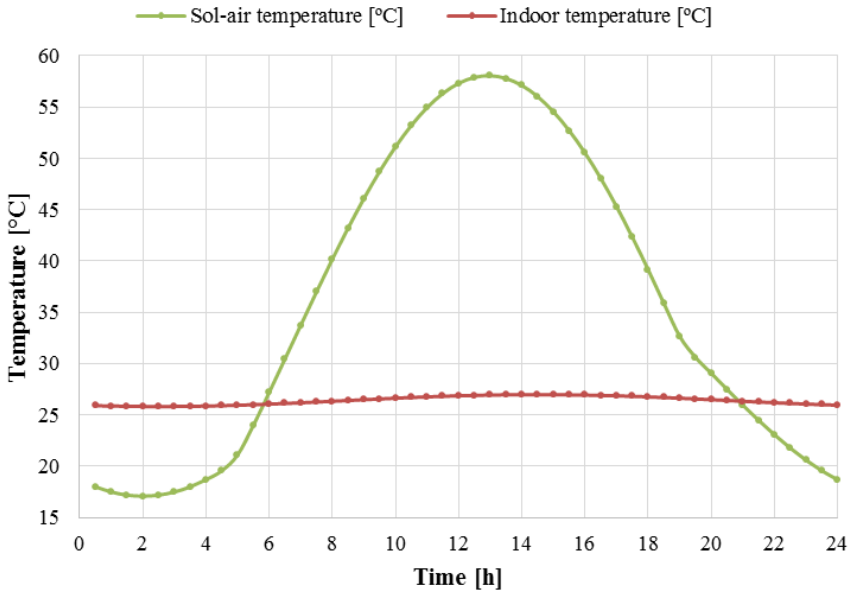

Figure 5.9: Variation of the indoor temperature for walls with outside insulation and taking into account the solar radiation in a summer day.

5.6.2. Study of the influence of solar radiation through windows

The main solar contributions in a building are produced through the windows. Therefore, it is interesting to analyse the influence of this energy in the indoor temperature. These contributions of energy can increase the indoor temperature in winter, however, they can produce an excess of temperature in summer so it is necessary look for a balance between this two situations.

The first step to study the influence of solar radiation is to add the solar radiation through windows to equation [Eq.4.44] and solve it using *Laplace* transformation.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

$$T_{int}(s) = \sum_i \frac{h_{int} \cdot A_i}{h_{int} \cdot \sum(A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V + C_{p,aire} \cdot s} \cdot T_{sup,i}(s) + \sum_i \frac{h_{int} \cdot A_0}{h_{int} \cdot \sum(A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V + C_{p,aire} \cdot s} \cdot T_{0,i}(s) + \frac{0{,}32 \cdot n \cdot V}{h_{int} \cdot \sum(A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V + C_{p,aire} \cdot s} \cdot T_{ext}(s) + \frac{1}{h_{int} \cdot \sum(A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V + C_{p,aire} \cdot s} \cdot Q_{internas}(s) + \frac{1}{h_{int} \cdot \sum(A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V + C_{p,aire} \cdot s} \cdot Q_{solar}(s)$$

[Eq.5.21]

This new term (Q_{solar}) depends on the orientation, the tilt and the properties of windows. So, solar contributions are equal to the direct solar radiation multiplied by the solar factor of the glass. The solar factor of the window is the relationship between total energy which enters the room through the glass and the incident solar energy. This total energy is the sum of solar energy that enters through direct transmission and energy transferred from the glazing to the indoor space [IDAE, 2007]

In this case, to analyse the influence of solar radiation, we use a glazed surface of 12 m^2 (20% of the surface of the facade). The window has double glazing with a transmittance of 3,1 W/m^2K and a solar factor of 0,75.

The Figure 5.10 shows the evolution during the winter of the indoor temperature taken into account the solar radiation. With the inside insulation, the temperature reaches a maximum of 8,04 ^oC. In the other case, with outside insulation, the maximum peak of temperature is 8,37^oC.

This difference in the maximum temperature reached is due to the wave lag which is produced by each type of enclosure. When insulation is on the outside and therefore the thermal mass is inside, the indoor temperature is more stable, and the solar radiation increases the indoor temperature during the hours with more sunshine. However, when the isolation is in the outside, the wave lag produces a

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

maximum temperature about 16:00, making this peak reached less than in the previous case.

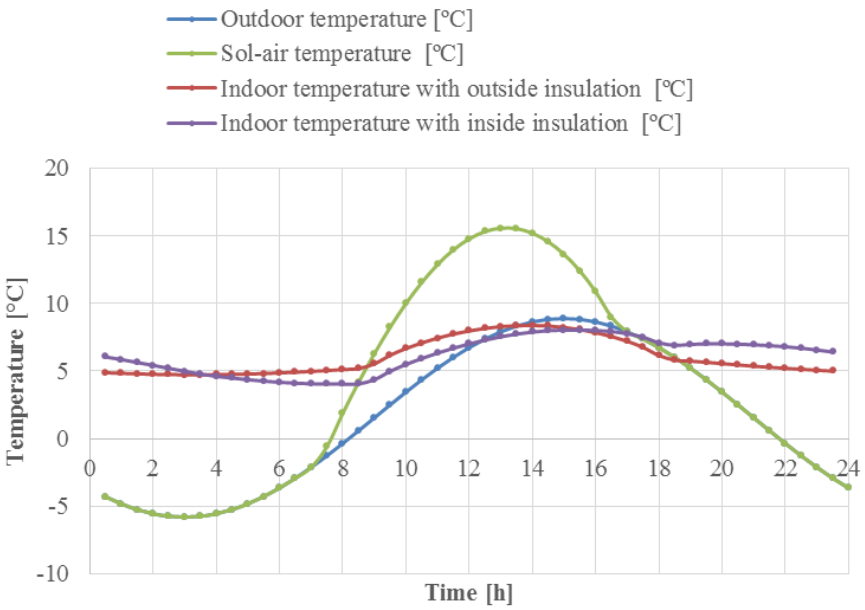

Figure 5.10: Variation of the indoor temperature for walls with inside and outside insulation and taking into account the solar radiation through the window during a winter day

If the influence of solar radiation during a summer day is evaluated, the same trend is found (Figure 5.11) In this case, if the insulation is inside, the temperature reachs 29,5*ºC*, while if the insulation is outside, the temperature reachs 28,23*ºC*. Therefore, design buildings taking into account the thermal mass and the solar radiation could help us to get more comfortable conditions during the summer and the winter.

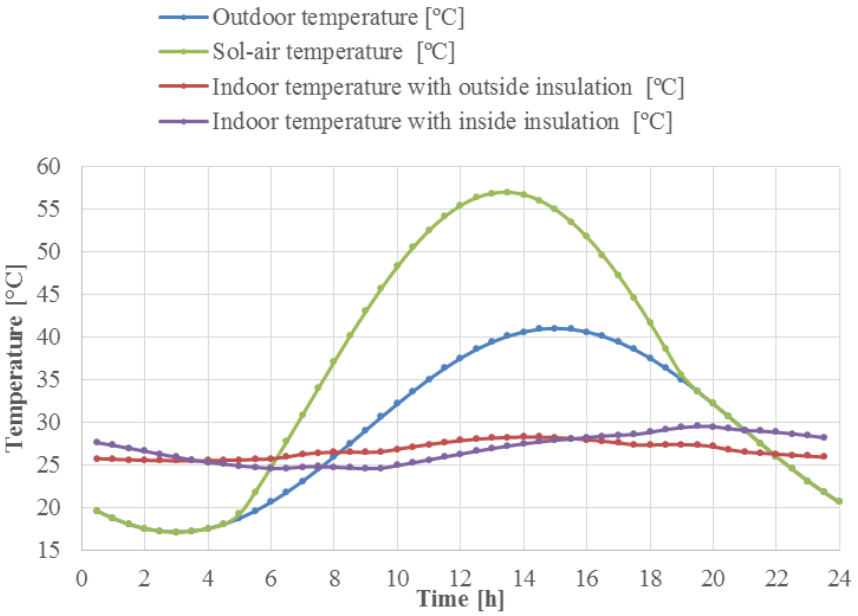

Figure 5.11: Variation of the indoor temperature for walls with inside and outside insulation and taking into account the solar radiation through the window during a summer day

5.7. DISCUSSION

Introducing solar radiation into the model allows for an accurate estimation of the indoor temperature of buildings. Taking into account this heat input allows evaluating the measures that prevent overheating in summer and maintaining a stable indoor temperature. In this case, the solar radiation is introduced into the model according to equation [Eq 5.17], which calculates the sol-air temperature. This way of introducing the radiation, allows coupling the solar radiation to the model described in the previous chapter.

Solar radiation through the walls of the building causes different disturbances in the indoor temperature depending on the location of the insulation. By introducing solar radiation into the model, there is an increase in temperature inside due to the heat that enters the building by conduction. During winter, a maximum temperature of

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

$7^{o}C$ is produced when the insulation is inside, while when the insulation is placed outside, the maximum temperature reached is $5{,}66^{o}C$.

However, in summer weather conditions, introducing the thermal mass from the outside generates maximum temperatures of 29,23 ^{o}C compared to the 25,82 ^{o}C that occur when the thermal mass is placed inside. In this case, the placement of the thermal mass inside would generate more stable temperatures, allowing reducing the maximum peak of energy consumption in summer.

Therefore, taking into account the influence of solar radiation using the sol-air temperature allows a better estimate of the energy demand of the buildings. These results agree with those obtained by Ramin et al (2021), where the use of a model based on the sol-air temperature, obtained a higher energy demand in cooling and a lower energy demand in heating.

The inputs of solar radiation through the windows, causes a greater change in the indoor temperature. In the case analysed, a low-quality window is used, in order to observe the influence of solar radiation on the indoor temperature. On the one hand, during the winter, the entry of solar radiation causes a greater oscillation when the thermal mass is placed inside (T_{max} = $8{,}37^{o}C$) compared to when the thermal mass is outside (T_{max} = $8{,}04°C$). On the other hand, in summer conditions, the maximum temperature reached with the internal thermal mass is $28{,}23^{o}C$ compared to $29{,}25^{o}C$ with the external thermal mass.

In both cases, the maximum temperature reached exceeds the maximum recommended temperature values, so the use of solar shadow devices would control the overheating generated by solar radiation.

5.8. CONCLUSIONS

The introduction of solar radiation in the model makes the system fits better to the reality and thus more precise results are obtained. The main conclusions obtained from this chapter are:

- Solar radiation through the enclosures does not generate large fluctuations in temperature. However, placing the insulation on

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

the inside and the thermal mass on the outside generates a higher indoor temperature during winter.

- In summer conditions, the flow of heat through the walls is reduced when the thermal mass is on the inside and the insulation on the outside.
- Solar contributions through the window generate a greater impact on the indoor temperature with respect to the heat flow through the enclosure.
- By including the solar contributions through the window, placement the thermal mass inside and the insulation outside generates higher temperatures in winter.

Considering the thermal inertia and the solar contributions in a building, we can design buildings more efficient and obtain more comfortable temperatures. Being able to predict the temperature inside a building is useful in the design of HVAC control systems. From the meteorological predictions an approximation of the evolution of the outside temperature can be obtained. In this way, a control system can be designed that anticipates outside temperature variations, in order to maintain the interior temperature in the comfort zone.

CHAPTER 6. ANALYSIS OF ECO-MATERIALS IN THE CONSTRUCTION SECTOR: EVALUATION OF THERMAL BEHAVIOUR AND LIFE CYCLE ASSESSMENT

This chapter is a reproduction of the following publication derived from the research carried out by the doctoral student during the training stage:

- Title: Analysis of biowaste-based materials in the construction sector: evaluation of thermal behaviour and Life Cycle Assesment (LCA)
- Authors: Vilaboa Díaz, A; Francisco López, A.; Bello Bugallo, P.M.
- Publisher: Springer
- Journal: Waste and Biomass Valorization
- ISSN: 1877-2641; eISSN: 1877-265X
- Impact Factor: 3.703 (2020)
- Year of publication: under review, 2021
- Contribution of the doctoral student: contribution to development of the research and writing the paper.
- Authorization of the journal/publisher for the use of the publication in the doctoral thesis is included in point 1b of the appendix "Author's Re-Use Rights", of the Publishing Agreement. The text is exactly transcribed below:
    - (b) Re-Use of the Version of Record (as defined below) of the Contribution or any part of it is permitted in a thesis written by the same Author, and the Author is entitled to make a copy of the thesis containing content of the Contribution available in a repository of the Author's academic institution

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

SUMMARY

The construction sector is responsible for the generation of 37% of waste and 50% of the extraction of raw materials in the European Union. The use of waste and biomass as construction materials contributes to reducing the consumption of natural resources. The objective of this work is to analyze the thermal behavior and the environmental impact associated with the use of sustainable materials in comparison to conventional materials.

A review of the state of the art of materials from waste and biomass is carried out. After the review, hemp concrete, isotex, bricks with 4 and 8% of Olive Core Flour (OCF) and bricks with 3 and 7% of Wheat Straw (WS) are selected as eco-materials for study. The eco-materials are evaluated, taking into account their thermal behaviour (decrement factor and time lag). In addition, the energy consumption of a model building is analyzed using selected eco-materials. Finally, each material is evaluated through Life Cycle Assessment (LCA), including Non-Renewable Energy (NRE), Cumulative Energy Demand (CED) and Global Warming Potential (GWP) as indicators.

The results obtained show that the thermal behavior of the materials improves when mixed with waste. Materials such as hemp concrete and isotex have a similar behavior to conventional materials but generate a lower environmental impact. Bricks with OCF and WS are the materials with the lowest environmental impact and with better thermal behavior than conventional brick.

The reuse of materials allows promoting the circular economy and progressing towards sustainable buildings from construction.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

6.1. INTRODUCTION

Reducing of energy consumption in buildings is one of the objectives set by the European Union in its roadmap towards a Low Carbon Economy in 2050. To limit the increase in global temperature below $2^{o}C$, CO_2 emissions must be reduced by 80-90% by 2050 compared to 1990 [EU, 2011]. However, as a result of the publication of the European Climate Law in 2021 (Regulation EU/2021/1119), the objective of the member states is to achieve climate neutrality by 2050. In addition, it establishes as an intermediate objective a reduction of greenhouse gas emissions of 55% by the year 2030.

European´s Union priority to achieve climate neutrality is based on the reduction of emissions, energy efficiency and the development of renewable energies. In these three areas, buildings are a strategic sector since they can actively participate in all three objectives. Their contribution to the European objectives will not only be based on reducing the energy demand of buildings, but will also contribute through the use of sustainable materials in construction. The materials manufacturing process has an associated energy consumption (Cumulative Energy Demand, CED), so it is necessary to know how much of that energy comes from renewable and non-renewable sources (Non-Renewable Energy, NRE), as well as establish the potential of global warming of each material (Global Warming Potential, GWP).

The use of waste for the production of eco-materials allows reducing the environmental impact associated with the production of materials. These regenerative economy techniques allow the growth of the sector without consuming ecosystem resources and reducing greenhouse gas emissions. Reducing the extraction of raw materials contributes to biodiversity conservation and protection and to the improvement of natural capital.

Figure 6.1 shows the tonnes of waste generated by activity in the European Union, observing that construction, mining and quarrying sectors generate the most tons of waste. The construction sector there is an increase in the amount of waste generated, going from 30% in 2004 to 37% in 2018 [Eurostat, 2020], producing the greatest increase in the waste generated.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

It is estimated that by the year 2050, the annual generation of waste will increase by 70% and the world consumption of resources will be equivalent to three planets [EU, 2020]. As can be seen in Figure 6.1, waste generation continues to increase and exceeds 2.500 million tons. The implementation of sustainable products will reduce the generation of waste. At this point, the use of sustainable materials in the construction and buildings sector could reduce the GHG emissions associated with the sector by 80% [EU, 2020]

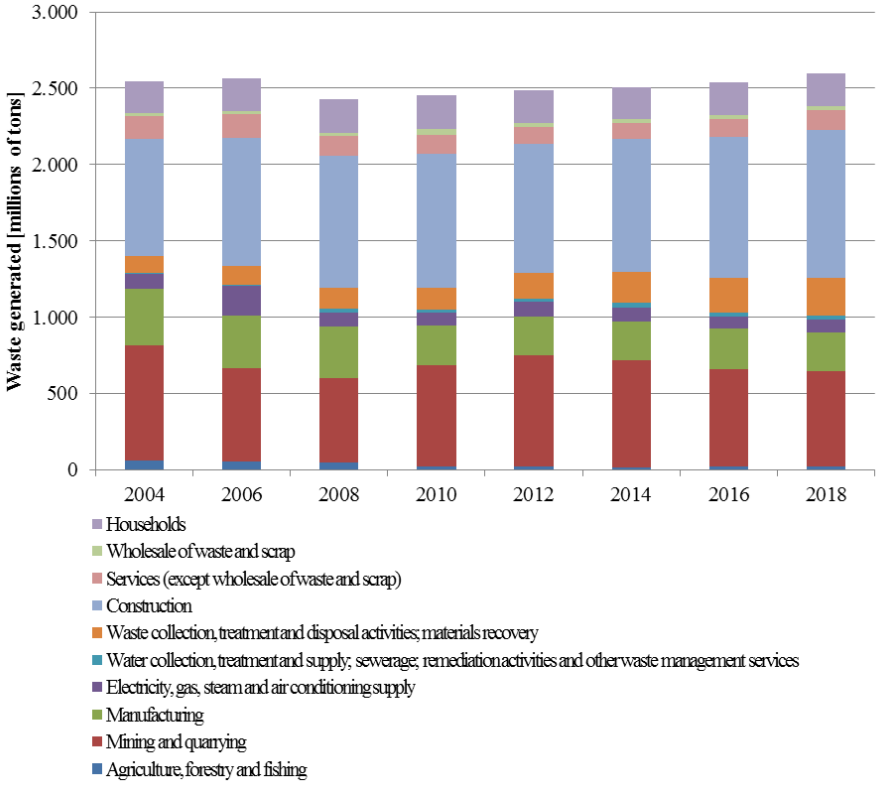

Figure 6.1: Total amount of waste generated in European Union [Data surce: Eurostat, 2020]

The selection of materials with a low-environmental impact in the building design phase can reduce CO_2 emissions by 27% [González et al, 2006]. The use of sustainable materials allows the reduction of the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

embodied energy of building (which is the energy used in the manufacture of materials). Taboada et al (2018) calculated embodied energy by evaluating the design and construction phase of a building obtaining that the use of recycled materials reduces embodied energy in the manufacture of materials by 53% compared to the use of conventional materials. Globally, including recycled materials and Best Available Techniques (BAT) in the sector, embodied energy can be reduced by a half.

Sustainable materials and BAT use in the construction sector, not only cause a reduction in waste in the sector, but could also generate a reduction in waste in the mining sector. Thus, the production of Ordinary Portland Cement (OPC) accounts for 7% of the world CO_2 emission and it is expected that in the next 30 years it will increase 4 times. The use of new formulations in cement production could reduce CO_2 emissions and production costs by 50% [Assi et al, 2018]

The incorporation of waste in the construction materials manufacture allows reducing CO_2 emissions. The use of recycled materials in the manufacture of concrete such as marble waste [Thakur et al, 2018] or waste metalized plastic fibres and palm oil fuel ash [Mohammadhosseini et al, 2018] are different examples. The production of concrete, incorporating recycled materials, does not have to harm the mechanical properties. Thus, the incorporation of 5% of silica stone waste (SSW) powder on concrete improves the tensile and compressive strength by 18% and 10%, due to the production of a material with a lower number of pores and greater density [Abbasi et al, 2020]

The use of sustainable materials in the construction of buildings promotes circularity throughout the life cycle of buildings. Waste is transformed into resources, returning the value chain. The regenerative economic model allows maintaining the usefulness and value of materials, allowing the regeneration of ecosystems and avoiding environmental degradation.

The thermal insulation produced by natural raw materials requires less energy consumption compared to those that come from artificial raw materials [Gaujena et al, 2020]. Agricultural wastes such as hemp have been shown to have good thermal and mechanical properties.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The use of this type of materials, due to its low cost, improves comfort and therefore leads to both social and economic sustainability [Maraveas et al, 2020]. According to the study carried out by Gaujena et al (2020), the thermal insulation of agricultural residues such as hemp, have thermal conductivities between 0,0544 to 0,0594 $W/m \cdot K$. However, the material must be prevented from get in touch with water. Due to its high water absorption capacity, it can increase its weight by 198% and its volume by 40%.

The eco-materials used in construction can have different origins and, therefore, each one must be evaluated in a specific way in order to value it. Pennachia et al, analysed the use of urban waste in its use for the building envelope to obtain *U-values* of 0,25 $W/m^2 \cdot K$. The wastes studies were included cardboard tubes, automobile tires, wood pallets, and plastic and glass bottles. The use of materials such as glass bottles, tires and wood pallets are more economically viable compared to a traditional structure [Pennacchia et al, 2016]

The application of circular and regenerative economy techniques on a large scale would mean an increase in GDP of 0,5% for the European economy in 2.030 and the generation of 700.000 jobs [EU, 2020]. The application of the regenerative economy in the construction sector through the introduction of sustainable materials will allow reducing the generation of waste in the construction phase and in the production of materials.

6.2. OBJECTIVES

In this chapter the thermal behaviour of buildings are evaluated by incorporating sustainable materials in the thermal envelope. The evolution of the temperature is analysed, in order to evaluate which eco-materials provide a more stable temperature. In this way, it is possible to select those sustainable materials based on the thermal comfort generated.

First, a brief review is made on the use of waste in construction materials. The eco-materials selected for the study are described in order to evaluate the previous studies and know their thermal properties.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Second, the thermal properties of the enclosures are evaluated. For this, each material is introduced in the model developed in previous chapters. In this way, we know for each thermal envelope the time lag and the decrement factor of each wall. The results are compared using thermal simulation software to obtain the energy demand of a building.

Finally, the environmental impact of each type of eco-material is evaluated and compared with conventional materials. The indicators used to assess the environmental impact are non-renewable energy (NRE), cumulative energy demand (CED) and global warming potential (GWP).

6.3. CASE STUDY

To evaluate the thermal properties of materials in the energy consumption of buildings, a prefabricated construction is selected. This type of construction is characterized by its low cost and by generating less waste during construction. Figure 6.2 shows a drawing of the building, which has a square geometry with a length of 6 x 11,1 meters, so it has a constructed area of 66,6 m^2.

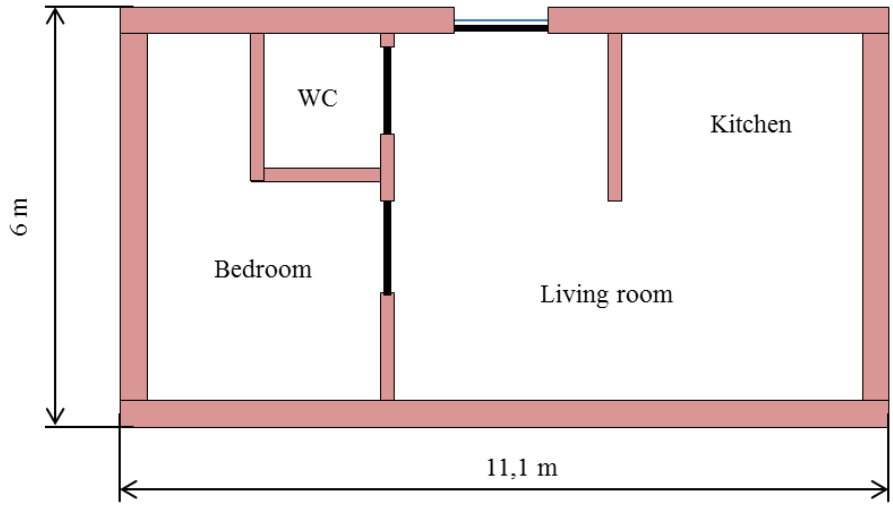

Figure 6.2: Drawing of the building to study

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The materials used for this modelling are listed in Table 6.1 as well as the values necessary for their application in the Lesosai software, which include the values of thermal conductivity (*W/m·K*), density (*kg/m*^{3}), and specific heat (*J/kg·K*). These values have been extracted from the software itself (*Lesosai*), which includes a database, or from de manufacturer.

Table 6.1: Original building materials description

Constructive Element	Materials	Conductivity [W/(m·K)]	Density [kg/m^3]	Heat capacity [J/(kg·K)]
Floor	Reinforce concrete	1,8	2.400	1.100
	Extruded polystyrene	0,036	25	1.400
	Cement mortar	1	1.700	1.000
	Parquet Floor	0,14	900	2.200
Wall	Granite	2,8	2.600	1.000
	Aquapanel Knauf	3	1.156	1.500
	Extruded Polyestyrene (XPS)	0,035	30	1.404
	Rock Wool, 100 kg/m^3	0,04	100	600
	Gypsum plasterboard	0,21	850	800
	Acrylpaint	0,2	1.050	1.400
Roof	Swisspor PUR Premium	0,021	30	1.404
	Steel	60	7.850	500
	Bitumen sealing	0,17	1.100	1.800
	OSB board, PF-glued, for exterior	0,13	600	2.160
	Rock Wool, 100 kg/m^3	0,04	100	600
	Gypsum plasterboard	0,21	850	800
	Acrylpaint	0,2	1.050	1.400

The floor consists of a reinforced concrete slab with cooperating sheet metal as permanent formwork, 8 *cm* thick extruded polystyrene, regularization mortar and final coating (floating flooring or ceramic coating).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The roof is composed of an 8 *cm* thick sandwich panel and a double layer of crossed asphalt fabric. Cover closure on 12 *mm* thick OSB boards, 4 *cm* thick rock wool and finally plasterboard (including interior paint).

The exterior walls are made of granite tiles, aquapanel system with baked cement board application, waterproof and fire resistant. It includes a 2 *cm* thick air box, 8 *cm* thick extruded polystyrene, 4 *cm* thick rock wool and a plasterboard system including interior paint (or ceramic coating on the toilet).

6.4. METHODOLOGY

To evaluate the importance of the introduction of new materials in the construction sector, in order to reduce waste and the consumption of natural resources, without neglecting thermal comfort, the study is carried out in the following steps:

- Analysis of eco-materials from waste.
  An analysis on waste reuse in the construction sector is carried out through a systematic review of main articles present in the databases such as "Web of Science", "Science Direct" and "Research Gate". This part aims to give an overview of the reuse of waste in construction and the implications from a thermal and structural point of view.
- Selection of eco-materials to study.
  The materials used in the different cases under study are described including their properties.
- Analysis of the thermal behaviour of the eco-materials.
  Using the mathematical model developed in CHAPTER 4, the thermal behaviour of eco-materials is analysed. In order to compare the results with conventional materials, the decrement factor and time lag of a 20 cm thick wall is studied.
- Analysis of energy demand for the different case studies.
  The next step makes a comparative between the type of materials and the energy demand of a construction that uses conventional materials and using different eco-materials. The simulation software used is *Lesosai*, which allows studying the efficiency of buildings with different materials.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

- Environmental impact analysis.
  An evaluation of the environmental impact of the materials used in the different scenarios is carried out to evaluate the most sustainable. The indicators used to analyze the environmental impact through the Life Cycle Assessment (LCA) of materials are: Non-Renewable Energy (NRE), Cumulative Energy Demand (CED) and Global Warming Potential (GWP).

6.5. DEVELOPMENT AND PRESENTATION OF RESULTS

6.5.1. Analysis of eco-materials from waste

Recycled materials can be reinjected into the economy as a secondary raw material and become part of the production process. The use of this type of materials allows reducing the consumption of raw material for the production of materials and reducing the environmental impact. There are different sustainable materials in the market that can be introduced in the processes and avoid extracting new raw materials. The recovery of waste and avoiding the extraction of raw materials (therefore minimizing the use of energy) allow evolving towards a regenerative economy and preserving the ecosystem.

The use of waste materials is extensive and numerous. This section aims to show a brief description of the ecomaterials from waste currently used in the construction sector.

6.5.1.1. Eco-materials from agricultural wastes

Agricultural wastes in the European Union represent 1% of the total (together with forestry and fishing) [Eurostat, 2020]. However, these wastes are generated all over the world, and there are numerous studies where they are used as construction materials.

Agricultural wastes are used mainly as insulating materials since they have thermal insulation very similar to conventional materials; however, they are very susceptible to humidity and biological attacks. This type of waste can be classified into two types: crushed stalks or husks and fibres [Gaspar et al., 2020]

One of the most widely used agricultural materials around the world is straw, especially in developing countries. Straw is an organic

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

and easily accessible material, so it is not necessary to transport it long distances [Cascone et al, 2019]. The insulating capacity of this material is known and depends on several factors such as the straw type used, the water content, the density of the bale, the gap between each bale, the density of the coating in the interstices, the orientation of the fibres, the nature and the thickness of the coatings [Chaussinand et al, 2015]. As an example, the use of straw as bales would allow to achieve thermal transmittance of walls below 0,15 $W/m^2 \cdot K$ [Mutani et al., 2020]. Regarding the use of this eco-material, it is necessary to consider important aspects such as fire resistance. When this type of material is packed, its fire resistance is comparable to conventional construction materials, however when the straw is dispersed it is highly flammable [Cascone et al, 2019]

Other authors analyse the utilization of another type of agricultural wastes. The use of Straw Fibres (SF) or Olive Fibres (OF) joined with silicate solution for the formation of insulating panels. Comparing these panels with EPS panels; to achieve *U-values* of 0,27 $W/m^2 \cdot K$, higher material thicknesses are needed but a lower annual energy demand is obtained [Liuzzi et al, 2020]. In other cases, the combination of cork fibre waste with cardboard can be used as reinforcement of the gypsum matrix. Adding 60% cork fibre reduces the thermal conductivity of the plaster from 0,223 $W/m \cdot K$ to 0,062 $W/m \cdot K$. By adding cardboard waste to the mixture, the thermal conductivity and sound absorption are slightly reduced but the compressive strength is improved [Sair et al, 2019]

Despite the great insulating capacity of agricultural residues, they can also be used in structural elements in combination with conventional materials used in the construction of buildings.

Sani et al (2017) studied the impact of introducing agricultural wastes on the thermal and mechanical properties of bricks. In the study, they introduce Wheat Straw (WS) and Olive Core Flour (OCF). The use of these residues in the elaboration of clay ceramics improves the thermal properties without damaging the mechanical properties and also reduces energy consumption in the manufacturing process. Among the results, they obtained that the use of 4% OCF reduces the thermal conductivity by 16% and in the case of using 8% OCF, it is

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

reduced by 28%. In both cases the mechanical strength remains above the industry standard. Furthermore, by adding 3 or 7% of WS, there is a reduction in thermal conductivity of 20 and 30%, respectively. However, in this case the mechanical strength is lower than the use of OCF. Other authors analysed the use of agricultural waste (such as rice straw, sugarcane bagasse and wheat straw ashes) with the Sludge of Water Treatment Plant (SWTP) to replace 50% of the clay. In these cases, the use of up to 10% of agricultural residues would allow the compression strength to be maintained within quality standards (> 8 *MPa*), thus reducing the environmental impact and reducing the demand for raw materials [Heniegal et al, 2020]

Agricultural wastes can also be incorporated intothe cement production. Pereira et al (2020) analysed the properties of coconut fibres to be used in cement matrices. Among the main properties of coconut fibres, the amount of lignin present stands out. Lignin would improve the mechanical properties of cement. Also, due to the low density of the coconut fibre, it would allow producing lighter types/blocks of cement. These improvements in mechanical properties were also found when adding Rice Husk Ash (RHA). Using 15% RHA improves the compressive strength by 20% [Zareei et al, 2017]. However, the addition of agricultural residues such as wheat straw (200 *g* of wheat straw for each 4,4 *kg* of cement), generate a compound with a lower resistance to compression, but better flexural tensile strength [Andres et, al 2015]

Numerous agricultural wastes can be used for the production of sustainable materials, both as thermal insulation and as part of structural elements. Each material must be evaluated individually to know the influence on the thermal and mechanical properties of the resulting compounds. However, the reuse of this waste has great potential to reduce the consumption of raw materials in the manufacture of construction materials.

6.5.1.2. Eco-materials from industry waste

Vegetable fibre residues from industry can be incorporated for the manufacture of eco-materials. The food industries generate large

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

amounts of waste that can be reused for the manufacture of construction materials.

Martinez et al (2012) studied the use of the waste generated in the production of beer for the manufacture of bricks. The bagasse residue generated can account for 65-81% of the raw material used. The use of 2,5% of bagasse in the manufacture of bricks (fired for 1 hour at 950^{o}C), produces a brick with an apparent density and a resistance to compression similar to that of pure clay. For higher bagasse concentrations, the thermal resistance of the brick increases, but the compressive strength decreases.

The Sugar Cane Bagasse Ash (SCBA) is generated as a secondary product of the process combustion of the sugar, alcohol and electricity factories. According to the study carried out by Tonnayopas (2013), the use of 30% SCBA in bricks produced at 1.050^{o}C allows maintaining the quality according to the Thai standard.

SCBA is a compound with a high concentration of silica, so it can also be used as an additive for the production of concrete or mortar. The use of 20% ultrafine SCBA in concrete production maintains the same mechanical response as a concrete prepared with Portland cement [Cordeiro et al, 2008; Cordeiro et al, 2009; Ganesan et al, 2007]. Zareei et al (2018) found that the use of 5% SCBA improves the durability and impact resistance of concrete. Ademas, in the production of materials, the demand for water increases with the amount of SCBA due to porosity and irregularity.

6.5.1.3. Eco-materials from sludge of water treatment plant (SWTP)

Sludge of Water Treatment Plant (SWPT) has a heterogeneous composition due to the different input sources. The organic matter content is between 60-80% in dry solid. The inorganic content of these residues (SiO_2, CaO, Al_2O_3, Fe_2O_3, MgO and P_2O_5) make their use of special interest [Chang, et al, 2020].

One of the potential uses of SWPT is for the production of ceramic tiles or bricks, even in combination with agricultural wastes [Heniegal et al, 2020]. Amin et al (2018) evaluated the addition of dried sewage sludge in percentages between 5 and 35% for the production of ceramic tiles. The maximum amount of added sludge

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

for the production of 7,5 *mm* tiles was 10% for tiles fired at 1150 *°C* (for water absorption>10%) and 7% (for water absorption <10%). According to the review made by Chang et al (2020), in the use of SWPT in the manufacture of ceramic materials, the increase in sewage sludge increases water absorption and porosity. In order not to affect long-term performance, the addition of sludge should be limited to 20%.

The generated sludge (wet or dry) can be used for the production of concrete, mixed with up to 15% of the weight in cement. This proportion allows producing a concrete without causing a significant reduction in compressive strength [Rabie et al 2019]. A higher contribution of sludge considerably reduces the compressive strength [Rabie et al 2019; Chang et al 2020]. However, when the sludge is previously incinerated, up to 25% of sewage sludge ash can be incorporated without affecting the compressive strength. The optimal mix is between 10-20% [Rutkowska et al, 2020]

6.5.1.4. Eco-materials from plastic waste

The production of plastic in the last decades has increased exponentially, reaching 322 million tons worldwide in 2015. The fate of plastics is distributed as follows: 39% are incinerated, 30% are recycled and 31% are buried [European Parliament, 2018]. The generation of plastic waste is an environmental problem that generates health problems, water pollution and soil contamination.

Plastic waste such as bottles, already mentioned in the introduction to this chapter, can become a sustainable and more economical proposal for the construction of thermal envelopes with *U-values* of 0,25 $W/m^2 \cdot K$ [Pennacchia et al, 2016]. Envelopes made with air-filled plastic bottles bonded with mortar have higher thermal resistance than traditional cement blocks, so they can be used as building units for partitions [Mansour et al, 2015]. Plastic waste can also be used in the form of fibres. The use of fibres in concrete mixtures (0-0,5%) reduces the resistance to compression; however, it increases the tensile strength, so the material obtained can be used on industrial floors or pavements [Khatab et al, 2019]

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Various studies analyse the introduction of plastic waste in combination with other types of waste. Mohammadhosseini et al (2018) has demonstrated that Waste Metallized Plastic (WMP) fibres have a good chance of being used as fibrous materials to improve the durability of concrete. The incorporation of Palm Oil Fuel Ash (POFA) into the WMP fibre increased the air content of the concrete mixes. Additionally, water absorption and sorptivity were reduced with volume fractions up to 0,75% for both Ordinary Portland Cement (OPC) and POFA-based. Therefore, the production of a durable and sustainable concrete is possible using WMP fibres. The addition of WMP produces higher tensile and flexural strength, but a reduction in compressive strength. The highest tensile and flexural strength is obtained with 0,5% WMP fibres for both an OPC-based composite and 20% POFA (replacing OPC) [Alyousef et al, 2020]

6.5.1.5. Eco-materials from construction waste

In 2018, in the European Union, the construction sector generated 973 million tons of waste [Eurostat, 2020]. Although much of the waste generated in the sector (concrete, brick, gypsum, wood, glass, metal, plastics, etc.) could be recycled, they end up in landfills. The reuse of Concrete and Demolition Waste (CDW) in the construction sector has become crucial to contain a large amount of waste generated and also as a form of sustainability.

Silgado et al (2018) analysed the environmental and economic impacts in the production of structural concrete. The use of recycled cement aggregates and recycled gypsum cement to produce structural concrete allows a cleaner production of concrete, causing a reduction in environmental impact and economic savings. The use of Fine Recycled Concrete Aggregates (FRCA) have better resistance to compression than those made with natural sand, however, the resistance to compression decreases with increasing the amount of FRCA. Moreover, the water consumption when using recycled sand is higher than in conventional mortars [Zhao et al 2015]

Ossa et al (2016) analysed the use of CDW for the construction of urban roads. Up to 20% of CDW could be reused while maintaining properties similar to conventional asphalt.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

6.5.1.6. Eco-materials from mining and quarrying waste

Another waste that can be reused for the production of sustainable materials is those that come from the mining and quarrying sectors, such as marble, granite or ceramics.

In the marble treatment process (processing, cutting and polishing), 20-35% of the original marble block is wasted. These wastes are harmful to health and cause a significant environmental impact on water, soil and air. There are several studies about marble residues in the production of concrete, brick and polymeric materials that show that these residues can bring numerous benefits when used in the manufacture of construction materials [Thakur et al 2018]

Khyaliya et al (2017) analysed the properties of mortar when fine marble residues are added instead of sand. They concluded that adding 25 to 50% reduces water requirements and improves mechanical properties and durability. For mixtures with 50% the maximum compressive strength and the minimum water absorption are obtained, however, with mixtures of 25% greater durability and stability are guaranteed. Regarding the concrete production, 10% of Portland cement could be replaced by marble slurry. With this mixture, a compressive strength greater than 40 *MPa* and flexural strength greater than 6 *MPa* at 28 days are guaranteed [Rana et al, 2015]. Also, the use of marble waste as an inert material can be used for the production of self-compacting concrete [Alyamaç et al, 2009]

Like marble dust, granite dust can also be used as a fine aggregate in mortars, observing similar behaviours. Fine aggregate in cement mortar mixtures with mixtures of 30 and 40%, a reduction in water requirements and an increase in compressive strength are observed [Gupta et al, 2018]

In the production of ceramic tiles, residues are also produced during the final polishing process. According to the study carried out by El-Dieb et al (2018), Ceramic Waste Powders (CWD), due to their similar characteristics to cement (includes more than 85% SiO_2 and Al_2O_3), have the potential to be used as an alternative ingredient in concrete. The compressive strength at 28 days, shows an increase of 4% for mixtures up to 20%. However, all mixtures with CWP (up to 40%) showed good development of compressive strength at 90 days,

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

reaching the minimum compressive strength. Other studies establish a substitution of 15% of CWP as a filling material in substitution of cement to produce self-consolidating concretes. With this percentage, a drastic reduction in strength is not observed in hardened concrete [Subaşı et al, 2017]

There is also the possibility of reusing mineral waste in the manufacture of different products. The kaolin processing industry generates a large amount of waste. There is also the possibility of reusing mineral waste in the manufacture of different products, such as paints. The kaolin processing industry generates a large amount of waste. The geotint, based on the kaolin residue, presented characteristics similar to those observed in industrialized paints: coating, fast drying and resistance, with good adhesion to the surface. Kaolin residues turned out to be a good material in the composition of soil-based paint, being a sustainable and economical alternative [Azevedo et al 2018]

6.5.2. Selection of eco-materials to study

The main standard for the selection of eco-materials is the availability of data on their thermal properties. Having the databases is essential to be able to carry out the simulations properly. The selected materials belong to the group of agricultural waste. Those waste types are widely used throughout the world. They are also materials with behaviours similar to conventional thermal insulation. In the following sections, the selected eco-materials are described in each scenario.

6.5.2.1. Hemp Concrete

Hemp concrete is made from hemp mixed with lime and water. It is an ecological, energy efficient and long-lasting material. It also has qualities of thermal insulation, is non-toxic and resistant to fire and pests. In addition, it is considered zero carbon as it stores active carbon from the atmosphere [Hempcrete]

The thermal properties of hemp concrete allow it to be used as an insulating material, since they have a conductivity between 0,05 – 0,16 $W/(m \cdot K)$ for a density between 220-550 kg/m^3, the specific heat varies depending on the density of the compound oscillating between

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

900 and 4.*700 J/(kg·K)* [Kinnane et al, 2015]. For the analysis, a thermal conductivity of 0,071 *W/(m·K)*, a density of 340 kg/m^3 and a heat capacity of 1.000 *J/(kg·K)* are used.

This material is introduced in scenario 1. The metallic structure is maintained and 15 *cm* of hemp concrete is included. In addition, 4 cm of expanded cork and 1 *cm* of plasterboard are included to close the structure.

6.5.2.2. Isotex

Isotex is a material made from pieces of wood that can be sawdust or discarded pallets. The use of waste makes it a more than ecological material, since it allows to value waste generated in the environment. The material has thermal and acoustic insulation qualities and, like hemp concrete, works by removing activated carbon from the atmosphere [Isotex].

The thermal characteristics are different from hemp concrete. It has a conductivity of 0,105 *W/(m·K)*, but with a higher thermal capacity of 1.500 *J/(kg·K)*.

Scenario 2 is include 25 cm of Isotex to close the structure. It also includes 4 cm of expanded cork, 1 cm of plasterboard and final paint. The main alterations are in the wall, and the only change in the ceiling is the replacement of the insulating material "rock wool" by an expanded cork (4 cm).

6.5.2.3. Olive Core Flour (OCF)

Scenarios 3 and 4 are the combination of the structural elements of the house in the conventional style but including bricks made with olive core flour (OCF) residues. Two variants are analysed, scenario 3 composes of bricks with 4% OCF and scenario 4 uses bricks with 8% OCF.

Different authors studied the thermal and mechanical properties of these compounds. The thermal conductivity for bricks with 4 and 8% OCF have a value of 0,42 and 0,36 *W/(m·K)* [Sani et al, 2017] [Aouba et al, 2016], and the density of both bricks varies between 1.760 and 1.586 kg/m^3 [Aouba et al, 2016] respectively.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Heat capacity is determined by the relationship between the specific heat of OCB (1.750 *J/(kg·K)*) [Sani et al, 2017] and of conventional brick (545 *J/(kg·K)*) [El Fgaier et al, 2015]. Therefore, the specific heat for 4 and 8% OCF bricks is 590 and 640 *J/(kg·K)*.

Scenarios 3 and 4 include 15 cm of 4 and 8% OCF brick with 4 *cm* of expanded cork insulation.

6.5.2.4. Wheat Straw (WS)

Scenarios 5 and 6 consist on the introduction of ceramic bricks made with 3 and 7% wheat straw (WS).

The thermal conductivity of the bricks is 0,40 and 0,35 *W/(m·K)* [Sani et al, 2017] with a density of 1.740 and 1.571 kg/m^3 [Aouba et al, 2016] respectively.

The specific heat for the WS considered was 2.181 *J/(kg·°C)* [Sani and Nzihou, 2017] and the value considered for the conventional brick was 545 *J/(kg·K)* [El Fgaier et al, 2015]. Therefore, the specific heat for 3 and 7% WS bricks is 595 and 660 *J/(kg·K)*.

Scenarios 5 and 6 include 15 *cm* of 3 and 7% WS brick with 4 *cm* of expanded cork insulation.

6.5.2.5. Summary of selected eco-materials

The materials described in the previous sections are part of the thermal envelope of the building. Table 6.2 summarizes the properties of the selected materials.

Table 6.2: Summary of eco-material properties

Scenarios	Materials	Conductivity [W/(m·K)]	Density [kg/m^3]	Heat capacity [J/(kg·K)]
1 (base case)	Hemp concrete	0,071	340	1.000
2	ISOTEX	0,104	510	1.500
3	4% OCF	0,42	1.760	590
4	8% OCF	0,35	1.586	640
5	3% WS	0,40	1.740	595
6	7% WS	0,35	1.571	660

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

These materials are included in the thermal envelope, establishing 6 different enclosure scenarios. The Table 6.3 summarizes the enclosures for each scenario under study. Only the walls and roof are described, while the floor is the same in all cases. Also, the thermal transmittance of each wall or roof is shown.

Table 6.3: Summary of scenarios to study to be analysed using Lesosai

Scenario	Element	U-value [W/(m²·K)]	Materials
0	Wall	0,2705	1,5 cm Granite + 1,25 Aquapanel Knauf + 8 cm XPS + 4 cm Rock Wool 100 kg/m3 +2,6 Gypsum plasterboard + 0,02 Acrylpaint
	Roof	0,1953	8 cm Swisspor PUR Premium + 1 cm Steel + 0,01cm Bitumen sealing + 1,2 cm OSB board + 4 cm Rock Wool 100 kg/m³ 1cm Gypsum plasterboard + 0,02 cm Acrylpaint
1	Wall	0,3002	**15 cm Hemp Concrete + 4 cm Expanded cork panels Growancork** + 2,6 Gypsum plasterboard + 0,02 Acrylpaint
	Roof	0,1953	8 cm Swisspor PUR Premium + 1 cm Steel + 0,01cm Bitumen sealing + 1,2 cm OSB board + **4cm Expanded cork panels Growancork** + 1cm Gypsum plasterboard + 0,02 cm Acrylpaint
2	Wall	0,2761	**25 cm ISOTEX + 4 cm Expanded cork panels Growancork** + 2,6 Gypsum plasterboard + 0,02 Acrylpaint
	Roof	0,1953	8 cm Swisspor PUR Premium + 1 cm Steel + 0,01cm Bitumen sealing + 1,2 cm OSB board + **4cm Expanded cork panels Growancork** + 1cm Gypsum plasterboard + 0,02 cm Acrylpaint
3	Wall	0,6064	**15 cm Brick OCF 4% + 4 cm Expanded cork panels Growancork** +0,5 cm cement mortar + 1 Gypsum plasterboard + 0,02 Acrylpaint
	Roof	0,1953	8 cm Swisspor PUR Premium + 1 cm Steel + 0,01cm Bitumen sealing + 1,2 cm OSB board + **4cm Expanded cork panels Growancork** + 1cm Gypsum plasterboard + 0,02 cm Acrylpaint
4	Wall	0,6322	**15 cm Brick OCF 8% + 4 cm Expanded cork panels Growancork** + 0,5 cm cement mortar + 1 Gypsum plasterboard + 0,02 Acrylpaint
	Roof	0,1953	8 cm Swisspor PUR Premium + 1 cm Steel + 0,01cm Bitumen sealing + 1,2 cm OSB board + **4cm Expanded cork panels Growancork** + 1cm Gypsum plasterboard + 0,02 cm Acrylpaint

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Scenario	Element	U-value [W/(m^2·K)]	Materials
5	Wall	0,6251	**15 cm Brick WS 3% + 4 cm Expanded cork panels Growancork** + 0,5 cm cement mortar + 1 Gypsum plasterboard + 0,02 Acrylpaint
	Roof	0,1953	8 cm Swisspor PUR Premium + 1 cm Steel + 0,01cm Bitumen sealing + 1,2 cm OSB board + **4cm Expanded cork panels Growancork** + 1cm Gypsum plasterboard + 0,02 cm Acrylpaint
6	Wall	0,6003	**15 cm Brick WS 7% + 4 cm Expanded cork panels Growancork** + 0,5 cm cement mortar + 1 Gypsum plasterboard + 0,02 Acrylpaint
	Roof	0,1953	8 cm Swisspor PUR Premium + 1 cm Steel + 0,01cm Bitumen sealing + 1,2 cm OSB board + **4cm Expanded cork panels Growancork** + 1cm Gypsum plasterboard + 0,02 cm Acrylpaint

6.5.3. Analysis of the thermal behaviour of the eco-materials

In the CHAPTER 4 of this work, the thermal behaviour of materials is analysed. Following the same criteria, the decrement factor and time lag of the eco-materials are evaluated for a 20 *cm* thick wall. In this way, the results can be compared with the conventional construction elements whose results are shown in Table 4.5 and Figure 4.9.

The simulation is carried out using the model described in CHAPTER 4 and taking into account the properties of the materials that are summarized in Table 6.2. To evaluate the thermal behaviour, a 20 cm thick wall is introduced into the model. The response of the system to a sine is be analysed.

In Figure 6.3, the response of the different eco-materials to sinusoidal disturbance is shown. All eco-materials generate a time lag between 6,7 and 10 hours. The material with the worst thermal response is brick with 4% OCF, generating a wave with a greater oscillation (4,9 *ºC*) and a lower time lag (6,72 hours). On the contrary, hemp concrete and Isotex produce a wave with a low oscillation of 1,3 and 0,6 *ºC* and a time lag of 9 hours.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

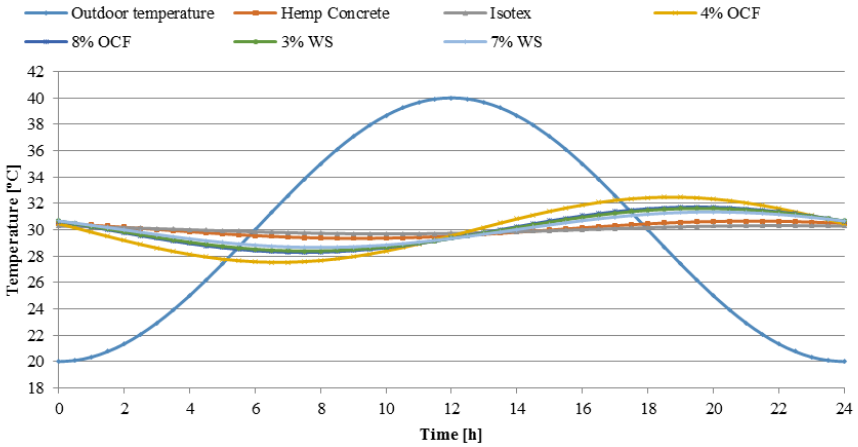

Figure 6.3: Representation the response in the inner surface of different eco-materials with a 20 cm thickness when the system is perturbed from a sine wave

In Figure 6.4, the results of the decrement factor and time lag for each material are shown. If the results obtained for eco-materials are compared with conventional materials, it is obtained that the addition of residues in the materials generates better thermal properties. In general, when compared with insulating materials, the results show a lower decrement factor and a higher time lag. This is due to the fact that the introduction of residues in the manufacture of materials makes them have a higher specific heat, so they have a greater capacity to accumulate heat.

Comparing conventional concrete with hemp concrete, it is observed that the thermal properties are very different. The decrement factor for hemp concrete has a value of 0,0655, while for conventional concrete it has a value of 0,6172. This is because hemp concrete has a low thermal conductivity (0,71 *W/(m·K)*) compared to concrete (2,5 *W/(m·K)*). However, the function of these materials is not comparable from a structural point of view, since hemp concrete does not have the compressive strength and tensile strength that conventional concrete has.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

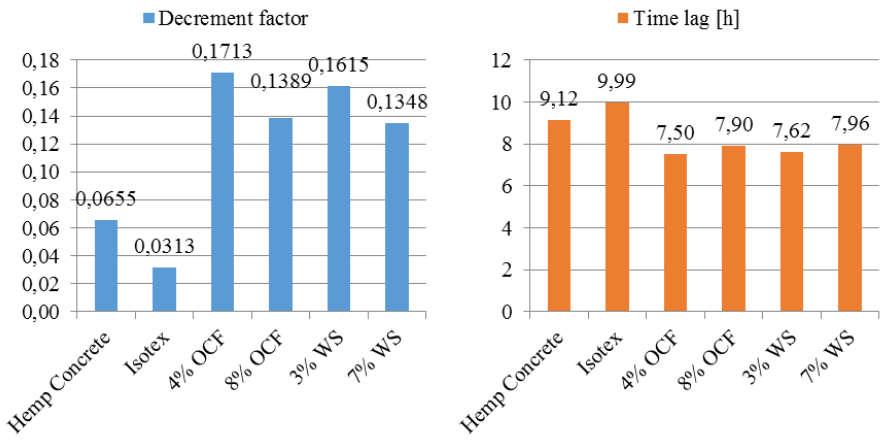

Figure 6.4: Decrement factor and time lag for eco-materials with 20 cm thickness

In the case of bricks, the addition of OCF or WS reduces the conductivity of the material, but on the contrary, a reduction in density and heating capacity is obtained. However, the introduction of recycled materials produces a more stable thermal response. The decrease factor for conventional bricks according to the simulation carried out in the first chapter is 0,2952, while the decrement factor is reduced by adding any of the residues. The lowest decrement factor has been obtained with 7% WS, reaching a value of 0,1348.

6.5.4. Analysis of energy demand for different case studies

From the construction information described, the energy efficiency of the 66,6 m^2 prefabricated house was analysed with the help of the Lesosai software. To carry out the simulation, the enclosures of the scenarios described above are used. The properties of the materials are already included in the software database. Those materials that are not in the database are added manually.

First, scenario 0 (base case) is analysed, which is the starting case. Figure 6.5 shows the Sankey diagram of the building. The Sankey diagram is provided by the Lesosai software. The annual energy consumption necessary to heat or cool the home is 10,7 kWh/m^2 and requires an installed power of 1,4 kW.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

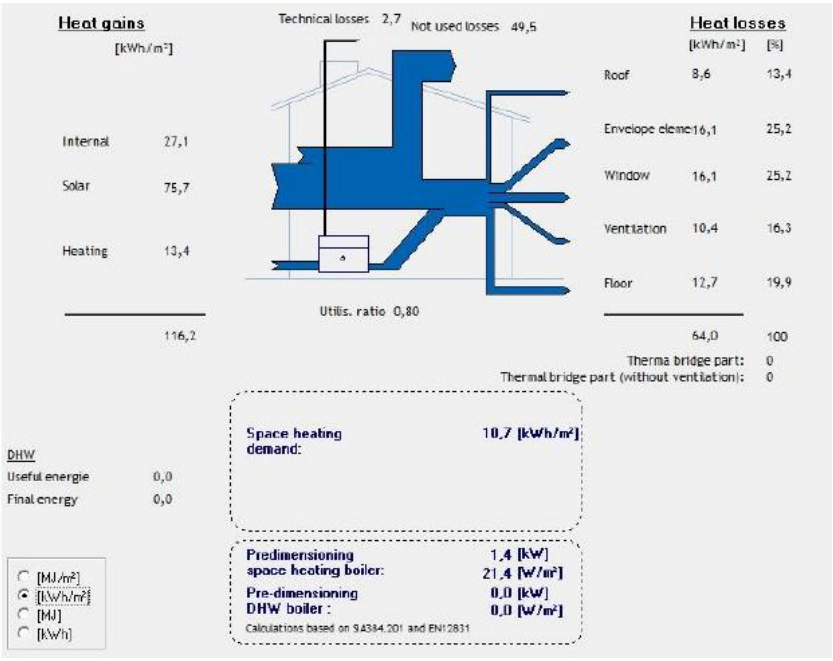

Figure 6.5: Sankey diagram for original scenario 0 (base case)

With the initial configuration, the energy losses are at 64,0 *kWh/m*^{2}. It should be noted that 16,1% (25,2 *kWh/m*^{2}) of the losses occur through the envelope and 8,6% through the roof (13,4 *kWh/m*^{2}). For the other scenario, the composition of the envelope and roof is varied, while the properties of windows, floor and ventilation remain constant.

To maintain the comfort temperature, the software calculates the energy contribution of the boiler (13,4 *kWh/m*^{2}) and takes into account the internal gains (27,1 *kWh/m*^{2}) and the solar inputs (75,7 *kWh/m*^{2}). Therefore, by modifying the properties of the enclosure, an increase in air conditioning consumption and therefore the installed power increases is caused.

Figure 6.6 and Figure 6.7 show the Sankey diagram in the case of use Hemp Concrete (scenario 1) and Isotex (scenario 2). Both cases have a similar behaviour with an annual energy consumption of 11,0 y

10,9 kWh/m^2. The difference concerning the scenario 0 (base case) is due to energy losses through the envelope.

On the roof, rock wool is replaced by expanded cork panels, however, as both materials have the same conductivity (0,04 $W/m{\cdot}K$), the thermal transmittance (0,1953 $W/(m^2{\cdot}K)$) is not altered. However, the compositions of the walls are different and their transmittance is higher than for scenario 0 (base case), so the losses through the walls are greater. Therefore to maintain the comfort temperature, the boiler must provide greater energy.

As can be seen in both figures, the highest percentage of energy losses occurs through the enclosures. The losses through the roof, the walls and the floor of the building are 59,7 and 58,7% of the total, for scenarios 1 and 2 respectively.

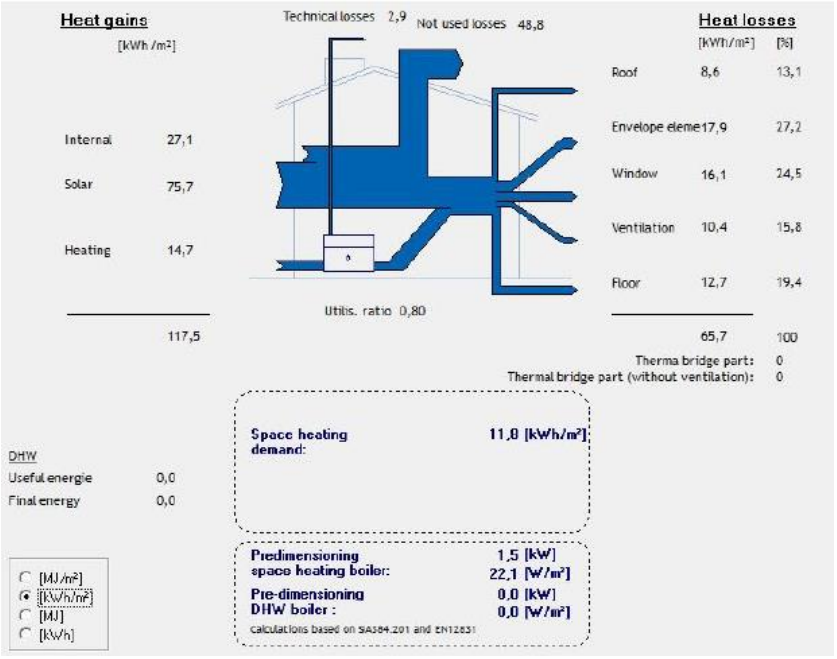

Figure 6.6: Sankey diagram scenario 1 (Hemp Concrete)

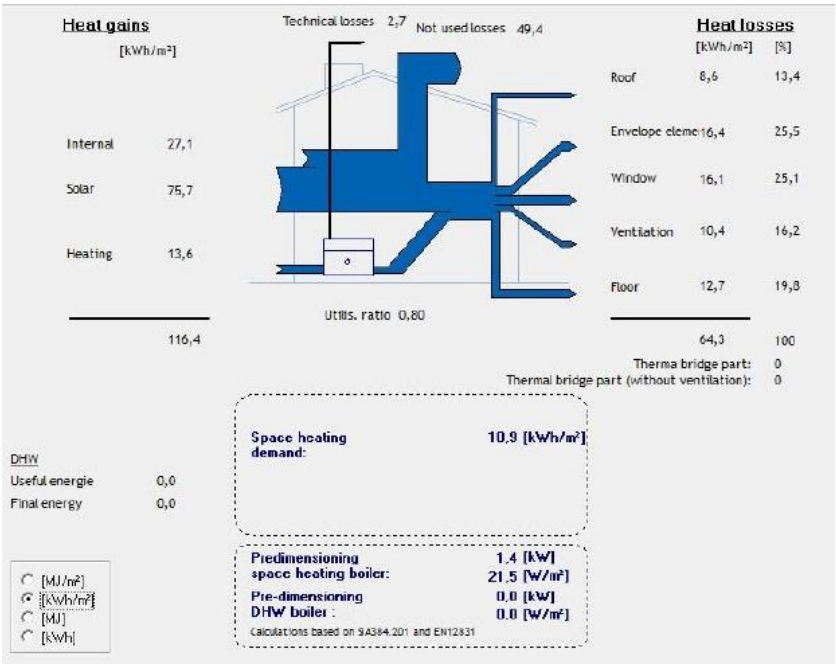

Figure 6.7: Sankey diagram for scenario 2 (Isotex)

Figure 6.8 and Figure 6.9 show the Sankeys diagrams in the case of using bricks with 4 and 8% of olive core flour (OCF). In both cases, an increase in annual energy consumption is observed concerning the the original and scenarios 1 and 2, having a value of 25,7 and 24,5 kWh/m^2. In these cases, it is necessary a boiler of 2,1 and 2,0 *kW* of power.

The high thermal conductivity of OCF bricks allows a greater heat flow through the walls, causing greater energy losses by conduction. Thus, for scenarios 3 and 4, the energy losses through the roof, walls and floors account for 69,0 and 68,3 % of the total losses. Due to this, having a boiler with a higher power to maintain the comfort temperature is necessary.

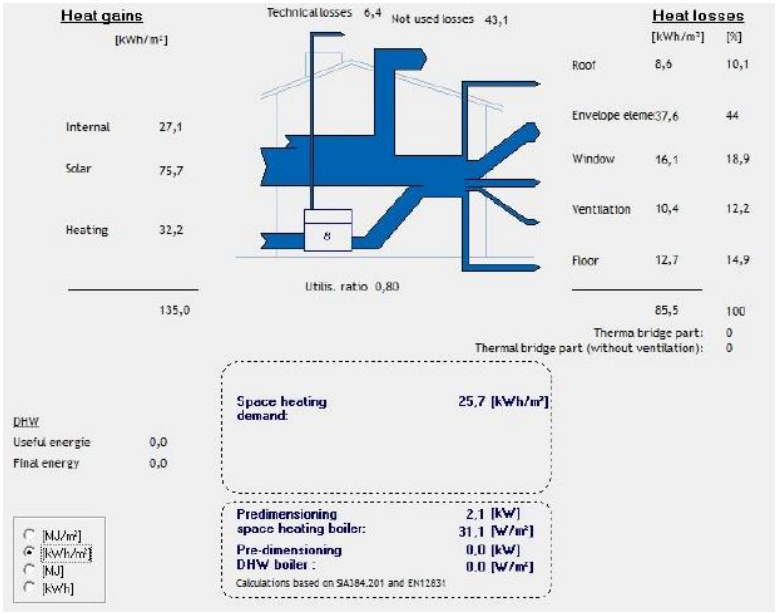

Figure 6.8: Sankey diagram for scenario 3 (4% OCF)

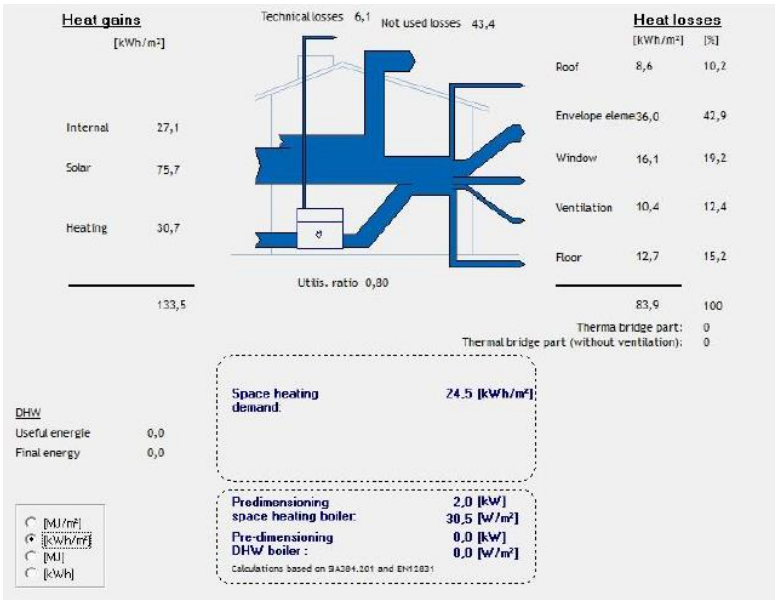

Figure 6.9: Sankey diagram for scenario 4 (8% OCF)

Finally, the sankey diagrams are shown for scenarios 5 and 6 (Figure 6.10 and Figure 6.11), which use bricks with wheat straw (WS) mixtures. The results show energy consumption values similar to scenarios 3 and 4 (OCF bricks), because the materials used have similar thermal characteristics.

Annual energy consumption for scenarios 5 and 6 is 25,4 and 24,3 kWh/m^2, with boiler powers of 2,1 and 2,0 *kW*, respectively. The percentage of energy losses for both scenarios across the entire envelope is 68,8 and 68,2%.

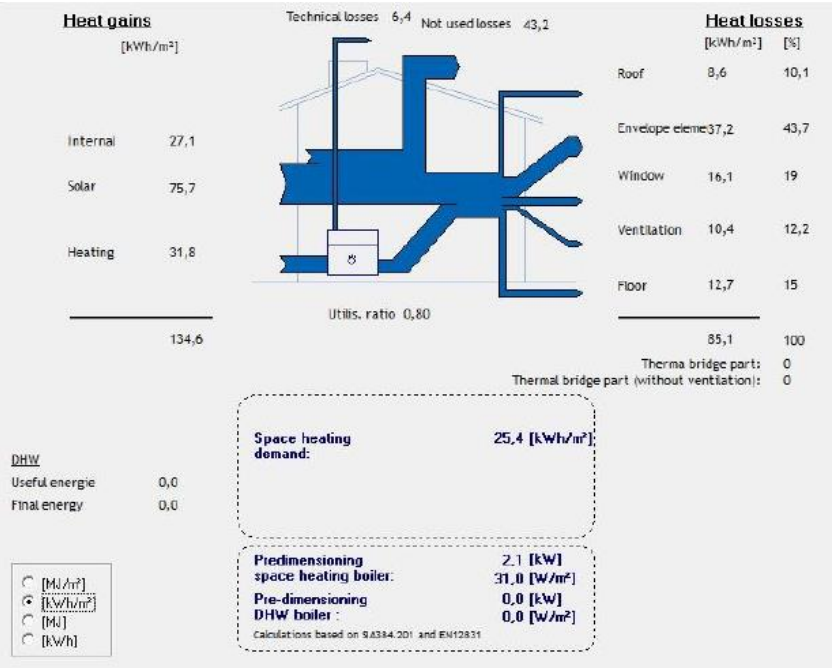

Figure 6.10: Sankey diagram for scenario 5 (3% WS)

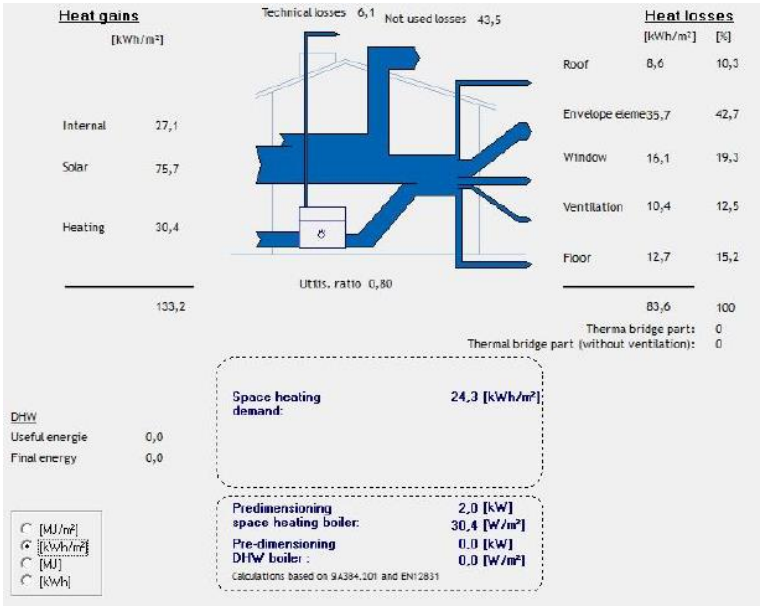

Figure 6.11: Sankey diagram for scenario 6 (7% WS)

The results obtained after performing the 6 simulations are summarized in Table 6.4. The table shows heating demand, boiler power, total energy inputs and total energy losses.

Table 6.4: Summary of simulations performed with Lesosai software

Scenario	Description	Space Heating Demand [kWh/m^2]	Power heating boiler [kW]	Heat Gains [kWh/m^2]	Heat Losses [kWh/m^2]
0	Base case	10,7	1,4	116,2	64,0
1	15 cm of Hemp Concrete	11,8	1,5	117,5	65,7
2	25 cm of Isotex	10,9	1,4	116,4	64,3
3	15 cm of 4% OCF	25,7	2,1	135,0	85,8
4	15 cm of 8% OCF	24,5	2,0	133,5	83,9
5	15 cm of 3% WS	25,4	2,1	134,6	85,1
6	15 cm of 7% WS	24,3	2,0	133,2	83,6

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The scenario that requires the lowest annual energy consumption is the base case that includes 8 *cm* of XPS and 4 *cm* of rock wool. The annual energy consumption for the base case is 10,7 kWh/m^2. The second best result has been obtained with sceario 2. In this case, an annual consumption of 10,9 kWh/m^2 is obtained with a facade composition of 25 *cm* of isotex (wood-cement block) and with 4 *cm* of insulating material of expanded cork. Scenario 1 has the third best performance with an annual consumption of 11,8 kWh/m^2 and a facade composed of 15 *cm* of hemp concrete and 4 cm of expanded cork insulating element.

In both cases, the installed power of the boiler would be between 1,4 and 1,5 *kW*, so very similar results are obtained with the three scenarios. The difference between these three scenarios is small, with a consumption variation between 0,2 kWh/m^2 and 1,1 kWh/m^2 per year and taking into account that the base case has a larger insulating element, which would be extruded polystyrene (XPS) and rock wool.

The cases under study with the highest energy consumption correspond to scenarios 3, 4, 5 and 6, all of them with a difference greater than the previous ones. Scenarios from 4 to 6 have similar compositions; the walls are made up of 15 *cm* of brick and 4 *cm* of insulation with expanded cork. The difference between the scenarios is found in the composition of the bricks. Scenario 6, with composite brick with 7% WS, presents the best performance, with an annual energy consumption of 24,3 kWh/m^2. Subsequently, the scenario with the best thermal performance is 4, with a composite brick with 8% OCF, with an annual consumption of 24,5 kWh/m^2. Finally, and with a higher energy consumption, there are scenarios 3 and 5, which use brick with 4% OCF and 3% WS, have an annual energy consumption of 25,7 and 25,4 kWh/m^2 respectively.

Based on the results obtained, the ceramic bricks that use a higher percentage of biomass increases the thermal resistance of the wall and therefore reduces energy losses by conduction. Increasing the percentage of biomass in bricks, generates a reduction in installed power of 0,1 *kW*, with a reduction in annual energy consumption of 2,2% for brick with OCF and 1,7% for brick with WS.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

6.5.5. Environmental impact analysis

In buildings, two different energy consumptions can be considered. Firstly, direct energy consumption in energy maintenance, and secondly, the energy consumed for the production of materials, construction and demolition. Balubaid et al (2014) define embodied energy as that energy used for the production of materials and the construction of the building. However, a more complete definition of embodied energy includes the total energy used in the construction, maintenance and demolition of the building [Azari et al 2018]

To evaluate the energy used in the production of construction materials, the entire manufacturing process must be taken into account, from the extraction of the raw material to the final consolidation of the product, also considering gas emissions into the atmosphere. To evaluate the Life Cycle Assessment of the materials, the following indicators are used:

- NRE: Non-renewable Energy. Indicates the amount of non-renewable energy used to manufacture a certain product, measured in *MJ* (mega joules).
- CED: Cumulative Energy Demand. Indicates the amount of total energy (renewable and non-renewable) that was used to manufacture a certain product, measured in *MJ* (mega joules).
- GWP: Global Warming Potential. It is the rate of greenhouse effect (CO_2, N_2O, CH_4, etc.), measured in *kg* CO_2*-eq*.

To assess the environmental impact of the different materials used in the scenarios, the previous indicators (NRE, CED, and GWE) are compiled in Table 6.5. These values are obtained from the Lesosai software databases, studies or manufacturers. The objective is to show the main materials used in each scenario to know the environmental impact in the manufacturing process, transportation and raw materials. Indicators are shown per kg of product, to be able to compare the data (*MJ/kg* or *kg* CO_2*eq/kg*)

Regarding conventional materials, most of the data shown in Table 6.5 have been obtained from the Lessosai Software database (OSB board, bitumen sealing, steel, Swisspor PUR Premium, acrylpaint, gypsum plasterboard, rock wool, extruded polystyrene (XPS). With the exception of Aquapanel Knauf, this is a lightweight

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

cement board for outdoor use, whose data has been extracted and processed from the technical specifications of the product.

Table 6.5: Indicators of Life Cycle Assessments of material materials

Material	NRE [MJ/kg]	CED [MJ/Kg]	GWP [Kg CO_2eq/kg]
Aquapanel Knauf	0,230	2,671	0,357
Extruded Polyestyrene (XPS)	98,58	100,29	13,89
Rock Wool, 100 kg/m^3	15,34	16,55	1,1
Gypsum plasterboard	5,87	6,23	0,364
Acrylpaint	15,19	15,69	1,362
Swisspor PUR Premium	101,91	104,34	7,18
Steel	27,8	28,9	1,83
Bitumen sealing	44,18	45,11	3,177
OSB board	13,42	35,82	0,64
Hemp Concrete	3,000	3,000	-0,268
Isotex	2,578	7,118	0,384
Brick OCF 4%	0,497	0,776	0,085
Brick OCF 8%	0,241	0,861	0,097
Brick WS 3%	0,589	0,785	0,083
Brick WS 7%	0,365	0,869	0,087

For the materials used in the different scenarios, the data has also been obtained from the manufacturers, such as Hemp Concrete and Isotex. Bricks with mixtures of OCF and WS, they have been calculated using different studies.

Figure 6.12 shows the differences in required energy and CO_2 eq for each material. The differences between the conventional materials and the eco-sustainable materials can be observed in the figure.

The scenario 0 (base case) was the one with the lowest energy consumption for heating, that is, of all the scenrios analysed it was the most efficient. However, when analysing the energy used to produce the materials and the CO_2 emission rates, it is observed that they have higher rates compared to eco-materials. The energy required to manufacture conventional materials is non-renewable, with the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

exception of the OSB panel that requires an energy of 35,82 *MJ/kg*, with more than 60% of this energy being renewable.

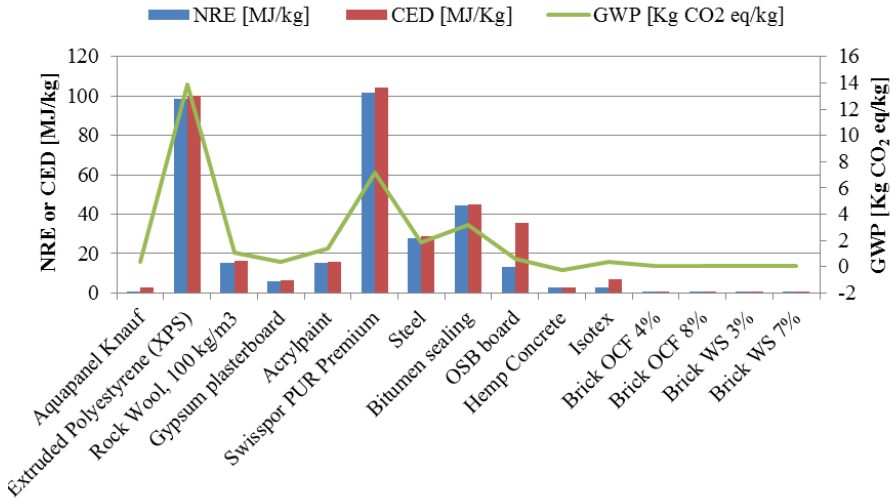

Figure 6.12: NRE, CED and GWP of materials

Isotex is the eco-sustainable material with the highest energy consumption and CO_2 emissions. The energy consumed for its manufacture amounts to 7,11 *MJ/kg* (of which 63% comes from renewable energy).

Hemp concrete requires very little energy to manufacture compared to other materials and exhibits negative carbon emission because during the growth of the hemp plant it absorbs CO_2 from the atmosphere and even after its use as concrete it continues to absorb CO_2 from the atmosphere.

As for bricks with mixtures of OCF and WS, they require very little energy compared to other materials and emit an equally small amount of CO_2. Therefore, despite their worst thermal behaviour, they are the materials with the lowest energy consumption in their manufacturing stage.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

6.6. DISCUSSION

Currently there is a wide variety of eco-materials from different waste that are viable for a sustainable construction. Although a brief review of the reuse of waste as substitutes for raw materials in construction materials has been carried out, the great potential they have in the construction sector is highlighted.

Construction is the sector that generates the highest percentage of waste, representing 37% of the total waste generated in the European Union [Eurostat, 2020]. The reduction of waste in the sector can be focused on two ways: introducing sustainable materials in the production of construction materials, or else, reusing the waste generated in the sector.

After the systhematic review, it is observed that the number of studies aimed at the reuse of waste in the production of construction materials has been increasing in recent years. This interest is caused by the policies of the European Union, so it is a fact that in the coming years there will be a strong introduction of eco-materials in the construction sector. Among the studies, it highlights the use of waste for the manufacture of thermal insulation, bricks, cement, mortar and concrete.

Among the main types of waste used for the manufacture of thermal insulation, agricultural waste stands out. Agricultural waste only represents 1% of the total waste generated, but due to its easy availability, it can be easily used and also at low cost. Although the thermal conductivity of agricultural residues is usually higher than conventional materials, in general an increase in thickness is necessary to achieve thermal resistance similar to conventional insulation. This type of waste can also be used in the structure of buildings in the production of bricks, providing them with greater thermal resistance.

Regarding the production of bricks, they can be produced with all the waste listed. In this case, the introduction of agricultural residues in ceramic brick mixtures, produce bricks with a lower thermal conductivity reducing the mechanical properties. In general, the addition of residues in the production of bricks reduces the compressive strength, so the mixtures must be analysed. However,

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

mixtures with marble or granite waste come to equal or exceed the mechanical properties of conventional brick.

Finally, the use of waste for the production of cement, mortar or concrete, causes an effect similar to the production of bricks. Adding certain residues causes variations in mechanical properties and durability concerning conventional materials, so the mixture must be controlled.

Therefore, eco-materials can be used as a structure or as thermal insulation. On the one hand, to use eco-materials as a structure, it is necessary to adapt the waste mixtures to meet quality standards, and to be able to guarantee minimum resistance. On the other hand, the use of eco-materials, such as agricultural waste, allows improving the thermal resistance of materials such as bricks or concrete and thus improving the thermal envelope.

In this case, the thermal implications of eco-materials in construction are analysed. The analyzed studies evaluate the thermal and mechanical properties of materials based on waste; however, no studies have been identified that apply the use of waste in the thermal envelope of buildings. Eco-materials from agricultural residues are selected due to the ease of obtaining data on their thermal properties.

In the first place, the thermal behaviour of 20 cm of eco-material against a sinusoidal disturbance is analysed. Among the results obtained, hemp concrete and Isotex stand out. Both materials allow obtaining very stable temperature waves with a decrement factor of 0,0655 and 0,0313. In addition, they generate a time lag greater than 9 hours. The results obtained with both materials are due to the introduction of agricultural residues in their production, which allow obtaining very low thermal conductivities (0,071 and 0,104 $W/(m \cdot K)$).

The use of bricks with mixtures of agricultural residues, offer a worse response than hemp concrete and Isotex. However, despite having a worse thermal behaviour, a smaller decrement factor and a greater time lag are observed compared to conventional brick. In CHAPTER 4, in Table 4.5, for the conventional brick, a decrement factor of 0,2952 and a time lag of 7,35 hours were obtained. For all bricks with mixed agricultural residues, the decrement factor is

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

reduced to 54% in the case of adding 7% WS. Regarding the time lag, it improves slightly increasing up to 8% for bricks with 7% WS.

If the 4 types of simulated bricks are compared, when the bricks have a greater quantity of agricultural residues, the wave generated on the surface is more stable. However, the compressive strength is reduced as more residues are added. Thus, in the case of bricks with 4 and 8% OCF, the compressive strength is 31,5 and 24,8 *MPa* and in the case of bricks with 3 and 7% WS, the compressive strength is 26,6 and 18,1 *MPa* [Aouba et al, 2016]. Therefore, taking into account the effect on both properties, OCF brick allows higher compressive strengths.

By introducing eco-materials into the model building and analysing the annual energy consumption using the Lesosai software, the energy performance of the materials can be analysed. The part of the thermal envelope that is modified between the scenarios is the wall. The wall of the base case has 1,5 cm granite, 1,25 *cm* of Aquapanel Knauf, 8 *cm* XPS and 4 cm Rock Wool, which means a total thickness of 14,75 *cm*, plus the inside layer with 2,6 *cm* of Gypsum plasterboard and 0,02 *cm* of Acrylpaint.

In scenario 1, the 14,75 *cm* are replaced by 15 *cm* of Hempconcrete and 4 *cm* Expanded cork panels Growancor. By introducing this eco-material, the heating demand of the building with respect to scenario 0 (base case) increases 1,1 kWh/m^2, and the power of the boiler by 0,1 *kW*. In scenario 2, the 15 cm Hempconcrete is replaced by 25 *cm* Isotex wood-cement block. In this case, the energy demand with respect to scenario 0 (base case) increases by 0,2 kWh/m^2, maintaining the same power as the boiler. However, in both cases, a thicker wall is needed to maintain the indoor temperature, since they have 4 *cm* of expanded cork panels growancor. Therefore, with both solutions, similar results are presented.

Finally, in scenarios 3, 4, 5 and 6, a higher energy demand is obtained compared to the previous scenarios. These scenarios use 15 cm of brick and 4 cm of expanded cork panels growancor However, if these scenarios are compared, it is obtained that the scenarios with the lowest energy consumption are those with the highest percentage of agricultural residues. The most efficient scenario is the one that uses

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

bricks with 7% WS. However, in these cases it would be necessary to increase the thickness of the thermal insulation to maintain an energy demand similar to the base case

One of the advantages of using eco-materials resides in the smoothness of the external temperature wave generated. The results obtained in CHAPTER 4, 20 *cm* of thermal insulation cause a wave with a decrement factor of 0,4927 and a time lag of 5,47 hours. After analysing the behaviour of all the ecomaterials, the results obtained show that all of them generate waves with a smaller decrement factor and a larger wave time lag (Figure 6.4). Therefore, the use of eco-materials make possible to maintain more stable comfort conditions.

Among all the alternatives studied, in addition to taking into account the energy consumption during the maintenance stage, the energy consumed in the preparation of the materials must be analysed. Thus, although scenario 0 (base case) is the most efficient, it uses materials with higher energy consumption in the manufacturing stage. This scenario is made up of materials with lower energy consumption and lower associated CO_2 emissions. Analysing all the parameters, scenario 2, which uses ISOTEX, has an energy consumption similar to the base case (10,9 compared to 10,7 kWh/m^2) and also presents more sustainable materials.

6.7. CONCLUSIONS

Construction is the sector that generates the greatest amount of waste, so it is necessary to rethink civil construction to reduce waste and consumption of natural resources. In this chapter a search has been carried out on the types of waste that can be introduced in the construction sector and it is analysed how it modifies the properties of conventional materials. The thermal properties of these new compounds were evaluated on the thermal comfort of the home and their environmental impact.

The main conclusions obtained from this chapter are:

- Agricultural waste can be used as thermal insulation due to its low conductivity; however, it has worse thermal properties than conventional materials. They can also be part of the structure of

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

the house in combination with bricks, improving the thermal properties.

- The introduction of residues in conventional materials (bricks, concrete, cement, mortars), in general, improves the thermal behaviour, but can affect the mechanical properties.
- The analysed eco-materials generate a better thermal response than conventional materials. Hemp concrete and Isotex are the materials that cause a softer temperature (lower decrement factor) and cause a wave with a greater phase shift (greater time lag).
- When analysing bricks with mixtures of OCF and WS, mixtures with a higher percentage of residues cause a wave with a lower decrement factor and a longer time lag. However, the results are worse than those obtained for Isotex and Hemp Concrete.
- From the point of view of energy efficiency, the scenario 0 (base case), built with convenciontal materials, has the best thermal performance (10,7 kWh/m^2). However, the main insulation used, XPS, generates a greater environmental impact of 13,89 $kg\ CO_2/kg$.
- Between analysed eco-materials, the scenario with isotex presents similar results to the base case. The energy consumption with isotex is 10,9 kWh/m^2 with a lower environmental impact than the base case with a value of 0,384 $kg\ CO_2/kg$.
- The eco-material with the lowest thermal performance is the OCF and WS bricks. Thermal performance improves as the amount of agricultural waste increases. The results obtained are far below the results obtained with Isotex or Hemp Concrete. However, these bricks have a better thermal response than conventional bricks.
- Materials such as hemp concrete, in addition to being a sustainable material and offering thermal performance similar to conventional materials, allows the absorption of carbon from the atmosphere.

The use of waste as a complement to construction materials allows reducing the environmental impact of buildings not only during the maintenance of buildings (thermal comfort) but also allows the construction of more sustainable buildings. The use of sustainable

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

materials in buildings helps to achieve the European objectives to achieve low carbon economy by the year 2050. The analyzed techniques allow a transition towards a regenerative economy, where ecosystems are not degraded and allow the economic growth of the sector.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

CHAPTER 7. STUDY OF THE INFLUENCE OF SOLAR SHADOW DEVICES IN THE SOLAR INPUTS OF BUILDINGS

This chapter is a reproduction of the following publication derived from the research carried out by the doctoral student during the training stage:

- Title: Study of the Influence of Solar Shading Devices in the Solar Inputs in Buildings
- Authors: Vilaboa Díaz, A; Bello Bugallo, P.M.
- Book title: Sustainable Energy Development and Innovation
- Book chapter: 51
- Publisher: Springer
- ISSN: 2522-8927
- DOI: https://doi.org/10.1007/978-3-030-76221-6_51
- Year of publication: 2021
- Contribution of the doctoral student: contribution to development of the research and writing the paper.
- Authorization of the journal/publisher for the use of the publication in the doctoral thesis is included in point 1b of the appendix "Author's Re-Use Rights", of the Publishing Agreement. The text is exactly transcribed below:
    - (b) Re-Use of the Version of Record (as defined below) of the Contribution or any part of it is permitted in a thesis written by the same Author, and the Author is entitled to make a copy of the thesis containing content of the Contribution available in a repository of the Author's academic institution

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

SUMMARY

The housing stock is responsible for 36% of the CO_2 emissions of the European Union. The sector is a candidate to become one of the strategic pillars for the decarbonization of the European Union. Much of the energy is used for heating, so the use of solar capture can be an ally for the reduction of CO_2 emissions associated with this field. However, as has been analyzed in previous chapters, it can generate situations of thermal stress and therefore, in summer, increase the demand for cooling in buildings.

In this chapter, the solar control systems for reducing the cooling consumption of the buildings are analysed. A comparative study is carried out between dynamic solar shadow devices and fixed solar systems, analysing the energy contributions in summer and winter depending on their characteristics.

Firstly, a systematic review of the main techniques for solar control in buildings is carried out, in order to identify fixed and mobile solar shadow systems that allow buildings to improve sustainability and comfort. Regarding fixed solar shadow systems, energy contributions in summer and winter are analyzed considering a window with different properties and different lengths of an awning. The combination of both parameters allows the control of solar radiation throughout the year. Due to the low adaptability of fixed solar protection systems, the efficiency of mobile solar systems is analyzed. To do this, the length and angle of an awning and its influence on the solar contributions towards the interior of the building are evaluated.

Dynamic solar control devices have more versatility than fixed systems. For a solar shadow device with a length of 1,5 m, the use of a dynamic solar shadow system allows reducing the solar energy inputs in summer by 29% compared to a fixed one.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

7.1. INTRODUCTION

The use of solar radiation can be an ally for reducing CO_2 emissions from the EU, reducing heating demand in cold months. However, poor control of solar radiation can become unwanted contributions in the summer months, increasing cooling energy demand. Therefore the solar shading devices become indispensable for the control of the thermal comfort of the building.

In addition to the solar shading devices, the optimal design of the type of window is one of the important points to consider in the initial design of the building. Several parameters for the selection of the optimal glazing must be taken into account.

The orientation of the facade is decisive for the optimal selection of the size of the glazed surface. There are studies that confirm that in the Northern Hemisphere, the placement of the glazed surface to the south, allows to optimize solar gains and reduce heating costs. Thus, the optimum proportion of glazing for south facades for moderate climates is between 38 and 42%, reducing this proportion with east and west orientations [Obrecht et at, 2019]

The thermal transmittance (*U-value*) and the solar factor of the window (*g-value*), are important parameters to take into account for selecting a window. A window with low *U-value* and a high *g-value*, allows reducing the energy demand in heating, however this type of configuration would increase the cooling energy demand. Thus, for example, according to studies obtained through mathematical models, depending on g-value, a reduction in U-value from 1,2 to 0,8 $W/(m^2 K)$ can reduce the demand for air conditioning by 5-15% [Grynning et al, 2013]. There are several type of the windows, the standard triple and quadruple glazing window models result in lower heating and cooling needs, while in the case of quintuple windows the results were opposite [Thalfeldt et al, 2015]

There are studies that confirm the results obtained by Grynning et al (2013), where simulations are carried out to calculate the energy demand in offices located in Sweden, also observing that an increase in the glazed area produces a higher consumption in heating and cooling [Poirazis et al, 2007]. Comparing a glazed surface of 30, 60 and 100%, for the surface of 60%, there is an energy increase of 23%

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

and for an area of 100% it produces an increase of up to 47%. This increase in the glazed area does not necessarily reduce the energy consumption in lighting that would represent 10% of the total energy consumed [Poirazis et al, 2007]

Ghosh et al (2018) in their study performed a similar simulation with the EnergyPlus Software, for a building located in India, obtaining similar results. The energy consumption increases with the glazed surface and also analyses the position of the window, obtaining that if it is placed inside, the cooling consumption decreases caused by the shadows.

The tinted of the glass can also become an important point to improve the energy efficiency of the glass; for example, a grey reflective glass window is the best energy efficient glass from the perspective of reduced cooling and heating loads collectively. However, for reducing the heating energy demand, bronze glass is the most efficient [Kumar et al, 2019]

The importance of selecting a good glazing will have an impact on the energy consumption of a building and therefore, it is necessary to find a balance between the *U-value* and the *g-value* to reduce the energy demand in the buildings. In climates where solar contributions reduce heating needs but increase cooling demand, the introduction of solar control systems helps to achieve more sustainable buildings.

In the selection of solar protections, Kuhn et al (2011) establish the determining factors of solar protection systems for de users: "Thermal comfort" and "Visual Comfort". The study also evaluates two control strategies for blinds, "Cut-off" strategy (when the sun shines directly on the facade, the slats are tilted towards the cutting position) and 'closed' strategy (the blind is fully extended and the slats are completely closed when the facade is irradiated directly by the sun). For the "cut-off" control, an average annual g-value of 0,19 - 0,20 is obtained, and for a "closed" control strategy an average value of 0,04 is obtained.

Kuhn (2017) performs a complete review of the state of the art of advanced solar control devices for buildings. The review describes the design options and evaluation criteria for advanced solar control systems.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

When establishing the type of solar shadow devices, not only the influence on the comfort conditions must be evaluated, but also the light quality. Nielsen et al compared the annual energy demand in air conditioning and lighting for offices in Denmark for three cases: without solar shading, with fixed solar shading, and with dynamic solar shading. The solar shading device used was the venetian blinds. The simulation showed that with the dynamic solar shading the total energy demand is reduced with respect to the fixed solar protection, obtaining a reduction of up to 16% [Nielsen et al, 2011] .Moreover, the use of venetian blinds as solar control systems based on the angle of solar incidence, allows to avoid the entry of direct solar radiation but improving lighting [Gomes et al, 2014]

Yao et al (2014) perform a simulation for a residential building showing similar results. In this case, with the use of solar shading device, the demand for heating and cooling is reduced by 30,8% with respect to an unprotected window. In addition, the use of solar protection improves of thermal comfort in summer by 21%.

Apart from conventional solar shading devices, there are new products that currently break into the market, such as smart windows or electrochromic glass. These glasses can change from transparent to opaque allow to regulating the amount of solar energy. This type of glass reduces the solar energy contributions by 59% compared to a conventional glass [Aldawoud, 2013]. Therefore, the smart glasses (SW) allow reducing the annual energy consumption modifying by the optical properties of the glass and controlling the heat flow. According to the numerical models developed by Dussaul et al (2013), energy consumption could be reduced up to 53%.

Finally, vegetation can be included as a passive solar control system. Trees can play an important role in reducing energy consumption since their leaves can block solar radiation, reducing thermal loads. They also produce a reduction in ambient temperature due to the evaporation of the water they transmit [Papadakis et al, 2001]. The use of plant-covered walls helps reduce heat transmission through the walls so they can become an important ally for the reduction of energy consumption in buildings [Eumorfopoulou et al, 2009]

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

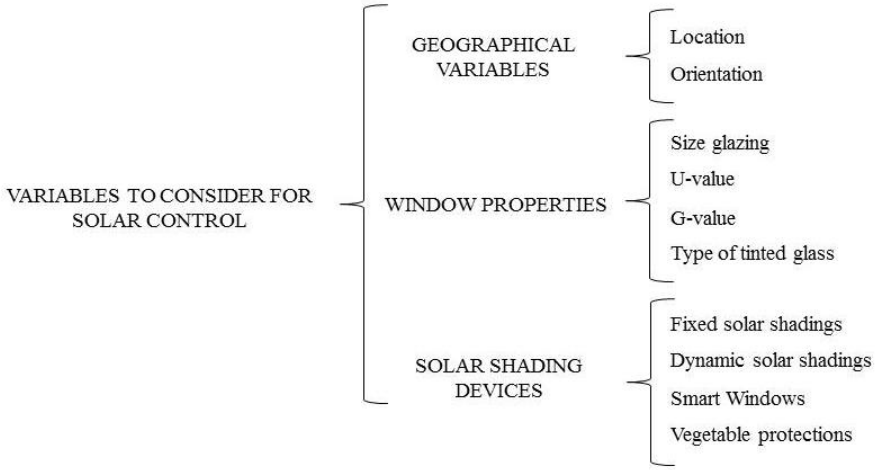

Figure 7.1: Summary of the variables to take into account for solar control in buildings

After analysing this brief introduction, solar control in buildings plays a fundamental role in the energy consumption. As a summary, Figure 7.1 is shown, in order to summarize the main factors to be taken into account for the control of solar radiation.

7.2. THEORETICAL CONCEPTS

In CHAPTER 5, the geometry of solar radiation is described. In summary, the incident total solar radiation (G_T) depends on the direct radiation ($G_{b,t}$), the diffuse radiation ($G_{d,t}$) and the shortwave radiation that is reflected in the Earth's surface or by nearby surfaces ($G_{r,t}$) [ASHRAE, 2011]

$$G_T = G_b \cdot cos\,\theta + G_{d,t} + G_{r,t} \qquad \text{[Eq. 7.1]}$$

Where: θ is the angle of the solar radiation on the surface to study.

Combining equation [Eq. 7.1] with the equations described in CHAPTER 5 (equation [Eq 5.8], [Eq 5.10] and [Eq 5.11]:

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

$$G_T = A \cdot e^{-\frac{B}{\sin \alpha_s}} \cdot \cos\theta + C \cdot G_d \cdot \left(\frac{1+\cos\beta}{2}\right) + G \cdot \rho \cdot \left(\frac{1+\cos\beta}{2}\right) \qquad \text{[Eq. 7.2]}$$

Where:

- G_T is the incident total solar radiation [W/m^2]
- G_d is the diffuse radiation on a horizontal surface [W/m^2]
- G is the global radiation on a horizontal surface [W/m^2]
- A is the apparent extraterrestrial irradiance [W/m^2]
- B is the atmospheric extinction coefficient.
- C is the proportion of diffuse radiation on the horizontal surface.
- α_s is the solar height [^{o}]
- θ is the angle of the sun rays on the surface to study [^{o}]
- β is the angle between the surface plane and the horizontal [^{o}]
- ρ is the terrestrial albedo.

Equation [Eq. 7.2] is used to calculate the incident solar radiation on the inclined surface and it is the main equation for the development of the work.

7.3. OBJECTIVE

The objective of this work is to evaluate the influence of solar shadow devices for the control of the energy obtained from the solar radiation.

First, an analysis of existing solar shadow device is carried out, analysing their advantages and disadvantages. In this way, the optimal solar protection is evaluated based on the particularities of the building.

Subsequently, the model used to obtain the results in the design of solar protections in the initial phase of building construction is described. In this case, the influence of the overhangs for solar control and the potential of dynamic solar shading device are analysed. In this way, the importance of the optimal dimensioning of the overhangs and awnings and the selection of the *g-value* of the window are analysed.

7.4. CASE STUDY

The simulations analysed in this study are carried out in different climatic zones of Spain. The north and south are taken as a reference. The location in the north of Spain is Ourense (42^o latitude), which has

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

a mild climate. The area of southern Spain selected is Murcia (38º latitude) with a dry climate according to the Köppen classification [AEMET, 2018]. The following table shows the main characteristics of the selected locations:

Table 7.1: Summary of characteristics of the selected locations

	OURENSE	MURCIA
Latitude	42° 19'	38° 0'
Average annual temperature [°C]	14,9	18,6
Lowest monthly average temperature [°C]	3,4 (January)	4,7 (January)
Highest monthly average temperature [°C]	30,6 (August)	34,2 (August)
Annual hours of sunshine [hours]	2054	2967

To carry out the study, the days of maximum and minimum solar declination are taken as a reference. When the declination angle is positive, the solar radiation affects above the equatorial plane. For negative declinations, the radiation affects below the equatorial plane. The maximum solar declination (23,45°), occurs in midsummer (June 20-21), reaching the Tropic of Cancer, while the minimum decline (-23,45°) occurs on the winter solstice (December 21-22), moment in which the sunlight reaches the Tropic of Capricorn.

The glazed surface taken as a reference consists of a height of 1,5 *m*. The particular conditions analysed at each point are described individually.

7.5. METHODOLOGY

The study is carried out in the following stages:

- First, a summary of the sun protection devices currently available is made, analyzing the advantages and disadvantages of each one.
- The efficiency of solar shading device is studied, analysing first the fixed solar shadings and the *g-value* of windows. The influence of the overhang is analysed according to the time of year and also the influence of the *g-value* of the glass.
- The performance of dynamic solar control devices are also analysed, showing the results that could be achieved with an awning.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

7.6. DEVELOPMENT AND PRESENTATION OF RESULTS

7.6.1. Summary of the solar control device for buildings

There are a great variety of solar shadow devices that allow improving thermal comfort inside buildings. As a starting point, a review for current solar shading systems is carried out and the main characteristics are summarized. The objective is to collect the maximum information available on current technologies.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 7.2. Summary of the solar control device for buildings [Based on Kuhn, 2017]

Solar control device	Description	Main Features
Venetian blind	- Mechanical element that is placed inside or outside window to regulate the entry of light. - Venetian blinds are defined by the slat design and the slat distance. It can also be divided into several sections to optimize solar control [Kuhn, 2017]	- Placed outside, they provide the same natural light but increase their protection against overheating [Kuhn, 2017] - The surface properties of the slats are very important, since excessive brightness can cause glare inside the building [Kuhn, 2017] - It can be placed after the construction of the building. - It can be regulated automatically or manually.
Roller blind	- Piece of fabric that is wrapped around housing and can be placed inside or outside window.	- The reflectance of the outer surface of the curtain and the direct-transmittance of solar radiation determines the solar-control performance [Kuhn, 2017] - It can be placed after the construction of the building. - It can be regulated automatically or manually.
Vertical louver blind	- Vertical strips of fabrics that can be rotated around vertical axes [Kuhn, 2017] - It can be placed inside and outside. Placed on the outside they use a more resistant material such as wood.	- Vertical shading devices are more effective for the eastern/western window [Li et al, 2016] - It can be placed after the construction of the building. - It can be regulated automatically or manually.

Solar control device	Description	Main Features
Awning	- Canvas cover or other fabric that extends to provide shade. - It is placed outside and can be fixed or mobile.	- The solar control depends on the properties of the material, especially solar absorptance and transmittance [Kuhn, 2017] - It can be placed after the construction of the building. - It can be regulated automatically or manually. - With automatic regulation, they can the length and angle to optimize solar gains in winter and avoid them in summer.
Pleated blind	- It consists of a pleated fabric [Kuhn, 2017] - It can be placed inside.	- The solar control depends on the properties of the material, especially solar absorptance and transmittance [Kuhn, 2017] - It can be placed after the construction of the building. - It can be regulated manually.
Curtain panel	- Curtain panels are moving parts that cover the windows inside the buildings. They are made mainly of fabrics - It can be placed inside and outside, although when they are placed outside, the material must be more resistant as metal fabrics [Kuhn, 2017]	- The solar control depends on the properties of the material, especially solar absorptance and transmittance [Kuhn, 2017] - Its main function is to totally or partially prevent the passage of light and visibility from the outside. - It can be placed after the construction of the building. - It can be regulated automatically or manually.

Solar control device	Description	Main Features
Roller shutter	- It is a mechanical element (slats) that is placed outside or inside a balcony or window to regulate light or privacy control. The laths can be made of polymer material or metal. [Kuhn, 2017]	- It can be used to solar control during the summer but avoid lighting regulation - It can be placed after the construction of the building but could be necessary a modification on the façade. - It can be regulated automatically or manually. - It is very important isolating the box where the slats is rolled, due to could be a weakness point of the thermal envelope.
Overhang	- It is a structural element that stands out from the wall that supports it.	- It is effective to avoid solar radiation in summer, due to the angle of solar radiation [Kuhn, 2017] - It is more effective with facades with south orientation [Kuhn, 2017] - The length of the overhang helps to reduce the energy cooling consumption in summer [Ghosh et al, 2018] - When the overhang is designed, the thermal bridge that is generated must be minimized.
Sun sail	- It is a versatile covers that offer shade and UV protection from the sun - They can be rigid and not retractable or retractable. Rigid sun sails also provide rain protection [Kuhn, 2017]	- The solar control depends on the properties of the material, especially solar absorptance and transmittance [Kuhn, 2017] - It can be placed after the construction of the building. - It can be regulated automatically or manually.

Solar control device	Description	Main Features
Solar-control glass panes or Smart Windows (SW)	- They are glasses that can have switchable or constant properties [Kuhn, 2017] - The glasses with constant properties are composed of nano layers that allow having a glass with low emissivity. [Kuhn, 2017]. This type of glasses also could be manufactured by tinting. - The glasses with switchable properties can change their visual and solar-control properties because of intrinsic or extrinsic triggers. In this category, different type can be differentiate: o Electrochromic glazing changes the transmittance by applying voltage. o Gaschromic glazings change the optical properties changing the oxidation state of the internal gas. o Photoelectrochromic glazings change the optical properties when the coating generates the voltage which is needed. o Photochromic glazing change to dark when they are irradiated by the sun. o Thermochromic layers change their colour depending on the temperature of the layer o Thermotropic layers change their scattering properties depending on the temperature. o Polymer-dispersed liquid-crystal layers change their scattering properties activating an electric field.	- About the tinting glass, a gray reflective glass window is the best energy efficient glass from the perspective of reduced cooling and heating loads collectively. However, if you only want to reduce the heating energy demand, bronze glass is the most efficient [Kumar et al., 2019] - Electrochromic glazing provides good visual contact with the outside but limited protection against glare [Kuhn, 2017] - Electrochromic glazing can reduces the solar energy contributions by 59% compared to a conventional glass [Aldawoud, 2013] - Photochromic glazing has a strong temperature dependence on the switching mechanism. They are used in sunglasses [Kuhn, 2017] - They are operated automatically optimizing solar energy, taking advantage of solar radiation in winter and minimizing solar contributions in summer. - Privacy can be managed without the need for curtains or similar. - The light and heat input can be regulated - It can be installed after the construction of the building

Solar control device	Description	Main Features
Transparent building-integrated PV-elements (BIPV)	- They are building elements that generate electricity at the same time - It can be used in substitution of transparent fabrics, screen-print glazing or static blinds [Kuhn, 2017]	- It can be installed after the construction of the building. - Renewable energy production integrating with the building elements of the building. - The installation cost can be amortized with the production of electrical energy
Transparent building-integrated solar thermal (BIST)	- BIST is defined as the "multifunctional energy facade" that allows to take advantage of the heat from solar radiation for heating, hot water, power generation and improve insulation [Zhang et al, 2015] - It can be used instead of static blind systems or fabrics to reduce the transmitted solar energy [Kuhn, 2017], - BIST can be classified according to the fluid to which solar radiation transmits heat [Zhang et al, 2015]: o Air o Water o Refrigerant o Phase changing materials	- System integrated in the structure of the building - In general it is an expensive system except in the case of air exchange, which reduces its cost. - When exchange with liquids occurs, leaks can occur and maintenance costs increase.

Solar control device	Description	Main Features
Plant-covered walls or vertical greening	- They are formed by climbing plants along a vertical wall. - Otele et al (2017) difference three types of plant covered –wall: - direct green façade - living wall system based on planter boxes - living wall system based on mineral wool	- Roots of climbing plants can damage the facade of the building [Manso et al., 2015] - Living wall system has a higher installation cost than green facades [Manso et al., 2015] - Improve the thermal resistance of the wall (R-value) by reducing its value [Otele et al, 2017] - Reduce heat flux losses, so reduce cooling needs in summer [Eumorfopoulou et al, 2009; Otele et al, 2017] - Could be integrated after construction building
Deciduous trees	- Deciduous trees are a type of trees that lose their leaves in the coldest and darkest seasons of the year: autumn and winter	- Avoid the passage of direct solar radiation in summer due to the shade produced by its leaves [Papadakis et al, 2009]. - In winter they allow solar radiation to pass because they lose their leaves. - Produce lower air temperatures in shaded areas due to evaporative cooling effect of the plants [Papadakis et al., 2009]

7.6.2. Study of the influence of the windows properties in solar contributions

The size and properties of the glass are parameters that influence the energy consumption of the building. Energy consumption increases with the size of the windows [Poirazis et al, 2007], reaching an adequate proportion between 38-42% for southern orientations in temperate climates [Obrecht et at, 2019]

In this first part of the study, the influence of the g-value of the window on the two climatic zones of Spain (Ourense and Murcia) is analysed. For this, 3 windows with different *g-value* are taken as reference. This modification of g-value allows greater or lesser passage transmission of radiation.

The glasses used for this study are summarized in the following table:

Table 7.3: Type of glasses used for simulations [Extracted from Climalit]

Case	Type of glass	U-value ($W/m^2 \cdot K$)	g-value
1	Single glass	5,7	0,83
2	Double glass - 4(12)4	1,7	0,50
3	Double glass with solar control - 6(12)6	1,6	0,10

The three selected glasses are simulated in different areas of Spain. To carry out the simulation, equation 7.1 is taken as a starting point, where the total incident solar radiation is defined.

The g-value is the overall energy transmission rate or ratio between the fraction of solar radiation transmitted by the translucent surfaces ($G_{T,WINDOW}$) and the external solar radiation (G_T), taking into account the possible solar protection.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

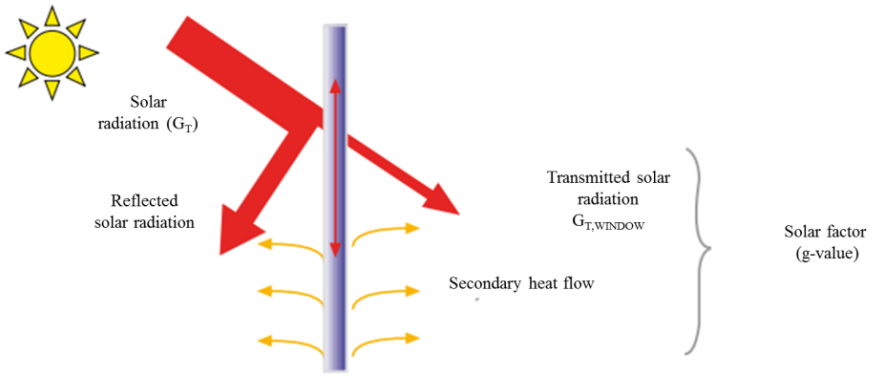

Figure 7.2: Global transmission of energy through glass

Therefore, the radiation transmitted is defined as follow:

$$G_{T,window} = G_T \cdot g_{value} \qquad \text{[Eq. 7.3]}$$

Combining expression [Eq. 7.3] with the equation of the incident total solar radiation [Eq. 7.2], the total energy transmitted is obtained. The results obtained are shown in Table 7.4.

Table 7.4. Summary of the solar radiation transmitted depending on the type of glass

	OURENSE		MURCIA	
Reference Day (dd/mm)	20/06	21/12	20/06	21/12
Solar Radiation on horizontal surface [kWh/m²·d]	9,60	2,86	9,61	3,56
Solar radiation on perpendicular surface south orientation [kWh/m2]	3,07	5,38	2,64	5,81
CASE 1: Single glass [kWh/m2·d]	2,55	4,46	2,19	4,83
CASE 2: Double glass - 4(12)4 [kWh/m2·d]	1,54	2,69	1,32	2,91
CASE 3: Double glass with solar control - 6(12)6 [kWh/m2·d]	0,31	0,54	0,26	0,58

The g-value of the window reduces proportionally the entrance of solar radiation inwards; *g-value* of 0,1, only allows 10% of solar

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

radiation, both in summer and winter. Therefore, it may be necessary to prioritize the entry of solar radiation in winter and avoid it in summer. Therefore, introducing solar shadow devices are essential to control solar contributions throughout the year.

7.6.3. Study of the influence of fixed solar shading device in solar contributions

The aim of this chapter is to analyse the length of the solar fixed protection. In summer, the angle of incidence of the sun's rays on the earth's surface is greater than in winter, this causes a greater contribution of solar energy and causing an increase in cooling needs in summer. On the contrary, in winter, incident solar radiation is a great ally to minimize energy consumption.

This study takes as reference the days of maximum and minimum solar declination and thus analyse the optimal length of sun protection. When the declination angle is positive, the solar radiation affects above the equatorial plane; while for negative declinations, the radiation affects below the equatorial plane. The maximum solar declination (23,45°), occurs in midsummer (June 20-21), reaching the Tropic of Cancer, while the minimum decline (-23,45°) occurs on the winter solstice (December 21-22), moment in which the sunlight reaches the Tropic of Capricorn. The Figure 7.3 shows the variation of the solar height in the solstices and in the equinoxes. The solar height (αs) is obtained in function of the angle of solar radiation (θs). The equation is obtained from ASHRAE (2011).

$$\alpha_s = 90° - \theta_s \qquad \text{[Eq. 7.4]}$$

$$cos\,\theta_s = cos\,\delta \cdot cos\,\lambda \cdot cos\,\tau + sin\,\delta \cdot sin\,\lambda \qquad \text{[Eq. 7.5]}$$

Where:

- δ is the declination angle [^{o}]
- λ is the latitude [^{o}]
- τ is the solar time.

The Figure 7.3 is obtained combining equation [Eq. 7.4] and [Eq. 7.5] for the two place selected:

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

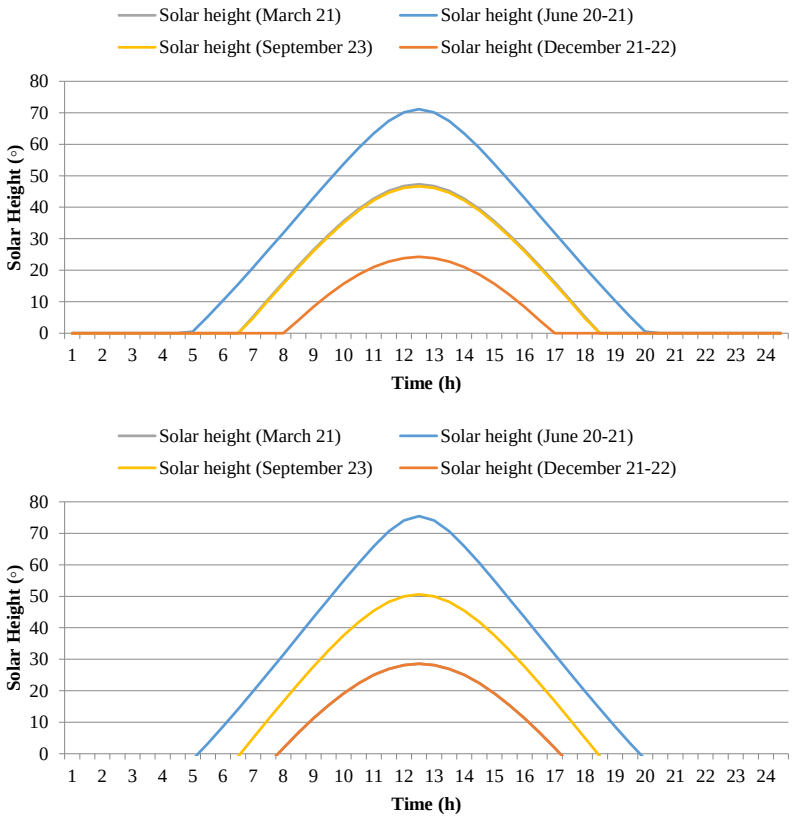

Figure 7.3: Solar height variation over the year. Ourense (on top) and Murcia (on bottom)

Due to the latitude difference of the selected places, the solar height is higher in Murcia than in Ourense, causing the incident solar radiation to be higher in Murcia.

To study the optimal design of solar shading devices, the influence of protection on the most unfavourable day of the year is studied. The data needed to calculate the shaded areas are shown in the graph below (Figure 7.4).

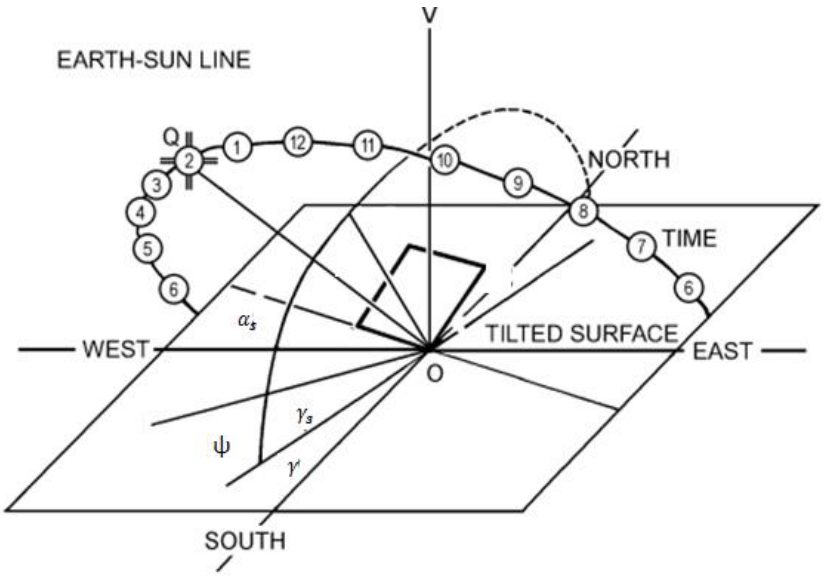

Figure 7.4: Solar angles with respect to a tilt surface (adapted from ASHRAE 2011)

Where:

- γs is the solar azimuth. The angle measured between the North cardinal point and the projection on the local horizontal plane of the line connecting the earth to the sun. The solar azimuth is negative direction East and positive direction West.
- γ is the surface azimuth. The angle measured between the North direction and the perpendicular to the wall.
- αs is the solar height. The angle measured between the sun and the local horizontal plane (Must be greater than 0°).
- ψ the difference between the solar azimuth and the surface azimuth (γs-γ) used positively (must be greater than 0° and less than 90°).

With these parameters, the projection of the sun rays on the window is calculated when it has a fixed solar shadow device. First, the equations for solar projection when the facade is south facing and with an overhang are obtained (Figure 7.5).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

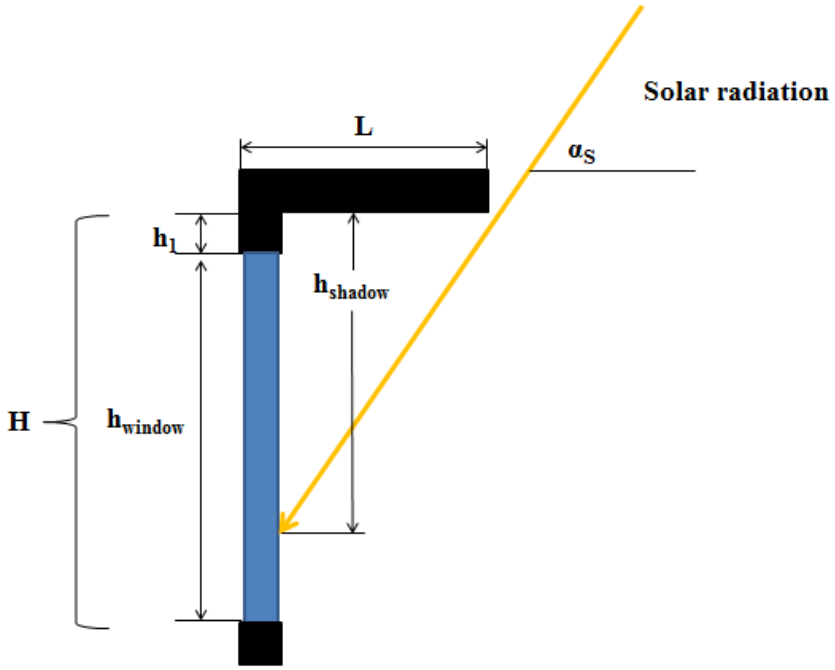

Figure 7.5: Solar projection on a window with an overhang

The shadow generated by the overhang depends on the position of the sun. Thus, the solar projection on the window is:

$$h_{shadow} = tg(\alpha_s) \cdot L \qquad \text{[Eq. 7.6]}$$

Where:

- H_{shadow}: projection of the sun rays on the window, taking into account the distance between the window (h_{window}) and the overhang [h_1]
- L: length of the overhang [m]

Finally, if the orientation of the facade (γ) is taken into account, the solar projection on the window is described as follows.

$$h_{shadow} = \frac{tg(\alpha_s) \cdot L}{cos(\gamma)} \qquad \text{[Eq. 7.7]}$$

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

For obtaining the incident solar radiation as a function of the length of the overhang is usued the equation [Eq. 7.7]. In this way, depending on the length of the overhang (*L*), the surface azimuth (γ) and the solar height (αs), the percentage of shade ($\%_{shadow}$) can be obtained depending on the total height of the window (*H*).

$$\%_{radiation} = \frac{\left(H - \frac{L \cdot tg(\alpha_s)}{cos(\gamma)}\right) \cdot 100}{H} \qquad \text{[Eq. 7.8]}$$

Combining the equation [Eq. 7.8] and [Eq. 7.1], the solar radiation when the window has an overhang can be obtained:

$$G_T = G_b \cdot cos\,\theta \cdot \%_{radiation} \cdot g_{value} + \left(G_{d,t} + G_{r,t}\right) \cdot g_{value} \qquad \text{[Eq. 7.9]}$$

With this equation, we can analyse the influence of the length of the overhang and the *g-value* of the window.

7.6.3.1. Study of the overhang length

As a starting point, the *g-value* is taken from 1, that is, all solar radiation crosses inwards with a south-facing window with a height (*H*) of 1,5 meters high.

The two analysed climatic zones (Ourense and Murcia) are taken as a reference for the day when the solar radiation reaches the highest and lowest position at noon using different lengths of the overhang. The following cases are assumed:

- CASE A: Overhang with a length of 0,5 meters.
- CASE B: Overhang with a length of 1 meter.
- CASE C: Overhang with a length of 1,5 meters.
- CASE D: Overhang with a length of 2 meters.

The results obtained for the location of Ourense (with latitude of 42º) are shown in Figure 7.6.

During the summer, when the heat contributions generate unwanted energy contributions, the use of fixed solar shading device allows to reduce the heat contributions by radiation. In this way, the cooling needs inside are reduced.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

In this case, during the summer the shade generates with an overhang height of 1,5 or 2 meters is not improved, because the shadow of the window exceeds its length. However, during winter, an excessive length of the overhang prevents the entry of solar radiation.

Figure 7.7 shows the results obtained for the location of Murcia (with a latitude of 38º), where the results are very similar to those of Ourense.

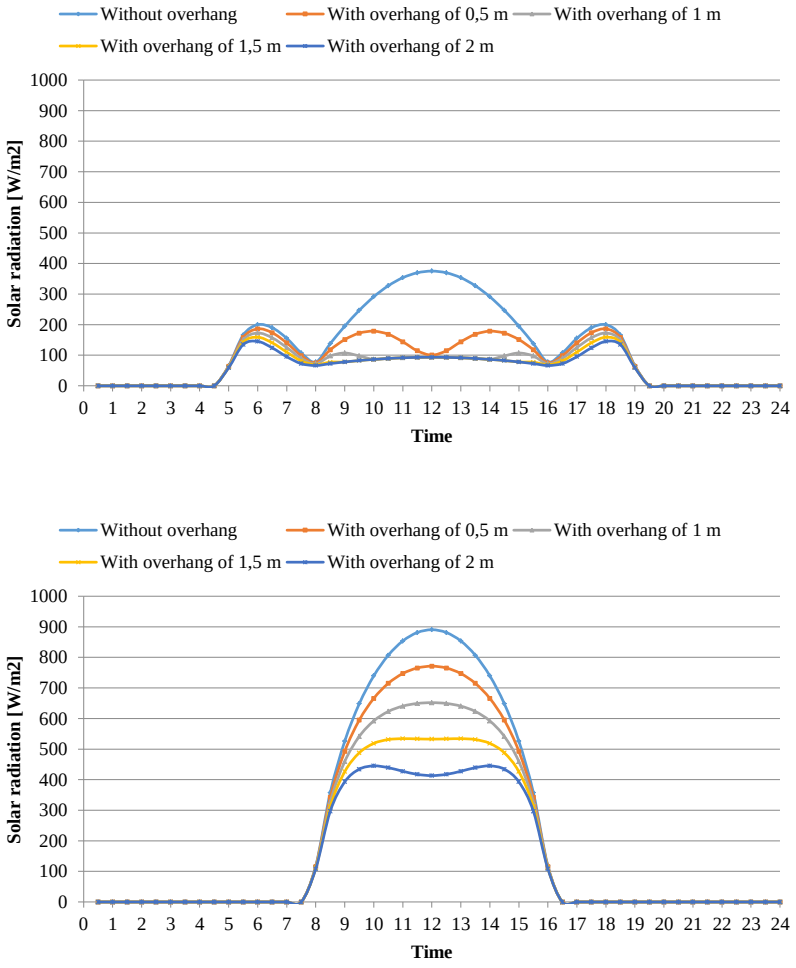

Figure 7.6: Solar radiation on window with south orientation and g-value of 1. Location in Ourense. Reference Day 20/06 (on top) and 21/12 (on bottom

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

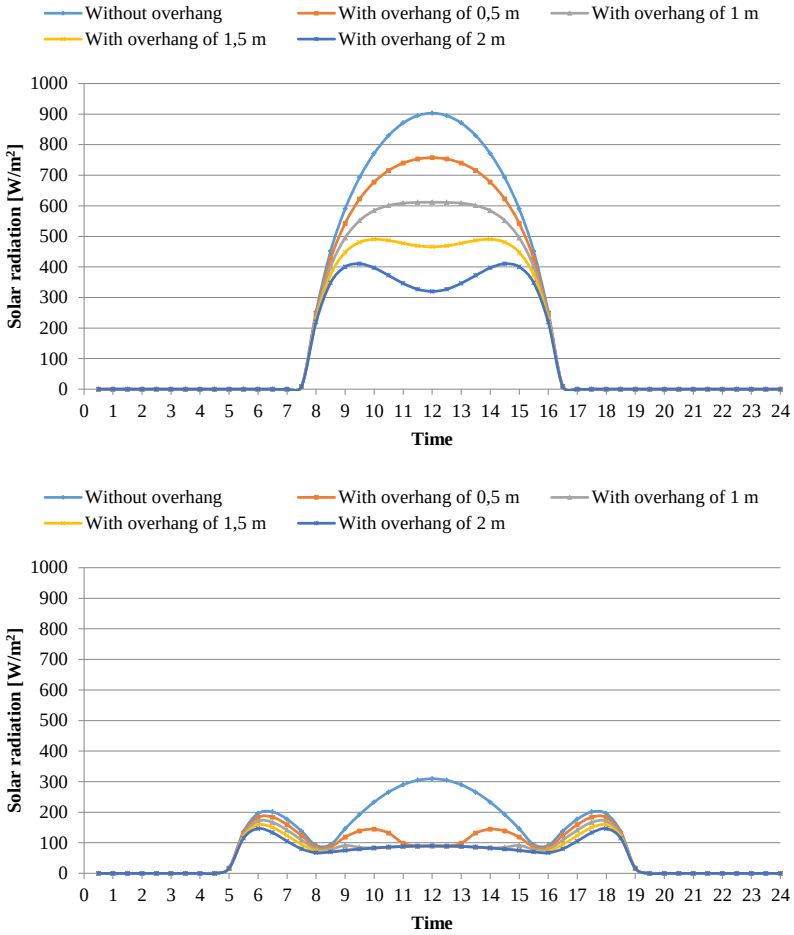

Figure 7.7: Solar radiation on window with south orientation and g-value of 1. Location in Murcia. Reference Day 20/06 (on top) and 21/12 (on bottom)

In Table 7.5, the energy received during the analysed day is shown. First, the energy received on the surface is shown and then the total energy that would pass through the window.

Table 7.5: Summary of the solar energy transmitted inwards the building in function of the length of the overhang (g-value of 1)

	OURENSE		MURCIA	
Reference Day (dd/mm)	20/06	21/12	20/06	21/12
Solar Radiation on horizontal surface [kWh/m^2·d]	9,60	2,86	9,61	3,56
Solar radiation on perpendicular surface south orientation [kWh/m^2·d]	3,07	5,38	2,64	5,81
CASE A: Overhang of 0,5 m [kWh/m^2·d]	1,99	4,82	1,74	5,11
CASE B: Overhang of 1 m [kWh/m^2·d]	1,53	4,27	1,46	4,40
CASE C: Overhang of 1,5 m [kWh/m^2·d]	1,41	3,72	1,35	3,70
CASE D: Overhang of 2 m [kWh/m^2·d]	1,34	3,17	1,28	2,99

The uses of overhangs produce shade on the glazed part of the window, so they avoid the entry of solar radiation. In the case of Ourense, the 1,5 meter overhang allows 45,9% of solar radiation to pass through in summer, however, when using the of 2 meter, 43,6% is reduced, so there is no great reduction in energy input in summer. However, in winter, the radiation input is 69,1% for the 1,5 meter overhang and 58,2% for the 2 meter overhang. This is because during the summer, the 1,5 meter overhang produces a total shadow on the window, however, during the winter, the sun's position is lower and the 1,5 meter overhang produces a shadow partial in the window, allowing the passage of solar radiation.

In the case of the city of Murcia, the results are very similar, however, for the 1,5 meter overhang, a contribution of solar radiation of 51,3% in summer and 63,7% in winter is obtained . The overhang with 1,5 m allows more radiation to pass in Murcia than in Ourense.

Figure 7.8 shows the percentage of solar radiation as a function of the length of the overhang. The graph shows the percentage of radiation that is transmitted through the window for overhangs of up to 5 meters (despite not being an adequate solution).

It is observed that from a certain length, the overhang barely reduces the entry of solar radiation in summer. However, solar contributions are reduced in winter, when they are necessary to reduce energy consumption in heating.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

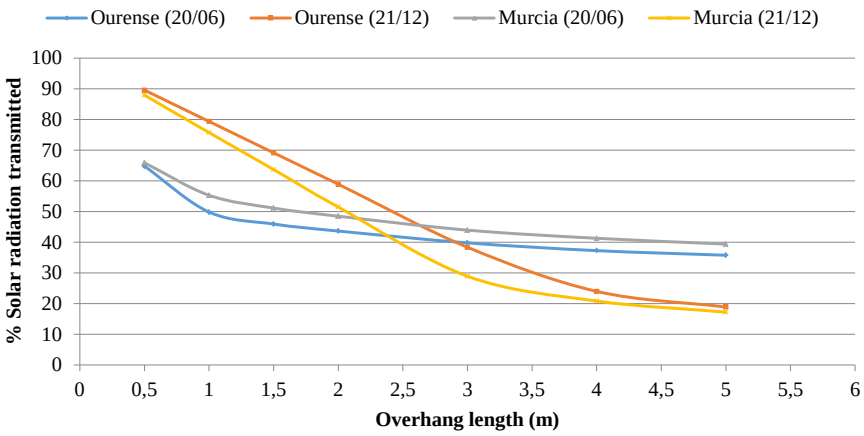

Figure 7.8: Reduction of solar radiation depending on the length of the overhang for a window with a height of 1,5 meters

7.6.3.2. Study of the overhang length and g-value of window

The length of the overhang avoid the direct solar radiation that falls on the window, thus allowing the diffusion of solar radiation and that emitted by the earth's surface to pass through.

The influence of the inputs of solar radiation towards the interior has been analysed by modifying the g-value of the window and the length of the overhang. The results of combining both solar protection systems are shown below. To do this, the 3 different proposed windows (CASE 1, 2 and 3) are evaluated with the 4 overhang options (CASE A, B, C and D). Therefore, a total of 12 cases are analysed for the two climatic locations (Ourense and Murcia) and at two different times of the year (06/20 and 12/21).

In Figure 7.9, the day of the year in which the sun reaches the highest position is analysed. By combining the g-value of the glass and the length of the cantilever, a reduction of the solar radiation input greater than 95% is achieved when a 1 meter length overhang is added (CASE 3-B, 3-C and 3-D).

With respect to CASE-1, where a g-value of 0,87 is used, reducing the solar radiation input by 17%, the introduction of overhangs for the control of solar radiation, allows to reduce between

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

40,6 – 58,3% solar radiation in Ourense, and between 53,1-65,4% in Murcia. The introduction of overhangs, greatly reduces the entry of solar radiation in Murcia, this reduction is greater, because the solar radiation has a greater inclination angle.

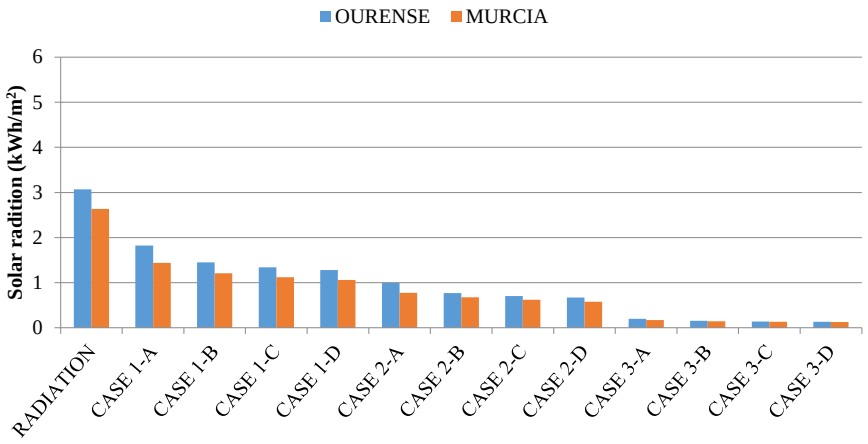

Figure 7.9: Solar radiation input during the day 20/06 in Ourense and Murcia for the 12 cases

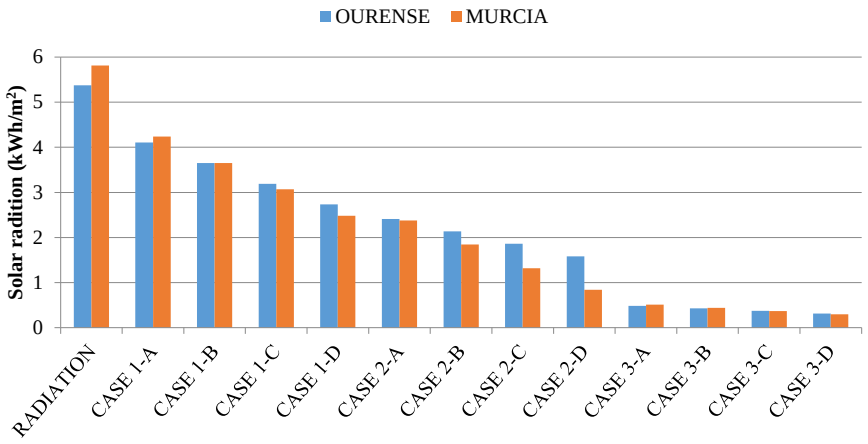

Figure 7.10: Solar radiation input during the day 21/12 in Ourense and Murcia for the 12 cases

Finally, with respect to case B, the entrance of solar radiation is avoided by 50% without using overhangs, in Ourense a reduction between 67,6 – 78,2% is reached and in Murcia between 74,7 – 81,1%

During winter (Figure 7.10), solar radiation must be used to reduce the energy used for heating. Therefore, analysing only this point of view, the option that allows a greater entry of solar radiation would be the cases in which the g-value has a value of 0,87 (CASE-1) and where the overhangs allow the passage of solar radiation. In these cases the solar radiation input is reduced to a greater extent in Murcia by increasing the length of the overhang. Thus, in Ourense for CASE-1, adding an overhang leads to a reduction between 23,6 -49,1% and in Murcia between 21,1-53,1%.

The control of solar radiation by means of fixed solar shading device is complex since it does not allow taking advantage of solar energy in winter and avoiding it in summer. Therefore, the introduction of systems that allow regulating solar contributions takes on a fundamental role in the construction of sustainable housing, so dynamic solar control systems are essential for new buildings.

7.6.4. Study of the influence of dynamic solar shading device in solar contributions

Unlike fixed solar shading device, dynamic solar shading devices allow regulating solar energy contributions in the building; this allows control the solar contributions. Therefore, these types of technologies maximize energy efficiency in buildings.

In winter, the main objective is to increase the collection of energy solar into the building for reducing the energy consumption destined for heating. Moreover, if the building has a good design of thermal inertia, this heat can be stored inside. On the contrary, in summer, solar inputs increase the cooling demand. In this case, solar shadow devices must avoid solar radiation towards the interior of the building.

This versatility allowed by dynamic solar shading device is the main advantage over fixed solar shading device. In order to achieve good results, a good sensorization and automation of the protections is

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

essential, as well as the adjustment of the position and the inclination of them.

In this part, the efficiency of a dynamic solar shadow device is analysed. In this case, the awnings are selected, because they are devices that can be easily automated and can produce a complete solar protection. In this case, the angle of inclination (βa) formed between the awning and the surface of the window is analysed (Figure 7.11).

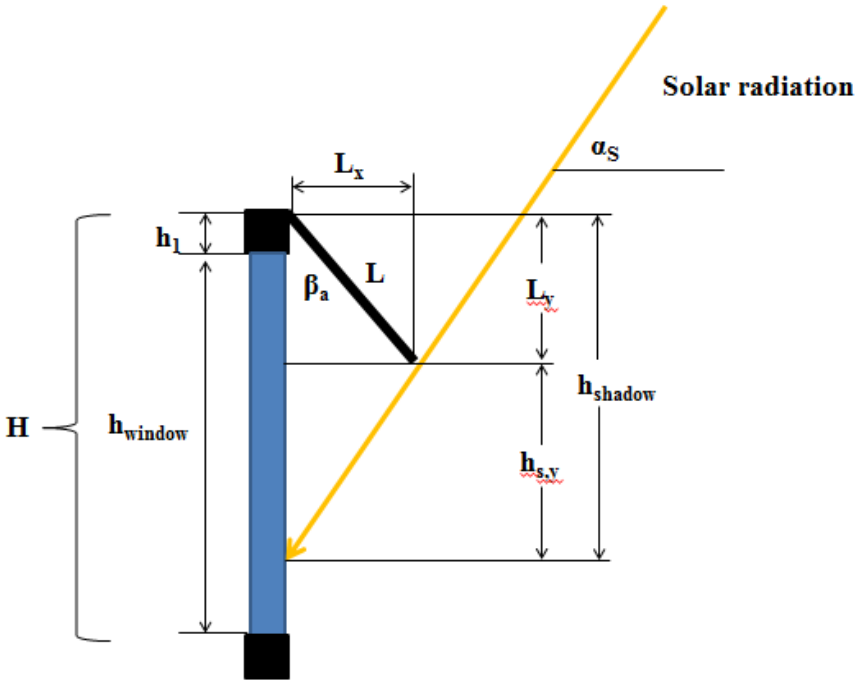

Figure 7.11: Solar projection on a window with a dynamic awning

The shade produced by the awning is formed by two variables:

- *Ly*: the projection of the awning itself on the surface of the glass.
- *hs, y*: the projection of solar radiation on the surface of the glass.

$$h_{shadow} = L_y + h_{s,y} \qquad \text{[Eq. 7.10]}$$

Where *Ly* and *hs,y* are defined as:

$$L_y = L \cdot cos(\beta_a) \quad \text{[Eq. 7.11]}$$

$$h_{s,y} = L_x \cdot tg(\alpha_s) \quad \text{[Eq. 7.12]}$$

Combining equations [Eq 5.10], [Eq 5.11] and [Eq 5.12] and expressing the length *Lx* as a function of the length of the awning (*L*), the total shadow projected on the window is obtained taking into account also the surface azimuth (γ):

$$h_{shadow} = \frac{L \cdot (cos(\beta_a) + sen(\beta_a) \cdot tg(\alpha_s))}{cos(\gamma)} \quad \text{[Eq. 7.13]}$$

Therefore the percentage of radiation incident ($\%_{radiation}$) on the window is:

$$\%_{radiation} = \frac{\left(H - \frac{L \cdot (cos(\beta_a) + sen(\beta_a) \cdot tg(\alpha_s))}{cos(\gamma)}\right) \cdot 100}{H} \quad \text{[Eq. 7.14]}$$

7.6.4.1. Study of the fixed angle awning

First, the influence of the awning angle at the inlet of solar radiation inward is analysed (Table 7.6).

Table 7.6: Solar energy input for a 1.5 m window depending on the awning angle

	OURENSE				MURCIA			
Awning angle [°]	90°	70°	50°	30°	90°	70°	50°	30°
CASE A: Awning of 0,5 m [kWh/m²·d]	1,99	1,83	1,80	1,93	1,74	1,62	1,58	1,67
CASE B: Awning of 1 m [kWh/m²·d]	1,53	1,36	1,25	1,20	1,46	1,30	1,20	1,15
CASE C: Awning of 1,5 m [kWh/m²·d]	1,41	1,21	1,07	1,01	1,35	1,16	1,02	0,97
CASE D: Awning of 2 m [kWh/m²·d]	1,34	1,10	1,00	1,00	1,28	1,05	0,96	0,96

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Continuing with the hypothesis assumed in the previous point, a window with a height (*H*) of 1,5 meters is taking as reference the day 06/20, day in which the sun reaches its maximum solar height. In Table 7.6, the inward energy input is shown starting from the length described in Cases A-B-C and D.

Varying the angle of the awning allows greater control of solar radiation, allowing direct solar radiation to be prevented. Therefore, being able to adjust the angle of the awning would reduce the entry of solar radiation in summer, and being a dynamic solar control system could allow the entry of radiation in winter. However, the length is also of particular importance, in the case of using a 0,5 m awning, it would not be enough to prevent the entry of solar radiation even if the angle between the awning and the window is reduced.

7.6.4.2. Study of the optimal angle awning

To maximize the shade produced by the awning, the angle between the awning surface and the solar radiation must be perpendicular.

$$\%_{radiation,min} \quad \rightarrow \quad \beta_a = \alpha_s \qquad \text{[Eq. 7.15]}$$

In this way, the entrance of solar radiation into the building can be avoided. Figure 7.12 shows the entry of solar radiation into Ourense as a function of the length of the awning and modifying the angle of the awning. In this way, between a 1,5 and 2 meter awning, there are no differences in the direct solar radiation input, so the only radiation inward is diffuse radiation.

As a summary, the energy input for awnings with different length and varying the angle depending on the solar height is shown. Table 7.7 shows the data for Ourense and Murcia for cases A, B, C and D. Varying the angle of the awning according to the solar height, greatly reduces the solar contributions, especially when the size of the awning is 1 meter or less.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

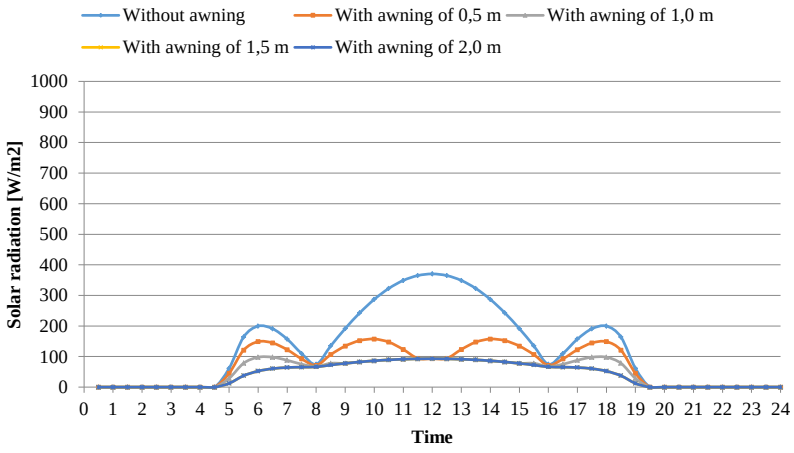

Figure 7.12: Solar energy input for a 1,5 m window varying the angle of the awning depending on the solar height (Ourense, Reference day 20/06)

Table 7.7: Solar radiation input depending on the length and varying the angle of the awning depending on the solar height (Reference day 20/06)

	OURENSE	MURCIA
CASE A: Overhang of 0,5 m [kWh/m^2·d]	1,71	1,53
CASE B: Overhang of 1 m [kWh/m^2·d]	1,18	1,13
CASE C: Overhang of 1,5 m [kWh/m^2·d]	1,00	0,96
CASE D: Overhang of 2 m [kWh/m^2·d]	1,00	0,96

Therefore, dynamic solar control systems must be automatic systems, which allow varying the length and angle depending on the solar position. The analysed system can be installed after the construction, so they are technologies to take into account in modifications in the current buildings.

Buildings must have monitoring and sensorization that automatically regulates solar control systems and thus optimize solar energy contributions from solar radiation, allowing the passage of energy during winter and avoiding it in summer.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

7.6.5. Analysis of current legislation

In 2018, Directive 2010/31/EU on the energy efficiency of buildings and Directive 2012/27/EU on energy efficiency are amended by Directive 2018/844. This modification aims to modernize the buildings of the European Union. The foundation of energy efficiency measures and the use of renewable energies will aim to decarbonize the current housing stock.

EU countries must establish strategies for the renovation of existing buildings. One of the strategies to take into account is the use of intelligent technologies that allow automation and control of buildings and devices that help regulate the comfort temperature [EC, 2018]. At this point, dynamic solar shading device play a fundamental role in preventing increases in the interior temperature of buildings and reducing energy consumption in air conditioning.

The Spanish regulations on Energy Saving and Efficiency in buildings had their last modification on 12/20/2019 in order to increase the requirement in terms of energy efficiency in buildings (DB-HE Energy Saving). Among others, a new parameter that measures the effectiveness of solar control systems is introduced, taking the month of July as a reference. It is established that the maximum monthly energy received from solar radiation is below 2 $kWh/(m^2 \cdot month)$, without taking into account the reflected radiation [Ministerio de Fomento, 2019]. The solar control described in the legislation must block solar radiation with mobile solar devices.

Because the regulations prioritize the use of dynamic solar shadow device, an awning is analysed which varies its angle depending on the position of the solar rays, taking into account the length (cases A, B, C and D).

Therefore, first, taking into account equation [Eq. 7.14] and [Eq. 7.15] the percentage of radiation blocked during the month of July for Ourense and Murcia. Figure 7.13 shows the incident solar radiation accumulated in the month of July that is able to enter into the building. A total of 12 cases are shown depending on the g-value of the glass and the length of the dynamic solar device (awning). In this case, a solar tracking system is analysed, so that the angle of the awning varies depending on the solar height.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

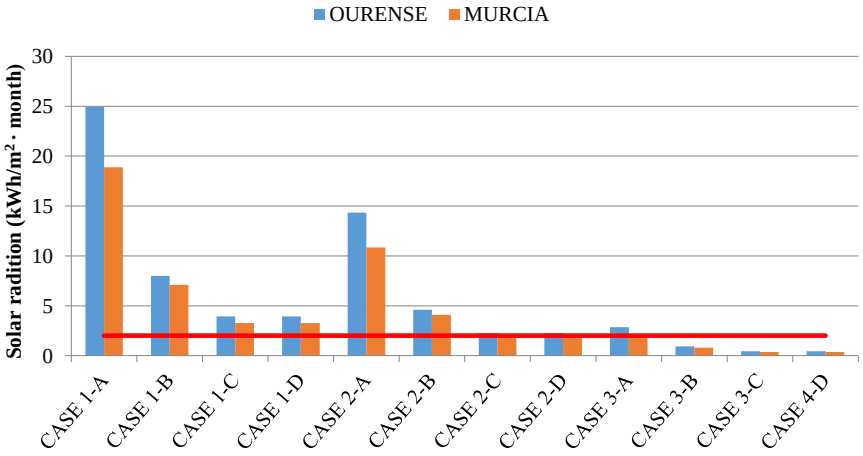

Figure 7.13: Solar energy input accumulated in the month of July

Table 7.8: Summary of the accumulated solar energy in July

CASE	g-value of window	Length of awning (m)	Compliance DB-HE Energy Saving Solar energy input accumulated in July [kWh/m²·month]	
			OURENSE	MURCIA
CASE 1-A	0,87	0,5	25,0	18,9
CASE 1-B	0,87	1	8,0	7,1
CASE 1-C	0,87	1,5	3,9	3,3
CASE 1-D	0,87	2	3,9	3,3
CASE 2-A	0,5	0,5	14,3	10,9
CASE 2-B	0,5	1	4,6	4,1
CASE 2-C	0,5	1,5	2,3	1,9
CASE 2-D	0,5	2	2,3	1,9
CASE 3-A	0,1	0,5	2,9	2,2
CASE 3-B	0,1	1	0,9	0,8
CASE 3-C	0,1	1,5	0,5	0,4
CASE 3-D	0,1	2	0,5	0,4

As can be seen in Table 7.8, with *g-value* of the window above 0,87 (CASE 1) does not allow compliance with current Spanish regulations in the two reference places. However, for a window with a g-value of 0,5 (CASE 2) and an awning length of 1,5 meters, In Murcia the regulations would be complied with (CASE 2-C and 2- D).

Finally, if case 3 is analysed, where the window has a *g-value* of 0,1. Despite having this low value, it would be necessary to use an awning of at least one meter in length.

Therefore, in order to maximize solar contributions in winter and minimize them in summer, the correct protection device must be selected. To maximize the solar contributions in winter, a glass with the maximum possible g-value is selected and that when adding sunscreen in summer, the total incident energy is less than 2 *kWh/(m^2·month)*.

Finally, current Spanish regulations is compared with one of the pioneer regulations in energy saving and efficiency in buildings, such as SIA regulations. Swiss regulations, SIA 2024, establish that for premises in general, if the maximum global incident radiation on the window exceeds 150 *W/m^2*, the incident global solar radiation must be reduced to 15%. Therefore, with respect to the point with the highest global radiation produced on 06/20, the incident radiation must be reduced to 15%. The results are showed in Figure 7.14.

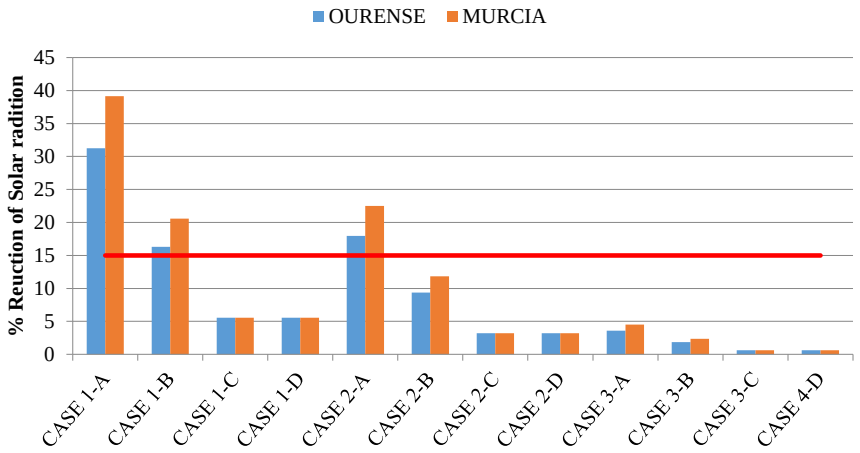

Figure 7.14: Reduction of global solar radiation for each CASE

For CASE 1 (*g-value* of window of 0,87), the objective of 15% is achieved, if a solar-controlled awning with a minimum length of 1,5 meters is used.

In the case of improving the *g-value* to 0,5 (CASE 2), the minimum awning length is reduced to 1 meter. Finally, when using a *g-value* of 0,1 (CASE 3), the use of solar control devices would not be necessary. Because a glass is used that only allows 10% of solar radiation to pass through.

Therefore, and as it has been shown previously, the combined use of a glass with a g-value and the appropriate solar control device, allow to optimize the use of solar radiation throughout the year.

7.7. CONCLUSIONS

Solar shading devices play an important role in the energy consumption of buildings. Currently, a wide variety of technologies for solar control are available on the market, from the simplest to developing technologies that not only prevent solar radiation, but also allow the energy from the sun to be reused. It is the job of engineers and architects to select the most appropriate technology from the initial phase of building design, in order to build energy-efficient buildings.

As demonstrated in this chapter, the selection of the *g-value* and the length of the overhang in the design stages of the building are important. Thus, longer lengths of the overhang allow minimizing solar radiation in summer and allowing the contribution of winter energy. On the contrary, low values of the g-value of the window will prevent the entry of solar radiation that benefits the reduction of cooling in summer, but increases the cooling needs in summer. Therefore, it is essential to find a balance between both parameters.

Dynamic solar control device have the versatility that the fixed system does not have. In the case analysed, the awnings can be an efficient and low-cost system to reduce the entry of solar radiation in summer.

In the case analysed in Ourense, for an awning with a length of 1,5 meters, placed perpendicular to the facade will allow the passage of 1,41 $kWh/m^2 \cdot day$, however with a mobile solar control system the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

solar contribution would be 1,00 $kWh/m^2 \cdot day$, that is, improves by 29% to fixed systems.

Finally, the potential of fixed solar shading device is highlighted, capable of preventing the entry of direct solar radiation but allowing the passage of diffuse solar radiation, so that they will maintain the lighting conditions inside the buildings.

At this point, the importance of sensorization and monitoring of buildings is essential, which would allow obtaining in real time the internal conditions of the buildings. In addition to a proper modelling of the building, where thermal inertia is included, it would allow adequate anticipation while maintaining comfort with minimum energy use.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

CHAPTER 8. REVIEW OF INDOOR AIR QUALITY AND VENTILATION SYSTEMS

This chapter is a reproduction of the following publication derived from the research carried out by the doctoral student during the training stage:

- Title: Environmental hazards beyond COVID-19: review of indoor air quality and ventilation systems
- Authors: Vilaboa Díaz, A; Bello Bugallo, P.M.
- Publisher: SAGE Journals
- Journal: Indoor and Built Environment
- ISSN: 1420-326X; eISSN: 1423-0070
- Impact Factor: 3,015 (2020)
- Year of publication: under review, 2021.
- Contribution of the doctoral student: contribution to development of the research and writing of the paper.
  Authorization of the journal/publisher for the use of the publication in the doctoral thesis.
  URL: https://uk.sagepub.com/en-gb/eur/journal-author-archiving-policies-and-re-use
  This URL is exactly transcribed below:
  "You may use the Final Published PDF (or Original Submission or Accepted Manuscript, if preferred) in the following ways:
  ...in your dissertation or thesis, including where the dissertation or thesis will be posted in any electronic Institutional Repository or database…"

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

SUMMARY

Ensuring adequate indoor air quality in buildings is not based on achieving only thermal comfort (humidity and temperature). There are more parameters that must be controlled for guaranteeing the health of the occupants. In order to evaluate which parameters affect indoor air quality, a bibliographic search of the Web Of Science (WOS) database with the terms "Indoor Air Quality" and "Ventilation and Air Conditioning" is performed. After the review, the results obtained are presented based on three fields: "Indoor air Quality", "Location" and "Ventilation".

During the literature review, a classification is made based on the three types of hazards to be controlled to ensure an adequate indoor air quality: chemical hazards, biological hazards and physical hazards. Among the chemical hazards, the pollutants with the greatest presence indoors are carbon dioxide (CO_2), particles (PM2.5 and PM10) and volatile organic compounds (VOC). Also, the articles are classified based on their location, observing that 79% of the publications correspond to residential buildings, office buildings and educational buildings. Finally, natural ventilation systems and HVAC systems are analysed.

CO_2 concentration is mainly produced by human respiration. Regarding VOCs, their emitting focus is found inside buildings, caused mainly by the type of materials. Natural ventilation systems and HVAC systems have proven to be effective in reducing the presence of these contaminants. However, with natural ventilation systems, it is not always possible to guarantee an adequate indoor air quality; mainly due to external conditions such as temperature, which can affect thermal comfort.

Biological hazards, in addition to the presence of moisture in materials, include HVAC systems as a possible source of emission. Therefore, the maintenance of these equipment must be periodic, in order to avoid the proliferation of bacteria and fungi.

Finally, a simulation of the evolution of the interior temperature is carried out as a function of the placement of the thermal mass. In addition, due to the recent news of COVID-19, the evolution of the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

CO_2 concentration is analyzed according to the number of people in order to keep the indoor air in healthy parameters.

8.1. INTRODUCTION

The achievement of NZEB implies very low consumption levels and therefore, the thermal envelope must be designed to guarantee these benchmarks. In addition, a good design of the envelope, would allow to reach stable temperatures and therefore to improve the indoor air quality, mainly avoiding humidity and condensation. In this way, according to the provisions of Directive 844/2018, the well-being and health of users is encouraged.

There are currently regulations that seek to establish a healthy air quality for people. One of the pollutants to avoid in buildings is the presence of radon gas. Directive 2013/59 establishes dealing with radon exposures in homes and public buildings in order to eliminate their presence in newly constructed buildings.

Radon gas is a source of ionizing radiation of natural origin. The main source of radon in homes comes from the decomposition of the existing radium in the soil that enters the homes. The presence of this gas in homes is associated with lung cancer [WHO, 2010]. According to WHO reports, on average the radon concentration in homes is between 20 and 150 Bq/m^3, proposing a reference level of 100 Bq/m^3 to minimize health risks due to exposure to radon inside of buildings.

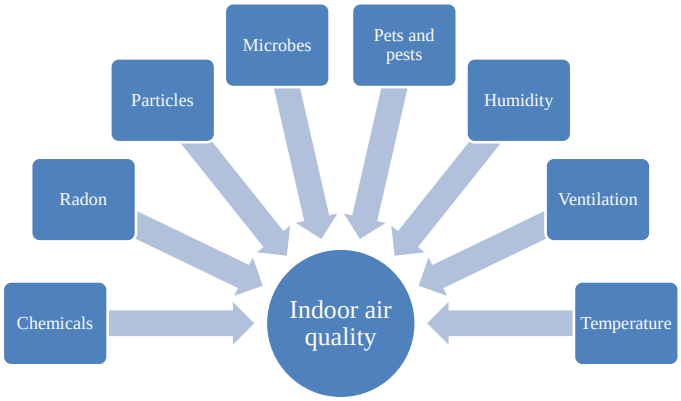

Figure 8.1: Hazards identification in indoor air quality [Data source: SCHER, 2007]

Indoor air may contain numerous types of pollutants; SCHER describes a number of factors that affect the quality of indoor air that users may be exposed to in public buildings (see Figure 8.1). The effects on health in people will depend on various factors such as age or the presence of cardiovascular diseases, in addition to toxicity, concentration and type of exposure to the pollutant [SCHER, 2007]

One of the basic requirements of air quality and that is easily perceived by users is the temperature and easily compensated with an air conditioning system and adequate thermal insulation. However, thermal insulation contributes to the water tightness of buildings and therefore normally increases ventilation needs. Ventilation should be adequate to remove contaminants and exposure to high levels of CO_2. It also helps to control the humidity inside the buildings; a high indoor humidity favours the proliferation of mold and condensation in the buildings. On the contrary, a low humidity rate causes skin effects such as dryness and skin rashes, as well as eye irritation and nasal dryness [SCHER, 2007]

In Spain, the basic health requirements are reflected in RD 2006/314 that has already been modified by RD 2019/732. The basic requirements for protection against moisture, air quality and exposure to radon gas are established.

The ventilation and air conditioning systems become tools that allow not only achieving an adequate thermal comfort, but also with the appropriate control systems allowing the achievement of adequate indoor air quality.

In residential buildings, as a general rule, there is no control of indoor air quality. In most homes there are no mechanical ventilation systems and therefore, it performs natural ventilation to renew the indoor air. In many cases, this natural ventilation may not be sufficient, and problems in the health of the inhabitants may appear.

Therefore, Ventilation and Air Conditioning systems play a fundamental role in achieving adequate air quality. Currently there are various studies on natural and mechanical ventilation systems and their effects on indoor air quality, so this chapter summarizes all the information available on “Ventilation and Air Conditioning” systems and their effects on “Indoor Air Quality”.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

8.2. METHODOLOGY

The systhematic review is carried out based on the relationship between "Ventilation and Air Conditioning" systems and "Indoor Air Quality". ASHRAE, in its Handbook "Fundamentals", defines ventilation as the intentional introduction of air from the exterior to the interior of buildings and it differentiates between two types of ventilation [ASHRAE, 2009]:

- Natural ventilation is the flow of air through open windows, doors and other planned penetrations of the building envelope, and is driven by natural and/or artificially produced pressure differentials [ASHRAE, 2009]
- Mechanical (or forced) ventilation is the intentional movement of air into and out of a building using fans and intake and exhaust vents [ASHRAE, 2009]

Taking into account these two types of air renewal systems, a review is performed based on those studies that are related to indoor air quality. First, a reading of the title, keywords and summary is carried out for the initial selection of the publications to be reviewed.

The selection criteria for the publications to be fully reviewed are based on the following premises:

- Publications on studies that measure indoor air quality based on the presence of pollutants and comfort parameters.
- Publications made using models related to indoor air quality based on any type of ventilation and air conditioning system.
- Publications related to studies on indoor air quality in different places (educational buildings, offices buildings and residential buildings).
- Publications related to indoor air quality in industrial settings are discarded.
- Publications that only deal with the effects of air quality on human health are discarded.
- Proceedings are discarded from the initial review.

Based on the one described in this point, the biographical search is performed in the Web Of Science database.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Finally, a case study is analyzed where the evolution of the interior temperature is evaluated based on the placement of the thermal mass and the insulation. The case study is analyzed using the model described in previous chapters. Due to the importance of ventilation in air quality, the evolution of CO_2 concentration is evaluated as a tool to maintain CO_2 concentration at safe values and prevent COVID-19 infections.

8.3. DEVELOPMENT

The results of the bibliographic search carried out on March 14, 2020, with the term "Indoor Air Quality" in Web of Science amount to a total of 12.166 (177 publications in 2020).The search was carried out in the title, in the abstract, in the author's keywords and in the Keywords Plus from the year 1900 to 2020. The first publications began to appear in the year 1970 but did not begin to be until the year 1990 when the number of publications regarding "Indoor Air Quality" begins to increase exponentially.

The same search was also carried out with the term "Ventilation and Air Conditioning", in this case, a total of 11.210 publications were made (157 publications in 2020), and in this case, the first publication was from the year 1927. For both subjects, 80% of the publications between 1900 and 2020 have been made in the last 15 years.

As can be seen in Figure 8.2, there is a correlation between the topics "Indoor Air Quality" and "Ventilation and Air Conditioning", therefore a joint search of Web Of Science is carried out for the systhematic review. After the joint search, including the title "Indoor air quality" and the topic "Ventilation and air conditioning", a total of 327 publications are displayed.

From the 327 publications, a selection of the most representative is made based on the title, Key Words and Abstracts. The proceedings are removed from the review, so that 279 publications are finally reviewed for the initial selection.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

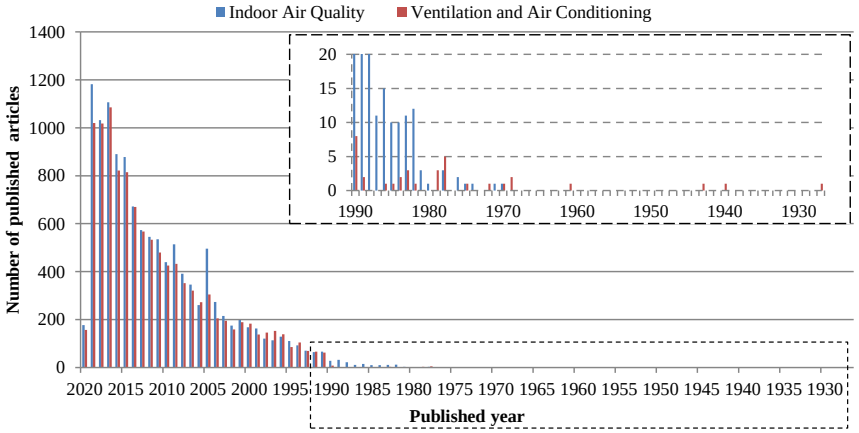

Figure 8.2: Number of publications according to Web of Science (1900 to 2020)

8.4. RESULTS

Based on the selection criteria in the previous section, a total of 104 publications are selected for review. After completing this first filter, the relevant publications for the study are included.

Finally, 52 articles were considered relevant and conclusive and are included in this chapter. A classification of each item is made according to the case study (residential buildings, educational buildings and office buildings), the type of hazard (chemical, biological or physical) and the type of ventilation (natural ventilation or HVAC).

After classifying the publications, a summary of the results obtained is shown in the Figure 8.3.

Regarding the location of the place under study, residential buildings represented the majority of publications with 36%, followed by office buildings and schools with 23% and 20% of publications, respectively. Finally they are included in the "Others" category, which represent 21%. In this category are studies related to other places such as commercial buildings, cafes, restaurants, hotels, and hospitals. It can be considered normal that 79% of studies are based on homes,

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

offices and schools, since much of people's time is spent in these spaces.

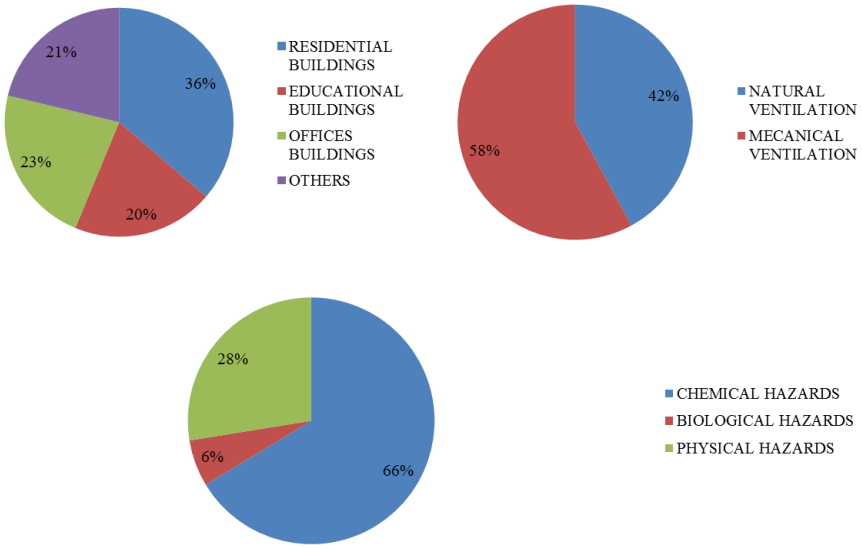

Figure 8.3: Percentage of publications based on case study (up to left) type of ventilation (up to right) and type of hazard.

Regarding the type of hazards related to indoor air quality, chemical hazards stand out, with 66% of the publications. In this type of hazards, there are many publications of contents related to the concentration of carbon dioxide (CO_2), particulate matter (PM2.5 and PM10) and volatile organic compounds (VOC). Second, there are physical hazards with 28%, where thermal comfort conditions are evaluated based on temperature and humidity. And lastly, with 6% of the publications are biological hazards.

Finally, regarding the type of ventilation, there is equality between the number of publications related to natural ventilation and HVAC systems, with 42% and 58% respectively.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

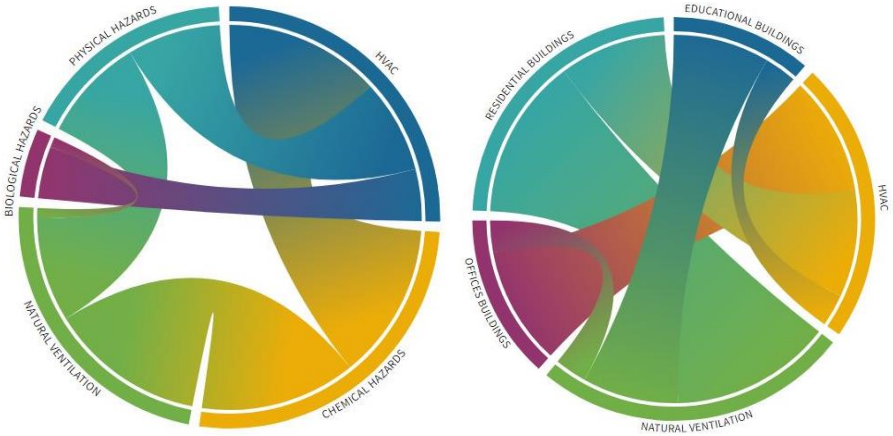

Figure 8.4: Chord diagram of the number of publications reviewed depending on the topic

In the systhematic review, a relationship between the subjects of the publications is observed. In Figure 8.4, the link between the type of ventilation and the type of danger in the indoor air and the relationship between the type of ventilation and the place under study is shown.

Analysing the relationship between the type of ventilation and the type of hazard, the publications related to natural ventilation and HVAC systems mainly deal with chemical hazards (CO_2, PM and VOC). Second, ventilation studies related to physical hazards (temperature and humidity) are prioritized. Regarding biological risks, the studies are entirely linked to HVAC systems.

Regarding the relationship between the studies that relate the ventilation systems and the different types of buildings, it is observed that both natural and forced ventilation are studied both in residential buildings and in schools. However, in office buildings, most of the studies are related to HVAC systems.

8.4.1. Indoor Air Quality

People spend up to 90% of the time indoors, such as housing, commercial spaces, offices and schools, among others. The concentration of pollutants in indoors is generally higher than

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

outdoors [ASHRAE, 2009]. Therefore, it is essential to have adequate indoor air quality in order not to harm people's health.

As indicated by SCHER (2007), there are different factors that affect indoor air quality and have been listed in Figure 4.17 (chemicals, radon, particles, microbes, pets and pests, humidity, ventilation and temperature). On the other hand, ASHRAE (2009) identifies four groups of classes of environmental stressors:

- Chemical hazards (Airborne chemical or particles).
- Biological hazards (bacteria, viruses, fungi ...).
- Physical hazards (levels of ionizing and nonionizing electromagnetic radiation, noise, vibration, illumination, temperature, and force).
- Ergonomic risks (awkward postures can damage muscles, nerves, and joints).

The ASHRAE (2009) classification identifies environmental stressors to ensure a healthy environment. Therefore, for the analysis of indoor air quality, ergonomic risks are not included, since they study the relationship between humans and their work environments. Considering the other three groups of the ASHRAE classification, it includes among the physical risks, the risks of radiation, noise, vibration and lighting, which the SCHER classification does not include.

In the systhematic review about indoor air quality, a total of 42 publications based on the study of chemical hazards and 25 publications focused on the study of physical hazards (temperature and humidity) have been selected. In 22 of the selected publications, indoor air quality is discussed based on both types of hazards, chemical pollutants and physical hazards.

Carbon dioxide (CO_2) is one of the chemical contaminants most mentioned in the reviewed publications. CO_2 is not considered a toxic air pollutant. CO_2 can be an asphyxiant, above 35.000 ppm, it produces a sensation of cause of shortness of breath [ASHRAE, 2009] and it is also related to poor student performance [Jhonson et al., 2018]

CO_2 is produced by human respiration and is one of the main pollutants that can be found in indoors [ASHRAE, 2009]. There are

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

studies that already demonstrate this correlation between the occupation of indoor spaces and the CO_2 concentration by taking data in public spaces [Ponsoni et al., 2010]. This increase in CO_2 concentration also causes an increase in relative humidity due to internal inputs, mainly generated by human activity and poor ventilation [Blaszczok et al., 2018]

Heracleous et al (2019) also observed in their measurements a correlation between the indoor CO_2 concentration and the outdoor temperature, the CO_2 concentration increases due to a reduction in the opening of windows. So, as the window opening time increases, the CO_2 concentration gradually decreases [Huang et al., 2018]. In this way, in warmer times of the year, the CO_2 concentration inside buildings is reduced due to increased ventilation through windows [Blaszczok et al., 2018]

Regarding the recommended CO_2 concentration limits, it varies depending on the association that establishes it. Firstly, Heracleous et al, indicates that according to Representatives of European Heating and Ventilation Associations (REHVA), the limit of maximum concentration of CO_2 in indoor spaces is 1.500 *ppm* [Heracleous et al., 2019]. Other public institutions establish more restrictive levels, thus, as published by Fernandez- Aguera et al (2019) and based on the available guidelines from the Madrid regional government, the CO_2 concentration indicated by adequate air quality is between 1.000 and 1.200 *ppm*. This limit is above that indicated by the European standard EN 13779, which establishes a low air quality with CO_2 concentrations above 1.000 ppm with respect to outdoor levels [Heracleous et al, 2019]. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), is more restrictive with the concentration limit and establishes a level of 1.000 to 1.200 *ppm* or 700 *ppm* above the outside air. [ASHRAE, 2009]

The presence of carbon monoxide (CO) inside homes is also mentioned. The main source of CO in indoor spaces comes from the inadequate combustion of fossil fuels, in addition there is also the possibility of an external infiltration of CO towards the indoors [WHO, 2010]. The CO concentration can also come from outside through ventilation systems [Che 2019]. The WHO exposure limits for

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

CO are 100 *mg/m*^{3} (15 min), *mg/m*^{3} (1 hour), 10 *mg/m*^{3} (8 hours), 7 *mg/m*^{3} (24 hours) [WHO, 2010]. Directive 2000/69/EC sets the CO exposure limit at 10 *mg/m*^{3} (8 hours).

Particles are also pollutants that can be present in buildings.. The chemical contaminants present in the air can be solid or liquid, among the typical examples of this type of pollutants are dust (0,1-100 μg), smoke (≈0.25 μg), vapours (<0,1 μg) and mists (0,5-30 μg) [ASHRAE, 2009]. WHO considers that the limit concentration of PM2,5 particles should be <25 μg / m^3 (24h mean) or <10 μg/m^3 (annual mean), with respect to PM10 particles the limit concentration should be <50 μg/m^3 (24h mean) or <20 μg/m^3 (annual mean) [WHO, 2005]

According to measurements made over 48 hours in Hong Kong by Cheung et al (2019), no correlation was found between the concentration of PM10 and PM2.5 particles. They also registered a higher concentration of particles indoors than outdoors, so the cooking process as the main source of PM10 and PM2.5 particles. In contrast, other studies detected an increase in particles from outdoor pollution in schools [Van der Zeel et al, 2017] and in residential buildings [Huang et al, 2018; Tong et al., 2016]. The particle concentration from the outside is determined by the wind speed and the distance to the focus of contamination. According to simulations carried out by Tong et al (2016), they find that the average concentration of indoor particles decreases exponentially with increasing wind speed towards the building and the concentration is reduced as the building is further away from the particle emitting focus. Due to the high concentration of particles outdoors, closing the windows in winter reduces the concentration of PM2.5 particles coming from the outside, although this causes an increase in the CO_2 concentration [Huang et al, 2018], it is also important to correctly locate the fresh air entry points to avoid the entry of particles [Tong et al, 2016] or the installation of filters in mechanical ventilation systems [Van der Zeel et al, 2017]

The presence of particles in indoors is also due to daily activities such as smoking, peaks of particulate emissions were registered even with natural ventilation systems [Abbas et al, 2015]. Also dust

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

resuspension was registered due to indoor activity [Bamparesos et al., 2018]

Another group of pollutants present in non-industrial spaces are Volatile Organic Compounds (VOC). These compounds are characterized by their volatility. Among them, compounds such as formaldehyde, benzene or toluene (among others) are highlighted [ASHRAE, 2009]. One of the most mentioned VOCs in the reviewed literature is. Formaldehyde (HCHO) levels were also detected as measured over a year in buildings in North China by Huang et al. Formaldehyde concentration under airtight conditions increases with outside temperature and peaks in the summer season [Huang et al, 2018], and also this concentration is usually higher in spring and lower in autumn [Yin et al, 2019]. This increase in the concentration of formaldehyde with temperature is due to the materials used, for example, the glue used in the wallpaper in the rooms. [Huang et al, 2018]. In fact, keeping the indoor temperature below 22 ^{o}C would help to keep the concentration of volatile organic compounds within healthy limits [Chatzidiakou et al, 2015]. Furthermore, the concentration of formaldehyde in the environment is reduced as the rate of air renewal increases [Dutton et al, 2014]

Formaldehyde is a colourless, flammable and highly reactive gas at ambient temperature. In ambient air, formaldehyde is quickly photo-oxidized in carbon dioxide. People can begin to perceive irritation with concentrations of 0,1 mg/m^3 (30-minute average concentration). The main sources of indoor formaldehyde appear from combustion processes, and materials such as furniture and products that contain resins, textiles, DIY products, cleaning products, shoe products, cosmetics, electronic products and paper products [WHO, 2010]. There is a negative correlation between the times of opening of windows with the concentration of formaldehyde. As the duration of the window opening increases, the formaldehyde concentration gradually decreases, showing that the window opening has a significant effect in reducing the formaldehyde concentration [Huang et al, 2018]

Also, the presence of radon in buildings must be taken into account. Radon is one of the main contributors to the dose of ionizing

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

radiation received by the general population and there are studies that associate it with lung cancer [WHO, 2010]. Stabile et al (2016) measured the concentration of radon in schools. The measurements showed that the radon concentration is only influenced by the emission from the soil. During the weekend (no school day, closed doors and windows), the radon concentration became 20% higher than the days of activity. The radon exposure limit according to Directive 2013/59 is 300 $Bqm/\ m^3$, while the WHO establishes the reference value in 100 Bqm/m^3.

In addition to the main pollutants that have been described above, it is also necessary to take into account the oxygen concentration as a parameter within the quality of the indoor air. Lei et al (2017), in their measurements made during the sleeping hours of a group of people, found that the oxygen concentration in unventilated rooms was below the recommended levels of 19,5%. [Lei et al., 2017]

According to ASHRAE (2009), another important factor linked to having adequate air quality is the biological hazards (bacteria, viruses, fungi ...). The growth of bacteria and fungi is related to the presence of high air humidity, condensation, and water damage that promote the survival and growth of bacteria and fungi [WHO, 2009]. The presence of people also causes an increase in air pollution by bacteria and fungi [Basinska et al, 2019] that can be aggravated by the lack of proper ventilation [Jung et al, 2015]. Furthermore, according to the study carried out by Bonetta et al (2009), HVAC systems can be another focus of biological contamination by proliferating bacteria and fungi in air filters. Also, it should be noted that the presence of fungal pollutants outdoors can cause a higher concentration of fungal pollutants indoors [Jung et al., 2015]

Temperature and humidity are the comfort parameters that affect physical conditions. The recommended design values of the indoor temperature for the design of residential buildings according to EN 15251, is a minimum of 20^{o}C and a maximum of 26^{o}C for winter and summer conditions, respectively [ECS, 2008]. According to the Spanish regulation, the indoor design temperature is between 21-23^{o}C in winter with a relative humidity of 40-50%, while in summer, the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

design temperature has to be between 23-25ºC with a relative humidity between 45-60% [RD 1027/2007]

Relative humidity is higher in indoors areas more frequented by people, since they are a constant source of humidity [Fernandez-Aguera et al. 2019]. The kitchen is the point of the house where the highest temperature and humidity is reached, as well as the clothes drying activities. According to the study carried out by Blaszczok et al in southern Poland, maximum temperatures of 31ºC and a relative humidity of up to 80% were recorded in the kitchen. However, the lack of human activity allows the lowest temperatures to be registered, such as in the case of unused rooms with a relative humidity of 40% [Blaszczok et al, 2018]. When the relative humidity is lower, a higher indoor temperature is tolerable. For example, for a humidity of 40%, the maximum temperature allowed to achieve adequate thermal comfort would be 29,1 ºC, while for humidity of 70%, the temperature would be 27ºC [Che et al, 2019]. A high temperature and humidity can promote the proliferation of molds [Vincent et al., 1997]

Following the literature review on indoor air quality, the origin of hazards that alter indoor air quality could be classified as either indoor or outdoor sources. The main indoor sources in buildings are due to human presence (breathing), human activity and the materials used inside. The outdoor sources of contamination, highlights the outdoor pollution and the climatic conditions, which affect the indoor temperature and humidity.

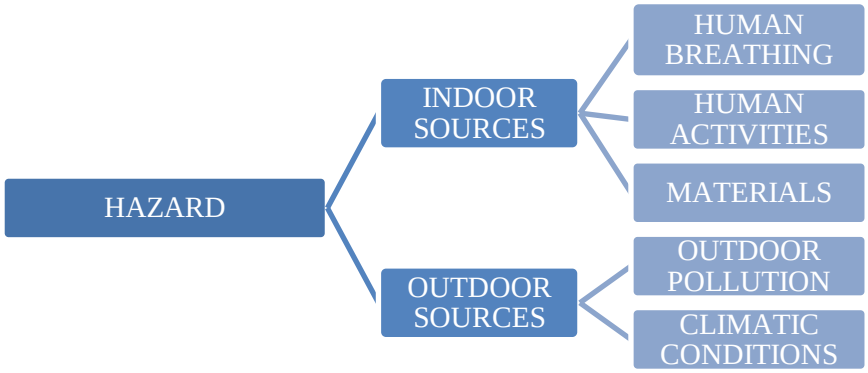

Figure 8.5 Summary of hazard sources

The human presence inside the building is responsible for changes in chemical, biological and physical hazards. Human respiration increases CO_2 levels and decreases O_2 concentration. The human presence also increases the presence of viruses, particles and fungi and they are also a focus of humidity and an increase in the indoor temperature. Therefore, the presence of people in indoor spaces causes a reduction in the indoor air quality, if adequate ventilation is not carried out. Also, human activity inside buildings such as smoking, cleaning, cooking, or indoor activity can be a focus of CO_2, particulate matter, and volatile organic compounds.

The materials used inside buildings (glues, resins, furniture,…) are also responsible for altering the indoor air quality, generating the presence of volatile organic components, especially formaldehyde. The use of more sustainable materials would avoid the presence of these compounds in buildings. Finally, the combustion of materials inside, are a source of chemical hazards that cause an increase in the concentration of CO_2, CO and volatile organic compounds.

External sources enter the interior through ventilation systems, both natural ventilation and forced ventilation. Among the main hazards that come from outdoors, particulate material stands out, specifically in buildings near industrial areas or a large flow of traffic. Furthermore, the concentration of CO and biological hazards could also be altered due to disturbances from the outside. HVAC systems also have an added hazard, as they can be a source of emitting biological hazards. However, these types of pollutant sources can be eliminated with proper maintenance.

8.4.2. Location of the case study

Among the reviewed bibliography, the case studies included are focused on residential buildings, educational buildings and office buildings, representing up to 79% of the reviewed publications. For this reason, the publications in these three locations are analysed in detail.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

8.4.2.1. Residential buildings

The number of studies related to indoor air quality in residential buildings is noteworthy. From the total systhematic review, 19 publications related to air quality in residential buildings have been selected.

A large part of residential buildings do not have mechanical ventilation systems and, therefore, the indoor air quality depends on the air renovations caused by natural ventilation. Natural ventilation in residential buildings, like open the windows is carried out depending on the weather season. Fernández-Agüera et al (2019), made measurements of CO_2 concentration for one year in buildings located in Madrid and Seville. As a result, it was obtained that the average concentration in the rooms was 1.895 *ppm* in Madrid (registering maximum values of 4.000 *ppm*) and 1.434 *ppm* in Seville (with maximum values of 5.000 ppm). Ventilation during winter is carried out for 10 - 30 min in the morning. However, in summer, due to the increase in ventilation through the windows, the CO_2 records in Madrid had average values of 466 *ppm* and in Seville values of 500 *ppm*, both with maximum peaks of 2.000 *ppm*.

Canha et al (2017) analyse the air quality while the people sleep under different types of ventilation. With the door and window closed, the highest levels of CO_2, CO and VOC are reached, while opening the window and door guarantees adequate ventilation. Not only the CO_2 concentration increase while people sleep, but also the O_2 concentration decreases (falling below the recommended levels of 19,5%) and the indoor temperature and humidity increase [Lei et al., 2019]. The use of air conditioning systems causes an accumulation of CO_2 levels with respect to natural ventilation, exceeding the recommended levels. According to the measurements made by Wong et al (2014), regarding the temperature and humidity in the rooms, natural ventilation presents higher values than the rooms with air conditioning, but the count of molds and fungi in the beds is slightly lower.

In addition to the presence of CO_2, indoor air quality can be disturbed by inadequate concentrations of PM and VOC's, mainly attributable to human activities such as cooking and drying clothes.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Regarding kitchens, CO_2 and PM10 concentrations have been recorded between 14 and 67% higher than in a living room [Cheunga et al. 2019]. Also, NOx and VOC may be present, but the use of existing hoods in kitchens can improve the indoor environment [Liu et al., 2019]. In old buildings, where firewood stoves still exist, incomplete combustion causes increased levels of CO and CO_2, as has already been measured in old Japanese houses [Wang et al., 2010]

Another factor that influences air quality is the outdoor pollution that causes indoor air quality to be unhealthy. When the external PM2.5 pollution is high, close the windows maintain the indoor concentration of PM2.5 within adequate values [Huang et al., 2018]. The study carried out by Abbas et al confirmed the correlation between the concentration of outdoor and indoor particles when ventilation is high (r=0,836), however, at low ventilation no correlation is observed (r=0,184). In addition, a higher concentration of fine particles with low ventilation was recorded, due to activities such as smoking and cleaning [Abbas et al., 2015]. However, this lack of ventilation increases CO_2 levels, so to avoid contamination by particles from the outside, fresh outdoor air must be filtered before being introduced into homes [Prasad et al., 2002]

CO_2 concentration is one of the main chemical hazards present in the indoor air of residential buildings, generated by humans and indoor activities. The renewal of air by natural ventilation guarantees adequate air quality, since it allows reducing CO_2 levels below 1.000 ppm. However, during winter air quality can decline, due to low ventilation rates, especially in cold regions. The places of the houses with the highest CO_2 rate have been located in kitchens and bedrooms. CO_2 in bedrooms is caused by poor ventilation during sleeping hours.

In homes, special attention must be paid to heat sources from the combustion of fuels inside the buildings, as in the case of stoves. Stoves can cause high levels of CO_2, CO, NOx and VOC, so it is essential to ensure adequate ventilation. It would be convenient to install sensors due to the presence of contaminants such as CO can cause death.

In buildings, the main source of external contamination is particulate matter. Buildings near industrial areas or areas of high

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

pollution caused by traffic significantly increase pollution by particles from the outdoors. So in these cases, buildings must have air treatment systems, in order to guarantee the entry of pollutants into the indoors.

8.4.2.2. Educational buildings

A total of 15 publications related to educational buildings are selected. The concentration of people in a small space, such as in schools, has a significant impact on air quality and affects the health and performance of students.

The main pollutants that are in classrooms is CO_2. According to a study carried out in a total of 40 US schools where measurements are carried out for 2 years involving a total of 220 classes, CO_2 concentrations of 1.171 ppm were obtained on average with a deviation of 319 ppm (registering maximums of 2.369 ppm). The average ventilation rate reached a value of 5,6 l/s person [Deng et al. 2019]. As Deng et al (2019)., Johnson et al (2018) also analysed indoor air quality in US schools, where CO_2 presence in the classrooms also stands out, with peaks exceeding 1.000 *ppm* being registered in 44 of 58 sampling points. Regarding CO, NO_2, VOC and formaldehyde, the levels recorded in schools are low, only punctual contamination from traffic close to educational centres are recorded. Additionally, low VOC levels can be limited by maintaining a reduced temperature within the classroom [Chatzidiakou et al, 2015]

Particle pollution problems are frequent in places with heavy vehicle traffic and industrial activity. Thus, in analyses of air quality in classrooms of Hong Kong, high levels of PM10 (between 21 - 617 $\mu g/m^3$) were identified due to outdoor contamination. Furthermore, as in US schools, CO_2 concentrations above 1.000 *ppm* are recorded [Lee et al, 2000]. A higher level of PM10 particles has also been registered indoors during the school year compared to the holiday season; this is because the students cause the resuspension of particles with their activity [Bamparesos et al, 2018]. In schools near areas of high outdoor pollution caused by industrial activity and vehicle traffic, the application of a fine filter can reduce the exposure of schoolchildren to air pollution. In schools near motorways in Germany, the installation of fine filters reduced the concentration of Black Carbon (BC) by

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

36%, and the concentrations of PM10 and PM2.5 decreased by 34 and 30% respectively [Van der Zeel et al, 2017]

In many cases, natural ventilation is the only way to renew indoor air. Heracleous et al (2019) carries out an experimental study in schools in Cyprus (Eastern Mediterranean region), where it analyses the variation in CO_2 concentration through natural ventilation by using windows. During heating periods and during consecutive classes, poor air quality is detected exceeding the CO_2 limit levels (1.500 *ppm*, according to the REHVA). Opening windows during rest periods (20 min) managed to reduce CO_2 concentration from 3.000 *ppm* to 530 *ppm*, maintaining thermal comfort. Even with classrooms at 50% capacity, recommended CO_2 levels can be exceeded [Rodrigues et al, 2019]

The automation of the closing and opening of windows is a mechanism that helps to keep the CO_2 concentration at acceptable levels. Taking into account the CO_2 concentration algorithm, stable CO_2 concentrations are guaranteed without affecting the thermal comfort of the users. In a case study of a classroom equipped with this automatic control system, the time with a CO_2 concentration greater than 1.500 *ppm* was three times less than in classrooms without control systems [Stazi et al., 2017]

Air renewal to guarantee adequate indoor air quality is linked to energy losses. Stabile et al, analyses energy losses in a school located in Italy, with an occupation of 2,2 m^2/p. According to EN 15251 standard, the minimum air renewal must be maintained at 2,76 h^{-1}. Manual ventilation, by opening windows, can produce between 19 and 33% of energy losses without guaranteeing the minimum air renewal rate and with average CO_2 concentrations above 1.000 ppm. With an appropriate mechanical ventilation system with heat recovery, an energy saving of 32% is estimated. [Stabile et al., 2019]

The season of the year has a significant impact on the CO_2 concentration inside the classrooms. During heating times, the air renewal is lower, reaching peaks of 5.000 *ppm* and average values ranging between approximately 1.400 and 3.000 *ppm*. However, during warmer times, the windows of the schools remain open, increasing the renovation rate, registering peaks of 2.000 *ppm* and

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

mean values of less than 1.000 *ppm* [Stabile et al, 2017; Stabile et al, 2016]. Currently, there are CO_2 simulations, carried out in classrooms taking into account factors such as number of students, open/closed doors and windows. These types of models would help the government establish criteria for decision-making in order to guarantee an adequate concentration of CO_2 and improve the health, performance and productivity of students [Yalçin et al., 2018]

In educational buildings, CO_2 is once again one of the most common chemical hazards, followed by particles and volatile organic compounds. The CO_2 concentration is higher in these buildings than in residential buildings, due to the higher occupancy. In those educational buildings that do not have automatic ventilation systems, it is recommended to carry out a renewal of air by natural ventilation for 10 and 20 minutes between rest periods, to guarantee CO_2 levels. However, this does not always guarantee adequate CO_2 levels and also causes considerable energy losses. However, CO_2 affects student performance, so it is essential to establish natural ventilation protocols during the day in this type of building.

As in residential buildings, the presence of volatile organic compounds has its origin in the materials used. So the control of the indoor temperature and the selection of suitable materials limit the presence of these compounds. Regarding the concentration of particles mainly from external contamination, the use of HVAC systems with adequate filters allows to significantly reduce the interior concentration of particulate matter. So the source of particles would be limited to human activity.

8.4.2.3. Offices buildings

Office buildings are places that provide people with a place to work. In these places, adult people spend their workday, in the case of Spain; it is 40 hours a week. The systhematic review carried out has found that 23% of the publications on air quality are focused on office buildings.

Temperature is an important parameter in offices that not only determines thermal comfort, but also is linked to employee performance and Sick Building Syndrome (SBS) [Fang et al, 2004].

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Most of the offices have air conditioning systems and therefore it is important to know the air flow profile and the distribution temperature. [Lin et al, 2005]. According to an empirical study carried out in offices in Thailand, the results showed that the range of temperature acceptability among workers was between 23 and 26^{o}C [Boonyayothin et al, 2011]. However, low temperatures (19^{o}C), resulted in a low level of dissatisfaction in Hong Kong offices [Lin et al, 2005], and while according to Kostianen et al (2008), with 22,5^{o}C of temperature, satisfaction levels of 80% are obtained.

The optimization of ventilation systems in these buildings not only lead to improvements in the indoor air quality, but also produce great energy savings. Thus, as reflected in the publication, savings of up to 50% have been obtained through air control depending on the CO_2 concentration and temperature, in addition to the installation of a dehumidifier at the air inlet and the improvement of the filters [Che et al, 2019]. Control systems based on the CO_2 balance, allow maintaining the levels within the adequate comfort range. Wong et al (2008) showed that the energy cost of maintaining the CO_2 levels in a Hong Kong office by 1000 *ppm*, would increase the energy cost by 56% compared to maintaining levels at 1200 *ppm*, also to maintaining levels at 1000 *ppm*, the acceptability of people would go from 81 to 86%.

Other mainly pollutants in office buildings are volatile organic compounds (VOC). Printers and photocopiers could be highlighted among some of the main sources. The air flow profile and the location of this equipment can cause the accumulation of these contaminants [Sekhar et al, 2004]. Regarding formaldehyde in offices, one of the sources is the treated wood products and it is affected by temperature and humidity. However, this pollutant can be reduced by increasing the ventilation rate, reaching a decrease from 14,4 to 5, 5% [Dutton et al, 2004]. The presence of bacteria must also be included, finding average values from 50 to 500 CFU/m^3, according to the study carried out in Italian offices [Bonetta et al, 2010]. Regarding the concentration of particles (PM10 and PM2.5), the indoor concentration is significantly related to the concentrations of outdoor particles both in winter and in summer. The concentration of PM10

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

particles is also generated from internal sources such as cleaning and construction [Che et al, 2019]

Regarding air infiltrations in offices, in general small offices have a higher rate of infiltration than larger offices, because the small office has more openings in the four walls, thus having a higher ratio of volume area than a larger office. Therefore, it allows a higher rate of infiltration air renewal than the large size ones [Dutton et al, 2014].

As a summary, the presence of people indoors also generates large concentrations of CO_2. However, this type of buildings are equipped with HVAC systems, so that the controls based on the CO_2 concentration and temperature, allow achieving adequate air quality and thermal comfort, prioritizing energy savings. Due to the high occupancy and the different thermal sensitivity of the occupants, an inadequate temperature can cause dissatisfaction among the employees. In this type of buildings, the concentration of volatile organic compounds predominates, coming from printers and furniture. These compounds are removed with HVAC systems; however, interior partitions and furniture layout influences air distribution and minimize compound removal. Proper maintenance of HVAC systems must also be performed to prevent the growth of bacteria and install the appropriate air filters to minimize the entry of particulate matter.

8.4.3. Ventilation

Ventilation is the key to maintaining indoor air quality within the appropriate healthy parameters. According to ASHRAE (2009), the exchange of indoor and outdoor air can be divided into two classifications. Ventilation is when there is an intentional exchange of air with the outside, and it can be subdivided in turn into natural ventilation and mechanical ventilation. Second, there is infiltration; it is the exchange of air through cracks or unintended openings and through the normal use of doors and windows. In this case, the bibliography about ventilation systems is analysed

It is not always easy to perceive by the occupants of a building a malfunction of the ventilation systems and it is only perceived when several parameters are above the comfort range. [Silva et al, 2017]. Furthermore, a lack of user understanding in the operation of HVAC

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

systems can lead to inadequate temperatures and poor air quality [Gupta et al, 2016], which can cause problems like throat irritation, nasal congestion or migraines [Vincent et al, 1997]

Air distribution in HVAC systems plays a fundamental role in achieving the right comfort conditions. Furniture surfaces greatly affect air diffusion and therefore ventilation efficiency [Hyeun Jun et al, 2018] and the removal capacity of pollutants present in the air [Lin et al, 2005]. Furthermore, if the room has interior partitions, the farther it is from the air entry point, the ventilation efficiency improves [Lee et al, 2004]

In order to achieve a suitable temperature profile, it is important to select the correct air flow temperature. Increasing air supply temperatures increases mean room temperatures [Zhang et al, 2005]. According to Yu et al (2009), the main factor to achieve an adequate distribution of air flow is the type of air supply: displacement ventilation (DV), personalized ventilation (PV) and under-floor air distribution (UFAD).

Displacement ventilation has a more uniform temperature distribution at the horizontal level, but there is always a vertical temperature gradient. If the air supply speed is low to mix and dilute the temperature of the cold supply air, it can cause discomfort for people due to the production of high stratification [Varodompun et al, 2007]. They allow for greater ventilation efficiency and better air quality due to the effect of stratification, but it can be reduced by opening doors and windows and changing the air flow [Yu et al, 2009]. The use of fans improves ventilation efficiency, thus larger size increases the total air flow and improves thermal comfort. According to simulations carried out, they eliminate the presence of contaminants, for sources located between 30 cm and 1 meter in height. The placement of the fans at a height between 30,1–30,9 cm eliminates the presence of contaminants with a flow air 12 *l/s*. Furthermore, with this provision, energy savings of up to 20,6% can be obtained [Abou Hweij et al, 2016]

Personalized ventilation allows a personalized adjustment of the environmental conditions by establishing personalized comfort conditions. This type of system allows removing particles of less than

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

2 *mm* but is not efficient in removing 7,5 *mm* particles [Yu et al, 2009]. The use of customized systems produce better thermal comfort and air quality when used with a stable air flow, compared to an intermittent flow. Besides operating stably, it produces greater energy savings. Thus, using PV with stable flow at 22*ºC* and 7,5 *l/s* accompanied by a Chilled Ceiling (CC) system, they achieve an energy saving of 8,14% compared to a CC at 17*ºC*. [Al Assaadet al, 2018]

Under-floor air distributions are efficient systems that have managed to produce savings of 20-35% and also, according to the surveys, 95% of people are satisfied with this air distribution system. [Yu et al, 2009]. In these systems, greater energy savings are produced when the height of the air return is reduced. Savings of 15,3% can be achieved compared to mixed systems, for a return air height of 1,3 meters [Heidarinejad et al, 2015]

HVAC systems must guarantee uniform air distribution and maintain adequate air quality with the lowest possible energy consumption. According to simulations carried out by Laverge et al (2011), savings of up to 60% can be achieved in the energy destined for ventilation by establishing adequate control strategies based on CO_2 concentration compared to control strategies based on relative humidity. In addition to establishing the appropriate setpoint, it can produce greater energy savings [Wong et al, 2008]. Furthermore, in air cooling systems, the installation of an air dehumidifier in the primary air treatment unit (PAU), reduces the energy consumption of cooling systems up to 50% [Che et al, 2019]. Another of the energy saving devices to consider is the economizer. Under typical California operating conditions, economizers provide additional ventilation air above the average minimum ventilation ratio for 79% of the occupied time [Dutton et al, 2014]

The CO_2 concentration is not significantly reduced by the air conditioning systems [Ponsoni et al, 2010]. Air conditioning systems cause higher CO_2 concentrations than the natural ventilation system, however, if air conditioning systems have a fresh air supply, CO_2 levels are lower. A similar behaviour occurs in the case of particle concentration, where the levels of particles similar to natural

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

ventilation systems do have fresh air intake [Wong et al, 2014]. It is also important to establish the optimal proportion of fresh air in relation to the total flow in air conditioning systems, to guarantee adequate air quality with minimum energy consumption; thus, savings of 6,5% can be achieved with fresh air ratios of 15% [Cheng et al, 2019]

Another problem to consider in HVAC systems are bacteria and fungi. According to the analysis carried out in offices by Vincet et al (1997), there is a higher concentration of bacteria and molds in the ambient air in HVAC systems than in natural ventilation systems. In addition, this behaviour is also observed in residential buildings [Wong et al, 2014]. Therefore, HVAC systems can be a focus of biological contamination. Bacteria and fungi can proliferate in air filters when the system is turned off and later spread through the air when the system is turned on. Therefore, a scheduled and periodic cleaning operation and maintenance activities for HVAC systems should be carried out as a preventive measure, including if water tanks are available [Bonnetta et al, 2009]. There are air treatment technologies such as ultraviolet germicidal irradiation (UVGI) that allow inactivating microorganisms (bacteria, fungi and viruses), so they could be a possible complement to these systems [Zhang et al, 2011]. Moreover, outdoor air can contain higher levels of fungus than indoor spaces, so an inadequate ventilation system significantly affects indoor fungal levels [Jung et al., 2015]

In the case of natural ventilation, the renewal of indoor air is carried out by the action of the wind or by the existence of a thermal gradient. In buildings that do not have an HVAC system, air renewal is mainly done by opening windows. A greater opening of the window, allows a higher rate of air renewal, thus maintaining CO_2 levels within the comfort range, however, an excessive opening can cause an inadequate temperature [Lei et al, 2017]. The opening of the windows are determined by levels of outside temperature, for example, in Mediterranean areas, the windows are kept closed when the outside temperature is below $15^{o}C$ [Heracleous et al, 2019]. The window opening time in spring and autumn has a similar duration. In general, when the heating systems are turned off, the opening time of

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

the windows increases, reaching a duration of 4,2 to 5,8 hours, according to studies carried out in North China. However, during the summer the opening time can reach 12 hours [Huang et al, 2018]

The opening of windows, under a perception criterion, suppose energy losses, thus, Stabile et al (2019) concluded that in these cases, the air renewal rate can be found between 0,43-0,88 h^{-1}, producing energy losses of heat between 8-15%.

There are passive systems for air renewal such as windcatchers. Jomehzadeh et al, carried out a systhematic review on the "windcatcher", in which it is revealed that these natural ventilation devices generally achieve an adequate Indoor Air Quality, providing an air supply rate between 5–27,1 *l/(s·per occupant)*. These devices allow CO_2 levels to be kept within the minimum requirements, especially when combined with other external openings [Jomehzadeh et al, 2017]

Ventilation systems allow controlling the quality of the indoor air, although they are able to guarantee better quality levels through mechanical ventilation systems than with natural ventilation systems. In forced ventilation systems, the distribution of rooms, furniture, supply air temperature, type of air supply, ratio of fresh inlet air and air filters are parameters to optimize to guarantee the elimination of contaminants inside and achieve adequate thermal comfort. Also, greater efficiency is achieved through the use of heat recovery units, air dehumidifiers and adequate air control systems.

A high vertical temperature gradient should be avoided and a uniform temperature distribution at the horizontal level should be maintained. To achieve these results, the use of air inlets by means of displacement ventilation is preferable. Moreover, they are also effective in removing indoor pollutants. However, personalized ventilation allows to adapt the thermal comfort individually, but they are not as effective in removing particles above 7,5 mm. Lastly, under-floor air distribution also guarantees good thermal comfort with energy savings of between 20-35%.

Regarding natural ventilation, one of the drawbacks is that it is carried out based on criteria of human perception. Therefore, adequate indoor air quality is not always guaranteed. In addition, ventilation in

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

winter causes energy losses and can also cause the entry of particles into the interior.

8.5. STUDY OF THE INFLUENCE OF VENTILATION IN BUILDINGS

In previous chapters, the influence of thermal mass on the indoor temperature of buildings was studied. In the chapter, a model is developed that calculates the temperature variation inside the building, based on the energy balance of the building. In the energy balance, heat exchange by conduction, air renewals and heat accumulation of the air is taken into account. Subsequently, energy contributions through solar radiation are included. In summary, the energy balance is shown below:

$$Q_{exterior\ surface}(t) + Q_{adjacent\ surface}(t) + Q_{infiltration\ and\ ventilation}(t) + Q_{internal\ gains}(t) + Q_{solar\ gains}(t) = Q_{accumulated}(t) \quad \text{[Eq.8.1]}$$

Where:

- $Q_{Exterior\ surface}$: heat losses through walls in contact with the outdoors.
- $Q_{Adjacent\ surface}$: heat losses through walls in contact with the indoors.
- $Q_{Infiltration\ and\ ventilation}$: heat losses due to unwanted air infiltration and ventilation.
- $Q_{Internal\ gain}$: heat input from electrical equipment, fuels and heat input due to human activity.
- $Q_{solar\ gains}$: heat input due to solar radiation through windows.
- $Q_{Accumulated}$: heat accmulated in the indoor air of the building.

In previous chapters the development of the model is shown. In summary, equation [Eq.8.1] is solved using the Laplace transformation through *Matlab*, obtaining equation [Eq.8.2]

The type dwelling under study throughout this document is located in Ourense and has an area of 80 m^2. The standard building has two walls in contact with the outside (total area of 120 m^2) and two walls in contact against living areas (total area of 96 m^2). The entire envelope surface is described in Table 4.11 of this document.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The influence of ventilation is evaluated in two cases, with inside thermal mass and with external thermal mass. The thermal mass is considered to be formed by concrete with a thickness of 20 *cm* and an insulation of 8 *cm*. Table 4.7 and Table 4.8 show the characteristics of the walls. Finally, it is considered that the walls against constant temperature areas found at 24*ºC* and the soil temperature is 22*ºC*.

$$T_{int}(s) = \sum_i \frac{h_{int} \cdot A_i}{h_{int} \cdot \sum(A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V + C_{p,aire} \cdot s} \cdot T_{sup,i}(s) + \sum_i \frac{h_{int} \cdot A_0}{h_{int} \cdot \sum(A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V + C_{p,aire} \cdot s} \cdot T_{0,i}(s) + \frac{0{,}32 \cdot n \cdot V}{h_{int} \cdot \sum(A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V + C_{p,aire} \cdot s} \cdot T_{ext}(s) + \frac{1}{h_{int} \cdot \sum(A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V + C_{p,aire} \cdot s} \cdot Q_{internal\ gains}(s) + \frac{1}{h_{int} \cdot \sum(A_i + A_{0,i}) + 0{,}32 \cdot n \cdot V + C_{p,aire} \cdot s} \cdot Q_{solar\ gains}(s) \quad \text{[Eq.8.2]}$$

The study consideres the most unfavourable climatic conditions registered in the city of Ourense. One of the days with the highest temperature corresponds to June 8, 2013. This day a maximum temperature of 40,99*ºC* and a minimum temperature of 17,08*ºC* was registered [Meteogalicia, 2018]

Regarding ventilation, the case study supposes natural ventilation due to the opening of windows. The reference value is taken from the study by Canha et al (2017), where they analyze different ventilation strategies in a room during sleeping hours.

In the study, the air change rates when the windows are closed is 0,67 ± 0,28 h^{-1}, so this data corresponds to air infiltration. While when opening a window with a surface area of 1,8 m^2, the ratio increases to 2,20 ± 0,86 *h-1* [Canha et al, 2017]. Despite the fact that the study is only carried out in one room, these values are taken for the case study.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

First, the response of the system is analysed, when the thermal mass is on the outside and the insulation on the inside, the result is shown in Figure 8.6:

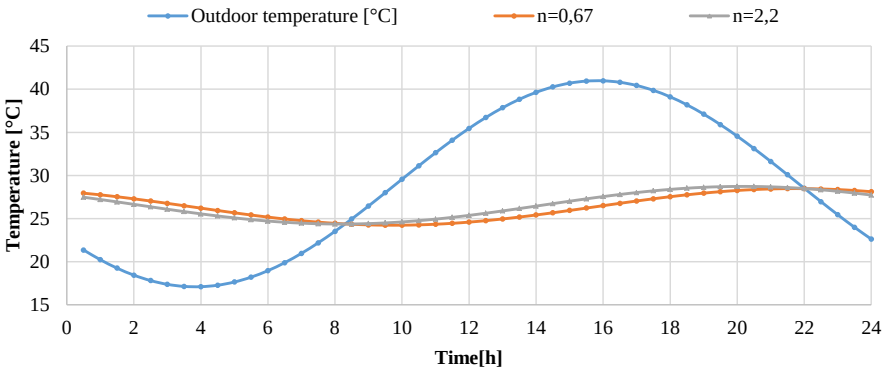

Figure 8.6: Evolution of the outdoor and indoor temperature for different air change rates (0,67 and 2,2h^{-1}) for enclosures with outside thermal mass

With a wave disturbance with an amplitude of 23,89 *ºC*, the response generated by the system considering an air change rates of 0,67 h^{-1}, reduces the wave amplitude to 4,24 *ºC*. Furthermore, as has already been evaluated in previous chapters, it causes a delay in the maximum temperature peak, which reaches 28,47 *ºC*. The maximum indoor temperature peak occurs at 22:00, that is, it delays the temperature peak by 5,5 hours. However, when performing ventilation with an air change rates of 2,20 h^{-1}, a maximum temperature of 28,7 *ºC* is reached at 20:00 and a temperature variation of 4,36 *ºC*. In this case, the maximum temperature peak is delayed 3,5 hours.

Regarding minimum temperatures, a lower temperature is reached with a higher ventilation rate in the early hours of the day. The minimum temperature reaches 24,36 *ºC*, compared to 17,09 *ºC* registered outside.

Figure 8.7 shows the response of the system in the case of having the inside thermal mass. The indoor temperature with the inside thermal mass is more stable. For air change ratio of 0,67 h^{-1}, the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

response generates a wave with amplitude of 0,78 *ºC* and a maximum temperature peak of 26,74*ºC*.

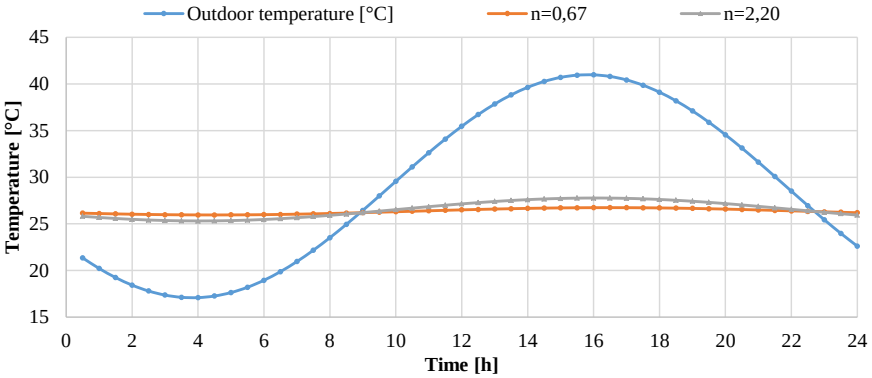

Figure 8.7: Evolution of the outdoor and indoor temperature for different air change rates (0,67 and 2,2h^{-1}) for enclosures with inside thermal mass

By introducing an air change ratio of 2,2 h^{-1}, the generated wave has an amplitude of 2,46*ºC*, generating a maximum temperature of 27,77*ºC*. The maximum peak indoors is equal to the maximum temperature peak outdoors, since it has the thermal mass inside. The response generated is so stable that it is easily influenced by the renewal of the outside air.

As a summary, Table 8.1 shows the response of each system to the two air change ratios analysed. Having inside thermal mass generates a more stable response. It also allows obtaining a lower maximum indoor temperature of 26,7*ºC*, compared to the 28,47*ºC* that is obtained with the outside thermal mass.

However, an increase in the rate of air change, when the thermal mass is inside, produces an increase in the temperature range of 215%, compared to an increase of 2,8% when the thermal mass is outside.

Opening the windows reduces the concentration of indoor air contaminants that has been shown throughout the systhematic review. However, under high temperature seasons, especially in summer, natural ventilation can end up causing thermal discomfort [Canha et al, 2017]. However, although the temperature increase is greater with walls with the thermal inertia inside, the maximum temperature

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

reached is still lower. However, the opening of windows during the first hours of the day should be prioritized, since it allows reducing the indoor temperature due to the low outdoor temperature.

Table 8.1: Summary of the evolution of temperature with the air change rate

	Type of wall	Outdoor temperature	External thermal mass	Inner thermal mass
Air Change Rates, n=0,67 h^{-1}	Maximum temperature [ºC]	40,98	28,47	26,74
	Minimum temperature [ºC]	17,09	24,23	25,96
	Temperature range [ºC]	23,89	4,24	0,78
Air Change Rates, n=2,20 h^{-1}	Maximum temperature [ºC]	40,98	28,72	27,77
	Minimum temperature [ºC]	17,09	24,36	25,32
	Temperature range [ºC]	23,89	4,36	2,46

In order to test the response of the mathematical model, the interior temperature is simulated with a window opening during the coldest hours of the day, with a wall with an inside thermal mass. This type of wall, due to its greater time lag, results in the highest interior temperature occurring 5,5 *hours* after the outdoor maximum temperature, so the maximum temperature is reached at 21:00.

Therefore, air losses due to infiltration (0,67 h^{-1}) were considered during the day, while at night, air renewal due to window opening was considered (2,2 h^{-1}). The simulation performed is shown in Figure 8.8. In this case, lower temperatures are achieved at night, taking advantage of the cooler air outside and maintaining the temperature more stable during the day.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

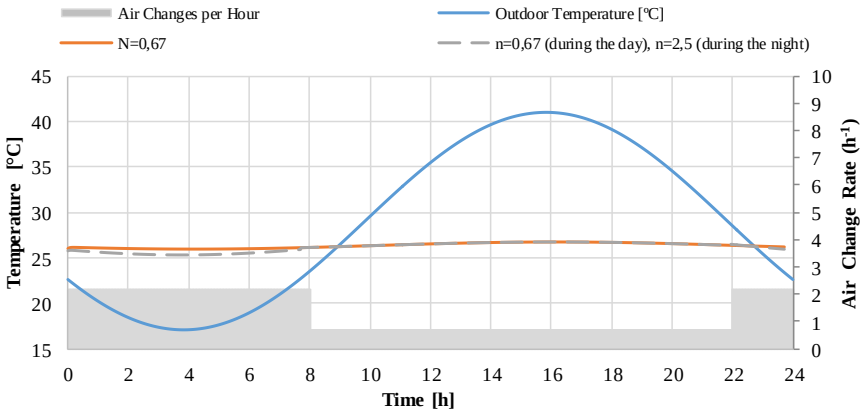

Figure 8.8: Evolution of the outdoor and indoor temperature for an air change rates of 0,67 h^{-1} during the day and 2,2h^{-1} during the night for enclosures with inside thermal mass

In this way, a maximum daily temperature of 26,74*ºC* and a minimum of 25,32*ºC* are reached. With the simulation carried out, the CO_2 concentration is not analysed so if the residential house were occupied during the day, it might be necessary to carry out ventilation to avoid a high concentration of CO_2. In this case, ventilation must be guaranteed throughout the day, to achieve greater energy efficiency, ventilation systems with heat recovery must be used.

Finally, according to the article by Fernandez-Aguera et al (2019), ventilation during the winter in buildings located in Spain was carried out between 10-30 *min* during the morning. In this case, the simulation is carried out for the model home in which natural ventilation is established for 30 minutes every two hours a long day. In this case, a wall with outside thermal inertia on the outside is considered.

The external conditions taken as a reference are those already mentioned in previous chapters. The reference values are from the city of Ourense, where on the reference day, the temperature varied throughout the day between 8.9 and -5.8 *ºC*.

The indoor conditions of the house are assumed that the parts against unheated spaces are at a temperature of 21 *ºC*. In addition, it is

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

assumed that the house has a heating system that makes the average temperature of the house is 19ºC.

The Figure 8.9 shows the simulation performed. As the thermal mass is placed outside, the response to the inside temperature has a greater oscillation. On the contrary, as expected, when opening the windows a reduction in the indoor temperature is obtained, being greater in the early hours of the day. The temperature can be reduced to 0,9 ºC when the window is opened for 30 min, so that undesired energy losses occur.

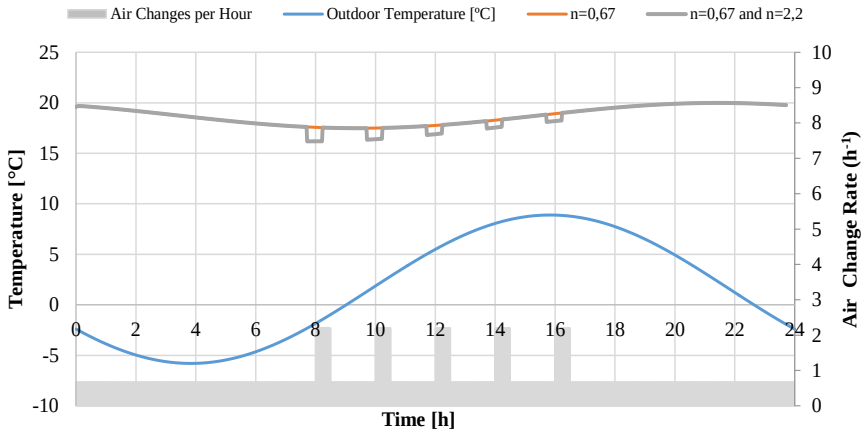

Figure 8.9: Evolution of the outdoor and indoor temperature for an air change rates of 0,67 h^{-1} and 2,2h^{-1} during the winter for enclosures with outside thermal mass

The renewal of air in buildings through windows generates significant energy losses and adequate indoor air quality cannot always be guaranteed without losing thermal comfort. Currently on the market there are air renewal systems that allow the exit of polluted air and the entry of fresh air, recovering the energy of the exhaust air. The heat recovery units in ventilation systems allow minimizing energy losses and introducing the necessary fresh air to guarantee adequate indoor air quality.

The heat recovery units allow bypassing the equipment. In this way, they allow the entry of fresh air into the interior of the house

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

when the outside temperature is lower, allowing to reduce the indoor temperature in summer. While during the day, the recovery system is operational to cool the outdoor air with the cooler indoor air.

In nearly zero-energy buildings, the use of heat recovery units is almost a necessity. Passive House buildings, heat recovery ventilation units are the key in terms of energy savings. Ventilation systems without heat recovery can lose 24 kWh/m2·yr, while in Passive House buildings the maximum heating demand is only 15 $kWh/m^2 \cdot yr$, with a ventilation system electrical consumption of 0,45 Wh/m^3 [iPHA]

8.6. COVID-19 AND INDOOR AIR QUALITY

On March 11, 2020, the WHO concludes in its assessment that COVID-19 can be considered a pandemic. COVID-19 is a disease caused by a coronavirus (known as SARS-CoV-2) first detected in late 2019 in China, in Wuhan province [WHO]. The human-to-human transmission mechanism for SARS-CoV-2 is through contact and inhalation of drops and respiratory aerosols emitted by a patient. It can also be produced by indirect contact between hands and contaminated objects [Ministry of Health, 2021]

Viruses were already included as a biological hazard within the ASHRAE classification along with bacteria and fungi [ASHRAE, 2009]. However, after this new global pandemic, ventilation systems and indoor air quality are becoming more important. The number of articles published in relation to indoor air quality had begun to increase since 1990, reaching more than 1.000 publications per year in 2017 (see Figure 8.2). Following the emergence of COVID-19, indoor air quality and proper ventilation in buildings began to be of greater importance. In 2020 with the term “Indoor air quality” in Web of Science, 1.474 articles were registered, an increase of 14,8% compared to 2019. Regarding the search “Ventilation and Air Conditioning”, in 2020 the published 1.257 articles, an increase of 9,5% compared to 2019 [WOS]

To guarantee adequate air quality and minimize the risk of SARS-CoV-2 spread, adequate air renewal is necessary. Therefore, during this period, many of the HVAC systems have been modified eliminating the recirculation of air and increasing the supply of air

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

from outside to inside. This change in the mode of operation generates higher energy consumption, registering increases of 128% compared to the period prior to the pandemic [Zheng et al, 2021]. The use of heat recovery units allows the recovery of 75% of the energy. To minimize the risk of contagion from these systems, HVAC systems should be disinfected periodically using chemical disinfection (1% hypochlorite). Furthermore, a temperature and humidity greater than $21^{o}C$ and 40% must be maintained to reduce the survival time of SARS-COV-2 [Elsaid et al, 2021]

Natural ventilation played a fundamental role in minimizing the presence of COVID-19, especially in schools. According to the analysis carried out by Park et al (2021) in schools in Korea, cross ventilation with window openings of 30% produced renewal rates of 11,20 h^{-1}. Under these conditions, the risk of infection was less than 1% in exposure times below 3 hours. Due to the high ventilation, there was a 22,5% increase in air conditioning consumption. The reduction of the duration of the classes, the increase of the working hours of the buildings and the virtual classes allow to reduce the number of people infected with the virus [Mokhtari et al, 2021]

However, despite maintaining natural ventilation in the classrooms, the minimum recommended CO_2 values (700 *ppm*) can be exceeded. According to the study carried out by Villanueva et al (2021) in classrooms of Central-Southern Spain, lower concentrations of CO_2 were detected in preschool classrooms, followed by primary classrooms and in higher concentration in secondary classrooms. The values recorded in secondary school classrooms registered CO2 concentrations above 2.000 *ppm*. In addition, PM2.5 and PM10 concentrations were recorded in the classrooms, exceeding the 8-hour exposure values set by the WHO (25 $\mu g/m^3$ and 50 $\mu g/m^3$ respectively). Alonso et al (2021) analysed indoor air quality and thermal comfort in winter in two classrooms located in Mediterranean Climate. Through the use of natural ventilation, the CO_2 concentration was reduced by 400 *ppm*, however, 60% of the hours the classrooms were outside the comfort zone.

The measurement of CO_2 concentration has become an indicator of adequate ventilation. However, if there is an air purification system

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

such as HEPA filters, they are capable of eliminating viruses, but not reducing the CO_2 concentration [Jones et al, 2020]. HEPA filters remove up to 99,7% of particles with a size of 0,3 μm. Furthermore, HEPA filters, ionizer filters and UVGI are also recommended for the current scenario [Agarwal et al, 2021]

The appearance of SARS-COV-2 has highlighted the importance of maintaining adequate indoor air quality in buildings to minimize infections. The current buildings were not prepared to guarantee adequate ventilation, so the use of natural ventilation has been essential to guarantee a healthy environment. However, due to the lack of facilities, thermal comfort in buildings has been reduced. Therefore, buildings must evolve and society must start investing in HVAC systems including monitoring systems. The measurement of indoor air quality in real time allows HVAC systems to adapt to the conditions of each moment.

To estimate the concentration of CO_2 inside a building, the balance used by Schibuola et al (2021) is used:

$$C(t) = C_{ext} + \frac{G \cdot 10^6}{\frac{ACH \cdot V}{3600}} - \left(C_{ext} - C_0 + \frac{G_{in} \cdot 10^6}{\frac{ACH \cdot V}{3600}} \right) \cdot e^{\frac{-ACH \cdot t}{3600}} \qquad \text{[Eq.8.3]}$$

Where

- $C(t)$: CO_2 concentration [ppm]
- C_{ext}: Outdoor CO_2 concentration [ppm]
- C_0: Initial CO_2 concentration [ppm]
- G_{in}: Indoor CO_2 generation (0,0041 l/s for men and 0,0035 l/s for women with sedentary activity).
- ACH: Air Changes per Hour [h^{-1}]
- V: Volume considered [m^3]
- t: time [s]

To continue with the study carried out in point 8.5, a building of 80 m^2 with a volume of 480 m^3 is considered. The air changes per hour considered are those indicated by Canha et al (2017); considering all the windows closed (0,67 ± 0,28 h^{-1}), and for natural ventilation (2,20 ± 0,86 h^{-1}). An outdoor and indoor CO_2 concentration of 400 ppm is considered.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

In Figure 8.10, the increase in CO_2 concentration for an *ACH* of 0.67 h^{-1} is shown. This value with the windows closed and corresponds to air infiltrations. Despite considering an area of 80 m^2, with 6 people inside, the CO_2 concentration is close to the recommended limit values (700 *ppm*) and with 8 people the recommended value is exceeded. On the other hand, with 8 people inside, it would take 2,5 hours to reach safe CO_2 values.

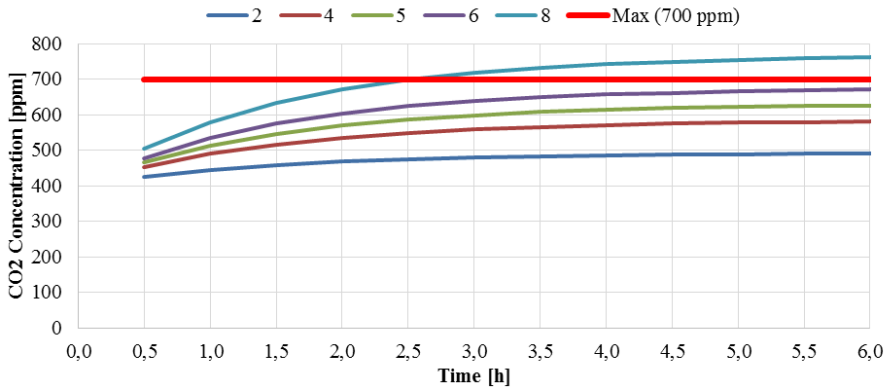

Figure 8.10: Evolution of CO_2 concentration as a function of the number of people considering an ACH = 0,67 h^{-1}

In the case of natural ventilation by opening windows (*ACH* = 2,2 h^{-1}), the maximum number of people allowed is 24 (Figure 8.11). However, the recommended limit is reached in 1,5 hours. With fewer people inside, the maximum CO_2 concentration is not reached.

Building ventilation must be adapted to the number of people inside. Carrying out natural ventilation helps to keep the CO_2 concentration within safe values but generating energy losses, so it can generate moments of thermal discomfort. Therefore, the use of mechanical ventilation with heat recovery and regulating according to the indoor concentration of CO_2 is one of the solutions to ensure adequate air quality with the least energy consumption.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

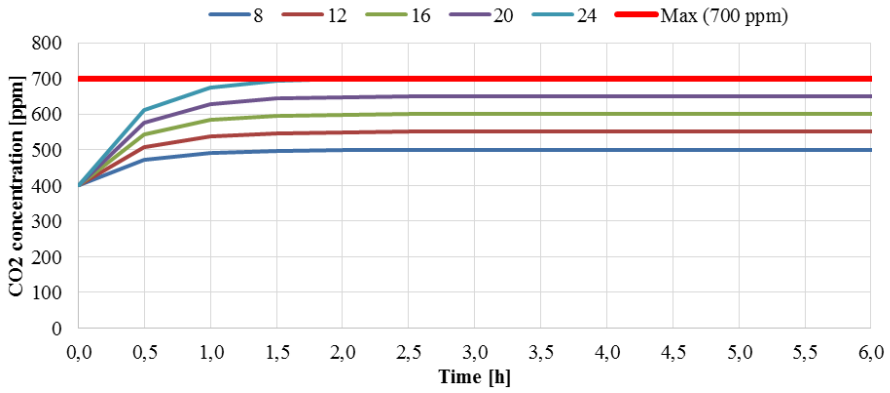

Figure 8.11: Evolution of CO_2 concentration as a function of the number of people considering an ACH = 2,20 h^{-1}

8.7. DISCUSSION

People spend about the 90% of the time indoors (homes, workplaces, and entertainment places). Knowing the air we breathe in these spaces is essential to guarantee a healthy environment, since it is related to respiratory diseases that affect the health. The inclusion of quality control parameters related to chemical and biological hazards complement those already used for thermal comfort.

Analysing the evolution of the related publications on "Ventilation and Air Conditioning" and "Indoor Air Quality", a rapid growth has been observed since 2005. The 79% of the publications have been made in the last 15 years, since the first publication registered in WOS in 1927. This increase in the number of publications may be due to the sensitization by the European Union to guarantee adequate air quality. In 2004 "The European Environment & Health Action Plan 2004-2010" was published, in which explicit reference is already made to improving indoor air quality [EU, 2004]. Subsequently, in 2005, the European Union began the INDEX Project, where a network of experts in the area of indoor air communication was created in order to develop a community action plan indicating, in addition to the pollutants present in European homes [EU, 2005]

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

One of the main pollutants present in indoor air is carbon dioxide (CO_2), produced mainly by human respiration. The CO_2 limits in indoor spaces, according to official organisms, are between 1.000 and 1500 *ppm*. In public or residential buildings that do not have HVAC systems, the main way to keep CO_2 levels within the recommended parameters is mainly done by natural ventilation. As can be seen in the Figure 8.4, there are a greater number of publications on natural ventilation and residential and educational buildings, however, the relationship of publications between natural ventilation and offices is poor.

The most used way to carry out natural ventilation is by opening windows. The opening of windows in a periodic and controlled way, allows reaching healthy levels in indoor spaces. However, one of the problems detected in this type of ventilation is that during cold seasons, indoor CO_2 levels increase. This is due to a reduction in natural ventilation caused by the low temperatures of the outside air, since in these cases it also represents a loss of energy. While in warmer times, the CO_2 concentration is maintained due to increased ventilation through the windows.

HVAC systems have been shown to be efficient in maintaining adequate air quality in relation to CO_2 concentration. However, these systems must be correctly designed, since an HVAC system without air renewal, causes higher levels of CO_2 inside and therefore, does not guarantee an adequate CO_2 concentration.

With a suitable and optimized HVAC system, adequate air quality and thermal comfort can be guaranteed. Ventilation strategies based on the analysis of CO_2 concentration, not only allow maintaining adequate air quality, but also several studies have obtained energy savings based on this type of control strategies. These types of control strategies have been tested in office buildings, obtaining good levels of satisfaction among users. Therefore, the optimization of HVAC systems should be achieved, as they allow reaching thermal comfort levels and adequate indoor air quality with the lowest energy consumption. For this, parameters such as the selection of the CO_2 setpoint, the ratio of fresh outside air to the total, analysis of air

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

distribution, air delivery temperature and use of heat recovery systems must be taken into account.

Another pollutant that affects indoor air quality and is also present in buildings is particulate matter (PM2.5 and PM10). Among the revised bibliography, it is highlighted that one of the main sources of particle contamination is from outdoors; there are also indoor sources of particles due to human activity such as cooking, cleaning and smoking. The particulate material from the outside penetrates inside the buildings through HVAC systems and by natural ventilation, especially in buildings near highways and sources of contamination. The main method to prevent this type of pollutants is the use of suitable filters in HVAC systems. In the case of natural ventilation, keeping the windows closed reduces the entry of particles into the interior, but can increase CO_2 levels due to lack of ventilation, so opening windows should be prioritized to those areas where fresh air can be more pure and maintain reduced air flow.

Finally, there is the presence of other indoor contaminants such as Volatile Organic Compounds, highlighting formaldehyde. The main emitting source of these compounds in buildings is related to the type of construction materials or objects present inside buildings, such as paints, glues, solvents and cleaning products, among others. Due to their high volatility, the presence of these compounds increases with temperature. However, the increase in the air renewal rate favours the reduction of these pollutants, thus improving indoor air quality.

Another of the dangers present in indoor air is the presence of biological contaminants. The amount of water available in the materials is the most important trigger for the growth of microorganisms, including fungi. Outdoor intake air can contribute to a higher concentration of bacteria and fungi inside homes. However, HVAC systems can be another source of contamination if proper maintenance is not performed on filter systems.

Regarding humidity and temperature, the influence of these parameters is known to guarantee thermal comfort. The humidity and temperature parameters are deviated from the comfort conditions due to human activity. Achieving adequate thermal comfort and air quality with natural ventilation systems is not always effective. Opening the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

windows in cold times in order to improve the indoor air quality, can cause drops in temperature and generate energy losses. Therefore, if it depends on human criteria, it will prioritize guarantee the indoor temperature. HVAC systems are efficient to establish an adequate temperature and humidity. However, parameters such as the discharge temperature, the fresh air ratio, the air distribution and analyse the layering to specify adequate thermal comfort must be optimized.

In the reviewed bibliography, the most studied types of pollutants that affect air quality include carbon dioxide, particulate matter, and volatile organic compounds, especially formaldehyde. In order to summarize the most important information collected, Table 8.2 is elaborated. The table shows the three types of hazards (chemical, biological and physical), with the main emission sources and ventilation proposals for the control of each parameter.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 8.2: Summary of indoor air quality parameters, sources and control ventilation

Hazard	Main sources	Ventilation
	CHEMICAL HAZARDS	
Carbon Dioxide (CO_2) **Limit:** <1500 ppm <1000 ppm (ASHRAE)	• Human breath. • Human activities such as cooking and drying clothes. • Combustion of fossil fuels in indoor spaces.	**Natural Ventilation:** • The opening of windows allows to maintain the CO_2 concentration in adequate values • During winter, the opening time is reduced, causing a higher concentration of CO_2 • In schools, it should be ventilated between breaks to avoid CO_2 accumulation. • Automation system of opening and closing of windows **HVAC Systems:** • The use of air conditioning systems can cause CO_2 if there is not an adequate supply of fresh air. • Ventilation control based on indoor CO_2 levels
Carbon Monoxide (CO) **Limit:** 10 mg/m3 (8 hours)	• Inadequate combustion of fossil fuels. • External infiltration of CO towards the interior	**Natural Ventilation and HVAC Systems:** • Increasing the ventilation rate reduces the CO concentration.

Particle Matter (PM2.5 and PM10). **Limit:** PM2,5: <25 µg/m^3 (24h mean) <10 µg/m^3 (annual mean) PM10: <50 µg/m^3 (24h mean) <20 µg/m^3 (annual mean)	• Human activities such as smoking, cleaning or cooking. • Indoor activities cause resuspension of particulate matter. • Pollution from outdoor (traffic or industrial activities).	**Natural Ventilation:** • Close the windows to avoid the external entrance of particulate matter. • Prioritize the opening of windows oriented towards areas with cleaner outdoor air. **HVAC Systems:** • The use of fine filters in systems with mechanical ventilation prevents the entry of particles into the interior.
Formaldehyde (HCHO) **Limit:** 0,1 mg/m3 (30-minute average concentration).	• The concentration of formaldehyde (and of volatile organic compounds) increases with temperature due to its low volatility. • The origin of these compounds comes from materials used indoors: glue, furniture, resins, DIY products, cleaning products, shoe products, cosmetics, electronic products and paper products. • Combustion of fossil fuels in indoors. • Pollution from outdoor traffic.	**Natural Ventilation and HVAC Systems:** • The concentration of formaldehyde is reduced by increasing the rate of air renewal • Keeping the indoor temperature below 22 ºC would help to keep the concentration of volatile organic compounds within healthy limits.
Radon **Limit:** <300 Bqm/m^3	• Radon comes from the decomposition of the existing radium in the soil	**Natural Ventilation and HVAC Systems:** • Increasing the ventilation rate reduces the indoor Radon presence.

BIOLOGICAL HAZARDS		
Bacteria, viruses and fungi	• The presence of high humidity, condensation and water damage that promotes the growth of bacteria and fungi. • Human activity is a focus of contamination of the air by bacteria, fungi and virus. • Presence of fungal pollutants from outdoors.	**Natural Ventilation and HVAC Systems:** •Lack of ventilation increases the concentration of bacteria and fungi. •HVAC systems can be another source of biological contamination. •Perform proper maintenance of HVAC systems. These systems can be a focus of biological contamination
PHYSICAL HAZARDS		
Temperature **Limit:** >20ºC in winter <26ºC in summer	• Energy losses due to the thermal envelope of the building. • HVAC systems not poorly designed or not optimized. • Excessive solar energy inputs. • Presence of people and electronic equipment increases the interior temperature. • Human activities such as cooking.	**Natural Ventilation:** • Natural ventilation has higher values of temperature and humidity than air conditioning systems **HVAC Systems:** • Adjust the air distribution temperature between 23 and 26ºC. • Select the appropriate air flow temperature and type of supply. • Adapting the supply air speed, a low speed can cause a greater stratification.
Humidity **Limit:** 40-50% in winter 45-60% in summer	• People are a source of moisture. • Human activities such as cooking or drying clothes indoors.	**Natural Ventilation:** • Natural ventilation has higher values of temperature and humidity than air conditioning systems **HVAC Systems:** • Installation of dehumidifier in the air inlet.

Regarding chemical hazards, WHO (2010) includes in its guide the selected contaminants to guarantee adequate indoor air quality, the following: benzene, carbon monoxide, formaldehyde, naphthalene, nitrogen dioxide, polycyclic aromatic hydrocarbons, radon, trichloroethylene, and tetrachloroethylene. ASHRAE (2019) also includes ozone, sulphur dioxide, and carbon dioxide as inorganic contaminants that must be taken into account to maintain adequate air quality. Finally, the European Union in the INDEX Project, where the action plan in the field of indoor air pollution is evaluated, also includes the following pollutants: acetaldehyde, toluene, xylene, styrene, ammonia and alpha fineno [EU, 2005]

In this review, citations were not found for all of the previously named chemical hazards. Carrying out an in-depth systhematic review of those chemical compounds would allow characterizing the compounds present in indoor air and their sources. Knowing the source of the different chemical dangers, it is possible to act on them, by using more sustainable materials that prevent the emission of compounds harmful to people's health.

The effect of different ventilation systems on the interior concentration of different compounds must also be evaluated. As already seen, ventilation helps to reduce the concentration of compounds such as CO_2, CO, formaldehyde and radon and to improve the indoor air quality. However, depending on the location of the buildings, the inadequate use of ventilation systems can aggravate the quality of the indoor air due to contamination from the outside. Therefore, the influence of ventilation on each one of the compounds must be evaluated in order to maintain adequate indoor air quality through the use of different materials in buildings, or technological improvements in ventilation systems.

Among the biological type pollutants, humidity and temperature conditions, as well as the presence of water, are key factors in the growth of microorganisms. Among the sources that emit these types of hazards, the construction elements of buildings take on special importance. Thermal bridges are a point in the building envelope, where the appearance of humidity is frequent, causing the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

proliferation of molds. Therefore, the constructive quality of buildings with a good thermal envelope, guarantee adequate indoor air quality.

There are several risk factors that have not been identified within the ASHRAE classification. In the case of "Physical hazards", temperature and humidity are environmental parameters that are taken into account to guarantee adequate air quality, but there is no mention of levels of ionizing and nonionizing electromagnetic radiation, noise, vibration, illumination and force.

8.8. CONCLUSIONS

The systhematic review carried out on the relationship between the topics "Indoor air quality" and "Ventilation and air conditioning" shows that they are topics with a greater presence in the scientific literature. The increase in the number of publications also shows greater interest in this area of work. The main conclusions drawn from this review are summarized below:

- The presence of CO_2 is mainly due to human action. Maintaining the CO_2 concentration with natural ventilation systems and manually is possible; however, it could be altered in cold times of the year, due to external factors such as temperature. The automation of both natural and HVAC ventilation systems guarantee adequate CO_2 values, without compromising thermal comfort.
- The main source of particulate matter comes from external pollution. The installation of filters in HVAC systems significantly reduces the presence of indoor particles. Regarding natural ventilation through the opening of windows, it may not be efficient if it is not used properly. Maintaining low ventilation and prioritizing the entry of fresh air in avoiding the particle emitting focus, helps control particulate matter indoors.
- The presence of volatile organic compounds is linked to temperature. The increase in temperature causes an increase in the air of these compounds, due to volatility. However, adequate ventilation maintains adequate indoor air quality. The selection of the appropriate materials in the construction of buildings contributes to reducing the presence of these compounds.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

- The use of HVAC systems can be a source of biological hazards, due to the proliferation of bacteria in the equipment while it is turned off. Therefore, regular maintenance must be carried out on this equipment in order to reduce the concentration of bacteria and fungi in the environment.
- The temperature and humidity in interior spaces is mainly altered by human presence. Natural ventilation systems, by manually opening windows, may not be modified for thermal comfort and adequate air quality.

Regarding the results detected when using the model developed throughout this work, in which the influence of thermal inertia on indoor temperature was analysed. The following conclusions were drawn.

- Buildings with inside thermal inertia generate a more stable indoor temperature. When applying natural ventilation by opening the windows, the indoor temperature experiments a greater oscillation and the resulting wave has the same phase as the wave of outside temperature.
- In buildings with outside thermal inertia, due to their configuration, the indoor temperature range throughout the day is greater than in buildings with the inside thermal mass. Therefore, when entering ventilation, the indoor temperature only changes in a 2,8%. Also produces a phase shift of the interior temperature wave.

Ventilation systems, both HVAC systems and natural ventilation systems, are capable of guaranteeing adequate air quality. HVAC systems are more effective in achieving Indoor Air Quality, since their operation can be automated by installing controls based on CO_2 concentration. However, when natural ventilation systems are used, the air renewal test depends on human factors, therefore air quality is not always guaranteed to be adequate and without affecting thermal comfort conditions.

Therefore, the improvement of current air conditioning systems should be proposed both in new buildings and in buildings already built. The replacement or improvement of these systems should not be

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

based only on energy efficiency objectives, but should be based on objectives of improvements in air quality.

The model proposed throughout this work allows us to also include the air renewal conditions of the buildings. The model allows taking into account the physical characteristics of the buildings in order to know the evolution of the indoor temperature. The time lag between the indoor and outdoor temperature is a parameter to take into account, to guarantee more stable temperatures or to be able to construct buildings that allow taking advantage of the time lag, to guarantee adequate temperatures during peak hours.

Furthermore, adequate ventilation allows maintaining the CO_2 concentration at safe values, and therefore reducing the spread of COVID-19. Ensuring an adequate CO_2 concentration depends mainly on the volume of the house, the number of occupants and the type of activity carried out. Therefore, the proper design of ventilation systems ensures a healthy indoor environment.

Currently, ventilation control systems take into account the parameters of temperature and air quality to guarantee ventilation that allows adequate conditions of comfort and indoor air quality. Knowing the building construction parameters can anticipate the control response by knowing how the temperature evolves.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

CHAPTER 9. INFLUENCE OF BUILDING DESIGN ON THERMAL COMFORT: ANALYSIS OF THERMAL INERTIA

This chapter is a reproduction of the following publication derived from the research carried out by the doctoral student during the training stage:

- Title: Influence of thermal inertia and ventilation in thermal comfort
- Authors: Vilaboa Díaz, A; Bello Bugallo, P.M.
- Publisher: Elsevier
- Journal: Energy for Sustainable Development
- ISSN: 0973-0826
- Impact Factor: 5,223 (2020)
- Year of publication: under review, 2021
- Contribution of the doctoral student: contribution to development of the research and writing of the paper.
- Authorization of the journal/publisher for the use of the publication in the doctoral thesis. URL:
  https://www.elsevier.com/about/policies/copyright/permissions
  The permission policy indicates that the author of a publication in the publisher has permission to use it both in the thesis document and in the defense. This URL is exactly transcribed below
  - Can I use material from my Elsevier journal article within my hesis/dissertation? As an Elsevier journal author, you have the right to include the article in a thesis or dissertation (provided that this is not to be published commercially) whether in full or in part, subject to proper acknowledgment; see the Copyright page for more information. No written permission from Elsevier is necessary. This right extends to the posting of your thesis to your university's repository provided that if you include the published journal article, it is embedded in your thesis and not separately downloadable.
  - Can I include/use my article in my thesis/dissertation? Yes. Authors can include their articles in full or in part in a thesis or dissertation for non-commercial purposes.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

SUMMARY

The appropriate design of the thermal envelope, the solar shadow devices and the ventilation allows reducing the energy demand in cooling and heating. In addition, the optimization of these elements must guarantee a healthy environment both from the point of view of thermal comfort and indoor air quality.

In this chapter, current models of thermal comfort are analysed in order to evaluate which of the techniques evaluated in this thesis have the greatest influence on thermal comfort. The use of models based on the thermal balance and the adaptive model in air conditioning systems allow significant savings compared to fixed setpoint systems.

Finally, taking into account that the thermal envelope has a fundamental role, the thermal comfort generated by a thermal envelope with different insulation locations and thermal mass are evaluated. In this way, it is shown that the placement of the thermal mass on the outside, allows achieving a greater degree of thermal comfort and also reducing the energy demand in cooling.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

9.1. INTRODUCTION

People have always tried to create a pleasant and comfortable environment to live. The development of technology has allowed human beings to adapt in search of more favourable environmental conditions. The use of hot and cold equipment helps to achieve an adequate temperature in summer and in winter. However, this higher energy consumption is not always accompanied by better thermal comfort conditions as it depends on more variables.

Thermal comfort, according to ASHRAE Standard 55, is defined as: "condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation". ASHRAE Standard 55, lists six factors that must be analysed and that defines the conditions for thermal comfort: Metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, humidity [ASHRAE, 2010]

In certain cases, extreme thermal conditions can affect human health (Thermal Stress). Fantozzi et al (2020), carried out a systhematic review, in which he compiled a list of 46 thermal comfort indictors and 35 heat stress indicators. Among the most historically used indicators, the "Predicted Mean Vote" indicator (PMV) for the evaluation of thermal comfort and the WBGT (wet bulb globe temperature) for the evaluation of thermal stress stand out, however, adaptive comfort models are also used today to estimate users behaviour. The PMV thermal comfort model is developed based on ASHRAE Standard 55. Therefore, achieving adequate thermal comfort does not only depend on physical factors such as air temperature, radiant temperature, air speed and humidity, but that also depends on human factors such as metabolic rate and clothing used.

Achieving adequate thermal comfort, through HVAC systems, involves energy expenditure and sometimes without achieving an adequate feeling of comfort. The development of the society produces an increase in the energy demand in air conditioning, on the one hand due to a greater demand on the set-point temperature and secondly due to the market penetration of air conditioning systems [Alnuaimi et al, 2020]

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Optimizing design parameters are essential for obtaining high-performance buildings. There are different standards, which evaluate the efficiency of the building. The German Passive House standard is based on the performance of the buildings, thus, it establishes heating and cooling needs of a maximum of 15 $kWh/(m^2 \cdot y)$, with a maximum limit that must not exceed 25^{o}C during 10% of the time and infiltration losses of 0,6 air changes per hour (ACH) [Schnieders et al, 2019]

The current Spanish building stock has a lot of capacity in improving the energy efficiency of buildings. The use of more restrictive regulations such as Minergie Standard compared to Spanish regulations, can lead to energy savings in heating of 89,1% in the renovation of buildings. Therefore, Spain has a clear potential for improvement in energy efficiency, improving the thermal envelope, thermal bridges and the introduction of passive elements [del Castillo et al, 2018]

There are numerous studies that evaluate the energy consumption of buildings based on design parameters. Xu et al (2018) evaluated the optimal insulation thickness, optimal glazing and window-to-wall ratio for a NEZB located in China using simulations. The highest energy saving ratio for heating was obtained by optimizing the window-to-wall ratio. For the east or west facade, a ratio between 12,5% allowed savings of 7,23%, while on the south face, the optimal ratio was obtained for 10%, obtaining savings of 6,68%. Khakian et al (2020) analysed the effect on energy consumption in a construction located in Iran, in which the orientation, window-to-wall ratio, glazing type and shading devices is evaluated. Optimizing these parameters would allow energy savings of 29% compared to conventional constructions.

The optimal urban design of a group of houses is also of particular importance. Fedorczak-Cisak et al (2020) develops a pioneering method in which not only takes into account parameters of energy consumption, but also includes parameters such as construction and organization costs, occupation costs, greenhouse gas emissions and personal criteria like architectural and urban designs. In addition of urban design, the optimization of the design parameters of

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

the buildings prior to construction, allow the construction of more sustainable buildings.

First, this chapter evaluates the thermal comfort parameters. Second, the design parameters of the buildings that allow maintaining adequate comfort conditions with an efficient consumption of energy resources are evaluated.

9.2. OBJECTIVE

The objective of this chapter is to present the current models that evaluate thermal comfort and analyse the relevant factors. This allows identifying the best technical solutions for the design or redesign in the construction of new buildings or their rehabilitation.

The definition of the comfort model according to the current state of art allows evaluating the improvement in thermal comfort depending on the location of the thermal inertia of the envelope. In CHAPTER 4, the evolution of the indoor temperature was defined as a function of the location of the thermal mass of the envelope. In this way, depending on the location of the thermal mass, the thermal comfort parameters are evaluated according to the current models.

Conclusions regarding the sustainable behaviour of buildings could contribute to approaches such as Nearly Zero-Energy Building.

9.3. METHODOLOGY

In the first part of the chapter, a review of the current state of art of comfort is made. There are many studies related to comfort in buildings, almost all of them based on thermal comfort, taking into account the characteristics of the thermal envelope and also some aspects such as the outdoor temperature, humidity, air conditioning system.

In CHAPTER 4, the influence of thermal inertia on the evolution of the indoor temperature of buildings was discussed. The evolution of indoor temperature has consequences associated with thermal comfort in buildings; therefore, using the tool developed by the University of California Berkeley, thermal comfort is evaluated in the case of introducing the thermal mass inside or outside the building.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

9.4. THERMAL COMFORT

Thermal comfort is a state in which a pleasant thermal sensation is felt with the environment and its evaluation is subjective based on people's criteria [ASHRAE, 2010]. Ensuring a comfortable thermal environment is considered the most important factor in achieving overall satisfaction with an indoor environmental quality [Frontczak et al, 2011]. For the evaluation of thermal comfort, two theories coexist with different approaches, one based on thermal balance and the other from an adaptive approach. The theory based on heat balance was developed using data from studies carried out in cold rooms, while the theory based on the adaptive model was developed using data from field studies [Fantozzi et al, 2020]

9.4.1. Heat balance method

Among the most used indicators to assess thermal comfort, is the "Predicted Mean Vote" (PMV) [Fantozzi et al, 2020]. The method of PMV, developed by Fanger in 1970, was based on an experiment carried out on 1.296 people, where he found a mathematical correlation between the general thermal sensation and the measured values of four environmental variables (air temperature, radiant temperature, air speed and humidity) and two individual variables (metabolic rate and clothing insulation) [Fanger, 1973]. According to ASHRAE Standard 55, the PMV is "an index that predicts the mean value of the votes of a large group of persons on the seven points thermal sensation scale". ASHRAE included the thermal sensation scale to predict the thermal comfort of people: +3 (hot), +2 (warm), +1 (slightly warm), 0 (neutral), -1 (slightly cold), -2 (cool), -3 (cold) [ASHRAE, 2009]

For the calculation of the PMV index, direct measurement of air temperature, air speed and humidity is required. Regarding individual variables such as metabolic rate and clothing isolation, they are variables that are tabulated and can be located in the ASHRAE Standard 55.

Regarding the average radiant temperature, ASHRAE Standard 55 defines it as "the temperature of a uniform, black enclosure that exchanges the same amount of thermal radiation with the occupant as

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

the actual enclosure". Therefore, it is an index that represents the exchange of radiation due to the difference temperature between people and the temperature of the surfaces. The average radiant temperature is calculated based on the temperature of the surfaces and the position with respect to the person. The calculation is made based on the following expression [ASHRAE, 2009]:

$$\bar{t_r}^4 = {t_1}^4 \cdot F_{p-1} + {t_2}^4 \cdot F_{p-2} + \cdots + {t_N}^4 \cdot F_{p-N} \quad \text{[Eq.6.1]}$$

Where t_N is the temperature of each surface and F_{N-1} is the angle factor between a person and the surface. ASHRAE also defines other ways to calculate the mean radiant temperature based on the surface temperature (t_{pr}) in the six directions (up, down, right, left, front, back). If the person is standing, the average radiant temperature is calculated as:

$$\begin{aligned}\bar{t_r} = \{0{,}08 \cdot [t_{pr}(up) + t_{pr}(down)] + 0{,}23 \cdot [t_{pr}(right) + t_{pr}(left)] \\ + 0{,}35[t_{pr}(front) + t_{pr}(back)]\} \\ \div [2 \cdot (0{,}08 + 0{,}23 + 0{,}35)]\end{aligned} \quad \text{[Eq.6.2]}$$

In the case that the person is sitting, the mean radiant temperature is defined as:

$$\begin{aligned}\bar{t_r} = \{0{,}18 \cdot [t_{pr}(up) + t_{pr}(down)] + 0{,}22 \cdot [t_{pr}(right) + t_{pr}(left)] \\ + 0{,}30[t_{pr}(front) + t_{pr}(back)]\} \\ \div [2 \cdot (0{,}18 + 0{,}22 + 0{,}30)]\end{aligned} \quad \text{[Eq.6.3]}$$

Using the six variables mentioned above, Fanger developed a model that quantifies comfort using the PMV indicator. Through the thermal balance of the body, he obtained the following expression collected from ISO7730.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

$$PMV = (0{,}303 \cdot e^{-0{,}0364 \cdot M} + 0{,}028) \cdot \{(M - W) - 3{,}05 \cdot 10^{-3} \cdot [5733 - 6{,}99 \cdot (M - W) - p_a] - 0{,}42 \cdot [(M - W) - 58{,}15] - 1{,}7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0{,}0014 \cdot M \cdot (34 - t_a) - 3{,}96 \cdot 10^{-8} \cdot f_{Cl} \cdot [(t_{cl} + 273)^4 - (\overline{t_r} + 273)^4] - f_{cl} \cdot h_c \cdot (t_{Cl} - t_a)\}$$ [Eq.6.4]

The clothing surface temperature (t_{Cl}), convective heat transfer coefficient (h_c) and the clothing surface area factor (f_{Cl}) are calculated variables by the next expressions:

$$t_{Cl} = 35{,}7 - 0{,}028 \cdot (M - W) - I_{Cl} \cdot \{3{,}96 \cdot 10^{-8} \cdot f_{Cl} \cdot [(t_{Cl} + 273)^4 - (\overline{t_r} + 273)^4] + f_{cl} \cdot h_c \cdot (t_{Cl} - t_a)\}$$ [Eq.6.5]

$$h_c = \begin{Bmatrix} 2{,}38 \cdot |t_{Cl} - t_a|^{0{,}25} \; for \; 2{,}38 \cdot |t_{Cl} - t_a|^{0{,}25} > 12{,}1 \cdot \sqrt{v_{ar}} \\ 12{,}1 \cdot \sqrt{v_{ar}} \qquad\qquad for \; 2{,}38 \cdot |t_{Cl} - t_a|^{0{,}25} < 12{,}1 \cdot \sqrt{v_{ar}} \end{Bmatrix}$$ [Eq.6.6]

$$f_{cl} = \begin{Bmatrix} 1 + 1{,}290 \cdot I_{Cl} \; for \; I_{Cl} \leq 0{,}078 \; m^2 \cdot K/W \\ 1 + 0{,}645 \cdot I_{Cl} \; for \; I_{Cl} > 0{,}078 \; m^2 \cdot K/W \end{Bmatrix}$$ [Eq.6.7]

Where:

- M is the metabolic rate [W/m^2]. 1 metabolic unit = 1*met* = 58,2 W/m^2
- W is the effective mechanical power [W/m^2]
- I_{Cl} is the clothing insulation [$m^2 \cdot K/W$]. 1 clothing unit = 1 *clo* = 0,155 $m^2 \cdot K/W$
- f_{Cl} is the clothing surface area factor
- t_a is the air temperature [^oC]
- $\overline{t_r}$ is the mean radiant temperature [^oC]
- v_{ar} is the relative air velocity [m/s]
- p_a is the water vapour partial pressure [Pa]
- h_c is the convective heat transfer coefficient [$W/(m^2 \cdot K)$]
- t_{Cl} is the clothing surface temperature [^oC]

The model must be resolved by iteration for the calculation of the convective heat transfer coefficient (*hc*) and the clothing surface temperature (*tcl*), so it must be solved using a computer program. However, the model can also be solved using tables for different

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

combinations of activity, clothing, operating temperature and relative velocity.

In addition to the PMV index, Fanger also establishes an index that establishes a quantitative prediction of the percentage of people dissatisfied with the thermal environment. The Predicted Percent Dissatisfied index (PPD) is also included in ISO7730.

$$PPD = 100 - 95 \cdot e^{(-0{,}03353 \cdot PMV^4 - 0{,}2179 \cdot PMV^2)} \quad \text{[Eq.6.8]}$$

The correlation between PPD and PMV has been established based on a statistical study carried out on 1.296 people with an exposure time of 3 hours at certain thermal conditions [INSH, 1983]. Dissatisfied people are those who do not vote -1, 0 or +1 and as can be seen in Figure 9.1, a PMV of 0 (neutral thermal comfort) corresponds to a percentage of dissatisfied of 5% [ASHRAE, 2009]. According to ISO7730, reference values for thermal well-being are required for a PMV between -0,5 to +0,5 or a PPD of 10%.

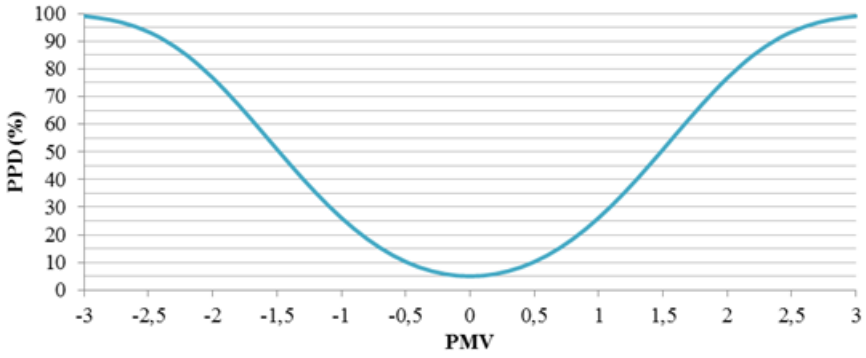

Figure 9.1: Predicted Percentage of Dissatisfied (PPD) vs Predicted Mean Vote (PMV)

The use of PMV and PPD has restrictions on its use according to ISO7730. It is recommended to use the PMV index when its value is between -2 and +2 and if the six main parameters are within the following values:

- *M* (metabolic rate) between 46 to 232 W/m^2 (0,8 to 4 *met*)

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

- I_{Cl} (clothing insulation) between 0 to 0,310 $m^2 \cdot K/W$ (0 to 2 *clo*).
- t_a (air temperature) between 10 to 30 ^oC
- $\overline{t_r}$ (mean radiant temperature) between 10 to 40 ^oC.
- v_{ar} (relative air velocity) between 0 to 1 *m/s*.
- p_a (water vapour partial pressure) between 0 to 2.700 *Pa*.

The preference for people from the same thermal environment does not mean that they have the same sensitivity to cold or heat. The feeling of comfort in individuals is influenced by age, sex, adaptation, seasonal and circadian rhythm, and warming or body limitations [Fanger, 1973]

To maintain thermal comfort, the human body must remove excess metabolic heat. People with low metabolic rate due to activity (<40 W/m^2) are more sensitive to changes in the thermal environment, compared to activities with higher metabolic rates [Dongmei et al, 2017]. According to statistical studies, older people and women tend to prefer higher ambient temperatures, so the difference in metabolism is usually compensated by the level of clothing insulation [Schaudienst et al, 2017]. Regarding the difference between men and women, women have a lower metabolic rate. However, because women's skin temperature and evaporative loss are slightly lower than men's, men and women seem to prefer the same thermal environment [Fanger, 1973]

Parameters such as temperature and humidity affects to the sensation of thermal comfort. The inhalation of air with low temperature and humidity is perceived by the user as cooler and less charged air; otherwise, high humidity or high air temperature increases the percentage of thermal discomfort. However, the thermal discomfort caused by humid skin, tolerates a higher humidity value, reaching an unsatisfied percentage of 9% for a relative humidity of 100% and a temperature of 20ºC in winter conditions [Toftum et al, 1998]. An inadequate temperature and humidity can imply productivity losses in work environments of up to 30%. A lower temperature should be established for the entire group and thus allow individual comfort to be adjusted by insulating the clothing. Regarding relative humidity, its effect is greater when the temperature is higher [Kosonena et al, 2004]

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

9.4.2. Adaptive method

Adaptive model of comfort assume that people are not passive subjects and interact with the environment in order to improve thermal comfort, that is, they adapt to the environment. The concept of "adaptation" is defined by Dear and Brager (1997) as the gradual decrease in the body's response to repeated environmental stimulation. They distinguish three categories of adaptation:

- Behavioural Adjustment: This category includes those actions carried out intentionally to achieve the desired thermal comfort. In this category there are actions such as: adjusting clothing to environmental conditions, changing the activity carried out, adjusting the ventilation system, opening windows, ...
- Physiological: it includes the physiological changes caused in people due to the exposure time of different environmental factors. In this category, genetic adaptation or "acclimatization" is distinguished
- Psychological: it refers to changes in the perception of comfort such as relaxation in environmental expectations indoors.

Therefore, adaptive comfort models start from the adaptation of people to define comfort temperatures [ASHRAE, 2009]. Initial studies by Humphreys in 1978 indicated that the adaptive model is determined by a series of constraints. Among the main restrictions are the climate, the culture and the buildings, in which the climate is the variable that most influences the comfort temperature. Furthermore, other circumstances that affect training are established, which are: working condition and social context, thermal control operated by other, conflicting requirements, personality, fashion, gender and health [Humphreys et al, 1998]. The equations obtained by Humphreys relate the comfort temperature (*tc*) and the average monthly outside temperature (T_0) for the following cases:

- Free running buildings (Natural ventilation):

$$t_c = 11{,}9 + 0{,}534 \cdot T_0\ [°C] \quad (R^2 = 0{,}97) \qquad \text{[Eq.6.9]}$$

- Buildings with HVAC systems

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

$$t_c = 23{,}9 + 0{,}295 \cdot (T_0 - 22) \cdot e^{-\left(\frac{T_0-22}{20\cdot\sqrt{2}}\right)^2} \quad (R^2 = 0{,}72) \qquad \text{[Eq.6.10]}$$

Adaptive models allow the design conditions to be established and the temperature set points of the building to be specified throughout the year [ASHRAE, 2009]. Dear and Brager (1997), through project RP-884, promoted by ASHRAE, carried out experimental data collection in the field of comfort and elaborated statistical models of comfort based on adaptation processes. The RP-884 database includes field studies carried out by other researchers, so it reached 21,000 rows of raw data [Dear et al, 1997]

The collected data allow them to obtain a model that relates the neutral indoor temperature (t_n) and the mean outdoor effective temperature (ET), for the following cases:

- Free running buildings (Natural ventilation) :

$$t_n = 18{,}9 + 0{,}255 \cdot ET \ (R^2 = 0{,}42) \qquad \text{[Eq.6.11]}$$

- Buildings with HVAC systems

$$t_n = 21{,}5 + 0{,}11 \cdot ET \quad (R^2 = 0{,}53) \qquad \text{[Eq.6.12]}$$

The mean outdoor effective temperature is defined as the arithmetic average of effective outdoor temperatures at 6 am and 3 pm [Dear et al, 1997]. In order to compare the expressions based on the average monthly outside temperature, Humphreys et al, carried out a review and corrections that increased the precision of the relationships developed by Dear and Brager. After correction, it was found that using the average monthly outside temperature (t_0) is as good an indicator as using the mean outdoor effective temperature (ET). Furthermore, neutral indoor temperature in the new data was approximately 2°C higher; this may be due to the adaptation of people to an increase in indoor temperatures during winter seasons [Humphreys et al, 2000]. The equations that relate neutral indoor temperature (t_n) and the average monthly outside temperature (T_0) are:

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

- Free running buildings (Natural ventilation) :

$$t_n = 13{,}5 + 0{,}546 \cdot T_0 \ \ (R^2 = 0{,}91) \qquad \text{[Eq.6.13]}$$

- Buildings with HVAC systems:

$$t_n = 22{,}2 + 0{,}003 \cdot {T_0}^2 \ \ (R^2 = 0{,}49) \qquad \text{[Eq.6.14]}$$

ASHRAE 55 applies the adaptive thermal comfort method to buildings with natural ventilation. The standard establishes that the indoor operating temperatures must be determined with an 80% compliance limit. In addition, the use of the model for the evaluation of comfort is subject to the following restrictions [ASHRAE, 2017]:

- There are no HVAC systems in operation.
- Metabolic rate of occupants between 1 to 1,3 *met*.
- The occupies can adapt their clothing between 0,5 to 1,0 *clo*.
- The outdoor temperature is between 10 and 33,5 *ºC*.

The clothing insulation and the air velocity are correlated with the indoor air temperature; clothing is inversely proportional to the increase to the indoor temperature and air velocity is directly proportional to the increase in indoor temperature. In high indoor temperature conditions, the increase of air velocity is generated by the use of fans, since the use of windows does not generate a great impact [Wu et al, 2019]. In situations where it is not possible to adjust clothing, activity or establish adequate air, the comfort zone of the adaptive approach is located at $\pm 2^{o}C$ [Nicols et al, 2002]

The adaptive comfort approach allows the design of comfortable buildings, especially with natural ventilation. It allows obtaining the comfort temperature, for a degree of acceptance of 80% of people [Nicol et al, 2002]. There are studies where they establish control systems based on adaptive approach, show energy savings without affecting the perception of comfort [McCartney et al, 2002]

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

9.5. ANALYSIS OF THERMAL COMFORT DEPENDING ON THE THERMAL ENVELOPE

The thermal envelope of buildings plays a fundamental role in the thermal balance of buildings. The increase of the insulation thickness, the energy consumption of the building tends to be reduced [Xu et al, 2018] and also the selection of the appropriate material, allows to improve the efficiency with the same thickness of insulation [Reza et al, 2020].

In CHAPTER 4 of the thesis, the influence of the placement of thermal inertia on the evolution of indoor temperature was analysed. In the Chapter, a model was developed capable of predicting the evolution of the indoor temperature, as a function of the variation of the outdoor temperature. The results obtained showed less variation when the thermal inertia of the wall was placed inside.

Now, the implications of thermal mass placement on the walls of buildings are analysed from point of view of thermal comfort. Since it is assumed that the building does not have an HVAC system, the adaptive comfort model is used to assess thermal comfort in the two case studies. The adaptive comfort model relates the outdoor temperature to the building's comfort temperature, so it can be used to help in the design phase of buildings [Nicols et al, 2002]

9.5.1. Case Study

The object of the study is to analyse the thermal comfort in buildings based on the use of a thermal envelope with the thermal mass inside or with the thermal mass outside.

In order to apply the ASHRAE Standard 55-2017, the following assumptions are made: the case study does not have HVAC systems, the metabolic rate of people are between 1-1,3 *met* and the occupants have the ability to adapt their clothing between 0,5-1 *clo*. An air speed of 0,3 *m/s* is assumed, however, in the case of obtaining an operating temperature higher than 25*ºC*, the standard contemplates the possibility of modifying the air speed to increase the feeling of comfort.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

9.5.1.1. Definition of outdoor conditions

Ourense is a Galician city that is known for its high temperatures in summer. The month of July of the year 2020 is taken as a reference. This month is characterized by the anticyclonic situation and warm air from the south, which caused one of the warmest months of the year. During the month of July, an average temperature of 25,4^{o}C was recorded, reaching a maximum temperature of 40,1^{o}C [Meteogalicia, 2020]

Table 9.1: Temperature values in the city of Ourense [METEOGALICIA, 2020]

	July 2020	Climate values (1972-2020)
Average temperature [ºC]	25,4	22,5
Average minimum temperature [ºC]	16,1	14,8
Absolute minimum temperature [ºC]	8,8 (03/07)	6,4 (08/07/1996)
Average maximum temperature [ºC]	34,7	30,2
Absolute maximum temperature [ºC]	40,1 (18/07)	42,6 (20/07/1990)

In order to evaluate the evolution of the indoor temperature, the outdoor temperature fluctuation selected is for the hottest day of the month of July (18th July 2020), with a maximum temperature of 40,1^{o}C and a minimum of 15,4°C. To comply with ASHRAE Standard 55-2017, the prevailing mean outdoor temperature is calculated with the last 7 previous days.

9.5.1.2. Definition of building model

The model building used for this study has a cubic shape with an area of 80 m^2 (8 x 10 m). The north and south facades have an area of 30 m^2 (10 x 3 m) and the east and west facades have an area of 24 m^2 (8 x 3m). All the facades are in contact with the exterior except the ground, which is at a constant temperature of 22^{o}C.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

For the analysis of thermal comfort, two types of facades are considered, with external insulation and internal thermal mass and with internal insulation and external thermal mass. The thickness of each component is selected in order to comply with current Spanish regulations. In the case of Ourense, a limit thermal transmittance of the walls in contact with the exterior of 0,49 $W/m^2 \cdot K$ is required, for the roof a limit value of 0,40 $W/m^2 \cdot K$ and for the floor a limit value of 0,7 $W/m^2 \cdot K$. Based on these values, the composition of the envelope is described in the following table:

Table 9.2: Description of the thermal envelope

Type of envelope	U lim [W/(m²K)]	Description	U [W/(m²K)]
External wall	0,49	20 cm concrete + 0,07 cm isolation	0,45
Roof	0,40	20 cm concrete + 0,08 cm isolation	0,40
Ground	0,7	20 cm concrete + 0,045 cm isolation	0,70

The thermal transmittance values of opaque closings according to Spanish regulations are above the recommended values according to the Passive-On study carried out in Spain, where transmittance values of 0,30 $W/m^2 \cdot K$ are recommended [FENERCOM, 2011]

9.5.2. Results

To predict thermal comfort, the ASHRAE Standard 55-2017 is used. The standard allows establishing what would be the acceptable thermal conditions for the occupants. As part of a naturally ventilated building, the adaptive method is used to assess comfort.

First, the prevailing mean outdoor air temperature shall be determined. The prevailing mean outdoor air temperature must be calculated by taking the arithmetic mean of the mean temperatures over the last 7 or 30 days. Since it is intended to analyse the thermal comfort during the hottest day of the month, which was 18th July 2020, the prevailing mean outdoor air temperature must be calculated for at least the last 7 previous days. Therefore, prevailing mean outdoor air temperature has a value of 24,3^{o}C (see Figure 9.2).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

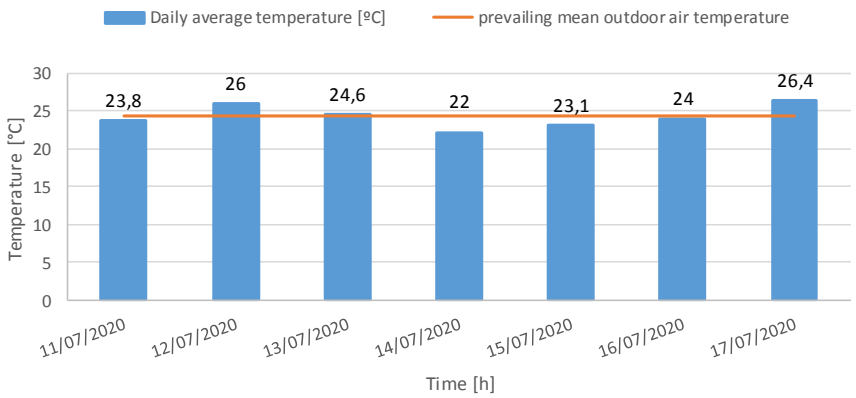

Figure 9.2: Average temperatures of the last 7 days prior to 18th July 2020

Once the prevailing mean outdoor air temperature has been established, the equations described in ASHRAE Standard 55-2017 are used to establish the operating temperature ranges that establish 80% acceptability. The operating temperature that defines 80% acceptability of the occupants is obtained from the following equations:

$$Upper\ 80\%\ acceptability\ limit\ t_0 = 21{,}3 + 0{,}31 \cdot \overline{t_{pma\ (out)}}\ [°C] \qquad \text{[Eq.6.15]}$$

$$Lower\ 80\%\ acceptability\ limit\ t_0 = 14{,}3 + 0{,}31 \cdot \overline{t_{pma\ (out)}}\ [°C] \qquad \text{[Eq.6.16]}$$

Applying equations [Eq.6.15] and [Eq.6.16] for a prevailing mean outdoor air temperature of 24,3^{o}C, an operating temperature between 21,8 – 28,8 ^{o}C is obtained for an acceptability of 80% of the occupants

The operating temperature is defined by means of the air temperature (*ta*) and the radiant average temperature (*tr*) and a coefficient *A*. The coefficient has a value of 0,6 for a speed of 0,3 *m/s*. The expression collected in the ASHRAE standard is:

$$t_0 = A \cdot t_a + (1 - A) \cdot \overline{t_r} \qquad \text{[Eq.6.17]}$$

In this case, the influence of the average radiant temperature is not taken into account when calculating the operating temperature. So the air temperature is equivalent to the operating temperature.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

In order to evaluate the comfort inside the buildings, based on the placement of the insulation and the thermal mass, the model defined in CHAPTER 4 is used for the previously defined case studies.

If the thermal mass is introduced on the outside and the thermal insulation on the inside, the variation of the indoor temperature is greater than when maintaining the thermal mass on the inside. In Figure 9.3, the evolution of the indoor temperature is shown as a function of the two types of envelope under study. The thermal inertia inside the enclosures produces a more stable indoor temperature oscillation (temperature oscillation of 0,8 ^{o}C) with respect to the envelope with thermal inertia on the outside (temperature oscillation of 7,5 ^{o}C).

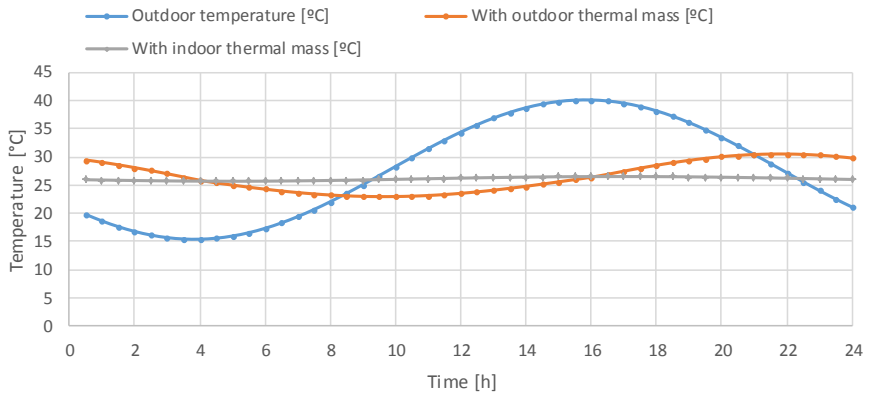

Figure 9.3: Evolution of the indoor temperature with the thermal mass outside and with the thermal mass inside.

Due to these temperature fluctuations, the comfort conditions inside the building vary throughout the day, so it is necessary to assess thermal comfort in both cases. When introducing the thermal mass inside, the minimum temperature reached is 25,7^{o}C at 10:00, while the maximum temperature reached is 26,5^{o}C at 22:00. When introducing the thermal mass outside, the minimum and maximum temperature reached is 23,0 and 30,5^{o}C, respectively. When such a small oscillation is produced, hardly a wave phase shift can be seen.

Therefore, comparing the indoor temperatures with the comfort temperatures, it is obtained that when the thermal inertia is placed

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

outside; the maximum temperature exceeds the comfort temperature, which would cause discomfort in more than 80% of the occupants. However, by having the thermal mass inside, the softening effect it has on the temperature, allows maintaining comfort for more than 80% of the occupants.

The tool developed by the University of California Berkeley, evaluate thermal comfort according to ASHRAE Standard 55-2017 [Taylor et al, 2020]. The tool also displays comfort limits for 90% occupant acceptability and also increases air speed. As a summary, Table 9.3 shows operating temperatures based on occupant acceptability and air velocity.

Table 9.3: Operating temperatures for different degree of acceptability of occupants and air speed [Extracted from Taylor et al, 2020]

Prevailing mean outdoor temperature [ºC]	24,3			
Air Speed [m/s]	0,3	0,6	0,9	1,2
Operative temperature for 80% acceptability [ºC]	21,8 to 28,8	21,8 to 30,0	21,8 to 30,6	21,8 to 31,0
Operative temperature for 90% acceptability [ºC]	22,8 to 27,8	22,8 to 29,0	22,8 to 29.6	22,8 to 30,0

In Figure 9.4, it is observed that when introducing the thermal mass inside, the indoor temperature is within the comfort limits that allow an acceptability of more than 90% of the occupations, which allows a feeling of comfort.

The temperature oscillation is greater when introducing the thermal mass outside. This temperature oscillation causes that when the maximum temperature of 30,5 *ºC* is reached, less than 80% of the occupants will be satisfied and therefore causes a "Too Warm" thermal sensation. The solution to this problem is obtained by increasing the air speed to 0,9 *m/s*, in this way, a degree of acceptance of the occupants of at least 80% is obtained, thus improving with the comfort conditions.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

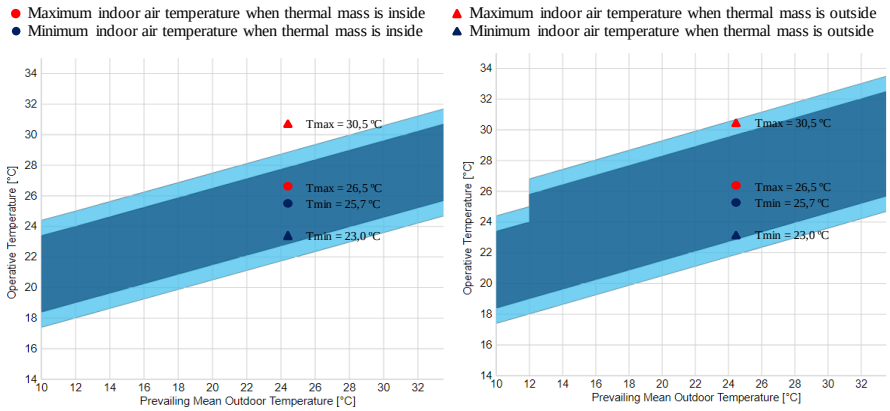

Figure 9.4: Evaluation of thermal comfort based on the position of the thermal mass. On the left with an air speed of 0,3m/s. On the right with an air speed of 0.9 m / s [Adapted from Taylor et al, 2020]

Therefore, the selection of a suitable thermal envelope not only reduces energy demand by improving the level of isolation, but also influences the comfort conditions of the occupants. In this analysed case, the envelopes have the same thermal transmittance; however, the placement of the thermal inertia on the outside causes high indoor temperatures, reducing comfort. In this case, increasing the air speed is a solution; however when it is not possible by natural means, the use of mechanical ventilation equipment is necessary, which implies extra energy consumption.

9.6. DISCUSSION

The thermal model developed by Fanger in controlled chambers, allows predicting the comfort temperature with more precision than buildings with natural ventilation. This is due to carrying out the studies in refrigerated chambers, which allows greater control over the environment.

However, the studies carried out by Fanger et al do not take into account the "adaptation" of people to the environment that is considered in the adaptive approach. Because of this, Dear and Brager carried out their studies based on field data and the ability to adapt to the environment of the people.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Comparing the regression coefficients of the models, it is observed that the adaptive control model allows obtaining a better estimate of the comfort temperature with natural ventilation systems. The PMV comfort model works best for buildings with HVAC systems but not in buildings with natural ventilation. [Yang et al, 2014]

However, despite the differences between the two models, they allow greater energy savings compared to fixed temperature control systems. When thermal comfort is not achieved passively, an air conditioning system is required to adjust the indoor air temperature. Wu et al (2020), performed a simulation between an air conditioning system based on conventional temperature control and between a control system based on thermal comfort (PMV). The control based on thermal comfort showed better results than conventional control systems, where 30% of the cases were outside the comfort limits (PMV < -0,5). Furthermore, the control system based on the PMV index, obtained a saving per day of 1,6%, because the control is based on the function of radiant temperature, air speed and humidity.

Adaptive control systems allow reducing the operating time of air conditioning systems. The adaptive comfort model takes into account the ability of people to adapt to the environment; they allow a wider comfort range to be obtained compared to the PMV model. Therefore, this type of model allows for a higher comfort temperature in summer and greater energy savings [Yang et al, 2014]. As an example, the study carried out by Albatayneh et al at the University of Newcastle (Australia), the comfort temperature established by fixed temperature control systems during the summer was established at 24*ºC*, compared to the stable temperature range by the comfort model adaptive (22,7*ºC*–29,7*ºC*). Adaptive control systems allowed reducing energy consumption compared to HVAC systems with a fixed set point up to 50%, maintaining the degree of acceptability of 80%. [Albatayneh et al, 2019]

Maintaining specific comfort parameters largely depend on the construction of the building. The optimal design of buildings allows reducing temperature fluctuations, optimizes solar inputs and establishing adequate ventilation.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The solar contributions in buildings can cause thermal dissatisfaction, especially when the occupants are within the affection radius. Hwang et al, analyse the impact of windows and solar shading devices on indoor thermal comfort. The selection of the suitable windows, allows controlling the feeling of comfort in the houses. First, the proper glazing properties, absorbance and transmittance must be selected. Low absorbance values produce a lower internal temperature and a low transmittance allows less radiation to be absorbed. The proper selection of these properties allows improving the thermal compliance. Regarding the size of the windows, the increase in WWR reduces thermal comfort, due to the greater amount of solar radiation. However, the use of solar shading devices such as overhang have a positive impact on thermal comfort, going from a PMV of 0,87 without overhang, to a PMV of 0,66 with an overhang of 4,8 meters [Hwang et al., 2011]

9.7. CONCLUSIONS

In this chapter, an analysis of thermal comfort is carried out and how it influences the design of buildings, especially thermal inertia.

The two theories of thermal comfort analysed coexist and are used depending on the type of ventilation. Fanger's studies in cold rooms allowed evaluating the percentage of satisfaction of people in controlled environments and it is currently used to evaluate comfort in buildings with HVAC systems. Because Fanger did not take into account the "adaptation" of people, Dear and Brager developed the comfort model taking into account the ability of people to adapt. The adaptive approach developed is currently used in buildings with natural ventilation systems.

Although both models are used with different ventilation systems, the use of this type of theory to control the indoor temperature allows obtaining considerable energy savings. Energy savings can reach 50% compared to fixed set point systems, keeping the degree of acceptability above 80% [Albatayneh et al, 2019]

The proper design of the enclosure improves thermal comfort while minimizing energy consumption. However, these elements also have implications in ensuring adequate air quality, especially in the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

appearance of mold and humidity due to poor thermal insulation and the appearance of VOCs due to the use of materials.

The use of natural ventilation systems or HVAC allows us to guarantee adequate air quality and thermal comfort. Therefore, the selection of the optimal ventilation is essential to guarantee an environment that guarantees adequate health conditions.

Due to the influence of the envelope design on thermal comfort, the impact of the location of the thermal mass is analysed. The main conclusions obtained when analysing thermal comfort depending on the placement of thermal insulation are summarized below.

- The thermal mass inside the building makes it possible to obtain more stable temperatures and maintain thermal comfort with a degree of acceptability greater than 80%.
- With inside thermal mass, the use of natural ventilation is enough to keep thermal comfort with acceptability greater than 90%.
- Placing the thermal mass on the outside produces a greater temperature fluctuation inside, causing maximum temperatures to be reached above the comfort range.
- Placing thermal mass outside causes the use of mechanical ventilation equipment to guarantee the comfort of at least 80% of the occupants. In this case, the air speed must be increased to 0,9 *m/s* to obtain a degree of acceptability of 80%.

The passive design of buildings not only allows the reduction of energy consumption, but also must guarantee adequate thermal comfort. Moreover, they must guarantee adequate indoor air quality, through the use of sustainable materials that allow minimizing the concentration of chemical hazards. Finally, buildings must have adequate ventilation that allows the air to be adequately renewed. In the case of HVAC systems, temperature control taking into account thermal comfort theories allow energy savings by guaranteeing thermal comfort.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

CHAPTER 10. BEST AVAILABLE TECHNIQUES FOR SUSTAINABLE AND COMFORTABLE BUILDINGS

SUMMARY

Throughout this study, techniques for the construction of sustainable and comfortable buildings are analyzed. Based on the analysis carried out in the different chapters, the candidate techniques for Best Available Techniques that allow progress towards a circular and regenerative economy are selected.

The inventory of Best Available Techniques relative to sustainability refers to the thermal envelope, sustainable materials, solar radiation and solar protection systems. These techniques allow the reduction of energy consumption in buildings, guaranteeing thermal comfort.

However, to maintain a healthy environment, not only adequate comfort must be guaranteed, but indoor air quality must also be maintained. To guarantee a healthy indoor environment, ventilation plays a fundamental role. Therefore, ventilation techniques (natural and mechanical) are included, which allow maintaining air quality within healthy parameters.

Finally, an inventory of Best Available Techniques is obtained that allow the achievement of sustainable and comfortable buildings, through circular and regenerative economy techniques.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

10.1. INTRODUCTION

Buildings must not only be efficient, but must guarantee adequate thermal comfort and indoor air quality. Throughout the Doctoral Thesis, techniques are analyzed that allow buildings to evolve towards sustainability and comfort through circular economy techniques (Best Available Techniques) to a long-term regenerative economy.

Directive 2010/75/EU on industrial emissions (integrated pollution prevention and control, IPPC) aims to prevent and control emissions to the atmosphere, water and soil, as well as the generation of waste derived from processes industrial. For the prevention and control of pollution, there is for each industry the documents called, Best Available Techniques Reference Document (BREF), which are documents that collect the Best Available Techniques (BAT) of the different industrial sectors and are of European scope [Torres et al, 2017]. Directive 2010/75/EU define Best Available Techniques (BAT) as the most effective and advanced stage in the development of activities and their methods of operation which indicates the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where that is not practicable, to reduce emissions and the impact on the environment as a whole [EU, 2010]

- "Techniques" include both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned.
- "Available Techniques" means those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator.
- "Best" means most effective in achieving a high general level of protection of the environment as a whole.

The Best Available Techniques Analysis proposed by Barros et al (2007) evaluates the candidate techniques for BAT following the methodology established by the European IPPC Bureau. The method considers environmental aspects, technical description of BAT,

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

benefits, side effects and economic aspects. This method was proposed and validated in a ceramic industry. The application of BAT analysis to evaluate candidate techniques for BAT has been used in different industries, such as cooked mussel processing industry [Bello Bugallo, 2012], fish and seafood caning industry [Bello Bugallo, 2013; Taboada et al, 2016], slaughterhouses [Bello Bugallo, 2014], tuna purse seiner [García Rellán, 2018] or dairy industry [Torres, 2017]

The Integrated Pollution Prevention and Control approach was developed in the European Union for the most potentially industrial polluting sources. The purpose of this chapter is to apply current methodologies and concepts to perform a BAT Analysis in the construction sector and to develop an inventory of candidate techniques for BAT. The candidate techniques should allow the sector to evolve towards pollution prevention with a circular and regenerative economy approach.

In order to the candidate techniques for BAT towards sustainability and comfort in buildings, a model is elaborated that allows knowing the indoor temperature in buildings based mainly on the configuration of the buildings, (CHAPTER 4), and on solar radiation (CHAPTER 5).

Sustainability is development that enables current needs to be met but without reducing the ability of future generations to meet their own needs. Efficient management of material and energy resources is essential.

In this context, CHAPTER 6 analyzes the BATs that allow the use of sustainable materials in construction. The use of these eco-materials allows reducing the energy consumption of buildings and the environmental impact associated with their production.

Another important factor to reduce energy consumption in buildings and therefore energy dependence is based on the proper control of solar radiation. CHAPTER 7 evaluates the techniques associated with solar shadow devices to maximize solar contributions in winter and avoid them in summer. However, during the development of the mathematical model in CHAPTER 4 and CHAPTER 5, techniques that towards sustainability are also

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

evaluated. Therefore the analyzed techniques related to the thermal envelope and solar radiation is included as BAT.

Regarding the comfort of buildings, they must guarantee both thermal comfort and healthy air quality. The main techniques evaluated include those that allow achieving adequate air quality developed in CHAPTER 8. In this chapter, a systematic review of the main dangers present in indoor air is carried out and current techniques for their control are evaluated.

The main factors to take into account to evaluate indoor air quality will be those established by SCHER, which describes 8 factors that affect air quality: chemicals, radon, particles, microbes, pets and pests, humidity, ventilation and temperature [SCHER, 2007]. These 8 factors that affect air quality are classified into four groups of environmental stressors by ASHRAE: chemical hazards (Airborne chemical or particles), biological hazards (bacteria, viruses, fungi ...), physical hazards (levels of ionizing and nonionizing electromagnetic radiation, noise, vibration, illumination, temperature, and force) and ergonomic risks (awkward postures can damage muscles, nerves, and joints).

Finally, thermal comfort is the feeling of thermal satisfaction that people want to achieve. Furthermore, it is included as one of the variables in the SCHER and ASHRAE classification. Achieving thermal comfort in buildings is closely related to their constructive elements and ventilation. Therefore in Chapter 9, comfort is defined and how it affects the design of buildings.

Therefore, this chapter compiles the BAT analyzed for the construction of sustainable and comfortable buildings. The techniques analyzed include aspects related to the thermal envelope, solar radiation and solar shadow devices, sustainable materials and indoor air quality.

The circular economy techniques analyzed allow progress towards regenerative techniques. A resilient economy that advances towards environmental sustainability and the reduction of the main climatic and environmental pressures associated with production and consumption.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

10.2. OBJECTIVE

The objective of this chapter is to carry out an inventory of candidate techniques for the best techniques available for the construction sector. The updated inventories of BAT are contributions, in the new approach of sustainable and comfortable buildings.

Inventories are obtained in the form of databases, taking into account aspects related to sustainability and comfort in each technique. This part opens a new approach in the way of treating the behavior of a building that generates jobs given the large number of typologies in the building and sectors.

10.3. METHODOLOGY

Best Available Techniques (BAT) are evaluated from the point of view of sustainability and comfort. Throughout this document, techniques for sustainable and comfortable buildings have been described. The techniques described have implications for sustainability and comfort.

The selection of candidate techniques for BAT to achieve sustainable and comfortable buildings has been carried out in the following stages:

- Study of techniques in the construction sector.
  The selection of candidate techniques for BAT refers to the main variables analyzed and that allow contributing towards the sustainability and comfort of the buildings. The design of an adequate thermal envelope, the use of sustainable materials and the use of passive techniques to control solar radiation, allow the optimization of material and energy resources in the sector, both in the maintenance of the building and in the construction stage. .
  These techniques, in addition to advancing towards sustainability, allow maintaining adequate thermal comfort in buildings. Although ventilation also has an influence on sustainability, it has a greater impact on the achievement of comfortable buildings, which guarantee adequate air quality and thermal comfort.
  The study of the techniques is carried out in the previous chapters through a systematic review of the state of the art.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

- Selection of candidate techniques for BAT
  The selection of candidate techniques for BAT is established based on the results obtained through the models and simulations carried out in each chapter. However, additional techniques are included based on the contribution towards the achievement of sustainable and comfortable buildings.

As a result, an updated inventory is shown and focused on the construction or renovation of buildings from the point of view of comfort and energy efficiency.

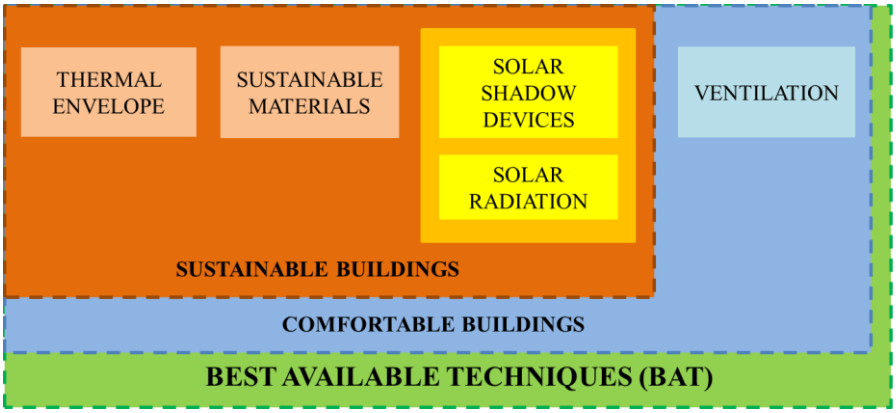

Figure 10.1: Table of the areas of the Best Available Techniques

10.4. RESULTS

Throughout this document, different techniques have been analyzed to improve efficiency and comfort in buildings. BAT should focus on reducing the demand for raw materials, water, energy, reducing waste generation and facilitating recycling; minimize atmospheric, acoustic and water pollution; limit the use of toxic and dangerous materials; increase the use of recyclable materials, and minimize the use of materials [Torres, 2021]

The following tables (Table 10.1, Table 10.2, Table 10.3,Table 10.4 and Table 10.5) summarize the BATs analysed regarding the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

thermal envelope, sustainable materials, solar radiation, solar shading devices and ventilation.

The techniques associated with the improvement of the thermal envelope significantly affect the energy consumption of the building. The use of an envelope with a low U-value directly affects the energy demand of the building and is a technique already used.However, the placement of the thermal mass and the insulation causes significant changes in the indoor temperature and also affects energy consumption and comfort. This technique allows obtaining a better energetic performance when the thermal mass is placed inside and the insulation outside. The creation of stable indoor temperatures also makes it possible to achieve adequate thermal comfort conditions for a longer period. Therefore, they contribute to achieving thermal comfort in buildings.

The selection of suitable materials for the construction of the thermal envelope also affects energy consumption and the thermal comfort of buildings. However, the use of sustainable materials from waste allows progress towards a regenerative economy that allows the construction of buildings without the need to extract new materials. The results show that it is possible to achieve buildings with an energy demand similar to those built with conventional materials and reduce the environmental impact in the production of the materials.

To reduce energy demand in buildings, it is essential to take advantage of energy from solar radiation. Considering the orientation, the size and the type of windows in the design phases of buildings, influences the energy demand of the building. However, sometimes it is not possible to find a balance between energy needs in summer and winter, so the use of solar shadow systems allows reducing the energy from solar radiation. The use of mobile solar shadow devices allows greater adaptation to the seasons. They are also techniques that can be used once the building is built.

Finally, the techniques to guarantee adequate indoor air quality are analyzed. Indoor air quality has been of greater importance since the appearance of COVID-19. Natural ventilation allows for healthy indoor air; however, sometimes it depends on the quality of the outside air, making this type of system inefficient. Regarding

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

mechanical ventilation systems, they allow achieving adequate air quality, however, a good design must be carried out and an adequate renewal rate must be established.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 10.1: Best Available Techniques regarding thermal envelope

Description	Techniques	Results
Thermal Envelope	▪ Increasing the thermal mass generates smaller peaks in the heating and cooling transmission load [Al-Saena et al, 2012] ▪ Regardless of where it is installed, increasing the thickness of the insulation reduces heat flow through the enclosure [Al-Saena et al, 2012; Ozel, 2014] ▪ The placement of the insulation on the outside generates a better thermal behaviour inside. In this case, the heating and cooling thermal load has a lower peak than when placing the insulation in the middle or inside the wall [Ozel, 2014] ▪ The use of a concrete with high density and low conductivity reduces the decrement factor and increases time lag [Kontoleon et al, 2013] ▪ The use of Phase Change Materials (PCM) as filling of the brick holes, allows reducing the temperature of the inner wall and the heat flow. The reduction is greater when the filling is done in the interior holes of the brick [Hichem et al, 2013] ▪ Use isolation techniques with environmental and economic improvements, such as vacuum insulation [Galvez-Martos et al, 2012]	▪ Placing the thermal mass in the inside, reduce de decrement factor and therefore generates more stable indoor temperature. In addition, this improves with the selection of materials with high density and low conductivity. [Al-Saena et al, 2012; Kontoleon et al, 2013] ▪ Placing the insulation on the outside generates more stable indoor temperatures throughout the day [Ozel, 2014] ▪ The use of plant-covered walls reduces the flow of heat through the walls and reduces the maximum and minimum temperatures inside and outside [Eumorfopoulou et al, 2009] ▪ The use of green roofs reduces the interior temperature in the upper floors of the building, while green facades improve thermal comfort throughout the buildings. These elements reduce the variation in the amplitude of the internal temperature wave and mean radiant temperature [Musy et al, 2017] ▪ The presence of VOCs in the environment increases with temperature [Chatzidiakou et al., 2015], so maintaining stable temperatures minimizes the presence of these compounds.

Description	Techniques	Results
	▪ Improve the thermal behaviour of buildings using cool, brown and green roofs [Galvez-Martos et al, 2012] ▪ The use of plant-covered walls improves passive design of buildings and reduces energy demand in cooling [Eumorfopoulou et al, 2009] ▪ Use of sustainable materials with the environment and people's health [Galvez-Martos et al, 2012]	▪ The use of sustainable materials in construction avoids the presence of compounds such as formaldehyde [WHO, 2010] ▪ Improved thermal insulation and thermal bridges reduces the risk of condensation and mold growth on interior walls.

Table 10.2: Best Available Techniques regarding sustainable materials

Description	Techniques	Results
Sustainable materials	▪ Agricultural residues can be used as thermal insulation. They have thermal properties similar to conventional insulation. ▪ The residues can be part of construction elements such as bricks, concrete, cement or mortars, improving their thermal properties. ▪ Mixtures of OCF and WS with a higher percentage of residues cause a wave with a lower decrement factor and a longer time lag ▪ The use of recyclable materials and minerals reduce by half the environmental impact of buildings, especially reducing the amount of energy in the manufacture of materials [Taboada et al, 2018]	▪ The introduction of agricultural residues in construction materials improves the thermal properties of the material. ▪ Materials, such as bricks with mixtures of OCF or WS, produce more stable temperatures than conventional bricks, improving thermal comfort. ▪ Hemp concrete and Isotex are the materials that cause a softer temperature (lower decrement factor) and cause a wave with a greater phase shift (greater time lag). ▪ Bricks with superior mixes of OCF and WS cause a wave with a lower decrement factor and a longer time tag. ▪ The use of materials from waste, allow to achieve thermal behaviors similar to conventional materials but with a lower environmental impact.

Table 10.3: Best Available Techniques regarding solar radiation

Description	Techniques	Results
Solar radiation	▪ Regarding windows, two fundamental factors must be taken into account, the wall-to-wall ratio (WWR) and the U-value of the windows. Regarding the U-value, low values imply less energy losses through sales, so the energy demand is reduced, however, the cost of the window increases as the U-value is reduced [Xu et al, 2018; Grynning et al, 2013] ▪ In warm regions, low window-to-wall ratios increase energy efficiency but reduce the light quality of the building, and energy consumption is further increased when the facade is facing south [Xu et al., 2018]. However, having a larger window size during winter reduces the energy demand in heating due to solar contributions [Reza et al, 2020] ▪ Optimize the orientation of the windows to take advantage of the maximum solar radiation in winter. In moderate climates of the northern hemisphere the optimal orientation is towards the south [Obrecht et al., 2019] ▪ Select glazing with a suitable g-value. Lowers g-value prevent the entry of solar radiation, thus reducing the energy demand in cooling. On the contrary, higher g-value allows the passage of solar radiation, reducing the energy demand for heating [Obrecht et al., 2019]	▪ The use of a window with a thermal bridge breakage and a lower U-value minimizes the appearance of humidity due to condensation and the appearance of mold. ▪ Solar contributions cause an increase in indoor temperature both in winter and summer. During the winter season, it improves thermal comfort, however during the summer; it can cause temperatures outside the comfort zone. ▪ Windows with high U-value, increase radiant temperature and improve thermal comfort

Table 10.4: Best Available Techniques regarding solar shadow devices

Description	Techniques	Results
Solar Shadow Device	▪ Prioritize the use of Dynamic Solar Shadow Device, in order to maximize the solar energy received and avoid it during warm seasons. ▪ Optimize the use of fixed solar shadow device. Prioritizing the contribution of solar radiation in winter and avoiding them in summer. ▪ Placing windows inward reduces the cooling demand caused by shadows [Ghosh et al, 2018] ▪ Select a suitable glass tint. Gray reflective glass windows reduce the energy demand for heating and cooling, while bronze glass windows reduce the demand for heating [Kumar et al., 2018] ▪ Use of smart glasses that modify their properties depending on the incident solar radiation [Dussaul et al, 2013] ▪ Installation of transparent building-integrated PV-elements (BIPV) allows the production of renewable energy and reduce solar contributions [Kuhn, 2017] ▪ Use of Transparent building-integrated solar thermal (BIST). It allows reducing energy demand by accumulating solar radiation into heat energy [Zhang et al, 2015] ▪ The use of trees as a passive element of solar control [Papadakis et al., 2001]	▪ The fixed solar shadow device must allow the contributions of solar radiation in winter in order to raise the temperature of the indoor air and reduce the energy consumption. ▪ During the summer, solar protections avoid an increase in indoor temperature due to solar contributions, thus maintaining thermal comfort ▪ The use of plants as a passive element of solar control allows maintaining a cooler air outside the walls due to the evaporative cooling effects of the plants. [Papadakis et al., 2001]

Table 10.5: Best Available Techniques regarding ventilation

Description	Techniques	Results
Ventilation	▪ Provide adequate daily ventilation by opening windows even in cold weather ▪ The automation of the closing and opening of windows is a mechanism that helps to keep the CO2 concentration at acceptable levels [Stazi et al., 2017] ▪ Avoid opening windows located towards areas with high contamination [Huang et al, 2018] ▪ Carry out proper maintenance of HVAC systems, especially filters [Bonetta et al., 2009] ▪ Establish an adequate indoor air renewal rate, to guarantee adequate indoor air quality. ▪ Establish an adequate indoor air distribution, which allows eliminating the presence of pollutants and guaranteeing thermal comfort [Hyeun Jun et al., 2018] [Lin et al., 2005] ▪ Establish an adequate air speed to avoid discomfort due to stratification [Varodompun et al., 2007]	▪ The opening of windows allow maintaining the levels of CO_2 and CO in healthy ranges [Heracleous et al., 2019] ▪ Increased ventilation reduces radon concentration. ▪ Increasing the ventilation rate reduces the concentration of particles inside the houses. ▪ Areas of high contamination can be a source of particles, so in these areas, reducing natural ventilation or the use of adequate filters in HVAC systems allows keeping the concentration of particles in healthy ranges [Huang et al, 2018] ▪ The filters of HVAC systems can be a source of bacteria and fungi, so regular maintenance must be carried out [Bonetta et al., 2009] ▪ The renewal of the air reduces the presence of microbes. However, the entry of microbes from the outside is also possible. ▪ Natural ventilation has higher values of temperature and humidity than HVAC systems. ▪ Low air velocity in HVAC systems causes cold air to not mix well and can cause discomfort due to stratification effect [Varodompun et al., 2007].

10.5. CONCLUSIONS

Based on the analyzes carried out in the previous chapters, the candidate techniques for Best Available Techniques are selected that allow efficient and comfortable buildings to be achieved through circular and regenerative economy techniques. The candidate techniques are framed within the thermal envelope, sustainable materials, solar shadow systems and ventilation.

The analyzed techniques related to the thermal envelope, solar radiation and solar shadow devices make it possible to reduce the use of energy resources and therefore reduce dependence on fossil fuels. These techniques allow progress towards sustainability, improving comfort in buildings and therefore the well-being of people.

The use of sustainable materials allows achieving the same thermal behaviour and thermal comfort as conventional materials. However, in this case, these techniques make it possible to reduce the use of waste and facilitate recycling and therefore minimize the extraction of raw materials. These techniques allow progress towards a regenerative economy, with the future purpose of using materials that can be valued and avoiding extracting new materials.

Finally, to obtain healthy buildings, adequate indoor air quality must be guaranteed. At this point, having adequate ventilation is essential to reduce the levels of exposure to hazards in the indoor air. Natural ventilation allows healthy levels to be reached; however, it is affected by outside environmental conditions. However, with respect to mechanical ventilation systems, the design is essential to guarantee a healthy environment.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

CHAPTER 11. CONCLUSIONS

In this Doctoral Thesis an analysis of the existing technologies for the construction of sustainable and comfortable buildings has been carried out. The analyzed techniques contribute towards a circular and regenerative economy, placing buildings as one of the strategic sectors for the achievement of European objectives.

Currently, the buildings sector is not only responsible for 40% of energy consumption in the European Union, but also consumes 50% of the raw materials extracted and generates 37% of waste. Therefore, the application of energy policies that promotes the renewal of the sector, which currently has 75% of its buildings inefficient; allow a step towards a low-carbon economy.

The construction sector must adapt and evolve towards a regenerative economy in order to contribute to the objectives set by the 8th Environment Action Program. The buildings have the capacity to contribute to an economy without waste, without greenhouse gas emissions and that the economic evolution of the sector is not linked to the consumption of natural resources and environmental degradation.

This study was developed in several chapters where different technologies that allow the energy sustainability of the sector are analysed. In each of the chapters, an introduction is made on the analysed technology and they are analysed and discussed from the point of view of energy efficiency or environmental health.

The starting point has been the creation of a model that allows analysing the thermal behaviour of a building considering its thermal inertia. The thermal envelope is the element of the building that has the greatest consequences on energy consumption; therefore, an adequate design IS essential to guarantee efficient energy consumption and adequate thermal comfort.

The developed mathematical model allows predicting the indoor temperature of a building taking into account energy losses through

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

the envelope (walls and windows) and ventilation. Furthermore, the solar contributions have an important weight on the thermal behaviour of the building, allowing its use in seasons of high energy demand. Therefore, the influence of solar radiation through the walls and windows of the building is included in the mathematical model, considering the thermal inertia of the building.

The construction of buildings with high thermal inertia makes it possible to generate stable indoor temperatures and therefore guarantee thermal comfort. Factors such as density, thermal capacity and thickness of materials, play a fundamental role in the accumulation of energy in buildings.

Materials such as granite or concrete have a high density, which gives them a greater capacity for energy storage. Therefore, despite their high conductivity, they allow a stable indoor temperature to be maintained when they are present with high thicknesses. Materials such as bricks have a better thermal behaviour than granite and concrete, due to their lower conductivity. The low conductivity value gives them a lower thermal diffusivity, generating a greater stability of the indoor temperature and a greater time lag. The characteristics of bricks can be improved, with phase change materials or by filling the interior holes.

Wood has been the material that has presented the best results, due to being the material with the highest heat capacity and its low conductivity. These two properties give the material a very low thermal diffusivity, being the material with the best thermal behaviour.

Regarding insulating materials, their thermal behaviour is better than concrete and granite, because it is the material with the lowest thermal conductivity that has been analysed. However, the potential for using this material lies in its low heat transmission, which is why in combination with materials such as concrete it can generate stable indoor temperatures. However, the arrangement of these materials plays a fundamental role in the indoor temperature.

In order to maximize the energy performance of the accumulated energy, the placement of the thermal insulation on the outside allows the stored energy to be redirected to the interior of the building,

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

maintaining more stable indoor temperatures. In this way, the thermal mass that is inside the building accumulates the energy inside and the placement of the insulation prevents the energy from flowing to the outside. This accumulated energy can come from heating systems or from renewable energy sources such as solar radiation. However, by placing the insulation inside the energy storage capacity is lost, resulting in greater thermal fluctuations inside the building.

Solar radiation is one of the energy sources that optimize the energy performance of buildings. Solar energy inputs are produced through the envelope and through the windows. The contributions of solar energy through the enclosures have less influence on the interior temperature compared to the contributions through the windows.

When the thermal mass is inside, the solar radiation through the wall produces a more stable temperature than when the thermal mass is outside. When the thermal mass is outside, higher temperatures are generated, but lower minimum temperatures are also generated.

The main energy input from solar radiation is produced through the windows. The solar contributions depend on the size, orientation and properties of the glass. In this case, when the building thermal mass is inside, it has a greater accumulation capacity, increasing the building's interior temperature. However, when the thermal mass is located outside, higher temperatures are reached, which can generate conditions of thermal discomfort. Taking into account the thermal inertia of the building, the solar contributions must be controlled in summer to avoid indoor temperatures outside the comfort zone and higher energy expenditure in cooling.

The mathematical model obtained has also made it possible to evaluate the influence of ventilation on the interior temperature of the building. In this case, buildings with a high accumulation of energy indoors have a greater variation in the indoor temperature, eliminating the entire time lag generated with the accumulation of energy.

Solar radiation can be an ally for the construction of buildings with high efficiency. Solar radiation makes it possible to reduce the energy demand of the home in winter, however, in summer it can lead to undesirable indoor temperatures and therefore higher energy expenditure in air conditioning. The main parameter that affects the

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

solar contributions to a home is the solar factor of the window, which prevents the proportional entry of solar radiation into the interior. However, a balance must be sought between the solar factor of the glass and the solar protection systems, since a low solar factor prevents the entry of solar radiation in summer but also in winter, minimizing the energy from the sun.

There are various types of solar protection systems, which can be incorporated into existing buildings and do not require large investments in their installation. However, automated systems make it possible to optimize the energy flow from the sun and minimize energy consumption, making an intelligent management of the contributions from solar radiation.

Other techniques analyzed are related to the use of waste and biomass as construction materials. Construction is the sector with the highest generation of waste in the European Union and with an upward trend in the coming years. Therefore, to obtain sustainable buildings, waste and biomass as construction materials must be introduced into the value chain. In this area, the sector has great potential for improvement and a wide range of materials to be used.

In this work, the thermal properties of construction materials with waste mixtures and biomass are analysed using the model developed in the first chapters as a starting tool. Also, simulation software is used for the energy analysis of a building built with different eco-materials.

In recent years there has been an increase in the number of studies related to the use of waste in the construction sector. The current European policies to achieve a low-carbon and circular economy, puts the reuse of waste in the construction sector in the spotlight.

The use of residues or biomass in combination with construction materials, generally improves the thermal properties, however, their mechanical resistance may be affected. Materials such as agricultural waste, despite not representing 1% of the waste generated, are already used as thermal insulation. However, in combination with materials such as bricks, they can form part of the building envelope, improving thermal resistance.

In order to analyse the thermal behaviour of eco-materials, the use of Hemp Concrete, Isotex, Olive Core Flour and Wheat Straw in a

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

typical building are analysed. Among the results obtained, it is obtained that the model with 15 cm of Hemp Concrete or the model with 25 cm of Isotex (material made from pieces of wood) can achieve a building with thermal performance similar to conventional materials. However, when using 15 cm bricks with OCF and WS mixtures, it is obtained that the energy demand of the building is greater. Moreover, materials such as Hemp Concrete and Isotex, presented a higher thermal behaviour than concrete (lower decrement factor and greater time lag). Therefore, they are materials that can be used in the sector and that also have the advantage that the environmental impact they generate is lower than conventional materials such as concrete or brick.

Based on the simulation carried out, it was obtained that the mixtures of OCF and WS, presented better thermal behaviour with respect to conventional brick and also, the properties improved when increasing the mixture of agricultural residues. Among the main advantages, the reduction in thermal conductivity, a lower decrement factor and an increase the time lag stand out. It should be taken into account that when incorporating residues the compressive strength is reduced with respect to conventional brick. This effect has also manifested itself in the production of cement, mortar or concrete.

Therefore, the introduction of waste in the value chain, allows reaching an energy demand similar to that built with conventional materials and also reducing its environmental impact in the construction stage. In this way, the circularity of the sector is promoted, increasing the recycled content in construction materials.

The sustainability of the construction sector involves the construction of buildings with high energy efficiency and low environmental impact, but also they must guarantee a healthy environment, guaranteeing adequate air quality and thermal comfort.

Interest in ensuring air quality in buildings has been increasing gradually over the last 15 years. However, as a result of the pandemic caused by COVID-19, the lack of facilities to guarantee adequate air quality was revealed. The increase in the frequency of air renewal has triggered a greater increase in energy consumption, especially in public buildings, due to the lack of heat recovery systems.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Viruses, as well as bacteria, were already included within the biological hazards according to the ASHRAE classification to guarantee a healthy indoor environment, where humans are the main source of emission.

There are a greater number of dangers in the indoor air, which must be controlled to guarantee a healthy environment, specifically in buildings with a high concentration of people. Among the chemical hazards, the concentration of CO_2 produced mainly by human respiration stands out. The control of this parameter has been used to control the dispersion of SARS-CoV-2, because it is a measurable and controllable parameter from the CO_2 concentration. The CO_2 concentration in the ambient air is controllable with a mechanical ventilation system, however, through natural ventilation, the CO_2 concentration is conditioned by the outside temperature and also by the quality of the outside air. Controlling CO_2 concentration through natural ventilation in cold seasons causes undesirable thermal comfort conditions, which is why interior ventilation is sometimes sacrificed to safeguard the interior temperature.

Another of the chemical hazards present inside buildings are PM2.5 and PM10. Among the main sources of PM concentration is human activity and proximity to industrial environments or those with high atmospheric pollution. The reduction of PM through natural ventilation may not be effective since it depends on the quality of the outside air, since it can increase the concentration of PM in the interior. Therefore, to control PM requires the use of adequate filters in ventilation systems and control of PM production sources.

The types of materials used inside buildings also are a source of indoor air pollution due to the presence of VOCs. These compounds increase the concentration of indoor air with increasing temperature and the control of this parameter is based on adequate ventilation and the use of sustainable materials.

Other pollutants present in the indoor air depend on the construction area of the building, such as radon gas, a source of ionized radiation that can cause lung cancer.

Based on the type of buildings, the presence of pollutants is different; however, they can and should be controlled. Current

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

ventilation systems make it possible to maintain adequate air quality and guarantee thermal comfort. However, thermal comfort within a home must not only be achieved through the use of HVAC systems, but also influence the design of the building.

Two theories for the analysis of thermal comfort coexist, the heat balance method, and the adaptive method. The heat balance method, based on the indicator "Predicted Mean Vote" (PMV), bases its study on a sample of populations in controlled cold rooms, however, it does not take into account the ability of people to adapt, which if they have the adaptive method. The adaptive method takes into account behavioural, psychological and physiological factors. The use of these theories in air conditioning systems allows generating energy savings with respect to fixed temperature set point systems.

The design of the building plays a fundamental role in ensuring adequate indoor thermal comfort. Both indoor temperature and humidity were considered physical hazards within the ASHRAE classification, therefore, they must be parameters to control to guarantee a healthy indoor environment.

In buildings with high thermal inertia that allow the achievement of more stable indoor temperatures, it generates a greater thermal comfort and avoids a situation of discomfort. However, in buildings with low thermal inertia, due to the temperature fluctuation that they generate inside the building, they can cause the interior conditions to leave the comfort zone and generate a percentage of satisfied lower than 80%. In these cases, the use of HVAC systems must compensate for this lack of thermal comfort.

The technologies analysed in this work are aimed at achieving efficient, comfortable and healthy buildings. Therefore, the main Best Available Techniques (BAT) related to thermal inertia, control of solar radiation, sustainable materials, indoor air quality and thermal comfort are identified that allow the achievement of smart and sustainable buildings.

The ambitious goals set by the European Union to achieve a low carbon economy by 2050, makes buildings one of the strategic sectors. The objective of the European Union of doubling the rate of renovation of buildings will allow taking a step towards the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

achievement of the objectives of reduction of emissions, also to creating green jobs and reducing energy poverty.

Improving energy efficiency in buildings will not only reduce energy consumption and greenhouse gas emissions into the atmosphere, but also will improve the security of energy supply in the European Union and reduce the energy dependence of the imports.

In addition, it is time to promote the use of sustainable materials in a sector that consumes 50% of the raw materials extracted and 37% of the waste generated. This mobilization of resources for the sector and the long durability of the buildings make it have enormous potential.

The analyzed techniques contribute to the construction of sustainable and comfortable buildings through circular and regenerative economy techniques. These techniques allow progress towards the decarbonization of the sector and the reduction of natural resources (energy and materials). Thus, the growth of the construction sector is decoupled from the use of natural resources and environmental degradation. Therefore, these techniques actively contribute to the objectives established in the 8th Environment Action Program of the European Union, allowing the sector to advance and prosper towards a regenerative economy.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

REFERENCES

Abbas, M.; Razzaq, S.; Shahzadi, R.; Rahman, A.; Manzoor, F.; Ali, Z. (2015). Determination of indoor and outdoor air quality under different ventilation conditions in a residential area of Lahore, Pakistan. Journal of Animal and Plant Sciences, 25(3), 672-676.

Abbasi, Saeed; Jannaty, Mohammad; Faraj, Rabar; Shahbazpanahi, Shahriar; Mosavi, Amir (2020). The Effect of Incorporating Silica Stone Waste on the Mechanical Properties of Sustainable Concretes. Materials 13(17).

Abou Hweij, Walid; Ghaddar, Nesreen; Ghali, Kamel; Habchi, Carine. (2016). Optimized performance of displacement ventilation aided with chair fans for comfort and indoor air quality. Energy and Buildings, 127, 907-919.

Agarwal, Nehul; Meena, Chandan; P Raj, Binju; Saini, Lohit; Gopalakrishnan, N; Kumar, Anuj; Balam, Nagesh; Alam, Tabish; Kapoor, Nishant; Aggarwal, Vivek (2021). Indoor air quality improvement in COVID-19 pandemic: Review. Sustainable Cities and Society, 70.

Agencia Estatal de Meteorología (2018). "Mapas climáticos de España (1981-2010) y ETo (1996-2016)".

Agencia Estatal de Meteorología: http://www.aemet.es/es/portada [Acceded Desembre 2019]

Al Assaad, Douaa; Ghali, Kamel; Ghaddar, Nesreen (2018). Effectiveness of intermittent personalized ventilation assisting a chilled ceiling for enhanced thermal comfort and acceptable indoor air quality. Building and Environment, 144, 9-22.

Al-Sanea, Sami A.; Zedan, M.F. (2011). Improving thermal performance of building walls by optimizing insulation layer distribution and thickness for same thermal mass. Applied Energy, 88 (9), 3113-3124.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Al-Sanea, Sami A.; Zedan, M.F.; Al-Hussain, S.N. (2012). Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential. Applied Energy, 89 (1), 430–442.

Albatayneh, Aiman; Alterman, Dariusz; Page, Adrian; Moghtaderi, Behdad. (2019). "The Significance of the Adaptive Thermal Comfort Limits on the Air-Conditioning Loads in a Temperate Climate. Sustainability". Sustainability, 11(2), 328.

Albayyaa, Haider; Hagare, Dharmappa; Saha, Swapan (2019). Energy conservation in residential buildings by incorporating Passive Solar and Energy Efficiency Design Strategies and higher thermal mass. Energy and Buildings, 182, 205-213.

Aldawoud A (2013). "Conventional fixed shading devices in comparison to an electrochromic glazing system in hot, dry climate". Energy and Buildings, 59, 104-110.

Alnuaimi, A.N.; Natarajan, S. (2020). The Energy Cost of Cold Thermal Discomfort in the Global South. Buildings, 10, 93.

Alonso, A.; Llanos, J.; Escandón, R.; Sendra, J.J. (2021). Effects of the COVID-19 Pandemic on Indoor Air Quality and Thermal Comfort of Primary Schools in Winter in a Mediterranean Climate. Sustainability, 13 (5).

Alqahtani, Fahad; Abotaleb, Ibrahim; Harb, Sara (2021). LEED Study of Green Lightweight Aggregates in Construction. Sustainability, 13(3).

Alyamaç, Kürşat; Ince, Ragip (2009). A preliminary concrete mix design for SCC with marble powders. Construction and Building Materials, 23 (3), 1201-1210.

Alyousef, Rayed; Mohammadhosseini, Hossein; Tahir, Mahmood; Alabduljabbar, Hisham (2020). Green concrete composites production comprising metalized plastic waste fibers and palm oil fuel ash. Materials Today: Proceedings, 39, Part 2, 911-916.

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (2009). ASHRAE Handbook: Heating, Ventilating, and Air-Conditioning Applications.

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (2009). ASHRAE Handbook: Fundamentals.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

American Society of Heating, Refrigerating and Air Conditioning Engineers (2010). Standard 55-2010, Thermal. Environmental Conditions for Human Occupancy; ASHRAE: Atlanta, GA, USA, 2010.

American Society of Heating, Refrigerating and Air Conditioning Engineers (2017). Standard 55-2017, Thermal. Environmental Conditions for Human Occupancy; ASHRAE: Atlanta, GA, USA, 2017

Amin, Sh.K.; Abd El Hamid, Eman; El-Sherbiny, S.A.; Sibak, H.A.; Abadir, M.F. (2018). The use of sewage sludge in the production of ceramic floor tiles. HBRC Journal, 14 (3), 309-315.

Andres, Dana; Manea, Daniela (2015). Innovative Building Materials Using Agricultural Waste. Procedia Technology, 19, 456-462.

Aouba, Laila; Bories, Cécile; Coutand, Marie; Perrin, B.; Lemercier, Hervé (2016). Properties of fired clay bricks with incorporated biomasses: Cases of Olive Stone Flour and Wheat Straw residues. Construction and Building Materials, 102, Part 1, 7-13.

AQUAPANEL® Outdoor Knauf. Avaliable: https://www.knauf.es. Accessed: January 2021

Asan, H. (2000). Investigation of wall's optimum insulation position from maximum time lag and minimum decrement factor point of view. Energy and Buildings, 32 (2), 197–203.

Assi, Lateef; Carter, Kealy; Deaver, Edward (Eddie) (2018); Anay, Rafal; Ziehl, Paul. "Sustainable concrete: Building a greener future". Journal of Cleaner Production, 198, 1641-1651.

Aste, Niccolò; Angelotti, Adriana; Buzzetti, Michela (2009). The influence of the external walls thermal inertia on the energy performance of well insulated buildings. Energy and Buildings, 41 (11), 1181-1187.

Aste, Niccolò; Leonforte, Fabrizio; Manfren, Massimiliano; Mazzon, Manlio. (2015). Thermal inertia and energy efficiency – Parametric simulation assessment on a calibrated case study. Applied Energy, 145, 111–123.

Attia, Shady; Eleftheriou, Polyvios; Xeni, Flouris; Rodolphe, Morlot; Ménézo, Christophe; Kostopoulos, Vassilis; Betsi, Maria;

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Kalaitzoglou, Iakovos; Pagliano, Lorenzo; Cellura, Maurizio; Almeida, Manuela; Ferreira, Marco; Baracu, Tudor; Badescu, Viorel; Crutescu, Ruxandra; Hidalgo Betanzos, Juan (2017). Overview and future challenges of nearly Zero Energy Buildings (nZEB) design in Southern Europe. Energy and Buildings, 155, 439-458.

Avendaño-Vera, Constanza; Martinez-Soto, Aner; Marincioni, Valentina (2020). Determination of optimal thermal inertia of building materials for housing in different Chilean climate zones. Renewable and Sustainable Energy Reviews, 131.

Awadh, Omair (2017). Sustainability and green building rating systems: LEED, BREEAM, GSAS and Estidama critical analysis. Journal of Building Engineering, 11, 25-29.

Azari, Rahman; Abbasabadi, Narjes (2018). Embodied energy of buildings: A review of data, methods, challenges, and research trends. Energy and Buildings, 168, 225-235.

Azevedo, Gislaine; Vital, Adriana De Fátima (2018). Aproveitamento do rejeito das indústrias de beneficiamento do caulim para a produção de tinta ecológica à base de terra. Tecnologia em Metalurgia Materiais e Mineração, 15(3).

Balubaid, Saeed; Mohamad zin, Rosli; Abd Majid, Muhd.Zaimi; Hassan, Jalees; Mardzuki, Samihah (2014). Embodied Energy in Building Construction. Journal Teknologi, 70 (7).

Barros, M.C.; Bello, P.; Roca, E.; Casares, J.J., 2007. Integrated pollution prevention and control for heavy ceramic industry in Galicia (NW Spain). Journal of Hazardous Materials, 141, 680-692.

Basinska, Malgorzata; Michalkiewicz, Michal; Ratajczak, Katarzyna (2019). Impact of physical and microbiological parameters on proper indoor air quality in nursery. Environment International, 132.

Barmparesos, N.; Assimakopoulos, M. N.; Assimakopoulos, V. D.; Loumos, N.; Sotiriou, M. A.; Koukoumtzis, A. (2018). Indoor Air Quality and Thermal Conditions in a Primary School with a Green Roof System. Atmosphere, 9, 75.

Bello Bugallo, Pastora M; Stupak, Anna; Cristóbal Andrade, Laura; Torres López, Rosa (2012). Material Flow Analysis in a

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

cooked mussel processing industry. Journal of Food Engineering, 113, 100–117.

Bello Bugallo, P.M. Cristóbal Andrade, L.; Magán Iglesias, A.; Torres López, R. (2013). Integrated environmental permit through Best Available Techniques: evaluation of the fish and seafood canning industry. Journal of Cleaner Production 47, 253-264.

Bello Bugallo, Pastora M.; Cristóbal Andrade, Laura, Agrelo de la Torre, Maria; Torres López, Rosa (2014). Analysis of the slaughterhouses in Galicia (NW Spain). Science of the Total Environment, 481, 656–661.

Beyeler, Franz; Beglinger, Nick; Roder, Ursina (2009). "Minergie: The Swiss Sustainable Building Standard," Innovations: Technology, Governance, Globalization, MIT Press, 4(4), 241-244.

Blaszczok, M.; Baranowski, A. (2018) Thermal improvement in residential buildings in view of the indoor air quality – Case study for polish dwelling". Architecture Civil Engineering Environmet, 3.

Boonyayothin, V.; Hirunlabh, J.; Khummongkol, P.; Teekasap, S.; Shin, U-C.; Khedari, J. (2011). Ventilation Control Approach for Acceptable Indoor Air Quality and Enhancing Energy Saving In Thailand. International Journal of Ventilation, 9(4), 315-326.

Bonetta, S.; Bonetta, Si.; Mosso, S.; Sampo, S.; Carraro, E. (2009). Assessment of microbiological indoor air quality in an Italian office building equipped with an HVAC system. Environmental Monitoring and Assessment, 161(1-4), 473-83.

Bouchair, Ammar (2008). Steady state theoretical model of fired clay hollow bricks for enhanced external wall thermal insulation. Building and Environment, 43 (10), 1603-1618.

BREEAM: https://www.breeam.com/

Cancelas Caso, José Antonio; Sirgo Blanco, José Ángel. Regulación y Control de Máquinas Navales. Universidad de Oviedo, reference page: http://isa.uniovi.es/docencia/ra_marina/ [Accessed: November 2014]

Canha, N.; Lage, J.; Candeias, S.; Alves, C.; Almeida, S. M. (2017). Indoor air quality during sleep under different ventilation patterns. Atmospheric Pollution Research, 8 (6), 1132-1142.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Cascone, Stefano; Rapisarda, Renata; Cascone; Dario (2019). Physical Properties of Straw Bales as a Construction Material: A Review. Sustainability, 11 (12), 3388.

Chang, Zhiyang; Long, Guangcheng; Zhou, John; Cong, Ma (2020). Valorization of sewage sludge in the fabrication of construction and building materials: A review. Resources, Conservation and Recycling, 154 (3).

Chatzidiakou, Lia; Mumovic, Dejan; Summerfield, Alex (2015). Is CO2 a good proxy for indoor air quality in classrooms? Part 1: The interrelationships between thermal conditions, CO2 levels, ventilation rates and selected indoor pollutants. Building Service Engineering, 36 (2).

Chaussinand, Adrien; Scartezzini, J.L; Nik, Vahid (2015). Straw bale: A waste from agriculture, a new construction material for sustainable buildings. Energy Procedia, 78, 297-302.

Che, Wen Wei; Tso, Chi Yan; Sun, Li; Ip, Danny Y. K.; Lee, Harry; Chao, Christopher Y. H.; Lau, Alexis K. H. (2019). Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system". Energy and Buildings, 201, 202-215.

Cheng, Yong; Zhang, Sheng; Huan, Chao; Oladokun, Majeed Olaide; Lin, Zhang (2019). Optimization on fresh outdoor air ratio of air conditioning system with stratum ventilation for both targeted indoor air quality and maximal energy saving. Building and Environment, 147, 11-22.

Cheunga, P. K.; Jim, C.Y. (2019). Indoor air quality in substandard housing in Hong Kong. Sustainable Cities and Society, 48.

Chi, Doris A.; Moreno, David; Navarro, Jaime (2018). "Correlating daylight availability metric with lighting, heating and cooling energy consumptions". Building and Environment, 132, 170-180.

Climalit: https://climalit.es/ [Accessed December 2019]

Congedo, Paolo; Baglivo, Cristina; Centonze, Giulia (2020). Walls comparative evaluation for the thermal performance

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

improvement of low-rise residential buildings in warm Mediterranean climate. Journal of Building Engineering, 28.

Cordeiro, Guilherme; Toledo Filho, Romildo; Tavares, Luis; Fairbairn, EMR (2008). Pozzolanic activity and filler effect of sugar cane bagasse ash in Portland cement and lime mortars. Cement and Concrete Composites, 30 (5), 410-418.

Cordeiro, Guilherme; Toledo Filho, Romildo; Tavares, Luis; Fairbairn, Eduardo (2009). Ultrafine Grinding of Sugar Cane Bagasse ash for Application as Pozzolanic Admixture in Concrete. Cement and Concrete Research, 39 (2), 110-115.

Dabbagh, M.; Krarti, M. (2020). Evaluation of the performance for a dynamic insulation system suitable for switchable building envelope. Energy and Buildings, 222.

Danielle E.M. Bond; Clark, William W.; Kimber, Mark (2013). Configuring wall layers for improved insulation performance. Applied Energy, 112, 235–245.

de Dear, Richard & Brager; Gail & D., Cooper (1997). Developing an Adaptive Model of Thermal Comfort and Preference - Final Report on RP-884. ASHRAE Transactions. 104.

Denga, S.; Lau, J. (2019). Seasonal variations of indoor air quality and thermal conditions and their correlations in 220 classrooms in the Midwestern United States. Building and Environment, 157, 79-88.

Domínguez, Manuel; García, David (2010). La impedancia térmica de los cerramientos. Nuevo concepto que puede facilitar de forma considerable el ahorro energético. Nueva Arquitectura.

Dongmei, P.; Zhongping, L.;Ning, M.;Mengjie, S. (2017). A study on the effects of different bedding systems on thermal comfort – quantifying the sensitivity coefficient used for calculating Predicted Mean Vote (PMV) in sleeping environments. Energy Procedia, 142, 1939-1946.

Dussault J. M., Gosselin L. Galstian T (2012). Integration of smart windows into building design for reduction of yearly overall energy consumption and peak loads. Solar Energy, 86 (11), 3405-3416.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Dutton, Spencer M.; Fisk, William J. (2014). Energy and indoor air quality implications of alternative minimum ventilation rates in California offices. Building and Environment, 82, 121-127.

EEA, European Environment Agency: https://www.eea.europa.eu/ [Accessed March 2021].

El-Dieb, Amr S.; Kanaan, Dima M. (2018). Ceramic waste powder an alternative cement replacement – Characterization and evaluation. Sustainable Materials and Technologies, 17.

El Fgaier, Faycal; Lafhaj, Zoubeir; Brachelet, Franck; Antczak, E.; Chapiseau, Christophe (2015). Thermal performance of unfired clay bricks used in construction in the north of France: Case study. Case Studies in Construction Materials, 3, 102-111.

Elsaid, Ashraf Mimi, and M Salem Ahmed (2021). Indoor Air Quality Strategies for Air-Conditioning and Ventilation Systems with the Spread of the Global Coronavirus (COVID-19) Epidemic: Improvements and Recommendations. Environmental Research, 199.

Eumorfopoulou E. A., K.J. Kontoleon K. J (2009). Experimental approach to the contribution of plant-covered walls to the thermal behaviour of building envelopes. Building and Environment, 44 (5), 1024-1038.

European Committee for Standardisation. UNI EN 15251—Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics; European Committee for Standardisation: Brussels, Belgium, 2008.

European Parliament. Plastic waste and recycling in the EU: facts and figures. Avaliable: https://www.europarl.europa.eu/news/en [Accessed: Decembre 2020]

Eurostat Database: https://ec.europa.eu/eurostat/data/database [Accessed: November 2020].

EU (2000), Directive 2000/69/EC of the European Parliament and of the Council of 16 November 2000 relating to limit values for benzene and carbon monoxide in ambient air.

EU (2002). Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

EU (2004), COM/2004/0416, Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee - "The European Environment & Health Action Plan 2004-2010".

EU (2005). "The INDEX project: Critical Appraisal of the Setting and Implementation of Indoor Exposure Limits in the EU".

EU (2006), COM/2006/583, Communication from the commission to the Commission to the Council and the European Parliament. "Mobilising public and private finance towards global access to climate-friendly, affordable and secure energy services: The Global Energy Efficiency and Renewable Energy Fund".

EU (2008), COM/2008/30 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - 20 20 by 2020 - Europe's climate change opportunity.

EU (2008), COM/2008/772, Communication from the Commission of 13 November 2008. "Energy efficiency: delivering the 20% target".

EU (2009). Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

EU (2009). Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020.

EU (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.

EU (2010) Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control).

EU (2011), COM/2011/109, Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions "Energy Efficiency Plan 2011".

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

EU (2011), COM/2011/112, Communication from the Commission to the European Parliament, the Council, the European Economic and social committee and the committee of the regions of 8 March 2011. "A Roadmap for moving to a competitive low carbon economy in 2050".

EU (2011), COM/2011/885 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Energy Roadmap 2050.

EU (2012). Consolidated version of the Treaty on the Functioning of the European Union.

EU (2012). Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements.

EU (2012). Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC.

EU (2013), COM/2013/169, Green Paper. "A 2030 framework for climate and energy policies".

EU (2013), Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom.

EU (2013), "Towards nearly zeroenergy buildings Definition of common principles under the EPBD. Final Report". 14 February 2013.

EU (2014), COM/2014/015 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A policy framework for climate and energy in the period from 2020 to 2030.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

EU (2014), COM/2014/330, Communication from the commission to the European Parliament and the Council. “European Energy Security Strategy”.

EU (2014), Framework for climate and energy. “Outcome of the October 2014 European Council”.

EU (2015). COM/2015/0614 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the loop - An EU action plan for the Circular Economy.

EU (2015). COM/2015/6317 Comminication from the Commission. Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation

EU (2016), COM/2016/0110 final. Communication from the Commission to the European Parliament, the Council. The Road from Paris: assessing the implications of the Paris Agreement and accompanying the proposal for a Council decision on the signing, on behalf of the European Union, of the Paris agreement adopted under the United Nations Framework Convention on Climate Change.

EU (2016), COM/2016/765. Proposal for a Directive of European Parliament and of the Council amending Directive 2010/31/EU on the energy performance of buildings.

EU (2016), COM/2016/0767. Proposal for a Directive of the European Parliament and the Councilon the promotion of the use of energy from renewable sources.

EU (2016), COM/2016/0860 final/2. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions and the European Investment Bank. Clean Energy For All Europeans.

EU (2016).Commission Recommendation (EU) 2016/1318 of 29 July 2016 on guidelines for the promotion of nearly zero-energy buildings and best practices to ensure that, by 2020, all new buildings are nearly zero-energy buildings.

EU (2018). COM/2018/029 final. Communication from the Commission to the European Parliament, the Council, the European

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Economic and Social Committee and the Committee of the Regions on a monitoring framework for the circular economy.

EU (2018), COM/2018/773 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions and the European Investment Bank. A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy.

EU (2018). Directive 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.

EU (2018), Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, amending Regulations (EC) No 663/2009 and (EC) No 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and repealing Regulation (EU) No 525/2013 of the European Parliament and of the Council

EU (2018), Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources.

EU (2018), Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency.

EU (2019), COM/2019/559. Report from de Commission to the European Parliament and the Council. Preparing the ground for raising long-term ambition EU Climate Action Progress Report 2019.

EU (2020). COM/2020/98 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions

EU (2020), COM/2020/80 final. Proposal for a Regulation of the European Parliament and of the Council establishing the framework

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law).

EU (2020), COM/2020/98 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A new Circular Economy Action Plan For a cleaner and more competitive Europe.

EU (2020), COM/2020/562 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our people.

EU (2020), COM/2020/563 final. Amended proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law).

EU (2020). COM/2020/652 final. Proposal for a Decision of the European Parliament and of the Council on a General Union Environment Action Programme to 2030.

EU (2020), COM/2020/662. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives.

EU (2020), COM/2000/772, Communication from the Commission of 20 November 2000. "Green Paper - Towards a European strategy for the security of energy supply".

EU (2020), COM/2020/788 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. European Climate Pact.

EU (2021), Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law').

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Evola, Gianpiero; Marletta, Luigi; Natarajan, Sukumar; Maria Patanè, Elisabettà (2017). Thermal inertia of heavyweight traditional buildings: experimental measurements and simulated scenarios. Energy Procedia, 133, 42-52.

Fang, L; Wyon, DP; Clausen, G; Fanger, PO (2004). Impact of indoor air temperature and humidity in an office on perceived air quality, SBS symptoms and performance. Indoor Air, 14 Suppl 7(s7), 74-81.

Fang, Zhaosong; Li, Nan; Li, Baizhan; Luo, Guozhi; Huang, Yanqi (2014). The effect of building envelope insulation on cooling energy consumption in summer. Energy and Buildings, 77, 197–205.

Fanger, P.O. (1973). Assessment of man's thermal comfort in practice. British journal of industrial medicine, 30 (4), 313-324.

Fantozzi, F.; Rocca, M. (2020). An Extensive Collection of Evaluation Indicators to Assess Occupants' Health and Comfort in Indoor Environment. Atmosphere, 11, 90.

Fedorczak-Cisak, M.; Kotowicz, A.; Radziszewska-Zielina, E.; Sroka, B.; Tatara, T.; Barnaś, K. (2020). Multi-Criteria Optimisation of an Experimental Complex of Single-Family Nearly Zero-Energy Buildings. Energies, 13, 1541.

Feng, Guohui; Chi, Dandan; Xu, Xiaolong; Dou, Baoyue; Sun, Yixin; Fu, Yao (2017). Study on the Influence of Window-wall Ratio on the Energy Consumption of Nearly Zero Energy Buildings. Procedia Engineering, 205, 730-737.

Fernandez-Aguera, J.; Dominguez-Amarillo, S.; Alonso, C.; Martin-Consuegra, F. (2019). Thermal comfort and indoor air quality in low-income housing in Spain: The influence of airtightness and occupant behaviour. Energy and Buildings, 199, 102-114.

Ferrari, S (2007). Building envelope and heat capacity: re-discovering the thermal mass for winter energy saving. 28th AIVC and 2nd Palenc Conference: Building Low Energy Cooling and Ventilation Technologies in the 21st Century.

Figueroa-Lopez, Anna; Arias, Alba, Oregi, Xabat; Rodríguez, Iñigo (2021). Evaluation of passive strategies, natural ventilation and shading systems, to reduce overheating risk in a passive house tower

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

in the north of Spain during the warm season. Journal of Building Engineering. 43.

Fiorito, Francesco; Cannavale, Alessandro ; Santamouris, Mattheos (2020). Development, testing and evaluation of energy savings potentials of photovoltachromic windows in office buildings. A perspective study for Australian climates. Solar Energy, 205, 358-371.

Frontczak, M.; Wargocki, P. (2011). Literature survey on how different factors influence human comfort in indoor environments. Building and Environment, 46 (4), 922-937.

Fundación de la Energía de la Comunidad de Madrid (FENERCOM) (2011). "Guia del Estándar Passive House: Edificios de condumo energético casi nulo".

Galvez-Martos, Jose-Luis & Styles, David & Schoenberger, Harald. (2012). Best Environmental Management Practice in the Building and Construction Sector.

Ganesan, K.; Rajagopal, K.; Thangavel, K (2007). Evaluation of Bagasse Ash as Supplementary Cementitious Material. Cement and Concrete Composites, 29 (6), 515-524.

García Rellán, A.; Vázquez Brea, C.; Bello Bugallo, P.M (2018). Towards sustainable mobile systems configurations: Application to a tuna purse seiner. Science of the Total Environment, 631–632, 1623–1637.

Gaspar, Florindo; Bakatovich, Aliaksandr; Davydenko, Nadezhda; Joshi, Arpan (2020). Building insulation materials based on agricultural wastes. Woodhead Publishing Series in Civil and Structural Engineering, 149-170.

Gaujena, B.; Agapovs, V.; Borodinecs, A.; Strelets, K (2020). Analysis of Thermal Parameters of Hemp Fiber Insulation. Energies, 13 (23).

Ghosh A., Neogi S (2018). "Effect of fenestration geometrical factors on building energy consumption and performance evaluation of a new external solar shading device in warm and humid climatic condition". Solar Energy, 169 94-104.

Gomes M. G.,Santos A. J., Rodrigues A. M. (2014). Solar and visible optical properties of glazing systems with venetian blinds:

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Numerical, experimental and blind control study. Building and Environment, 71, 47-59

Gomez, M.C.T; Cullote, F.; Bugallo, P.M.B (2018). Sustainable Production and Use of Buildings: A Circular Economy Prospective. Proceedings of the 7th International Conference on Engineering for Waste and Biomass Valorisation, July 2-5, 2018. Prague, Czech Republic.

González, María Jesús; Navarro, Justo García (2006). Assessment of the decrease of CO2 emissions in the construction field through the selection of materials: Practical case study of three houses of low environmental impact. Building and Environment, 41 (7), 902-909.

Gupta, Rajat; Kapsali, Mariam (2015). Empirical assessment of indoor air quality and overheating in low-carbon social housing dwellings in England, UK. Advances in Building Energy Research, 10 (1), 46-68.

Gupta, Lalit; Vyas, Ashok (2018). Impact on mechanical properties of cement sand mortar containing waste granite powder. Construction and Building Materials, 191, 155-164.

Grynning, Steinar; Gustavsen, Arild; Time, Berit; Jelle, Bjørn Petter (2013). Windows in the buildings of tomorrow: Energy losers or energy gainers?. Energy and Buildings, 61, 185-192.

Hall, Monika; Geissler, Achim; Burger, Bastian (2014). Two Years of Experience with a Net Zero Energy Balance – Analysis of the Swiss MINERGIE-A® Standard. Energy Procedia. 48, 1282-1291.

Heidarinejad, Ghassem; Fathollahzadeh, Mohammad Hassan; Pasdarshahri, Hadi (2015). Effects of return air vent height on energy consumption, thermal comfort conditions and indoor air quality in an under floor air distribution system. Energy and Buildings, 97 (15), 155-161.

Hempcrete walls: building journal. Available: http://hempcretewalls.com/. Accessed: January 2021.

Heniegal, Ashraf; Ramadan, Mohamed; Naguib, Ahmed; Agwa, Ibrahim (2020). Study on properties of clay brick incorporating sludge of water treatment plant and agriculture waste. Case Studies in Construction Materials, 13.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Heracleous, C.; Michael, A. (2019). Experimental assessment of the impact of natural ventilation on indoor air quality and thermal comfort conditions of educational buildings in the Eastern Mediterranean region during the heating period. Journal of Building Engineering, 26.

Hichem, Necib; Noureddine, Settou; Nadia, Saifi; Djamila, Damene (2013). Experimental and Numerical Study of a Usual Brick Filled with PCM to Improve the Thermal Inertia of Buildings. Energy Procedia, 36, 766–775.

Himes, Austin; Busby, Gwen (2020). Wood buildings as a climate solution. Developments in the Built Environment, 4.

Huang, K.; Song, J.; Feng, G.; Chang, Q.; Jiang, B.; Wang, J.; Sun, W.; Li, H.; Wang, J.; Fang, X. (2018). Indoor air quality analysis of residential buildings in northeast China based on field measurements and longtime monitoring. Building and Environment, 144, 171-183.

Humphreys, Michael; Nicol, Fergus. (1998). Understanding the adaptive approach to thermal comfort. ASHRAE Transactions. 104. 991-1004.

Humphreys, Michael & Nicol, Fergus. (2000). Outdoor Temperature and Indoor Thermal Comfort: Raising the Precision of the Relationship for the 1998 Ashrae Database of Field Studies. AHSRAE Trans. 206. 485-492.

Hwang, Ruey-Lung; Shu, Shiu-Ya. (2011). Building envelope regulations on thermal comfort in glass facade buildings and energy-saving potential for PMV-based comfort control. Building and Environment, 46 (4), 824-834.

Hyeun Jun Moon, Jong-Ryeul Sohn & Taeyon Hwang (2018). Indoor Air Quality Performance of Ventilation Systems in Classrooms. Journal of Asian Architecture and Building Engineering, 15 (2), 343-348.

IDAE (2007), Instituto para la Diversificación y Ahorro de la Energía. Guía Técnica para la Rehabilitación de la Envolvente Térmica de los Edificios.

IDAE, (2008), Instituto para la Diversificación y Ahorro de la Energía. Soluciones de Acristalamiento y Cerramiento Acristalado.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

IDAE (2011), "Proyecto SECH-SPAHOUSEC: Análisis del consumo energético del sector residencial en España".

IDAE Database: https://www.idae.es/estudios-informes-y-estadisticas [Accessed: June 2020]

Ihara, Takeshi; Gustavsen, Arild; Petter Jelle, Bjørn (2015). Effect of facade components on energy efficiency in office buildings. Applied Energy, 158, 422–432.

INSHT (1983), NTP 74: Confort térmico - Método de Fanger para su evaluación.

Instituto Eduardo Torroja de Ciencias de la Construcción con la colaboración de CEPCO y AICIA (2010). "Catálogo de Elementos Constructivos del Código Técnico".

ISO 7730:2005. "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".

iPHA, International Passive House Association: https://passivehouse-international.org/index.php [Accessed: May, 2020]

Isohemp Natural Building. Avaliable: https://www.isohemp.com/. [Accessed: January 2021]

Isotex. Wood Cement Blocks and Floor Slabs. Available: https://en.blocchiisotex.com/. [Accessed: January 2021]

IPCC (2014). Cambio climático 2014: Informe de síntesis. Contribución de los Grupos de trabajo I, II y III al Quinto Informe de Evaluación del Grupo Intergubernamental de Expertos sobre el Cambio Climático.

Johnson, D. L.; Lynch, R. A.; Floyd, E. L. ; Wang, J.; Bartels, J. N. (2018). Indoor air quality in classrooms: Environmental measures and effective ventilation rate modeling in urban elementary schools. Building and Environment, 136, 185-197.

Johnson, D. L.; Lynch, R. A.; Floyd, E. L. ; Wang, J.; Bartels, J. N. (2018). Indoor air quality in classrooms: Environmental measures and effective ventilation rate modeling in urban elementary schools. Building and Environment, 136, 185-197.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Jomehzadeh, F.; Nejat, P.; Calautit, J. K.; Yusof, M. B. M.; Zaki, S. A.; Hughes, B. R.; Yazid, M. N. A. W. M. (2017). A review on windcatcher for passive cooling and natural ventilation in buildings, Part 1: Indoor air quality and thermal comfort assessment. Renewable and Sustainable Energy Reviews, 70, 736-756.

Jung, Chien-Cheng; Wu, Pei-Chih; Tseng, Chao-Heng; Su, Huey-Jen (2015). Indoor air quality varies with ventilation types and working areas in hospitals. Building and Environment, 85, 190-195.

Jones, E.; Young, A.; Clevenger, K.; Salimifard, P.; Wu, E.; Luna, M.L.; Lahvis, M.; Lang, J.; Bliss, M.; Azimi, P.; et al. Healthy Schools: Risk Reduction Strategies for Reopening Schools; Harvard, T.H., Ed.; Chan School of Public Health: Boston, MA, USA, 2020.

Khakian, R.; Karimimoshaver, M.; Aram, F.; Zoroufchi Benis, S.; Mosavi, A.; Varkonyi-Koczy, A.R. (2020). Modeling Nearly Zero Energy Buildings for Sustainable Development in Rural Areas. Energies, 13, 2593.

Khatab, Hadeel; Mohammed, Samaher; Hameed, Laith (2019). Mechanical Properties of Concrete Contain Waste Fibers of Plastic Straps. IOP Conference Series: Materials Science and Engineering, 557.

Khyaliya, Rajendra; Kabeer, K. I. Syed; Vyas, Ashok (2017). Evaluation of strength and durability of lean mortar mixes containing marble waste. Construction and Building Materials, 147, 598-607.

Kinnane, O., McGranaghan, G., Walker, R., Pavia, S., Byrne, G., & Robinson, A. (2015). Experimental investigation of thermal inertia properties in hemp-lime concrete walls. In Proceedings of the 10th Conference on Advanced Building Skins (pp. 942-949). Economic Forum.

Kinley, Richard (2016). What Now? Climate Change and Energy after Paris. Keynote, University of Cambridge on 22 January 2016.

Kontoleon, K.J.; Eumorfopoulou, E.A (2010). The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. Building and Environment, 45 (5), 1287-1303.

Kontoleon, K.J., Theodosiou, Th.G., Tsikaloudaki, K.G (2013). The influence of concrete density and conductivity on

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

walls thermal inertia parameters under a variety of masonry and insulation placements. Applied Energy, 112, 325-337.

Kosonena, R.; Tanb, F. (2004). Assessment of productivity loss in air-conditioned buildings using PMV index. Energy and Buildings, 36 (10), 987-993.

Kosseckaa, Elisabeth; Kosnyb, Jan (2020). "Influence of insulation configuration on heating and cooling loads in a continuously used building". Energy and Buildings, 34 (4), 321–331.

Kostiainen, T.; Welling, I.; Lahtinen, M.; Salmi, K.; Kahkonen, E.; Lampinen, J. (2008). Modeling of Subjective Responses to Indoor Air Quality and Thermal Conditions in Office Buildings. HVAC&R RESEARCH, 14 (6), 905-923.

Kuczynski, Tadeusz; Staszczuk, Anna (2020). Experimental study of the influence of thermal mass on thermal comfort and cooling energy demand in residential buildings. Energy, 195 (1).

Kuhn T. E., Bühler C., Platzer W. J. (2001). Evaluation of overheating protection with sun-shading systems. Solar Energy, 69 (6), 59-74.

Kuhn, Tilmann E.; Herkel, Sebastian; Frontinia, Francesco; Strachan, Paul; Kokogiannakis, Georgios (2011). Solar control: A general method for modelling of solar gains through complex facades in building simulation programs. Energy and Buildings, 43, 19–27.

Kuhn T. E. (2017). State of the art of advanced solar control devices for buildings. Solar Energy, 154, 112-133.

Kumar G. K., Saboor S., Kumar V., Kim K., Babu T. P. (2018) "Experimental and theoretical studies of various solar control window glasses for the reduction of cooling and heating loads in buildings across different climatic regions". Energy and Buildings, 173, 326-336.

Laaouatni, Amine; Martaj, Nadia; Bennacer, Rachid; Lachi, Mohammed; El Omari, Mohamed; El Ganaoui, Mohammed (2019). "Thermal building control using active ventilated block integrating phase change material". Energy and Buildings, 187, 50-63.

Laverge, J.; Van Den Bosschea, N.; Heijmans, N.; Janssen, A. (2011). Energy saving potential and repercussions on indoor air

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

quality of demand controlled residential ventilation strategies. Building and Environment, 46 (7), 1497-1503.

Lee, H; Awbi, HB (2004). Effect of internal partitioning on indoor air quality of rooms with mixing ventilation - basic study. Building and Environment, 39 (2), 127-141.

Lee, K.-I (2020). Improvement of Indoor Thermal Environments through Green Refurbishment. Sustainability, 12, 4933.

Lee, S.C; Chang, M. (2000). Indoor and outdoor air quality investigation at schools in Hong Kong. Chemosphere, 41, 109–113.

Lei, Z.; Liu, C.; Wang, L.; Li, N. (2017). Effect of natural ventilation on indoor air quality and thermal comfort in dormitory during winter. Building and Environment, 125, 240-247.

Leskinen, Niina, Jussi Vimpari and Seppo Junnila (2020). A Review of the Impact of Green Building Certification on the Cash Flows and Values of Commercial Properties. Sustainability, 12.

Li, He; Jia; Hongwei, Zhong, Ke; Zhai; Zhiqiang (2021). Analysis of factors influencing actual absorption of solar energy by building walls. Energy, 215 (8).

Li L.,Qu M., Peng S. Performance evaluation of building integrated solar thermal shading system: Building energy consumption and daylight provision. Energy and Buildings, 113, 189-201.

Liang, Xinxin; Wang, Yaodong; Royapoor, Mohammad; Wu, Qibai; Roskilly, Tony (2017). Comparison of building performance between Conventional House and Passive House in the UK. Energy Procedia, 142, 1823-1828.

Lin, Z; Chow, TT; Tsang, CF; Fong, KF; Chan, LS. (2005). Effect of air supply temperature on the performance of displacement ventilation (Part II) - Indoor air quality. Indoor and Built Environment, 14(2), 103-115.

Lin, Z; Chow, TT; Fong, KF; Tsang, CF; Wang, QW (2005). Comparison of performances of displacement and mixing ventilations. Part II: indoor air quality. International Journal of Refrigeration, 28 (2), 288-305

Liu, Sumei; Dong, Jiankai; Cao, Qing; Zhou, Xiaojie; Li, Jian; Lin, Xiaorui; Qing, Ke; Zhang, Weizhen; Chen, Qingyan. (2019).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Indoor thermal environment and air quality in Chinese-style residential kitchens. Indoor Air, 30 (2).

Liuzzi, Stefania¸ Rubino, Chiara; Martellotta, Francesco; Stefanizzi, Pietro; Casavola, Caterina; Pappalettera, Giovanni (2020). Characterization of biomass-based materials for building applications: The case of straw and olive tree waste. Industrial Crops and Products, 147.

Llamosas, A. del Castillo; Gomez, M.C. Taboada; Bugallo, P.M. Bello (2018). Towards Sustainable Construction Systems: Application to Redesign Conventional Buildings. Proceedings of the 7th International Conference on Engineering for Waste and Biomass Valorisation. July 2-5, 2018. Prague-Czech Republic.

Maalouf, Chadi; Tran Le, Anh Dung; Lachi, Mohammed; Wurtz, Etienne; Mai, Ton (2011). Effect of moisture transfer on thermal inertia in simple layer walls, Case of a vegetal fibre material. International Journal of Mathematical Models and Methods in Applied Sciences, 5, 33-47.

Magrini, Anna; Lentini, Giorgia; Cuman, Sara; Bodrato, Alberto; Marenco, Ludovica (2020). From Nearly Zero Energy Buildings (NZEB) to Positive Energy Buildings (PEB): the next challenge - The most recent European trends with some notes on the energy analysis of a forerunner PEB example. Developments in the Built Environment, 3.

Manso M., Castro-Gomes J. (2015). Green wall systems: A review of their characteristics. Renewable and Sustainable Energy Reviews, 41, 863-871.

Mansour, Ashraf; Ali, Subhi (2015). Reusing waste plastic bottles as an alternative sustainable building material. Energy for Sustainable Development, 24, 79-85.

Maraveas, C (2020). Production of Sustainable Construction Materials Using Agro-Wastes. Materials, 13(2), 262.

Marincic, Irene (1999). Respuestas térmicas dinámicas en edificios: Control térmico a través de la climatización natural. Tesis Doctoral, Universitat Politècnica de Catalunya, Barcelona, Junio de 1999.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Martín, Silvia; Mazarrón, Fernando R; Cañas, Ignacio (2010). Study of thermal environment inside rural houses of Navapalos (Spain): The advantages of reuse buildings of high thermal inertia. Construction and Building Materials, 24 (5), 666–676.

Martinez, M. L.; Eliche, D.; Cruz, N.; Corpas, F. A (2012). Utilization of bagasse from the beer industry in clay brick production for building. Materiales de Construcción, 62 (306), 199-212.

Mazarrón, Fernando R; Canas, Ignacio (2008). Exponential sinusoidal model for predicting temperature inside underground wine cellars from a Spanish region. Energy and Buildings, 40 (10), 1931–1940.

McCartney, Kathryn; Nicol, Fergus (2002). Developing an adaptive control algorithm for Europe. Energy and Buildings, 34 (6), 623-635.

Meteogalicia. http://www.meteogalicia.es/ [Accessed: January 2018]

Meteogalicia (2020), "Informe Climatolóxico mes de Xullo de 2020".

MINERGIE. Available online: https://www.minergie.ch/

Ministerio de Fomento (2013), Orden FOM/1635/2013, de 10 de septiembre, por la que se actualiza el Documento Básico DB-HE «Ahorro de Energía», del Código Técnico de la Edificación, aprobado por Real Decreto 314/2006, de 17 de marzo.

Ministerio de Fomento, Observatorio de Vivienda y Suelo (2014). Boletín Especial Censo 2011 Parque edificatorio.

Ministerio de Fomento (2014). Estrategia a largo plazo para la rehabilitación energética en el sector de la edificación en España en desarrollo del Artículo 4 de la Directiva 2012/27/UE.

Miniterio de Fomento (2019). "Documento Básico HE Ahorro de Energía".

Ministerio de Sanidad (2021). Informacion Científica-Técnica: Enfermedad por coronavirus, COVID-19.

Minunno, Roberto; O'Grady, Timothy; Morrison, Gregory; Gruner, Richard (2020). Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. Resources Conservation and Recycling. 160.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Mohammadhosseini, Hossein; Tahir, Mahmood Md. (2018). Durability performance of concrete incorporating waste metalized plastic fibres and palm oil fuel ash. Construction and Building Materials, 180, 92-102.

Mokhtari, Reza; Jahangir, MH (2021). The effect of occupant distribution on energy consumption and COVID-19 infection in buildings: A case study of university building. Building and Environment, 190.

Musy, Marjorie; Malys, Laurent; Inard, Christian (2017). Assessment of Direct and Indirect Impacts of Vegetation on Building Comfort: A Comparative Study of Lawns, Green Walls and Green Roofs. Procedia Environmental Sciences, 38, 2017 603-610

Mutani, G.; Azzolino, C.; Macrì, M.; Mancuso, S. (2020). Straw Buildings: A Good Compromise between Environmental Sustainability and Energy-Economic Savings. Applaied Science, 10 (8), 2858.

Navarro Márquez, José Antonio (2002). "Sistemas de medida y regulación". Ediciones CEYSA.

Nicol, J.F.; Humphreys, M.A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. Energy and Buildings, 34 (6), 563-572.

Nielsen M. V., Svendsen S., Bjerregaard Jensen L. (2011). Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight. Solar Energy, 85 (5), 757-768.

Obrecht T. P.,Premrov M., Leskovar V. Z. (2019). Influence of the orientation on the optimal glazing size for passive houses in different European climates (for non-cardinal directions). Solar Energy, 189, 15-25.

Orosa, José A.; Oliveira, Armando C (2012). A field study on building inertia and its effects on indoor thermal environment. Renewable Energy, 37 (1), 89–96.

Ossa, A.; García, J.L.; Botero, E (2016). Use of recycled construction and demolition waste (CDW) aggregates: A sustainable alternative for the pavement construction industry. Journal of Cleaner Production, 135, 379-386.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Ottelé M., Perini K. (2017). Comparative experimental approach to investigate the thermal behaviour of vertical greened façades of buildings. Ecological Engineering, volume 108, Part A, 152-161.

Ozel, M.; Pihtili, K (2007). Optimum location and distribution of insulation layers on building walls with various orientations. Building and Environment, 42 (8), 3051-3059.

Ozel, M. (2014). Effect of insulation location on dynamic heat-transfer characteristics of building external walls and optimization of insulation thickness. Energy and Buildings, 72, Pages 288–295.

Papadakis G. Tsamis P., Kyritsis S (2001). An experimental investigation of the effect of shading with plants for solar control of buildings. Energy and Buildings, 33 (8), 831-836.

Park, Sowoo; Choi, Younhee; Song, Doosam; Kim, Eun (2021). Natural ventilation strategy and related issues to prevent coronavirus disease 2019 (COVID-19) airborne transmission in a school building. Science of The Total Environment, 789, 1.

Passive House Institute. Passive House requirements. Available online: https://passivehouse.com/ [Accessed: April 2021]

Pearsson, Mari-Louise; Roos, Arne; Wall, Maria (2006). Influence of window size on the energy. Energy and Buildings, 38 (3), 181-188.

Pennacchia, E.; Tiberi, M.; Carbonara, E.; Astiaso Garcia, D.; Cumo, F (2016). Reuse and Upcycling of Municipal Waste for ZEB Envelope Design in European Urban Areas. Sustainability, 8, 610.

Pereira, Tamires; Silva, Danillo; Eugênio, Tony; Scatolino, Mário; Terra, Isabelle; Fonseca, Camila; Bufalino, Lina; Mendes, Rafael; Mendes, Lourival (2020). Coconut fibers and quartzite wastes for fiber-cement production by extrusion. Materials Today: Proceedings, 31 (2), S309-S314.

Piccardo, Chiara; Dodoo, Ambrose; Gustavsson, Leif (2020). Retrofitting a building to passive house level: A life cycle carbon balance. Energy and Buildings, 223.

Poirazis H., Blomsterberg A., Wall M. (2008). Energy simulations for glazed office buildings in Sweden. Energy and Buildings, 40 (7), 1161-1170.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Ponsoni, K.; Gonçalves Raddi, M. S. (2010). Indoor Air Quality Related to Occupancy at an Airconditioned Public Building" Brazilian Archives of Biology and Technology, 53, 99-103.

Prasad, R.K.; Uma, R.; Kansal, A.; Gupta, S.; Kumar, P.; Saksen, S. (2002). Indoor air quality in an air-conditioned building in New Delhi and its relationship to ambient air quality. Indoor and Built Environment, 11 (6), 334-339.

Rabie, Ghada; El-Halim, Hisham; Rozaik, Ehab (2019). Influence of using dry and wet wastewater sludge in concrete mix on its physical and mechanical properties. Ain Shams Engineering Journal, 10 (4), 705-712.

Rahla, K.M.; Mateus, R.; Bragança, L (2021). Implementing Circular Economy Strategies in Buildings—From Theory to Practice. Appl. Syst. Innov., 4, 26.

Raefat, Saad; Garoum, Mohammed; Souihel, Mohammed; Laaroussi, Najma (2017). Thermal transmittance comparison between multilayer walls made from hollow fired clay and plaster-granular cork bricks using electrical analogy. Energy Procedia, 139, 596-601.

Rana, Aditya; Kalla, Pawan; Csetenyi, Laszlo J (2015). Sustainable use of marble slurry in concrete. Journal of Cleaner Production, 94, 304-311.

Ramin, Hadi; Hanafizadeh, Pedram; Behabadi, Mohammad (2015). Comparative study between dynamic transient and degree-hours methods to estimate heating and cooling loads of building's wall. Computational Applied Mechanics, 46, 153-165.

Real Decreto 2429/1979, de 6 de julio, por el que se aprueba la norma básica de edificación NBE-CT-79, sobre condiciones térmicas en los edificios.

Real Decreto 314/2006, de 17 de marzo, por el que se aprueba el Código Técnico de la Edificación.

Real Decreto 1027/2007, de 20 de julio, por el que se aprueba el Reglamento de Instalaciones Térmicas en los Edificios.

Real Decreto 732/2019, de 20 de diciembre, por el que se modifica el Código Técnico de la Edificación, aprobado por el Real Decreto 314/2006, de 17 de marzo.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Ribero, Óscar; Pedraza, Deisy; Alvarado, Yezid; Gasch, Isabel (2016). Economic benefits of LEED certification: A case study of the Centro Ático building. Revista Ingenieria de Construccion, 31(2),139-146.

Ridley, Ian, Clarke, Alan; Bere, Justin; Altamirano, Hector; Lewis, Sarah; Durdev, Mila; Farr, Andrew (2013). The monitored performance of the first new London dwelling certified to the Passive House standard. Energy and Buildings, 63, 67-78.

Rodrigues, F.; Feliciano, M. (2019). Improving indoor air quality of naturally ventilated classrooms in the northeast of portugal. Environmental Engineering & Management Journal (EEMJ), 18 (7),1423-1437.

Rohdin, Patrik; Molin, Andreas; Moshfegh, Bahram (2014). Experiences from nine passive houses in Sweden – Indoor thermal environment and energy use. Building and Environment, 71, 176-185.

Rosso, F.; Peduzzi, A.; Diana, L.; Cascone, S.; Cecere, C. A (2021). Sustainable Approach towards the Retrofit of the Public Housing Building Stock: Energy-Architectural Experimental and Numerical Analysis. Sustainability, 13 (5), 2881.

Rutkowska, G.; Wichowski, P.; Franus, M.; Mendryk, M.; Fronczyk, J. (2020) Modification of Ordinary Concrete Using Fly Ash from Combustion of Municipal Sewage Sludge. Materials, 13, 487.

Sair, Said; Bouchaib, Mandili; Taqi, M.; Abdeslam, El Bouari (2019). Development of a new eco-friendly composite material based on gypsum reinforced with a mixture of cork fibre and cardboard waste for building thermal insulation. Composites Communications, 16, 20-24.

Sani, R; Nzihou, A. (2017). Production of clay ceramics using agricultural wastes: Study of properties, energy savings and environmental indicators. Applied Clay Science, 146, 106-114.

Schnieders, J., Eian, T.D., Filippi, M. et al. (2020). Design and realisation of the Passive House concept in different climate zones. Energy Efficiency, 13, 1561-1604.

Schaudienst, Falk; Vogdt, Frank U. (2017). Fanger's model of thermal comfort: a model suitable just for men?. Energy Procedia, 132, 129-134.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Schibuola, Luigi; Tambani, Chiara (2021). High energy efficiency ventilation to limit COVID-19 contagion in school environments. Energy and Buildings, 240.

Schwartz, Yair; Raslan, Rokia (2013). Variations in Results of Building Energy Simulation Tools, and Their Impact on BREEAM and LEED Ratings: A Case Study. Energy and Buildings. 62, 350-359.

Scientific Committee on Health and Environmental Risks (SCHER) (2007). "Opinion on risk assessment on indoor air quality".

Sekhar, SC; Willem, HC. (2004) "Impact of airflow profile on indoor air quality - a tropical study". Building and Environment, 39, (3), 255-266.

SIA (Société suisse des Ingénieurs et des Architectes) Cahier technique 2024. Conditions d'utilisation standard pour l'énergie et les installations du bâtiment. Zürich (Suisse), 2006.

Silgado, S. S.; Valdiviezo, L. C.; Domingo, S. G.; Roca, X (2018). Muilti-criteria decision analysis to assess the environmental and economic performance of using recycled gypsum cement and recycled aggregate to produce concrete: The case of Catalonia (Spain). Resources, Conservation & Recycling 133, 120-131.

Silva, M. F.; Maas, S.; de Souza, H. A.; Gomes, A. P. (2017). Post-occupancy evaluation of residential buildings in Luxembourg with centralized and decentralized ventilation systems, focusing on indoor air quality (IAQ). Assessment by questionnaires and physical measurements. Energy and Buildings, 148, 119-127.

Stabile, L.; Massimo, A.; Canale, L.; Russi, A.; Andrade, A.; Dell'Isola, M. (2019). The Effect of Ventilation Strategies on Indoor Air Quality and Energy Consumptions in Classrooms. Buildings, 9 (5), 10.

Stabile, L.; Dell'Isola, M.; Russi, A.; Massimo, A.; Buonanno, G. (2017). The effect of natural ventilation strategy on indoor air quality in schools. Science of The Total Environment. 595, 894-902.

Stabile, L.; Dell'Isola, M.; Frattolillo, A.; Massimo, A. (2016). Effect of natural ventilation and manual airing on indoor air quality in naturally ventilated Italian classrooms. Building and Environment, 98, 180-189.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Stazi, Francesca; Vegliò, Ambra; Di Perna, Costanzo; Munafò, Placido (2012). Retrofitting using a dynamic envelope to ensure thermal comfort, energy savings and low environmental impact in Mediterranean climates. Energy and Buildings, 54, 350–362.

Stazi, F.; Naspi, F.; Ulpiani, G.; Di Perna, C. (2017). Indoor air quality and thermal comfort optimization in classrooms developing an automatic system for windows opening and closing. Energy and Buildings, 139, 732-746.

Stéphan, E.; Cantin, R.; Caucheteux, A.; Tasca-Guernouti, S; Michel, P. (2014). Experimental assessment of thermal inertia in insulated and non-insulated old limestone buildings. Building and Environment, 80, 241–248.

Subaşı, Serkan; Öztürk, Hakan; Emiroglu, Mehmet (2017). Utilizing of waste ceramic powders as filler material in self-consolidating concrete. Construction and Building Materials, 149, 567-574.

Taboada Gomez, M.C.; Magan Iglesias, A.; Torres López, R.; Bello Bugallo, P.M. (2016) Towards sustainable systems configurations: application to an existing fish and seafood canning industry. Journal of Cleaner Production 129, 374-383.

Torres Lopez, E.R.; Doval Leira, R.; Galera Martínez, M., Bello Bugallo, P.M (2017). Integrated environmental permit through Best Available Techniques: Evaluation of the dairy industry. Journal of Cleaner Production, 162, 512-528.

Taboada Gomez, M.C.; Culotte, F.; Bello Bugallo, P.M. (2018). "Sustainable production and use of buildings: acircular Economy". WasteEng2018 Conference, Prague, July 2-5, 2018.

Tavares, P.F.; Gaspar, A.R.; Martins, A.G; Frontini F (2014). Evaluation of electrochromic windows impact in the energy performance of buildings in Mediterranean climates. Energy Policy, 67, 68-81.

Thakur, Anil Kumar; Pappu, Asokan; Thakur, Vijay Kumar (2018). Resource efficiency impact on marble waste recycling towards sustainable green construction materials. Current Opinion in Green and Sustainable Chemistry, 13, 91-101.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Thalfeldt M., Kurnitski J., Voll H. (2015). "Comparison of simplified and detailed window models in office building energy simulations". Energy Procedia, 78, 2076-2081

Toftum, Jørn; Jørgensen, Anette S; Fanger, P.O. (1998). Upper limits of air humidity for preventing warm respiratory discomfort. Energy and Buildings, 28 (1), 15-23.

Toftum, Jørn; Jørgensen, Anette S; Fanger, P.O. (1998). Upper limits for indoor air humidity to avoid uncomfortably humid skin. Energy and Buildings, 28 (1), 1-13.

Tong, Z.; Chen, Y.; Malkawi, A.; Adamkiewicz, G.; Spengler, J. D. (2016) Quantifying the impact of traffic-related air pollution on the indoor air quality of a naturally ventilated building. Environment International, 89–90, 138-146.

Tonnayopas, Danupon (2013). Green Building Bricks Made with Clays and Sugar Cane Bagasse Ash. Conference: The 11th International Conference on Mining, Materials, and Petroleum Engineering. November 2013.

Topriska, E.; Kolokotroni, M.; Melandri, D.; McGuiness, S.; Ceclan, A.; Christoforidis, G.C.; Fazio, V.; Hadjipanayi, M.; Hendrick, P.; Kacarska, M.; Peñalvo López, E.; Petersen, K.L.; Steinbrecher, J. (2018). The Social, Educational, and Market Scenario for nZEB in Europe. Buildings, 8, 51.

Torres Lopez, Edelina Rosa (2021). Hacia una industria alimentaria sostenible en Galicia: de la politica de prevencion y control de la contaminacion a la economia circular. Universidad de Santiago de Compostela.

Truong, Harley; Garvie, Andrew M (2017). Chifley Passive House: A Case Study in Energy Efficiency and Comfort. Energy Procedia, 121, 214-221.

Tyler Hoyt, Stefano Schiavon, Federico Tartarini, Toby Cheung, Kyle Steinfeld, Alberto Piccioli, and Dustin Moon (2019). CBE Thermal Comfort Tool. Center for the Built Environment, University of California Berkeley. Webpage: https://comfort.cbe.berkeley.edu/ [Accessed: July 2020]

United Nations (2015). Paris Agreement

US Green Building Council: https://www.usgbc.org

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Van der Zee1, S. C.; Strak, M.; Dijkema, M.B.A.; Brunekreef, B.; Janssen, N. A. H. (2017). The impact of particle filtration on indoor air quality in a classroom near a highway. Indoor Air 2017, 27 (2).

Vanhoutteghem, Lies; Skarning, Gunnlaug Cecilie; Hviid, Christian; Svendsen, Svend (2015) .Impact of façade window design on energy, daylighting and thermal comfort in nearly zero-energy houses. Energy and Buildings, 102, 149-156.

Varodompun, Jatuwat; Navvab, Mojtaba (2007). HVAC ventilation strategies: the contribution for thermal comfort, energy efficiency, and indoor air quality. Journal of Green Building, 2 (2), 131–150.

Verbeke, Stijn; Audenaert, Amaryllis (2018). Thermal inertia in buildings: A review of impacts across climate and building use". Renewable and Sustainable Energy Reviews, 82 (3), 2300-2318.

Villanueva, Florentina; Notario, Alberto; Cabañas, Beatriz; Martin, Pilar; Salgado, Sagrario; Gabriel, Marta (2021). Assessment of CO2 and aerosol (PM2.5, PM10, UFP) concentrations during the reopening of schools in the COVID-19 pandemic: The case of a metropolitan area in Central-Southern Spain. Environmental Research, 197.

Vincent, D; Annesi, I; Festy, B; Lambrozo, J. (1997). Ventilation system, indoor air quality, and health outcomes in Parisian modern office workers. Environmental Research, 75 (2), 100-112.

Wang, Y.; Yoshino, Y.; Kumagai, K.; Takahashi, M. (2010). A Study on Actual Conditions of Thermal Environment and Indoor Air Quality in a Japanese Traditional House Corresponding to Sericulture. Journal of Asian Architecture and Building Engineering, 9 (2).

Wong, L. T.; Mui, K. W.; Shi, K. L.; Hui, P. S. (2008). An energy impact assessment of indoor air quality acceptance for air-conditioned offices. Energy Conversion and Management, 49 (10), 2815-2819.

Wong, N.H.; Huang, B. (2004). Comparative study of the indoor air quality of naturally ventilated and air-conditioned bedrooms of residential buildings in Singapore. Building and Environment, 39 (9), 1115-1123.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Worden, Kelly; Hazer, Meghan; Pyke, Christopher; Trowbridge, Matthew (2020). Using LEED Green Rating Systems to Promote Population Health. Building and Environment, 172.

World Health Organization (2005). "Air Quality Guidelines Global Update 2005".

World Health Organization: "Listings of WHO's response to COVID-19". Web page: https://www.who.int/news/item/29-06-2020-covidtimeline [Accessed: June 2021]

World Health Organization (2009). "WHO guidelines for indoor air quality : dampness and mould".

World Health Organization (2010). "WHO guidelines for indoor air quality: selected pollutants".

Wu, J.; Li, X.; Lin, Y.; Yan, Y., Tu, J. (2020). A PMV-based HVAC control strategy for office rooms subjected to solar radiation. Building and Environment, 177.

Wu, Zhibin; Li, Nianping; Wargocki, Pawel; Peng, Jingqing; Li, Jingming; Cui, Haijiao. (2019). Adaptive thermal comfort in naturally ventilated dormitory buildings in Changsha, China. Energy and Buildings, 186, 1, 56-70.

Xue, Peng; Li, Qian; Xie, Jingchao; Zhao, Mengjing; Liu, Jiaping (2019). Optimization of window-to-wall ratio with sunshades in China low latitude region considering daylighting and energy saving requirements. Applied Energy, 233–234, 62-70.

Xu, X.; Feng, G.; Chi, D.; Liu, M.; Dou, B. (2018). Optimization of Performance Parameter Design and Energy Use Prediction for Nearly Zero Energy Buildings. Energies 2018, 11, 3252.

Yalcin, N.; Balta, D.; Ozmen, A. (2018). A modeling and simulation study about CO2 amount with web-based indoor air quality monitoring. Turkish Journal of Electrical Engineering and Computer Sciences, 26 (3), 139-01402.

Yang, Liu; Yan, Haiyan; Lam, Joseph C. (2014). Thermal comfort and building energy consumption implications – A review. Applied Energy, 115, 164-173.

Yang, Shen; Goyette Pernot, Joelle; Jörin, Corinne; Hirzel, Helene; Perret, Vincent; Licina, Dusan (2020). Energy, indoor air quality, occupant behavior, self-reported symptoms and satisfaction in

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

energy-efficient dwellings in Switzerland. Building and Environment, 171.

Yao J. (2014). An investigation into the impact of movable solar shades on energy, indoor thermal and visual comfort improvements. Building and Environment, 71, 24-32.

Yin, Haiguo; Liu, Chunxue; Zhang, Leiming; Li, Angui; Ma, Zhenjun (2019). Measurement and evaluation of indoor air quality in naturally ventilated residential buildings. Indoor and Built Environment, 28 (10).

Yu, B. F.; Hu, Z. B.; Liu, M.; Yang, H. L.; Kong, Q. X.; Liu, Y. H. (2009). Review of research on air-conditioning systems and indoor air quality control for human health. International Journal of Refrigeration, 32 (1), 3-20.

Zareei, S.A.; Ameri, F.; Dorostkar, F.; Ahmadi, M (2017). Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica: Evaluating durability and mechanical properties. Case Studies in Construction Materials, 7, 73-81.

Zareei, Seyed Alireza; Ameri, Farshad; Bahrami, Nasrollah (2018). Microstructure, strength, and durability of eco-friendly concretes containing sugarcane bagasse ash. Construction and Building Materials, 184, 258-268.

Zhang X., Shen1 J., Tang L., Yang1 T., Xia1 L., Hong1 Z., Wang1 L., Wu Y., Shi1 Y, Xu P., Liu S. (2015). Building Integrated Solar Thermal (BIST) Technologies and Their Applications: A Review of Structural Design and Architectural Integration. Journal of Fundamentals of Renewable Energy and Applications, 05(05).

Zhang, Yinping; Mo, Jinhan; Li, Yuguo; Sundell, Jan; Wargocki, Pawel; Zhang, Jensen; Little, John C.; Corsi, Richard; Deng, Qihong; Leung, Michael H. K.; Fang, Lei; Chen, Wenhao; Li, Jinguang; Sun, Yuexia (2011). Can commonly-used fan-driven air cleaning technologies improve indoor air quality? A literature review. Atmospheric Environment, 45 (26), 4329-4343.

Zhao, Zengfeng; Rémond, Sébastien; Damidot, Denis & Xu, Weiya (2015). Influence of fine recycled concrete aggregates on the properties of mortars. Construction and Building Materials, 81, 179-186.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Zheng, Wandong; Hu, Jingfan; Wang, Zhaoying; Li, Jinbo; Fu, Zheng; Li, Han; Jurasz, Jakub; Chou, S.K.; Yan, Jinyue (2021). COVID-19 Impact on Operation and Energy Consumption of Heating, Ventilation and Air-Conditioning (HVAC) Systems. Advances in Applied Energy, 3.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

DIFFUSION OF RESULTS

PUBLICATIONS IN SCIENTIFIC BOOKS AND JOURNALS

Vilaboa Díaz, A; Bello Bugallo, P.M. (2022) Development and application of a thermal comfort model in buildings. Renewable Energy and Environmental Sustainability, 7. DOI: https://doi.org/10.1051/rees/2021038

Vilaboa Díaz, A; Bello Bugallo, P.M. (2021) Study of the influence of solar shading devices in the solar inputs in buildings. In: Sustainable Energy Development and Innovation, 51. Springer, ISSN 2522-8927, https://doi.org/10.1007/978-3-030-76221-6_51

Vilaboa Díaz, A; Francisco López, A.; Bello Bugallo, P.M. (2021). Analysis of biowaste-based materials in the construction sector: evaluation of thermal behaviour and Life Cycle Assesment (LCA). Waste and Biomass Valorization. (under review)

Vilaboa Díaz, A; Bello Bugallo, P.M. (2021). Environmental hazards beyond COVID-19: review of indoor air quality and ventilation systems. Indoor and Built Environment (under review)

Vilaboa Díaz, A; Bello Bugallo, P.M. (2021). Influence of thermal inertia and ventilation in thermal comfort. Energy for Sustainable Development (under review)

PROCEEDINGS IN INTERNATIONAL CONFERENCES

Vilaboa Díaz, A.; Álvarez Iglesias, J.C; Bello Bugallo, P.M. Study of the effects of mass and thermal inertia in buildings and their implications in the indoor temperature. 6th International Conference on Engineering for Waste and Biomass Valorisation - WasteEng16. Albi (France), May 23-26, 2016.

Vilaboa Díaz, A; Del Castillo Llamosas, A.; Bello Bugallo, P.M. Valorisation of residual energy in confort buildings: the relevance of solar inputs and thermal inertia. 7th International Conference on

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Engineering for Waste and Biomass Valorisation - WasteEng18. Czech Republic, July 2-5, 2018.

Vilaboa Díaz, A; Bello Bugallo, P.M. Development and application of a thermal comfort model in buildings. World Renewable Energy Congress - WREC 2020. Lisbon, July 26–30, 2021.

Vilaboa Díaz, A; Bello Bugallo, P.M.. Study of the influence of solar shading devices in the solar inputs in buildings. World Renewable Energy Congress - WREC 2020. Lisbon, July 26–30, 2021.

Vilaboa Díaz, A; Bello Bugallo, P.M. Analysis of eco-materials in the construction sector: evaluation of thermal behaviour and Life Cycle Assesment (LCA). 9th International Conference on Engineering for Waste and Biomass Valorisation – WasteEng2022. Copenhagen (Denmark), June 27-30, 2022 (under review)