

SCHOOL OF ARCHITECTURE, PLANNING AND LANDSCAPE, NEWCASTLE
UNIVERSITY

**ASSESSING THE THERMAL
PERFORMANCE OF PHASE CHANGE
MATERIALS IN COMPOSITE HOT
HUMID/HOT DRY CLIMATES**

*An examination of office buildings in Abuja-
Nigeria*

Doctor of Philosophy
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TITLE PAGE

Thesis Title: Assessing the thermal performance of Phase Change Materials in composite hot humid/hot dry climates: *An examination of office buildings in Abuja-Nigeria.*

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ABSTRACT

The aim of this study is to investigate the possibility of using Phase Change Materials (PCM) in improving indoor thermal comfort while conserving electricity in office buildings in the composite Hot Humid/Hot Dry climate of Abuja, Nigeria. The first stage is a quantitative investigation of electricity consumption in 15 Nigerian office Buildings. Purpose-built mechanically cooled office buildings are selectively chosen across major Nigerian cities and climates. The surveyed data is analysed and used to construct a hypothetical office building as a base case. Scientifically validated software DesignBuilder v3 and EnergyPlus V6 and V7 are used for the parametric analysis of simulation results. The building simulations are used in two stages, firstly to test passive and climatically responsive scenarios to reduce electricity consumption then secondly to study the potential benefit of incorporating PCM in the building fabric and its effect on thermal comfort and electricity conservation.

Results show that cooling, lighting, and appliance loads account for approximately 40%, 12% and 48% respectively of electricity consumption in the buildings audited. Power outages are frequently experienced necessitating alternative power usage. A data collection method is presented for energy auditors in locations where alternative back-up power is essential.

Simulation results indicate that the magnitude of energy saving can be achieved by optimizing the passive and climate sensitive design aspects of the building and an electricity saving of 26% is predicted. Analysis indicates that it is difficult to achieve thermal comfort in office buildings in Abuja without mechanical cooling. Adding such a PCM to the building fabric of a cyclically cooled mechanical building may alleviate indoor discomfort for about 2 hours in case of power outage and is predicted to save 7% of cooling load. Cyclic cooling is the cooling of the interiors long enough to maintain comfort for a maximum duration within the working hours. The use of lightweight partitions instead of the heavyweight ones common in Nigeria is shown to a 2-fold improvement in consumption. Adding a PCM to light-weight partition walls with transition temperature of 24°C, conductivity of 0.5W/m K, and a thickness of 10mm gives the best predicted energy savings.

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2. Batagarawa, A. (2012) 'Benefit of conducting energy calculations in the built environment of Nigeria', *West Africa Built Environment Research (WABER)*. Abuja. West Africa Built Environment Research (WABER)

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DEDICATION

I dedicate this endeavour to Allah
without whose blessing I will not be
alive and able.

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TABLE OF CONTENTS

1	CHAPTER 1	1
1.1	Overview	2
1.2	Aim	2
1.3	Research objectives	2
1.4	Scope	3
1.5	Outline methodology	3
1.6	Outline limitations	5
1.7	Background- Energy generation and consumption in Nigeria	5
1.7.1	Energy generation	8
1.7.2	Deterioration in energy supply	9
1.8	Energy conservation and climate	10
1.8.1	Bio-climatic design	14
1.8.2	Energy efficiency in office buildings	15
1.8.3	Thermal comfort in office buildings	18
1.9	Outline of chapters - Thesis plan	25
1.9.1	Chapter One	25
1.9.2	Chapter Two	26
1.9.3	Chapter Three	26
1.9.4	Chapter Four	26
1.9.5	Chapter Five	26
1.9.6	Chapter Six	27
1.9.7	Chapter Seven	27
1.9.8	Chapter Eight	27
1.10	Conclusion	28
2	CHAPTER 2	30
2.1	Overview	32
2.2	Phase Change Materials (PCM)	32

Preambles

2.2.1	Applications	33
2.2.2	Building applications	34
2.2.3	Climate	38
2.3	Properties of PCMs	39
2.3.1	Limiting properties of PCM	40
2.3.2	Thermo-physical properties	42
2.3.3	Chemical classification of PCM	51
2.4	Application of PCMs	58
2.4.1	Method of containment and incorporation of PCM	58
2.4.2	Building component	66
2.5	Conclusions	75
2.5.1	Thermo-physical properties of PCM	76
2.5.2	PCM can be chemically tailored to fit different contexts	77
2.5.3	PCMs perform better with a large surface area	77
2.5.4	PCMs suitable for the Nigerian climate have not been studied	78
3	CHAPTER 3	79
3.1	Overview	81
3.2	Context	83
3.3	Research aim	83
3.4	Research objectives	83
3.5	Research strategy	84
3.6	Research design	86
3.6.1	Descriptive research design	86
3.6.2	Quasi-experimental research design	86
3.7	Research methods	89
3.7.1	Sampling	89
3.7.2	Data collection	96
3.8	Analysis	99

Preambles

3.8.1	Statistical analysis	99
3.8.2	Degree-day	100
3.8.3	Parametric analysis with computer simulations	101
3.9	Computer simulation software packages	104
3.9.1	Modelling with DesignBuilder	106
3.9.2	Simulations with EnergyPlus	107
3.10	Limitations	110
3.10.1	Fieldwork stage	111
3.10.2	Simulation stage	112
3.11	Reliability, Replicability and Validity	114
3.12	Ethical issues	115
3.13	Conclusions	116
4	CHAPTER 4	118
4.1	Overview	120
4.2	Building energy calculations: PCM thermal performance testing	120
4.2.1	Analytic testing	120
4.2.2	Experimentation	122
4.2.3	Computer Simulating PCM applications	124
4.3	Limitations of analysing PCMs with computer simulations	126
4.4	Validation	129
4.4.1	Validating the two sets of results	130
4.4.2	Validating the user's ability and the capability of the software	130
4.5	Conclusion	140
5	CHAPTER 5	142
5.1	Overview	144
5.2	Introduction	145
5.3	Walk-through	146
5.3.1	Electricity usage	147

Preambles

5.4	Analysis- Degree-days.....	150
5.4.1	Base temperature	151
5.4.2	Base-load.....	154
5.5	Results.....	154
5.6	Building descriptions	154
5.6.1	Physical building characteristics	155
5.6.2	Electricity demand and supply in the buildings	159
5.7	Normalized End-uses.....	165
5.7.1	Cooling.....	168
5.7.2	Appliances.....	168
5.7.3	Lighting.....	168
5.8	Degree day calculations	169
5.8.1	Building 1.....	169
5.8.2	Building 2.....	170
5.8.3	Building 3.....	171
5.8.4	Building 4.....	172
5.8.5	Building 5.....	173
5.9	Conclusion.....	174
6	CHAPTER 6.....	176
6.1	Overview	178
6.2	Context- Abuja city.....	178
6.2.1	Abuja climate	180
6.3	The base-case modelling.....	181
6.3.1	Fieldwork data.....	183
6.3.2	Nigerian building code.....	187
6.3.3	Bio-climatic design literature	188
6.3.4	Optimal design variables for parametric analysis	193
6.4	Results and discussion	204

Preambles

6.4.1	Geometry and Orientation.....	204
6.4.2	Glazing.....	208
6.4.3	Shading	209
6.4.4	Air-tightness.....	210
6.4.5	Insulation.....	211
6.4.6	Natural Ventilation	212
6.5	Bioclimatic model.....	213
6.6	Conclusion.....	214
7	CHAPTER 7.....	217
7.1	Overview	219
7.2	Modelling PCM in EnergyPlus	220
7.2.1	The base-case	221
7.2.2	PCM wall construction	225
7.3	PCM thermo-physical properties.....	226
7.4	Testing for PCM optimum performance.....	228
7.4.1	Dependent variables.....	228
7.4.2	Independent variables kept constant.....	228
7.4.3	Independent variables examined	231
7.4.4	Test case.....	232
7.4.5	Assumptions	232
7.5	Results and discussion	232
7.6	Optimizing PCM thermo-physical properties	235
7.6.1	Transition Temperature analysis	235
7.6.2	Thickness and conductivity analysis	241
7.7	Optimizing PCM operation strategies	245
7.7.1	Day-time natural ventilation	249
7.7.2	Day-time natural ventilation and night purge	252
7.7.3	Mechanical day-time cooling and night-purge.....	255

Preambles

7.7.4	Setback cooling	260
7.7.5	Cyclic cooling	268
7.8	Retrofit flexibility of PCMs in office buildings in Abuja.....	272
7.9	Thermal indices for evaluating PCM performance: Air and Operative temperature.....	279
7.10	Conclusion.....	284
8	CHAPTER 8.....	289
8.1	Overview.....	291
8.1.1	Phase Change Materials (PCM) gap in knowledge.....	291
8.1.2	A method for collecting complex electricity consumption data in places suffering power shortages.....	293
8.1.3	Aggregated electricity consumption in Nigerian office buildings	294
8.1.4	Opportunity for energy conservation.....	294
8.1.5	Computer simulation for energy conservation with PCMs.....	295
8.1.6	Bio-climatically optimizing thermal and energy performance of buildings	296
8.1.7	PCM performance in office buildings	298
8.2	Contributions to knowledge	301
8.2.1	Data collection for power outage	302
8.2.2	Aggregate electricity consumption for Nigerian office buildings.....	302
8.2.3	Bio-climatic office model for Abuja	302
8.2.4	PCM thermo-physical properties suitable for Abuja.....	302
8.2.5	Cyclic mechanical cooling strategy.....	302
8.2.6	PCMs on lightweight partitions.....	303
8.3	Recommendations and future work.....	303
8.3.1	Micro-encapsulated PCM in sandcrete blocks	303
8.3.2	PCM in hot and dry climates.....	304
8.3.3	Field validation of results.....	304

Preambles

8.3.4	PCM in active systems.....	304
9	APPENDICES	305
9.1	Appendix A- Energy audit questionnaire	305
9.2	Appendix B to D-	316
10	REFERENCES	317

LIST OF FIGURES

Figure 1-1 Electricity consumption pattern in Nigeria published by the Central bank of Nigeria (Oyedepo, 2012).....	11
Figure 1-2 Energy supplied by type in Nigeria (International Energy Agency, 2007) ..	12
Figure 1-3 Triangle for low energy building design (Haase and Amato, 2006) ranking the efficiency of energy conservation, efficiency and renewable energy	14
Figure 1-4 Thesis structure.....	25
Figure 2-1 PCM melting temperature and enthalpy from Baetens <i>et al.</i> (2010), showing PCM suitable for domestic heating/cooling in the range of 0-65°C (Agyenim <i>et al.</i> , 2011) and 15-90°C (Farid <i>et al.</i> , 2004).....	33
Figure 2-2 Classification of variables studied in literature	37
Figure 2-3 Enthalpy of PCM composite showing hysteresis (Kuznik and Virgone, 2009b)	41
Figure 2-4 Super-cooling	42
Figure 2-5 Sensible and latent heat.....	43
Figure 2-6 Walling system with copper foam integrated PCM panelling and ventilation holes (Isa <i>et al.</i> , 2010).....	48
Figure 2-7 Walling system - wallboard finishing (Isa <i>et al.</i> , 2010).....	49
Figure 2-8 Forced ventilation for PCM layer (Isa <i>et al.</i> , 2010).....	50
Figure 2-9 Chemical classification of PCM (Pasupathy <i>et al.</i> , 2008a).....	51
Figure 2-10 PCM limited by incomplete charge/discharge: air temperature (grey without PCM, black with PCM), ambient temperature (dotted) from Voelker. <i>et al</i> (2008). The dashed circle shows a functioning cycle, while the line circle shows the decrease in function due to hysteresis.....	56
Figure 2-11 Microcapsule (Tyagi <i>et al.</i> , 2011) and sphere shaped microencapsulated PCM with polymer coating (Isa <i>et al.</i> , 2010).	62
Figure 2-12 Types of microencapsulation (Tyagi <i>et al.</i> , 2011).....	63
Figure 2-13 Cubicles testing Mopcon concrete.....	64
Figure 2-14 Effect of PCM of different transition temperature on indoor air temperature 14-16 November in Beijing, China (Zhou <i>et al.</i> 2007)	68
Figure 2-15 Passive sail with night time cooling	70
Figure 2-16 Operation of active sail (Susman <i>et al.</i> , 2010)	71
Figure 2-17 Experimental house Tsinghua University, Beijing, China (Zhang <i>et al.</i> , 2006)	73

Preambles

Figure 3-1 Overall research methodology.....	82
Figure 3-2 Method of calculation of building energy consumption	85
Figure 3-3 Dependent and independent variables	88
Figure 3-4 Climatic classification in Africa (UNEP/GRID, 2002)	91
Figure 3-5 Air temperature profiles for some Nigerian cities (Nigerian meteorological agency)	92
Figure 3-6 Air temperature profiles for Lagos (Nigerian meteorological agency) and thermal comfort band based on the neutrality temperature and EN15251	94
Figure 3-7 Air temperature profiles for Kaduna (Nigerian meteorological agency) and thermal comfort band based on the neutrality temperature and EN15251	94
Figure 3-8 Air temperature profiles for Abuja (Nigerian meteorological agency) and thermal comfort band based on the neutrality temperature and EN15251	95
Figure 3-9 Data collection procedure	98
Figure 3-10 Parametric analysis procedure.....	102
Figure 3-11 Weather file input in EnergyPlus.....	103
Figure 3-12 DesignBuilder model design hierarchy.....	107
Figure 3-13 EnergyPlus energy calculation schematic (EnergyPlus 2010).....	109
Figure 4-1 Results of experiment compared to simulation by Pasupathy <i>et al.</i> (2008a)	125
Figure 4-2 Configuration of building construction 1) 50 mm wood plate (outer layer), 2) 10 mm plaster, 3) 50 mm polystyrene, 4) 13 mm plaster, 5) 5 mm Energain® PCM from Kuznik <i>et.al.</i> (2009b).....	131
Figure 4-3 Test room for validation as presented in experiment (left) and Model by researcher using Designbuilder visualization plug-in (right).....	133
Figure 4-4 Radiative heat flux achieved by the solar simulator in experiment.....	135
Figure 4-5 Modelling the solar simulator in EnergyPlus.....	136
Figure 4-6 Schedule operating the solar simulator.....	136
Figure 4-7 Schedule for cooling and heating in EnergyPlus.....	137
Figure 4-8 Synthetic air inlet temperature profile mimicking day and night temperature by Kuznik <i>et.al.</i> (2009b)	139
Figure 4-9 Inlet air temperature profile achieved in the testroom by researcher, thermal guard air temperature showing temperature in climatic chamber maintained at 20.5°C	139

Preambles

Figure 4-10 Measured air temperature for the testrooms with and without PCM by Kuznik *et. al* (2009b). T₁ and T₂ are probes at two different heights in the same room. 140

Figure 4-11 Comparison of result of simulated PCM effect predicted by EnergyPlus and experiment 140

Figure 5-1 Methodology of energy audit 145

Figure 5-2 Demand versus supply 148

Figure 5-3 Example of a good performance line (Day *et al.*, 2003)..... 153

Figure 5-4 Example of a bad performance line illustrated in this research 153

Figure 5-5 Sandcrete block unit (Nigerian building code) 156

Figure 5-6 Internal venetian blinds..... 156

Figure 5-7 Single glazed, bronze tinted, aluminium framed windows and doors 157

Figure 5-8 Water pump to back-up central water supply which also is scarce 160

Figure 5-9 Makeshift battery storage for ICT showing poor positioning in the heat of the mechanical cooling system's exhaust and weather elements 160

Figure 5-10 Lighting systems showing the range of available lighting from inefficient tungsten lamps to more efficient fluorescent lamps 161

Figure 5-11 Split unit cooling system..... 163

Figure 5-12 Electricity consumption disaggregated by end uses 166

Figure 5-13 End-use electricity consumption in 5 buildings audited 167

Figure 5-14 Building 1 Performance line 170

Figure 5-15 Building 1 Combination chart 170

Figure 5-16 Building 2 performance line..... 171

Figure 5-17 Building 2 combination chart 171

Figure 5-18 Building 3 performance line..... 172

Figure 5-19 Building 3 combination chart 172

Figure 5-20 Building 4 performance line..... 173

Figure 5-21 Building 4 combination chart 173

Figure 5-22 Building 5 performance line..... 174

Figure 5-23 Building 5 combination chart 174

Figure 6-1 Abuja city districts- highlighting Phase 1 179

Figure 6-2 Abuja ambient air temperature (°C) comparing weather data from Metenorm (used in EnergyPlus) and Nigerian meteorological agency (NIMET) 180

Figure 6-3 Optimizing procedure for bio-climatic model..... 182

Preambles

Figure 6-4 Base-case morphology	183
Figure 6-5 Sun path diagram for Abuja (www.gaisma.com/en/location/abuja.html) ..	192
Figure 6-6 Parametric analysis procedure.....	194
Figure 6-7 Illustration of default shading options in DesignBuilder (2011).....	197
Figure 6-8 Modelling shading with default DesignBuilder values (2011)	198
Figure 6-9 Good infiltration default by DesignBuilder	199
Figure 6-10 Poor infiltration default by DesignBuilder.....	200
Figure 6-11 Visuals of the base-case model Designbuilder model on the left and CAD drawing on the right. All dimentions in meters.....	203
Figure 6-12 Comparison between square and rectangle planned base-case- Arrow showing best orientation for rectangular plan with principal axis lying along east-west	206
Figure 6-13 Electricity consumption across geometries and orientations	208
Figure 6-14 Bio-climatic model	214
Figure 7-1 Optimizing procedure for PCM Model.....	220
Figure 7-2 Visuals of the base-case model: DesignBuilder model on the left, CAD drawing on the right. All dimentions in meters.....	222
Figure 7-3 PCM wall system.....	226
Figure 7-4 Graph showing enthalpy as a function of transition temperature.....	230
Figure 7-5 Test case modelled in DesignBuilder	232
Figure 7-6 Passive use with natural ventilation.....	237
Figure 7-7 Night-time mechanical cooling	239
Figure 7-8 Day-time mechanical cooling.....	241
Figure 7-9 Thickness and conductivity analysis	244
Figure 7-10 Abuja ambient air temperature- showing comfort band calculated by Neutrality temperature	247
Figure 7-11 Optimizing operational strategies (NV=Natural ventilation, MC=Mechanical cooling)	247
Figure 7-12 Degree of discomfort for rooms of different orientations and between PCM and plain walls.....	252
Figure 7-13 Night-purge strategy	256
Figure 7-14 Design-day indoor temperatures with natural ventilation.....	263
Figure 7-15 Power outage simulations for PCM of transition temperature 21°C on March 21	265

Preambles

Figure 7-16 Power outage simulations for PCM of transition temperature 24°C March
21 265

Figure 7-17 Power outage simulations for PCM of transition temperature 36°C March
21 266

Figure 7-19 Relationship between mechanical cooling duration and comfort maintained
during power outage 267

Figure 7-18 Power outage simulations for PCM: Air versus Operative temperature as
index of thermal comfort..... 268

Figure 7-20 Lightweight construction for partitions 272

Figure 7-21 Comparing PCM performance between lightweight and heavyweight
partitioning 275

Figure 7-22 Air temperature versus operative air temperature: Maximum and minimum
in August 281

Figure 7-23 Air temperature versus operative air temperature: Maximum and minimum
in March 282

Figure 7-24 Air temperature versus operative air temperature: Variance 283

Figure 7-25 Electricity conservation..... 286

LIST OF TABLES

Table 1-1 Nigerian natural resources (Sambo, 2009)	7
Table 1-2 Thermal comfort indices	21
Table 1-3 Indoor comfort criteria for mechanically cooled office buildings by EN15251 (Olesen, 2010)	24
Table 2-1 Studies reviewed	35
Table 2-2 Authors of PCM studies and variable ranking	36
Table 2-3 Studies that examined the effect of climate.....	38
Table 2-4 Properties of a good PCM	40
Table 2-5 Properties of organic and inorganic PCMs.....	52
Table 2-6 Organic PCM and properties Feldman et al. 1993 in (Kelly, 2010).....	53
Table 3-1 Mapping research objectives to chapters and their progression	84
Table 3-2 Climate classification by different authors.....	90
Table 3-3 Climatic data of some Nigerian cities	92
Table 3-4 Justification of collected data	97
Table 3-5 Examples of simulation software.....	105
Table 4-1 Comparison of validation techniques Judkoff et al., 2008b	130
Table 4-2 Building materials used in Kuznik et.al. (2009b).....	131
Table 4-3 Thermo-physical properties of building materials from Kuznik <i>et.al.</i> (2009b)	134
Table 5-1 Energy audit buildings' descriptions	155
Table 5-2 Electricity supplied by back-up power generator in the 15 buildings audited (NA indicates lack of data).....	165
Table 5-3 Electricity consumption by aggregate end-use.....	167
Table 6-1 Sources of base-case variables	183
Table 6-2 Building characteristics recorded during energy audits in the field- used in constructing the base-case	184
Table 6-3 Calculated U-values of building components using CIBSE (2007) methodology.....	185
Table 6-4 Building thermo-physical characteristics used to calculate u-values from CIBSE (2007) guidelines	186
Table 6-5 Spatial plan development showing GFA- Gross floor area, CFA- Conditioned floor area and number of employees across 10 buildings audited having adequate data	187

Preambles

Table 6-6 Nigerian climate classification and bioclimatic options based on (Ogunsote, 1991; Haase and Amato, 2006; Mustafa, 2008)- showing highlighted composite climate suitable for Abuja.	190
Table 6-7 Design variables for parametric analysis	195
Table 6-8 Examined independent variables	196
Table 6-9 Default glazing U-values from DesignBuilder	197
Table 6-10 Base-case common variables and their sources	202
Table 6-11 Testing geometry and orientation	207
Table 6-12 Testing glazing.....	208
Table 6-13 Testing shading	210
Table 6-14 Testing air-tightness	211
Table 6-15 Testing insulation.....	212
Table 6-16 Naturally ventilated base-case	213
Table 7-1 PCM base-case input variables.....	223
Table 7-2 PCM wall system	226
Table 7-3 Thermo-physical properties of PCM from literature	227
Table 7-4 Thermo-physical properties of PCM treated with Darkwa and O’Callaghan’s Gaussian formulation (2006).....	230
Table 7-5 PCM Enthalpy (Thermal Energy) based on Darkwa and O’Callaghan (2006)	231
Table 7-6 Thermo-physical properties: Transition temperature simulations.....	233
Table 7-7 Thickness and conductivity simulations	234
Table 7-8 Operational strategies simulations	234
Table 7-9 Passive use of PCM with natural ventilation.....	236
Table 7-10 Night-time mechanical cooling.....	238
Table 7-11 Day-time mechanical cooling	240
Table 7-12 Variables for optimizing thickness and conductivity.....	242
Table 7-13 Thickness and conductivity analysis.....	243
Table 7-14 Base-case variables for optimizing operational strategy.....	245
Table 7-15 Optimizing operational strategies (NV=Natural ventilation, MC=Mechanical cooling)	248
Table 7-16 Day-time natural ventilation: Design day analysis for coldest and hottest days using operative air temperature (MRT-Mean Radiant Temperature, MAT- Mean	

Preambles

Air Temperature and MOT- Mean Operative Temperature). Bold font denotes uncomfortable hours 250

Table 7-17 Degree of discomfort calculation adapted from degree hour method..... 251

Table 7-18 Degree of discomfort for night-purge (Natural ventilation=NV) 253

Table 7-19 Day-time natural ventilation and night purge: Design day analysis for coldest and hottest days using operative air temperature (MRT-Mean Radiant Temperature, MAT- Mean Air Temperature and MOT- Mean Operative Temperature) 254

Table 7-20 Mechanical cooling and night-purge strategy 255

Table 7-21 Mechanical cooling: Air versus operative temperature as indicators of annual comfort work-hours 257

Table 7-22 Day-time mechanical cooling: Design day analysis for coldest and hottest days using operative air temperature (MRT-Mean Radiant Temperature, MAT- Mean Air Temperature and MOT- Mean Operative Temperature). Bold font denotes uncomfortable hours 258

Table 7-23 Day-time mechanical cooling and night purge: Design day analysis for coldest and hottest days using operative air temperature. Bold font denotes uncomfortable hours 259

Table 7-24 Transition temperatures for power outage simulations 260

Table 7-25 Temperature difference between natural ventilation (NV) and mechanical cooling (MC) 262

Table 7-26 Duration of comfort maintained during power outage after mechanical cooling MC (TT is transition temperature) 266

Table 7-27 Monthly comfort in naturally ventilated base-case (MC=1, NV=0) 269

Table 7-28 Cyclic cooling 270

Table 7-29 Cyclic cooling: Design day analysis for coldest and hottest days using operative air temperature (MRT-Mean Radiant Temperature, MAT- Mean Air Temperature and MOT- Mean Operative Temperature). Bold font denotes uncomfortable temperatures 271

Table 7-30 Lightweight construction for partitions..... 272

Table 7-31 PCM wall system 273

Table 7-32 PCM with lightweight construction 274

Table 7-33 Cyclic cooling with PCM in all walls: Design day analysis for coldest and hottest days using operative air temperature (MRT-Mean Radiant Temperature, MAT-

Preambles

Mean Air Temperature and MOT- Mean Operative Temperature). Bold font denotes uncomfortable temperatures 277

Table 7-34 Cyclic cooling with PCM only in lightweight partitions: Design day analysis for coldest and hottest days using operative air temperature (MRT-Mean Radiant Temperature, MAT- Mean Air Temperature and MOT- Mean Operative Temperature) . Bold font denotes uncomfortable temperatures..... 278

Table 7-35 Air temperature versus operative air temperature; NV=Natural Ventilation, NP=Night Purge, MC= Mechanical cooling, CC=Cyclic Cooling, HW=Heavyweight, LW=Lightweight 280

Table 7-36 Difference in annual discomfort hours between air and operative hours... 283

Table 7-37 Simulation breakdown..... 287

LIST OF EQUATIONS

Equation 1-1	22
Equation 1-2	22
Equation 2-1	45
Equation 3-1	93
Equation 3-2	100
Equation 4-1	121
Equation 4-2	121
Equation 5-1	148
Equation 5-2	148
Equation 5-3	148
Equation 5-4	149
Equation 5-5	149
Equation 5-6	149
Equation 5-7	150
Equation 5-8	150
Equation 5-9	154
Equation 5-10	159
Equation 5-11	159
Equation 5-12	164
Equation 6-1	181
Equation 6-2	185
Equation 7-1	229
Equation 7-2	253
Equation 8-1	294
Equation 8-2	297

***1* CHAPTER 1**

INTRODUCTION: NIGERIAN BUILDINGS AND ENERGY USE

Contents

1.1 Overview

1.2 Aim

1.3 Research objectives

1.4 Scope

1.5 Outline methodology

1.6 Outline limitations

1.7 Background- Energy generation and consumption in Nigeria

1.8 Energy conservation and climate

1.9 Outline of chapters- Thesis plan

1.10 Conclusion

Problem	Chapter one: Introduction- 'Nigerian buildings and Energy use'		
Theoretical framework	Chapter two: Literature review- 'Phase change materials as energy conservation mechanisms in buildings'		
Methodology	Chapter three: 'Methodology'	Chapter four : 'Validation study'	
Results	Chapter five: 'Disaggregating primary electricity consumption for office buildings in Nigeria'	Chapter six: 'Optimizing thermal and energy performance of buildings'	Chapter seven: 'PCM performance in office buildings'
Conclusion	Chapter eight: Conclusion		

1.1 Overview

This chapter explores Nigerian energy generation, distribution and consumption. Nigeria is rich in natural resources yet it is plagued by power shortages. This situation is mainly caused by the having a single failing state-owned central power company which handles generation, transmission and distribution. As a result of the power shortages, people and institutions depend on individual alternative sources of power. These alternative resources work with the principle of energy conservation at their core. Therefore energy conservation is pivotal to reducing the over-reliance on a failing system and also any alternative electricity source. Conserving energy also helps mitigate climate change, improve national security and economic growth, and save on energy costs for the building user.

It is estimated that at present, buildings contribute as much as one third of total global greenhouse gas emissions and consumes up to 40% of all energy (Adeleke, 2010). Within buildings, energy consumption of up to 36% is related to the type of materials making up the fabric (Haase and Amato, 2006). A combination of active and passive design features holistically integrated in initial stage of building design, by all stakeholders, in a project can contribute in energy savings of between 50-55% (Ochoa and Capeluto, 2008).

Energy storage is examined in this thesis as a form of energy conservation in the building fabric. Energy storage in walls, ceilings and floors of buildings is possible by incorporating some suitable Phase Change Materials (PCM) in them to absorb and release heat when the PCMs change phase. PCM technology in buildings has the potential to promote energy conservation through passive cooling according to Rahman *et al.* (2008).

The methodology employed to investigate the problem and a description of the outline of the thesis structure are discussed in this chapter.

1.2 Aim

The aim of this investigation is to evaluate the potential of incorporating PCMs in office buildings in Abuja in order to conserve energy within the context of an overburdened and failing central power utility in Nigeria.

1.3 Research objectives

The objectives of the study are:

1. To examine the need for energy conservation within the context of the electricity shortage supply in Nigeria
2. To search for the knowledge gap within literature for PCMs used for energy conservation and thermal comfort within the composite hot and dry/hot and humid climate of Abuja
3. To validate the computer software's and user's ability to simulate PCMs in buildings
4. To develop a method for collecting electricity consumption data in places suffering from power shortages
5. To investigate electricity consumption within office buildings in Nigeria
6. To determine the potential for energy savings within the cooling load
7. To create a base-case for testing the performance of PCMs
8. To optimize a model for a PCM suitable for office buildings in Abuja
9. To evaluate the potential effect of incorporating PCMs in the building fabric on thermal comfort and energy consumption

1.4 Scope

The scope of this research covers electricity conservation in mix-mode office buildings in the composite hot and dry/hot and humid climate of Abuja, the capital city of Nigeria. A mix-mode office building relies on both natural ventilation and mechanical cooling to achieve comfort for the occupants of the building. Energy storage is evaluated as an energy conservation mechanism in office buildings. Office buildings consume 40% portion of total energy globally and in Nigeria (Adeleke, 2010).

Office buildings are chosen as opposed to residential or industrial buildings because:

1. Residential buildings generally do not have regular operational schedules or keep adequate electricity consumption data required for a detailed study
2. Industries are few, mostly due to the energy crises beleaguering the nation. They also are usually mix-use complexes which may not be suitable for this research

1.5 Outline methodology

A quantitative research strategy using cross-sectional method of data collection is employed for this investigation. An energy audit is conducted to collect data in the field. The research instruments utilized for the energy audits include:

1. Self-administered questionnaires
2. Unstructured non-participant observation: This is the process of observing building occupants/operation during a stage in the energy audit called the walk-through. It is considered unstructured because the occupants' behaviour are not interfered with while non-participant means the researcher tries not to inhibit the occupants' behaviour by their presence. This is an attempt to capture realistic occupant use of electricity
3. Literature review of national statistics, building regulations, and climatic data

Selected sampling is adopted for this research. The selection is due to:

1. Availability of data: This is the most important criteria for choosing a building. Data required include building plans, utility bills, operational reports etc. The data must also be for a suitably long period of time, usually a minimum of a year
2. Access into the building: To conduct a site survey and questionnaire distribution and collection
3. Building type: The feature of building type used as a selection criterion is Heating Ventilation and Conditioning (HVAC), occupancy status and site electricity metering etc. Based on HVAC, mix-mode buildings employing a combination of natural ventilation and air condition are selected. Single use occupancy status and availability of site electricity metering are key
4. Time and finance: These constraints also affected the sample selection

The analyses conducted on the collected data employed descriptive and inferential statistical techniques. Descriptive statistics are used to calculate average, maximum and minimum values. Inferential statistics include degree day calculations which are based on correlation techniques.

To examine the performance of PCM in Nigerian offices, quasi-experiments using computer simulations are analysed by statistical techniques. The statistical and simulation methods constitute the procedure of conducting a parametric analysis. The combination of computer software DesignBuilder and EnergyPlus are used for the simulations. DesignBuilder is employed to model geometry and EnergyPlus to simulate the PCM performance. A detailed methodology is presented in Chapter 3.

1.6 Outline limitations

The limitations encountered may be broadly classified into field-work stage and simulation stage limitations.

The limitations experienced when conducting the fieldwork include:

1. Access to buildings and building documents
2. Unreliable feedback from questionnaires
3. Inadequate records
4. Confidentiality for some companies
5. Insecurity
6. Sampling issues
7. Poor electricity consumption data records
8. Effect of researcher on the research process

The following are limitations encountered during the simulation stage:

1. Climatic data errors
2. Occupant behaviour
3. Erratic power supply
4. Thermal calculations
5. Validation of software
6. Cost of software and training
7. Researcher's inexperience and other human error

These limitations are discussed in detail in Chapter 3, section 3.10.

1.7 Background- Energy generation and consumption in Nigeria

Nigeria is a country highly endowed with energy resources such as crude oil, natural gas, coal, cassiterite, columbite and tar sand as shown in Table 1-1. In addition, there are substantive potentials for renewable energy resources such as hydro, solar, wind, biomass, wave and tidal, and some geothermal (Ibitoyea & Adenikinju, 2007). Only biomass; in the form of animal, agricultural and wood residues, fuel-wood and hydropower have been and are still being exploited as a renewable resource. In recent times, the rate of exploitation of fuel-wood is greater than its regeneration and adequate intervening measures are necessary for fuel-wood usage to remain sustainable (Akinbami, 2001).

A member of the Organization of the petroleum exporting countries (OPEC), Nigeria has proven oil reserves of 36.2 billion barrels, the tenth largest reserves in the world.

Most of the reserves are located in the Niger River Delta. Nigeria ranks as the world's eighth largest exporter of oil and the United States' fifth largest source of imported oil. Proven natural gas reserves are estimated at 182 trillion cubic feet, the seventh largest reserves in the world and the largest in Africa. Recoverable coal reserves amount to 209 million short tons (mmst). However, Nigeria's coal industry suffers from extremely low productivity and high transportation costs (EIA, 2008).

Electricity is indisputably the fundamental energy resource for industrial, commercial and domestic activity in the modern world. Although a major oil producer and investor in the electricity sector, Nigeria holds a low 69th place in per capita electricity consumption globally (CIA World factbook, 2011). The country has large amounts of natural resources utilized for energy generation (both conventional and renewable sources); but yet experiences unexpected and long periods of power outage, or fluctuating currents (Adelaja *et al.*, 2008; Uyigue *et al.*, 2009). Ibitoye and Adenikinju (2007) estimate that up to 54% of the population (81 million) are unconnected to the national grid, especially those in remote areas. Political instability, mismanagement, limited funds, long period of return of investment and maintenance neglect all result in electricity generation deficit, poor utility performance, and weak transmission and distribution infrastructure. These factors all contribute to the electricity crisis in Nigeria. There are presently more than 150 million people living in Nigeria according to IEA, (2008), and the power sector is only capable of generating around 3,500 MW of electricity. This is well below all economic projections and the country's consumer and business needs, despite government investment of around USD1 billion annually in the sector (Corporate Nigeria, 2011).

Akinlo (2009) and Emeka (2010) investigate the causality relationship between energy consumption and economic growth for Nigeria during the period 1980 to 2006 and 1978 to 2008 respectively. Results show there is a unidirectional Granger causality running from electricity consumption to real Gross Domestic Product (GDP) in Nigeria. By implication, the country is shown to be highly energy dependent, thus satisfactory supply of electricity is a leading indicator of economic growth.

Resource type		Reserves	Production	Domestic utilization
Crude oil (barrels/day)		35 billion barrels	2.5 million	450,000
Natural gas (cubic ft/day)		187 trillion SCF	6 billion	3.4 billion
Coal and lignite		2.2 billion tonnes	22.1 tonnes/day	22.1 tonnes/day
Tar sands		31 billion barrels equivalent	-	-
Large hydro-power (MW)		15,000	1,938	1,938
Small hydro-power (MW)		3,500	30	30
Solar radiation		3.5-7.0 kWh/m ² /day	-	-
Wind		2-4 m/s at 10m	-	-
Biomass	Fuel-wood	11 million hectares of forest and woodland	> 1.2 tonnes/day	0.12 million tonnes/day
	Animal waste	211 million assorted animals		0.781 million tonnes of waste/day
	Energy crops and Agric. residue	72 hectares of agric land		0.256 million tonnes of assorted crops/day
Nuclear		Not available	-	-

Table 1-1 Nigerian natural resources (Sambo, 2009)

Despite these resources in Table 1-1, a typical Nigerian building experiences power failure or voltage fluctuations about seven times per week, each lasting for about two hours, without the benefit of prior warning (Adenikinju, 2005). Another study by Uyigüe, Agho *et al.* (2009) report that 99% of 150 respondents randomly selected in

Lagos, Benin City and Abuja say they experience over 24 hours of continuous power cuts.

1.7.1 Energy generation

The 1995 distribution of energy consumption- the most current found in literature- typifies the current energy supply mix in Nigeria. It shows that, of the total energy consumed, fuel wood has the lion share of 50.45% followed by petroleum products with 41.28% share. Natural gas consumed 5.22% and hydroelectricity 3.05% (Akinbami, 2001 cited in(Ikuponisi, 2004)).

Electricity in Nigeria is generated through three major sources: hydro, thermal and fossil fuels. The Nigerian power sector was managed by the National Electric Power Authority (NEPA) as an integrated utility responsible for generation, transmission and distribution all in the same organization. However, the failure of NEPA to provide adequate and reliable electricity to consumers despite billions of US Dollars of investment expenditure has generated a confidence crisis in the industry.

The Nigerian government in an attempt to resolve the energy crisis passed an electricity liberalization law in 2005 which set up a sector regulator called Power Handling Company of Nigeria (PHCN). The regulator stripped NEPA of its monopoly and unbundled it into a grid, six generation firms and 11 distribution companies.

Furthermore, the government put plans in motion to privatize these sectors to finance and organize development. However, the general population resists many efforts associated with privatizing the energy sector rooted in the negative experience of many Nigerians with the introduction of a private sector in previous government endeavours (Kennedy-Darling *et al.*, 2008).

Although the installed capacity of the existing power stations is 5906MW the maximum load ever recorded is 4,000MW. For a country of more than 150 million people, this indeed is grossly inadequate to meet electricity demand. The World Bank estimates that in Nigeria the per capita electricity consumption is 120.5 kWh. Compared to the annual world average of 2803 kWh in 2009, a 23-fold difference compared to that of Nigeria. Furthermore, IEA (2008) indicates that electrification rates for Nigeria are 47% for the country as a whole. In urban areas, 69% of the population had access to electricity compared to rural areas where electrification rates were 26%. Approximately 81 million people out of 150 million do not have access to electricity in Nigeria with particular

difficulties facing rural electrification raising a number of issues for African governments.

In 2012, a new fiscal framework called the multi-year tariff order II (MYTO II) that is expected to correct the low pricing of power that investors claim makes their investments uneconomical was introduced.

1.7.2 Deterioration in energy supply

The national electricity grid presently consists of nine generating stations; 3 hydro and 6 thermal. The Transmission network is made up of 5000km of 330KV lines, 6000km of 132KV lines, 23 of 330/132KV sub-stations and 91 of 132/33KV sub-stations. The distribution sector is comprised of 23,753km of 33kv lines, 19,226km of 11kv lines, 679 of 33/11kv sub-station. There are also 1790 distribution transformers and 680 injection substations (Bureau for Public Enterprises, 2009). Presently most of the generating units have broken down due to limited available resources to carry out the required maintenance. The transmission lines are radial and are overloaded. The switchgears are obsolete while power transformers are poorly maintained. Overall transmission and distribution losses are in the range of 30–40%. This claim by the Bureau has been contested by Energy Sector Management Assisted Program ESMAP (2005) claiming that in the absence of new technology as is currently the case in Nigeria, this figure can be as high as 88%.

The grid structure itself is unstable and vulnerable to sabotage (Kennedy-Darling *et al.*, 2008). People illegally connect their buildings to the grid without a meter or use residences for other purposes thereby using more energy and overwhelming the grid causing power shortages. In 1990, the World Bank estimated the economic loss to Nigeria from the state-owned central power company's inefficiency at about 1 billion Nigerian Naira (approximately £3,918,040 GBP in December 2012).

In office buildings, changing the location or type of business and private back-up power provision are methods of coping with the erratic power supply experienced in Nigeria. The most common approach is through private power generation (Adenikinju, 2005). Lee and Anas (1991) in (Adenikinju, 2005) report that small-scale enterprises spend as much as 25% of the initial investment on self-provision of a back-up generator. Project financiers also insist that firms seeking project loans must make provisions for

investments in back-up power generator to deal with the power problems (Ajayi, 1995 cited in (Adenikinju, 2005)).

Akinlo (2009) gives the following recommendations:

1. Government must ensure regular growth of electricity supply to boost the economic growth
2. There is need to rehabilitate the existing infrastructure and facilities
3. Greater investment provisions should be made by involving private capital
4. The country should continue to investigate and explore the possibilities of renewable energy for electricity generation to ensure uninterrupted energy supply
5. To reduce electric distribution and transmission losses and current monopoly power enjoyed in electricity transmission, distribution and sales should be split through privatization to enhance efficiency and greater output
6. Government should ensure appropriate pricing of electricity in the country
7. The consumers should be made aware of the importance of efficient use of electricity

1.8 Energy conservation and climate

It is estimated that buildings contribute as much as one third of total global greenhouse gas emissions and consumes up to 40% of all energy (Adeleke, 2010). This is primarily through the use of fossil fuel during their operational phase. Given the massive growth in new construction in developing countries such as Nigeria and the inefficiencies of existing building stock worldwide, if nothing is done, greenhouse gas emissions from buildings will be more than double in the coming years (Adeleke, 2010).

Figure 1-1 shows the electricity growth pattern in the different sectors in Nigeria. As at 2009, the residential sector consumes the most energy, followed by commercial and street lighting, and trailing behind is the industrial sector. This is an indication of the decline in the industrial sector due to poor energy supply. It is also an indication that conservation and efficient measures in residential and commercial sectors may yield significant energy savings.

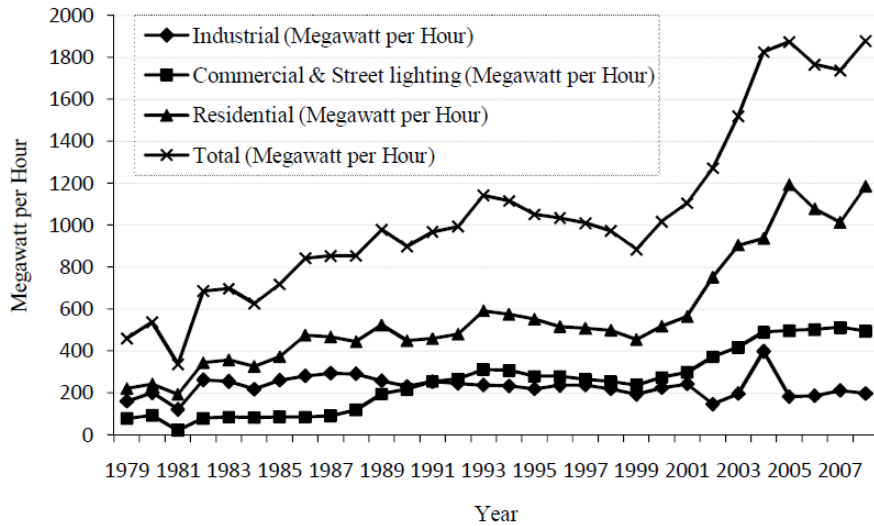


Figure 1-1 Electricity consumption pattern in Nigeria published by the Central bank of Nigeria (Oyedepo, 2012)

Total energy consumption in Nigeria was 18,051 gWh in 2009 according to the International Energy Agency (IEA, 2009). Combustible renewables and waste accounted for 80.2% of total energy supply due to high use of biomass to meet off-grid heating and cooking needs, mainly in rural areas, see

Figure 1-2. Natural gas and oil similarly supplied 9.9% and 9.4% of energy respectively. Hydro power supplied the least energy in the mix at 0.5%.

Uyigüe et al.(2009) claim that of the approximately 12% energy delivered by the utility (ESMAP, 2005), half of the energy is wasted due to inefficient user behaviour. There is obviously a need for not just cost-effective buildings, but also healthier and more productive living environment. The relationship of buildings with their environment; determines a building's sustainability. Architecture that raises standards and promises improved quality of life can help to achieve these sustainability goals (Edem, 2010). Energy conservation and efficiency practices and technologies should be actively promoted to ensure rationalized consumption of energy in the country (Sambo, 2008).

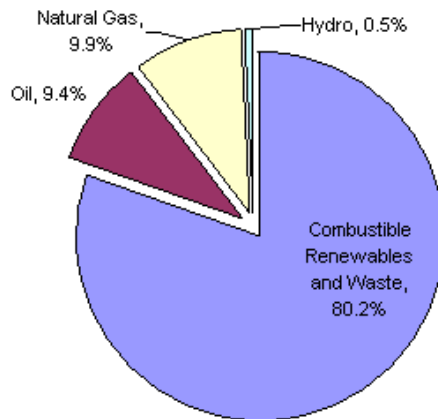


Figure 1-2 Energy supplied by type in Nigeria (International Energy Agency, 2007)

Electricity conservation policies can be initiated without deteriorating side effects on the economy as shown by Akinlo (2009) and Emeka (2010). Energy conservation can result in increased financial capital, environmental quality, national security, personal security, and human comfort.

So far, barriers of energy conservation and efficiency development in Nigeria according to Uyigüe, Agho *et al.* (2009) include:

1. Inefficient lighting with 65% of our respondents using incandescent light bulbs of 40-200 watts
2. Poor occupant control leaving lights on overnight in unoccupied areas and security lights left on during the day
3. Proliferation of private water boreholes in an effort to achieve regular water supply. In addition to power outages or as a result of, there are also water shortages experienced in Nigeria
4. Poor land use policing evidenced by industrial activities in residential areas
5. Inefficient use of electrical appliances
6. Purchase of Second hand appliances
7. Lack of policy and legislation
8. Lack of awareness
9. Lack of trained personnel and energy efficiency professionals
10. Importation of used machines
11. Lack of research materials on energy efficiency

12. Inefficient metering system
13. Low electricity pricing
14. Proliferation of inefficient equipment
15. Desire to minimize initial cost
16. Low income
17. The most significant is the fact that 99% of the respondents do not get electricity supply for up to 24 hours straight. There is a general feeling of injustice over the fact that the state is asking the public to save energy when they are not supplied the energy to save

To overcome these barriers, there is a need to live within global constraints and to ensure more fairness in access to limited resources. This concept drives this work to adopt the concepts of sustainable development.

In order to achieve sustainable development in the power sector, a holistic approach to balancing economic prosperity, social wellbeing and environmental quality is required. Sustainable development is also required for developing the built industry and saving electricity (Sambo, 2009).

Technological advances and policy have been advocated as the main solution to rise in energy consumption (Mockett, 2011); however this argument lacks a sustainable and holistic approach to energy conservation and efficiency. Up to 20% overall energy conservation is possible by including passive design concepts in buildings.

A further 40% can be saved by using a combination of passive and advanced energy systems (Santamouris *et al.*, 1996).

The triangle for low energy building design is shown in Figure 1-3. Mockett (2011) goes further to say a more sustainable built environment requires a holistic approach that marries efficiency and conservation of traditional buildings and technological advances. Energy savings in Nigeria will lead to personal income saving; reducing the building of more power stations allowing the funds to be spent on other sectors of the economy; improve access to energy; and decrease load shedding.

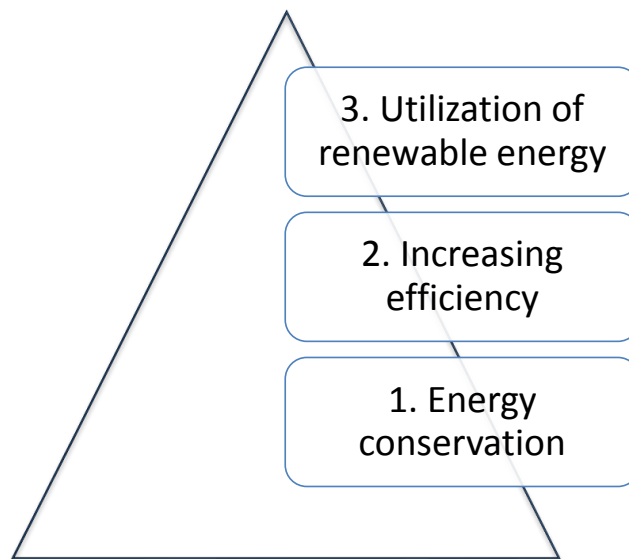


Figure 1-3 Triangle for low energy building design (Haase and Amato, 2006) ranking the efficiency of energy conservation, efficiency and renewable energy

1.8.1 Bio-climatic design

A bio-climatic system uses design features such as shading, orientation, insulation and thermal mass of the building to reduce or eliminate the heating and cooling requirements of the zone (Khalifa and Abbas, 2009). Bioclimatic principles affect the energy flows within a building, such as heat transfer through building fabric or from internal gains. Adopting bioclimatic design principles saves energy as buildings are designed based on natural ventilation, local climate and materials, and using renewable and clean technologies.

The Nigerian -climate may be broadly classified as tropical according to Komolafe (1988). Correct site orientation of buildings for thermal efficiency paying attention to solar radiation and the resultant heat load, wind direction and force and topography of the site are beneficial. Open facades should face north or south as much as possible to avoid direct radiation from the east and west. In hot areas, screening of openings and protection from the sun is always necessary. This is because the intensity, duration and the angle of incidence of solar radiation to a particular surface are the main determinants of the design precautions necessary for comfort. These techniques are used within the climatic and building use context to achieve thermal comfort.

Six established bio-climatic design strategies in the design stage have been highlighted by Haase and Amato (2006):

1. Thermal mass effect
2. Exposed mass + night purge ventilation
3. Passive solar heating
4. Natural ventilation
5. Direct evaporative cooling
6. Indirect evaporative cooling

In addition, Ogunsote (1991) advises a good design for thermal comfort in the Nigerian climate should observe the following considerations:

- Orientation of the buildings
- Cross ventilation within the habitable rooms
- Solar control and appropriate shading techniques
- Appropriate and correct use of vegetation and
- Air humidification or evaporative cooling
- Use of appropriate properties of materials like heat storage and insulation

The built environment in Nigeria comprises of ‘modern’ buildings that seldom adopt the bioclimatic approach to buildings. These buildings play a major role in the rise of electricity consumption required for cooling (Santamouris, 2007). Unjustifiable cooling loads lead to absolute increase in energy consumptions; and peak electricity loads; deteriorated indoor air quality and; associated environmental and climate dangers. Solar radiation is a time-dependent energy source with an intermittent character and the peak solar radiation occurs near noon. Thermal energy storage can provide a reservoir of energy to enable its use at a more suitable time, thereby bridging the gap between mismatched energy supply and demand and will be further discussed in Chapter 2.

1.8.2 Energy efficiency in office buildings

Energy consumption in office buildings is significant in Nigeria compared to the consumption of other building types as shown in Figure 1-1. A review of literature shows only one study of electricity consumption and demand in a Nigerian context by Adelaja (2008). The complex studied is the University of Lagos, Nigeria. The complex

is classified into three: faculty and service, residential and commercial areas. Electricity accounts for 97% of energy use. Other sources of energy are kerosene, liquefied petroleum gas, diesel, charcoal and firewood, mainly used for cooking. The major end-uses are space cooling and lighting accounting for 33% and 7% respectively. The remaining 60% percent is consumed by other appliances which include refridgerators, computers, laboratory machines and water heating.

Due to the paucity of electricity use data in Nigerian office buildings, a field data collection exersize is required. Significant energy conservation is possible only through targeted attempts at specific end-uses that consume substantial electricity. This field data collection is further discussed in Chapters 3 and 5.

Energy in office buildings is mainly consumed for heating, cooling, lighting and operating office equipment purposes (Santamouris and Dascalaki, 2002). Factors that affect energy use specifically in offices according to Action Energy (2003) are building quality, occupancy and management.

End-uses for electricity are (Action Energy, 2003):

1. Heating and domestic hot water (DHW)
2. Cooling
3. Fans, pumps and controls
4. Humidification and dehumidification
5. Lighting
6. Office equipment
7. Catering
8. Other electricity – including lifts, print rooms, and energy use outside the measured treated area, for instance by plant room or exterior lighting
9. Computer and communications rooms – including air-conditioning of their dedicated suites

Due to the way offices are run and occupied, estimating energy use through records is more straight-forward than residential areas. In Nigeria the industrial sector is on the decline see Figure 1-1. Investigating energy use therefore requires a comprehensive study from sources that are available and easily extracted.

The erratic electricity supply in Nigeria has resulted in reliance on ‘back-up’ power generators. The trend of using fossil based fuel to power back-up generators in Nigeria has negative impacts on climate change, pollution, and profit for businesses. Long term

solutions are required in sector reforms; decentralization of the power sector; and sustainable development and consumption across all sectors. Energy conservation and efficiency in electricity consumption is necessary to decrease loads on a failing network. Provision of back-up and other alternative generators including those requiring renewable energy sources in the short term are required. Also required are efforts aimed at reducing greenhouse gas emissions from the existing building stock which account for 40% of global emissions (Poel *et al.*, 2007; Howe, 2010). Only electricity will be discussed for the purpose of this investigation as it constitutes the bulk of energy consumption in Nigerian buildings (Batagarawa *et al.*, 2011).

Chung and Hui (2009) in their work report that information for measuring energy efficiency in office buildings is gathered from utility billing data, on-site survey and measurement, and site operational records. To compare the energy use of different entities, there is a need to normalize the energy use with floor area and/or operational hours to obtain the energy efficiency then ranked in a benchmarking table. Climate adjustment of energy use data may be involved if the information on degree-day is available and the energy data involves different climate conditions. The degree-day value is defined as the difference between daily mean temperature and the defined base temperature.

A joint study by the U.S. Department of Energy (DOE) and Energy Information Administration (EIA) (1995) measures commercial energy efficiency in the United States based on energy end-use intensities. Some indicators have been developed, such as space-heating intensity (normalized by square foot hour and heating degree-day), and lighting intensity (normalized by lighted square foot hour). Another survey study was reported by e-Energy in Singapore, and the corresponding energy efficiencies were calculated with occupancy rate and operating hour normalization. Normalization is further discussed in Chapter 4.

The proper use of the energy in a building reduces operational costs in two ways (Neto and Fiorelli, 2008) by:

1. Reducing cost
2. Preventing legal penalties

Chung and Hui (2009) argue that the major contribution of improved energy efficiency is increased savings, not less energy usage. Energy consumption of up to 36% is attributed to materials making up the building fabric (Haase and Amato, 2006). A

combination of active and passive design features holistically integrated in initial design stage by all stakeholders in a project can contribute in energy savings of between 50-55% (Ochoa and Capeluto, 2008).

Energy storage is essential whenever there is a mismatch between the supply and consumption of energy (Voelker *et al.*, 2008). In buildings, this mismatch may be that of solar energy. Energy storage may be used to store unwanted heat energy to be utilised at other times or extracted out of the building. Energy storage is also used reduce or shift peak electricity consumption caused by heating or cooling.

In addition Atul Sharma (2009) reports that one of the options to combat climate change is to develop energy storage devices which fall under energy conservation. These devices are as important as developing new sources of energy. Energy storage not only reduces the mismatch between supply and demand but also improves the performance and reliability of energy systems and plays an important role in conserving the energy. It leads to saving of premium fuels and makes the system more cost effective by reducing the wastage of energy and capital cost.

Energy storage in the walls, ceilings and floors of buildings is possible by incorporating PCM in the building fabric to adsorb solar energy at daytime when PCM change phase from solid to liquid state. When the room temperature falls down at night, PCM releases the energy and freezes back to solid phase. PCM technology in buildings has the potential to promote energy conservation through passive cooling in hot climates where high energy use of an air conditioning system is required according to Rahman *et al.* (2008).

1.8.3 Thermal comfort in office buildings

In this study, the thermal comfort indices used to evaluate comfort are dry bulb air and operative temperatures. Operative temperature is used in addition to air temperature because operative temperature is the combined effect of air and surface temperatures which has been shown to be a more robust index than air temperature alone.

Comment [A1]: addition

Thermal comfort- in the context of hot climates requires and is dominated by cooling (Ogunsote, 1991; Adelaja *et al.*, 2008; Isa *et al.*, 2010). Adelaja (2008) surveyed energy consumption in a university complex and cooling accounts for largest demand (33%) of all primary energy use.

There are six major factors that determine comfort (CIBSE, 2007). They are:

1. Ambient air temperature
2. Humidity
3. Radiation
4. Air movement
5. Clothing
6. Activity

Other factors such as age, sex, body shape, state of health, ethnic grouping and diet may have some effect on thermal comfort but research (Nicol *et al.*, 2012) shows they are not significant. The six major variables that are used to evaluate thermal comfort are also used to formulate thermal indices. These thermal comfort indices for building users according to Santamouris (2007) are evaluated in two ways: rational and adaptive techniques

- The 'rational' approach, also called heat balance approach evaluates the response of people to the thermal environment in terms of the physics and physiology of heat transfer between a body and its surroundings. Rational approach is dependent on physiological and physics to achieve comfort; whereas the adaptive approach lays emphasis on occupants and controls. The rational approach may be empirical or analytical. The empirical approach uses fieldwork to study comfort, whereas the analytic approach relies on climatic chamber and statistical examinations and relationships between the variables contributing to comfort. The analytical approach suffers from formulation and laboratory measurement errors and empirical studies have shown people are more adaptive to discomfort than what is predicted by analytical solutions (Nicol *et al.*, 2012). In the rational approach, an index is produced based on the responses of subjects in constant-temperature conditions in climate. An obvious limitation is the attempt to tailor such an index to express the response of people in varied and dynamic conditions of daily life
- An adaptive approach on the other hand, concentrates on gathering data about the thermal environment and the simultaneous thermal response of subjects in real situations, interventions by the researcher being kept to a minimum (Nicol *et al.*, 2012). Whereas the comfort temperatures for rational approach are static, those for adaptive approach are more dynamic in response to intrinsic weather variations. The difference between the rational and adaptive approach is mainly

the ability of people to react in ways which tend to restore their comfort with a change in the thermal condition that causes them to experience thermal discomfort

Both approaches are based on thermal indices which are divided into 2; direct and derived indices. Direct indices are those variables that are measured directly and affect thermal comfort such as dry bulb temperature, relative humidity, air velocity, activity, clothing and mean radiant temperature. Direct indices are used to calculate derived indices such as:

- Neutrality temperature, T_n
- Operative temperature, T_{op}
- Predicted mean vote-percentage people dissatisfied, PMV-PPD
- Effective temperature, ET
- Standard effective temperature, SET

The indices are shown in Table 1-2. The simpler the index chosen, the more likely it is to prove satisfactory and the simplest index of all is the dry bulb temperature (DBT) (Macpherson, 1962; Nicol *et al.*, 2012). DBT is the most common index for the specification of comfort. However, for the measurement of the magnitude of discomfort or stress some other index must be found, which recognizes the other environmental factors such as humidity, radiation and air movement.

Comment [AGB2]: addition

Name	Neutrality temperature (T_n)	Predicted mean vote-people dissatisfied (PMV-PPD)	Effective temperature (ET)	Standard effective temperature (SET)
Source	Humphreys' (1975)	Fanger, P O (1970)	Houghten and Yagloglou (1923)	Gagge et al.(1986)
Approach	Adaptive	Rational and analytic	Rational and analytic	Rational and analytic
Factors	DBT of exterior and interior	Clothing, metabolic rate, DBT, mean radiant temperature, humidity and air-speed	Relative humidity, air velocity, air temperature and clothing	Skin temperature, skin wettedness
Negative	Adaptive mechanisms of occupants seem un-quantifiable, it overlooks the effect of humidity, and air movement.	>/= 5% of the population would be dissatisfied even under the "best" conditions, overestimates warm discomfort especially in warm climates.	Effect of radiant heat energy is neglected, overestimates the effect of humidity especially at lower temperature, exaggerates the stress imposed by air velocity in hot environments	Limited to standard conditions, source of measurement error is large due to many variables

Table 1-2 Thermal comfort indices

1.8.3.1 Neutrality temperature

Neutrality temperature is also known as comfort temperature. Neutrality temperature is an adaptive thermal index. It is the temperature at which the body is comfortable, requiring neither cooling nor heating. Comfort temperature in naturally ventilated buildings depends on the outdoor temperature (Nicol and Humphreys, 2001). Nicol and Humphreys (2001) have shown that for naturally ventilated buildings the relationship between comfort temperature T_c and ambient temperature T_o as Equation 1-1:

$$T_c = 13.5 + 0.54 T_o \quad \text{Equation 1-1}$$

In a situation where there was no possibility of changing clothing or activity and where air movement cannot be used, the comfort zone may be as narrow as $\pm 2^\circ\text{C}$. In other more adaptive environments, the comfort zone may be as wide as $\pm 7^\circ\text{C}$ (Nicol *et al.*, 2012).

Neutrality temperature may also be calculated using the formula shown in Equation 1-2 by de Dear and Brager (1998).

$$T_n = 17.8 + 0.38(T_{ave}) \quad \text{Equation 1-2}$$

Where T_n is neutrality temperature, and T_{ave} is mean monthly temperature. It should be noted that this equation is similar to Equation 1-1 and is adopted for use as the equation for Neutrality temperature in this research. This index is adopted for its adaptability to ambient environmental conditions and to evaluate indoor comfort in naturally cooled buildings.

Comment [A3]: addition

1.8.3.2 Operative temperature

Operative temperature is an adaptive and derived measure of thermal comfort. Surface temperature affects the mean radiant temperature and in the case where the surface temperature and air temperature are different, the operative temperature is adopted as a more valid thermal index (CIBSE, 2007). The Operative temperature is the average of the Zone Mean Air Temperature and Zone Mean Radiant Temperature (EnergyPlus, 2011). Mean air temperature is simply the dry bulb air temperature whereas the mean radiant temperature (MRT) is a means of expressing the influence of surface temperatures on occupant comfort. In EnergyPlus, the average Mean Radiant Temperature (MRT) of the zone is calculated assuming that the person is in the centre of the zone.

Comment [A4]: addition

Operative temperature is used as a comfort index in addition to Neutrality temperature due to its suitability to evaluate the effect of PCMs on surface as well as air temperatures. Evaluating air temperature alone might lead to erroneous results as shown in the analyses in Section 7.7.

1.8.3.3 PMV-PPD

Predicted mean vote (PMV) and percentage people dissatisfied (PPD) is an example of a rational approach. PMV-PPD index sets out to predict the average comfort vote on a 7-scale ranking based on the 6 factors in Table 1-2. The index includes a simplified interpretation of the ranking to an output of percentage of people dissatisfied within a given set of conditions (Nicol *et al.*, 2012).

The relationship for buildings which are heated or cooled is complex because when a building is heated or cooled the indoor temperature is decoupled from the outdoor temperature and the indoor temperature is more directly governed by occupants' behaviour. However, so long as the change is sufficiently slow such as between seasons, people will adapt to a range of temperatures. This relationship is represented by a rational index linking occupant comfort to the running mean of the current outdoor ambient temperature again (Nicol *et al.*, 2012). Such indices ignore occupant behaviour. The European standard EN15251 (Olesen, 2010) in Table 1-3 shows the limits set for comfort in a mechanically cooled office building. The comfort band sits between 22°C and 27°C. The appropriate category for this research has been highlighted in bold text. It is calculated based on the PMV-PPD index.

Category	Explanation	Temperature range for cooling 0.5 clo in offices (°C)
I	High level of expectation used for sensitive and fragile occupants	23.5-25.5
II	Normal expectation for new buildings and renovations	23-26
III	Moderate expectation for existing buildings	22-27
IV	Values outside criteria I-III only acceptable for limited periods	NA

Table 1-3 Indoor comfort criteria for mechanically cooled office buildings by EN15251 (Olesen, 2010)

1.8.3.4 Effective Temperature

Another example of rational thermal index is the Effective Temperature (ET) index. Effective temperature is the temperature in an environment with 100% humidity and no air movements which will induce the same level of thermal comfort as in the present situation. Ogunsote and Prucnal-Ogunsote (2002) conducted a study in Zaria, Nigeria comparing the ET comfort range and ET indicates that 22°C to 27°C are assumed for thermal comfort for the Tropics. This range coincides with that of EN15251 (Olesen, 2010) in Table 1-3. However, Ogunsote and Prucnal-Ogunsote (2002) conclude that the most appropriate comfort range should be 20°C to 25°C. The study is limited by the scope and duration, but it however questions the generalizability of the ET index in different contexts.

1.8.3.5 Standard effective temperature

Standard effective temperature SET* index attempts to improve ET to relate to real conditions. SET* is the dry-bulb temperature of a hypothetical environment at 50% relative humidity for subjects wearing clothing that would be standard for the given activity in the real environment. Furthermore, in this standard environment, the same physiological strain, i.e. the same skin temperature and skin 'wettiness' and heat loss to the environment, would exist as in the real environment. Effective temperature can then be related to subjective response under standardised conditions of 0.5 clo, 1met, and 50% relative humidity. The measurement procedure is to determine DBT and MRT

(or operative temperature), then air velocity (v), evaluate the metabolic rate (M) and clothing (clo), then predict the average body temperature (T_b).

1.9 Outline of chapters - Thesis plan

The thesis consists of eight chapters as shown in Figure 1-4 and discussed below:

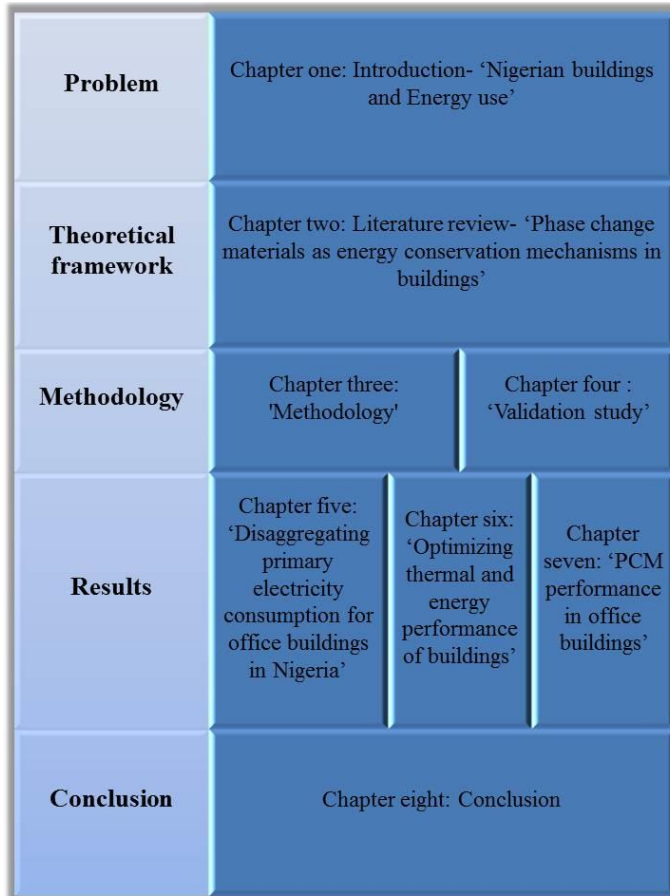


Figure 1-4 Thesis structure

1.9.1 Chapter One

This is the introduction chapter titled 'Nigerian buildings and Energy use'. To build a context behind the need for a study into energy conservation, it discusses electricity generation, distribution, transmission and consumption. The place for energy conservation and efficiency is grounded theoretically.

1.9.2 Chapter Two

Chapter 2 is the literature review titled ‘Phase Change Materials as energy conservation mechanisms in buildings’. The objective is to search for the knowledge gap within literature for PCM used for energy conservation and thermal comfort within buildings in Nigeria hot and humid, and hot and dry climate. The chapter is the theoretical framework with which PCM may be optimized for the context of the research. A brief history of the development of PCM, its various applications, thermo-physical and chemical classifications are reviewed. The development history shows the ways in which PCM are incorporated within the building applications, and ways of optimizing its thermal and energy performance.

1.9.3 Chapter Three

Chapter 3 is the ‘Methodology’ chapter and one of its objectives is to evaluate the methods of calculating the potential for energy savings with PCM. Another objective is to develop a method for collecting electricity consumption data in places suffering from power shortages. In Chapter 1, this problem is highlighted as a significant one in Nigeria. The same chapter brought to light the need to conduct a field energy auditing exercise. A method to successfully collect electricity consumption data is presented.

1.9.4 Chapter Four

Chapter 4 is the Study dealing with validating the results of the simulations predicted by the different versions of EnergyPlus for the base-case with PCM and without. The objective is to evaluate the different methods of calculating the potential for energy savings with PCM. They include Analytical (Theoretical) testing, Laboratory and Field experimentation and Computer simulation (Numerical testing). A discussion of the benefit and limitations of each method is conducted in this chapter and computer simulations are shown to be more suitable for this study.

1.9.5 Chapter Five

Chapter five: The chapter is titled ‘Disaggregating primary electricity consumption for office buildings in Nigeria’. This chapter discusses the primary field data collection exercise conducted in Nigeria. The objective is to investigate the electricity consumption within office buildings in Abuja

The sampling issues, energy audit process, and a report of the results are presented. It also reports the results of a degree day and descriptive statistical analyses. The results provide the description and breakdown of how electricity is used into end-use aggregates.

Disaggregating electricity consumption enables the next objective. The objective is to determine the potential for energy savings within the cooling load.

1.9.6 Chapter Six

The chapter looks at ‘Optimizing thermal and energy performance of buildings’. The chapter reports the bio-climatic optimization process of office buildings’ design features for electricity conservation and thermal comfort in Nigerian office buildings. The variables examined are bio-climatic design variables such as orientation, glazing, shading, airtightness and insulation. This is achieved using building energy modelling and simulation software, DesignBuilder and an internal EnergyPlus simulation engine as discussed in Chapter 2 and later in this chapter.

The above process is conducted to achieve another objective; to create a base-case for testing the performance of PCMs. The bio-climatic optimization process is required because testing PCM systems on a poorly designed building might give erroneously superior results simply because there is so much room for energy savings. Testing PCM systems on a thermally optimized base-case building on the other hand will provide reasonable results.

1.9.7 Chapter Seven

The chapter is titled ‘PCM performance in office buildings’. One of the objectives is to create an optimized model for a PCM system for office buildings in warm climates. The bio-climatic model presented in Chapter 6 is used to analyse the effect of varying thermo-physical properties of the PCM system on electricity consumption and thermal comfort. in the form of a parametric analysis process using building energy calculation software, EnergyPlus.

1.9.8 Chapter Eight

The other objective is to evaluate the potential effect of incorporating PCMs in the building fabric on thermal comfort and energy consumption. The performance in

operational mode of the PCM is analysed using degree day and descriptive statistics. The result is a PCM model for use in office buildings in Nigeria.

1.10 Conclusion

It is estimated that buildings contribute as much as one third of total global annual greenhouse gas emissions, primarily through the use of fossil fuel during their operational phase and consumes up to 40% of all energy in Nigeria, similar to global trends (Adeleke, 2010). In addition, Nigeria suffers from an energy crisis which manifests in power outages despite being highly endowed with natural energy resources (Ibitoyea & Adenikinju, 2007). Due to the power outages, the built environment has adapted to interrupted electricity supply by installing back-up power generators fuelled mostly by diesel and petrol.

Energy conservation and efficiency practices and technologies are required to ensure rationalized consumption of energy in Nigeria (Sambo, 2008). This is desirous due to wasteful and inefficient use of electricity in residential, offices buildings, and industries as reported by Uyigue *et al.*(2009).

Energy consumption in office buildings is one of the highest compared to the consumption of other building types. Energy in office buildings is mainly consumed for thermal comfort, lighting and operating office equipment purposes (Santamouris and Dascalaki, 2002).

The aim of this investigation is therefore to evaluate the potential of incorporating PCM systems in composite hot humid/ hot dry climates in order to conserve energy in office buildings within the context of an overburdened and failing central power utility in Nigeria.

A quantitative research strategy using cross-sectional method of data collection is employed to achieve the objectives of the study which are:

1. To build a context behind the need for a study into energy conservation in Nigeria
2. To search for the knowledge gap within literature for PCM used for energy conservation and thermal comfort within warm-humid climates
3. To validate the computer software's and user's ability to simulate PCMs in buildings
4. To develop a method for collecting electricity consumption data in places suffering from power shortages

5. To investigate the electricity consumption within office buildings in Nigeria
6. To determine the potential for energy savings within the cooling load
7. To create a base-case for testing the performance of PCMs
8. To optimized model for a PCM system for office buildings in warm climates
9. Evaluate the potential effect of incorporating PCMs in the building fabric on thermal comfort and energy consumption

Apart from PCMs, bioclimatic design principles are adopted to save energy because buildings are designed based on natural ventilation, local climate and materials, and using renewable and clean technologies (Khalifa and Abbas, 2009).

Chapter 2 is the literature review titled 'Phase Change Materials as energy conservation mechanisms in buildings'. It is centred on a description of Phase Change Materials (PCMs) properties and their application in the built environment as an energy conservation mechanism.

2 CHAPTER 2
LITERATURE REVIEW:
PHASE CHANGE MATERIALS AS ENERGY CONSERVATION
MECHANISMS IN BUILDINGS

Contents
2.1 Overview
2.2 Phase Change Materials (PCM)
2.3 Properties of PCMs
2.4 Applications of PCMs
2.5 Conclusions

Problem	Chapter one: Introduction- 'Nigerian buildings and Energy use'		
Theoretical framework	Chapter two: Literature review- 'Phase change materials as energy conservation mechanisms in buildings'		
Methodology	Chapter three: 'Methodology'	Chapter four : 'Validation study'	
Results	Chapter five: 'Disaggregating primary electricity consumption for office buildings in Nigeria'	Chapter six: 'Optimizing thermal and energy performance of buildings'	Chapter seven: 'PCM performance in office buildings'
Conclusion	Chapter eight: Conclusion		

2.1 Overview

Firstly, this chapter reviews Phase Change Materials (PCMs) used in building applications. The history of its development in the built environment properties and performance are discussed. The properties and applications of PCMs are covered. The properties studied are the thermo-physical and chemical properties. Under applications, the ways in which PCM are encapsulated and incorporated within the building applications in different conditions are studied. The theoretical framework with which PCM may be optimized for different climates is also studied. Finally the various ways that PCM thermal and energy performance are calculated are discussed.

2.2 Phase Change Materials (PCM)

The study of Phase Change Materials (PCM) was pioneered by Maria Telkes (1900 – 1995). She is the designer of the first residential solar heating system and inventor of many solar-powered devices in the 1940s. In 1948 the first experimental house using solar heating was built under her supervision in Dover, Massachusetts. Through the course of her life, she obtained about 20 patents covering areas such as distillation equipment, portable desalination of seawater on life rafts and heat and cold storage. Heat and cold storage systems using PCM did not receive much attention however, until the energy crisis of late 1970s and early 1980s where it was extensively researched for use in different applications especially for solar heating. After the energy crisis, this spike in interest waned until a combination of environmental problems, imminent energy shortage and the high cost of energy and new power plants created the current requirement for advancing new technologies, especially in reducing energy consumption in buildings. The need to store excess energy that would otherwise be wasted and also the need to bridge the gap between energy demand and supply is essential (Agyenim, 2009).

PCMs fall under a class of thermal storage system known as latent heat thermal energy storage system. Kuznik *et al.* (2008a) describe PCM as materials having an interesting feature to store latent heat energy, as well as sensible energy. As the temperature increases, the material changes phase from solid to liquid. As this physical reaction is endothermic, the PCM absorbs heat. Similarly, when the temperature decreases, the material changes phase from liquid to solid. As this reaction is exothermic, the PCM releases heat. PCM acts as a stabilizer for temperature fluctuations between high peaks and low troughs so that temperatures inside the building rise and fall more slowly than external temperatures and maximum and minimum temperatures are less extreme. This

reduces the amount of heating or cooling required and therefore reduces fuel consumption as well as CO₂ emissions.

2.2.1 Applications

The following industry applications have been recognized for PCM technology by Pasupathy *et al.*, (2008b) and Atul Sharma, (2009):

- Building applications
- Packaging
- Garments
- Technology
- Waste heat recovery
- Load levelling for power generation

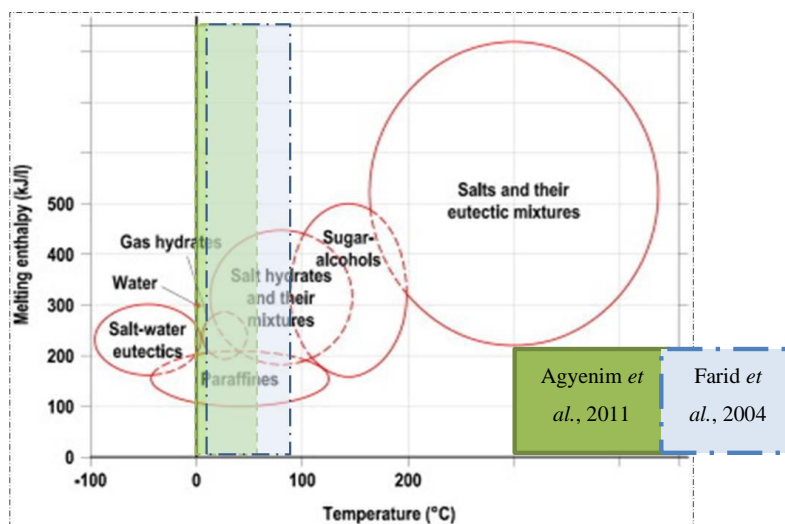


Figure 2-1 PCM melting temperature and enthalpy from Baetens *et al.* (2010), showing PCM suitable for domestic heating/cooling in the range of 0-65°C (Agyenim *et al.*, 2011) and 15-90°C (Farid *et al.*, 2004)

This investigation is concerned only with building applications with a focus on possible indoor temperature regulation leading to thermal comfort and energy conservation.

Thermal comfort for humans is achieved within a very narrow range of temperature as discussed in Chapter 1. This narrow range required for human comfort raises interest in

the possibility of using PCMs as a heat storage mechanism within buildings. According to Farid *et al.* (2004), PCM that melt below 15°C are used for storing coolness in air conditioning applications, while materials that melt above 90°C are used for absorption refrigeration. All other materials that melt between these two temperatures can be applied domestic building applications as shown in Figure 2-1. On the other hand, Agyenim *et al.* (2011) report that PCMs suitable for domestic heating/cooling are in the range of 0 to 65°C also shown in Figure 2-1. The diagram also shows the different classes of PCMs and their melting points and enthalpy.

2.2.2 Building applications

By their nature, buildings have large surface areas and consequently a large potential for thermally storing energy (Ortiz *et al.*, 2010). Latent heat thermal energy storage such as that provided by PCM is a particularly attractive technique in buildings because it provides:

1. Temperature regulation
2. Energy conservation
3. Peak-load shifting to off-peak rate times

Within the literature reviewed, temperature regulation is the chief indicator of PCM performance followed by electricity consumption and then peak-load shifting.

The electricity consumption of a test space is recorded or predicted over regular time intervals to study the performance of PCMs in the space (Castell *et al.*, 2010a). It may be recorded in addition to surface temperature of a building fabric (Khalifa and Abbas, 2009) or air temperature of the test space (Zhou *et al.*, 2007).

Peak-load shifting also involves the collection of electricity consumption data, then using it to examine how PCMs can shift the peak consumption to off-peak times (Zhang *et al.*, 2005; Atul Sharma, 2009; Diaconu and Cruceru, 2010). For off-peak electricity storage, PCM can be melted and solidified to store energy in the form of latent heat thermal energy and the energy is then available at a suitable time. So, if latent heat thermal energy storage systems are coupled with the active systems, it will help in reducing the peak load and thus electricity costs can be reduced by keeping the demand nearly constant, or shifting the peak to cheaper tariffs. This is only beneficial in countries that have varying electricity tariffs over the course of a day. Nigerian electricity tariffs are fixed for the different classes of users (NERC, 2013). Therefore, peak-load reduction is limited as an indicator of PCM performance in Nigeria.

2-Literature review: Phase change materials as energy conservation mechanisms in buildings

Like many other technologies, the success of PCM systems depends more in the way of use than in the PCM product itself. PCMs are thus evaluated in literature under two general classifications:

- Properties
- Applications

Both factors are heavily dependent upon effective melting and solidification of the PCM (Kuznik *et al.*, 2008a).

Thirty-four studies have been reviewed in this chapter as shown in Table 2-1. Table 2-2 shows the variables have been studied and ranked according to how frequently the variables have been studied. The variables studied and their classifications are shown in Figure 2-2.

1	Ahmet, 2005	18	Kuznik and Virgone 2009b
2	Alawadhi 2008	19	Kuznik et al., 2011
3	Atul Sharma, 2009	20	Li et al., 2009
4	Cabeza et al., 2007	21	Mehling et al., 2008a
5	Castell et al., 2010a	22	Pasupathy et al. 2008a
6	Castello et al. 2008	23	Susman et al., 2010a
7	Castellón et al., 2010	24	Tay et al. 2012
8	Chen <i>et al.</i> 2008	25	Voelker et al., 2008
9	Darkwa and O'Callaghan 2006	26	Xiao <i>et al.</i> 2009
10	de Gracia et al., 2012	27	Xu et al., 2005
11	Diaconu and Cruceru 2010	28	Zalba et al., 2003
12	Farid et al., 2004	29	Zalba et al. 2004b
13	Gunther et al., 2007	30	Zhang, 2004
14	Isa et al., 2010	31	Zhang et al. 2005
15	Kelly, 2010	32	Zhang et al. 2006
16	Khalifa and Abbas, 2009	33	Zhou et al. 2007
17	Kuznik and Virgone, 2009a	34	Zhu et al., 2010

Table 2-1 Studies reviewed

2-Literature review: Phase change materials as energy conservation mechanisms in buildings

Properties			Applications			Applications		
Variable	Frequency	Studies	Variable	Frequency	Studies	Variable	Frequency	Studies
1. Transition temperature	11	25, 24, 13, 14, 5, 27, 32, 33, 17, 22,2	6. Micro-encapsulation	10	20, 9, 13, 15, 16, 1, 14, 30, 31, 10, 5, 29, 27, 32, 33, 17, 7, 23, 26, 22, 11, 2	15. Building component	26	12, 20, 1, 30, 10, 5, 29, 27, 32, 33, 17, 7, 23, 26, 22, 11, 2, 19
2. Thickness and conductivity	18	1, 17, 25, 32, 34, 6, 18, 9, 15, 30, 32, 33, 17, 26, 2, 19	7. Macro-encapsulation	5	12, 25, 34, 28, 10, 6, 8, 18, 20, 9, 13, 15, 16, 1, 14, 30, 31, 10, 5, 29, 27,32, 33, 17, 7, 23, 26, 22, 11	16. Climate	14	12, 1, 30, 10, 5, 29, 32, 33, 17, 26, 22, 11, 2
3. Enthalpy	7	8, 13, 15, 14, 32, 17, 22	8. SSPCM	5	28,10,6,8,18,20,9,13,15,16,14,30, 31,10,5,29,27,32,33,17	17. Temperature	10	20, 1, 5, 33, 17, 7, 26, 22
4. Other Thermo-physical properties	22	25, 12, 24, 9, 20, 18, 8, 6, 28, 4, 7, 23, 26, 22, 11, 2, 19, 29, 27, 32, 33, 16, 1, 14, 30, 31, 10	9. Lightweight	9	12, 20, 10, 32, 33, 17, 7, 22, 2	18. Peak-load shifting	3	25, 7, 2
5. Chemical classification	15	34, 28, 24, 6, 8, 18, 20, 9, 13, 15, 16, 1, 14, 30, 31, 10, 5, 29, 27, 32, 33,18,7, 23, 26, 22, 11, 2, 19	10. Heavyweight	5	1, 3, 29, 19	19. Cost	5	
			11. Analytic calculations	5	13, 31, 10, 27, 32, 22	20. Electricity consumption	5	30, 5, 29, 26, 2
			12. Computer simulation	8	12, 1, 17, 7, 26, 11, 2	21. Transition time	3	27, 33, 26
			13. Lab experiment	12	18, 20, 9, 14, 30, 31, 10, 27, 17, 7, 23, 19	22. Active mode	8	12, 30, 5, 29, 27, 33, 26, 11
			14. Field experiment	9	12, 5, 29, 32, 26, 22, 11	23. Passive mode	9	12, 1, 14, 5, 29, 17, 26, 11

Table 2-2 Authors of PCM studies and variable ranking

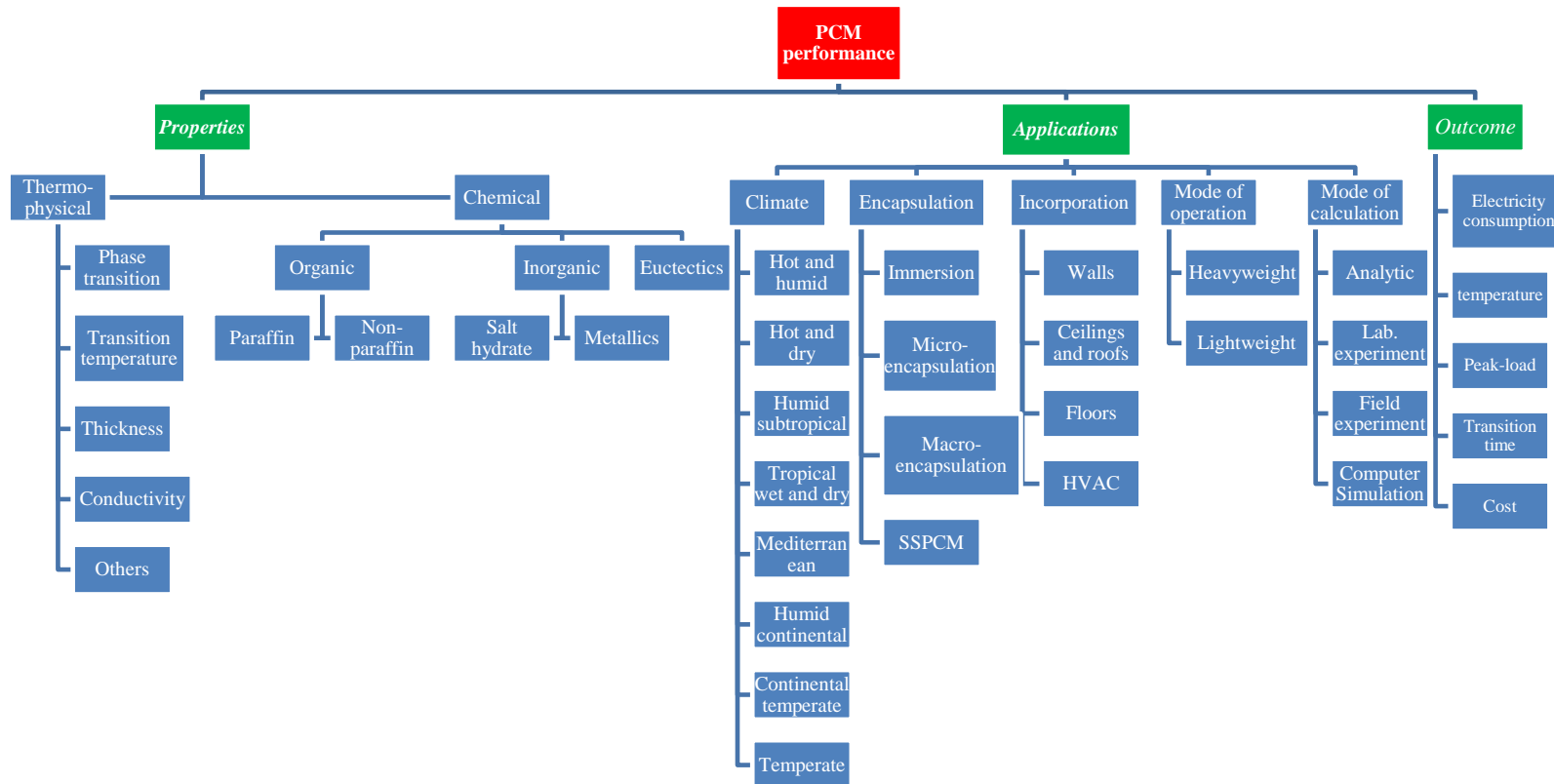


Figure 2-2 Classification of variables studied in literature

2.2.3 Climate

PCM performance has been shown to be dependent on transition temperature. The transition temperature itself is dependent on average room temperature and subsequently on climate. In naturally ventilated buildings especially, effective melting and solidification is significantly affected by climate. Considering this, there is a conspicuous gap in literature covering the effect of climate specifically, on PCM performance across different climatic zones.

Location	Climate	Reference
Lleida, Spain	Humid subtropical	Cabeza et al., 2007 and de Gracia et al., 2012
Germany	Temperate	Voelker et al., 2008
London	Temperate	Susman et al., 2010a
Malaysia	Hot and humid	Isa et al., 2010
Beijing	Humid continental	Xiao et al. 2009, Xu et al., 2005, Zhang et al. 2005, Zhang et al. 2006, Zhou et al. 2007
Lyons, France	Mediterranean	Kuznik and Virgone, 2008b and 2011
Chennai- India	Tropical wet and dry	Pasupathy et al. 2008a
Algeria	Continental temperate	Diaconu and Cruceru 2010

Table 2-3 Studies that examined the effect of climate

Within the studies reviewed, only a fourth is based on a climatic context. The climates are shown in Table 2-3. It is apparent that the eight climates covered are not representative of the climates found in other parts of the world. None of the climates studied fall within a composite of hot and humid and hot and dry as experienced in a large swathe of Nigeria. None of the studies cover West Africa and the only hot and humid climate studied is a preliminary one (Isa et al., 2010) in Malaysia which is yet to publish measured or predicted results. On-going research is being conducted to evaluate the performance of copper foam enhanced PCM building fabric of a model of terrace houses in hot and humid Malaysia in a climatic laboratory chamber (Isa *et al.*, 2010). Diaconu and Cruceru (2010) study the influence of different parameters and system variables to establish a PCM system in Algeria, a continental temperate climate which – complemented with passive strategies (solar gains, natural ventilation) – reduces the

thermal comfort related energy consumption in buildings. The system variables include transition temperature, air velocity and location in the building. In their investigation, PCM impregnated wallboards are combined in different configurations with insulation within the fabric of the building. They proposed a new type of PCM composite wall system for year-round thermal energy management; the novelty being that the two different PCMs have different values of the thermo-physical properties. Numerical test were carried out and results achieved are peak cooling/heating load reduction of 35.4%; reduction of the total cooling load was 1%. However, it is expected that once the parameters of the wall system are adjusted, higher value of annual energy savings for cooling can be achieved; annual energy savings for heating is 12.8%. It should be noted that this study indicates the possibility of combining PCMs to achieve required thermo-physical properties.

The climate based thermo-physical properties of PCM in Nigeria such as transition temperature and thickness therefore remain unstudied as far as the literature studied are concerned.

2.3 Properties of PCMs

PCMs should have a large latent heat and high thermal conductivity. They should have a transition temperature lying in the practical range of operation, melt congruently with minimum sub-cooling and be chemically stable, low in cost, non-toxic and non-corrosive. Therefore, PCMs have certain properties that need to be optimized (Atul Sharma, 2009; Agyenim *et al.*, 2011) as shown in Table 2-4.

However, no single PCM has achieved all the required properties in Table 2-4 so a suitable system using available materials is required to balance lacking properties with enhancements such as containment and increasing conductivity (Mehling *et al.*, 2008). The limitations limiting the uptake, the thermo-physical and chemical properties of PCM are discussed in this section.

Thermo-physical properties	Suitable phase-transition temperature
	High latent heat of transition
	High conductivity
	High density
	Small volume change
	Low vapour pressure
Chemical properties	No super-cooling: Self nucleation means they crystallize with little or no super-cooling and usually non-corrosiveness
	Favourable phase equilibrium: Congruent melting means melt and freeze repeatedly without phase segregation and consequent degradation of their latent heat of fusion
	Sufficient crystallization rate
	Long-term chemical stability
	Compatibility with materials of construction
	No toxicity
	No fire hazard

Table 2-4 Properties of a good PCM

2.3.1 Limiting properties of PCM

Properties that limit the performance of PCM are:

- Hysteresis
- Incongruent melting
- Super- cooling

Hysteresis is a limitation of all PCMs generally whereas incongruent melting and super-cooling is a limitation particular to inorganic PCMs.

2.3.1.1 Hysteresis

Hysteresis is experienced during night time if temperatures are not cool enough for solidification (Bony and Citherlet, 2007). PCM forfeit a part of their characteristic heat storage capacity after a few consecutive hot days, if they cannot be sufficiently discharged. Efficient night cooling can counteract such effects (Conrad Voelker, 2007).

Hysteresis seen graphically is a simple shift of the enthalpy curve according to a differential temperature defined with one parameter as shown in Figure 2-3.

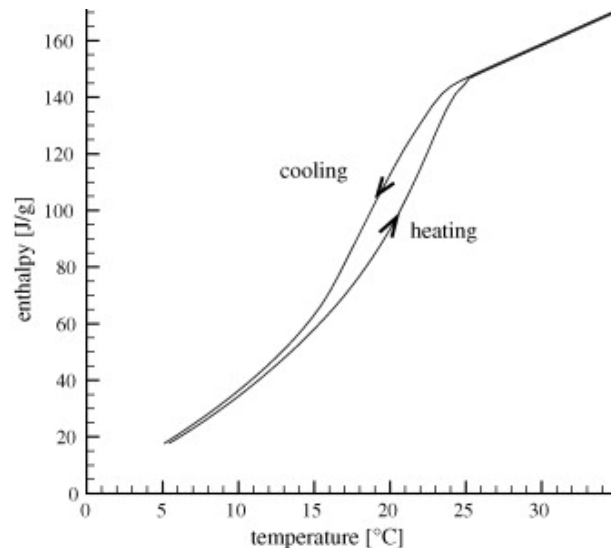


Figure 2-3 Enthalpy of PCM composite showing hysteresis (Kuznik and Virgone, 2009b)

2.3.1.2 Incongruent melting

Incongruent melting occurs when the PCM particles are not entirely soluble in its water of hydration at the melting point. Due to density difference, the lower hydrate settles down at the bottom of the container. This result in an irreversible melting/freezing of the particle which goes on decreasing in quantity with each cycle. The problem of incongruent melting can be tackled by mechanical stirring, encapsulating the PCM to reduce separation, adding thickening agents which prevent setting of the solid salts by holding it in suspension, use of excess of water so that melted crystals do not produce supersaturated solution and modifying the chemical composition of the system.

2.3.1.3 Super-cooling

Super-cooling according to Gunther et al. (2007) can badly affect storage performance. When a molten PCM is cooled below its melting temperature, it usually starts solidifying. However, in some cases, the solidification is inhibited and initiated only at a lower temperature, called nucleation temperature. Fang and Medina (2009) report that when the temperature reaches a value low enough, the PCM's solidification process will be suddenly triggered by some disturbance from the environment resulting in a large

amount of heat suddenly released at that moment. Between the melting temperature and the nucleation temperature, the PCM is in a metastable sub-cooled state.

Super-cooling results in a delay of the phase change as shown in Figure 2-4 and should be considered during thermal calculations for PCM to achieve optimum results (Kuznik and Virgone, 2009b).

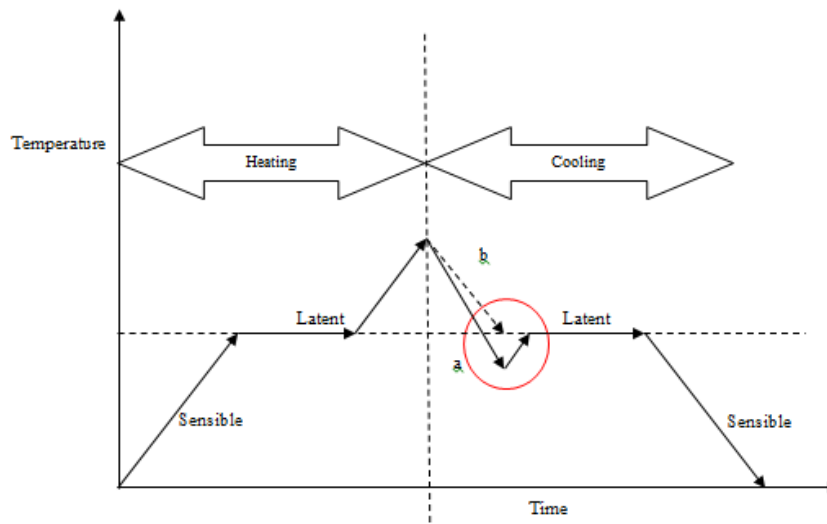


Figure 2-4 Super-cooling

A solution to the super-cooling problem is to add a nucleating agent; which provides nucleation in which solidification crystal formation is initiated. Another possibility is to retain some crystals, in a small cold region, to serve as nuclei.

2.3.2 Thermo-physical properties

This section describes thermo-physical properties of PCM that affect its performance in building applications. They are:

- Phase transition
- Transition temperature
- Thickness
- Conductivity
- Other thermo-physical properties

2.3.2.1 Phase transition

As has been mentioned, PCMs have the ability to change phase while absorbing and releasing energy. According to Agyenim *et al.* (2011) PCMs have this ability through:

- I. Sensible Heat Storage (SHS)
- II. Latent Heat Storage (LHS)

The two phenomena are shown in Figure 2-5.

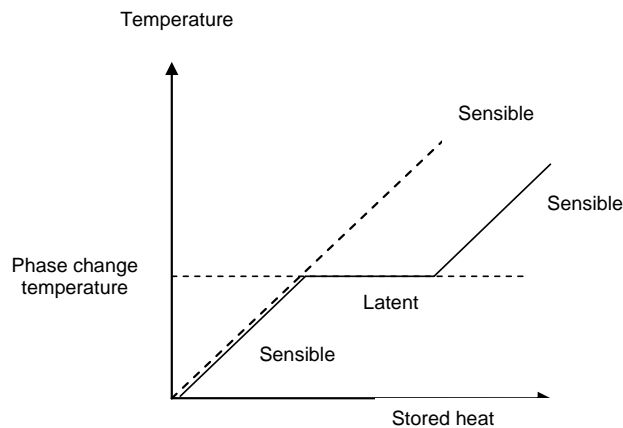


Figure 2-5 Sensible and latent heat

Another type of energy storage is through thermo-chemical systems. These systems rely on the energy absorbed and released in breaking and reforming molecular bonds in a completely reversible chemical reaction. Thermo-chemical energy storage has not as yet been used in practical applications and both technical and economical questions have yet to be answered for some of the possibilities proposed (Atul Sharma, 2009).

I. Sensible Heat Storage (SHS)

Sensible Heat Systems (SHS) store energy by raising the temperature of a solid or liquid. SHS systems utilize the heat capacity and the change in temperature of the material during the process of heating and cooling. The amount of heat stored depends on the specific heat of the medium, the temperature change and the amount of storage material.

II. Latent Heat Storage (LHS)

Latent Heat Storage (LHS) is based on the heat absorption or release when a storage material undergoes a phase change. Phase change can be in the following form: solid–solid, solid–liquid, solid–gas, liquid–gas and vice versa. In solid–solid transitions, heat is stored as the material is transformed from one crystalline to another. Solid–solid

PCMs offer the advantages of less stringent container requirements and greater design flexibility. These transitions generally have small latent heat and small volume changes than solid–liquid transitions. Solid–gas and liquid–gas transition have higher latent heat of phase transition but their large volume changes on phase transition are associated with the containment problems and rule out their potential utility in thermal-storage systems. Large changes in volume make the system complex and impractical. Solid–liquid transformations have comparatively smaller latent heat than liquid–gas. However, these transformations involve only a small change (of order of 10% or less) in volume. Solid–liquid transitions have proved to be economically attractive for use in thermal energy storage systems.

Initially, solid–liquid PCMs perform like conventional storage materials; their temperature rises as they absorb heat. As the temperature reaches the PCM's melting point, it changes phase from solid to liquid. At the range of phase change, the temperature does not increase even though they continue to absorb heat. This process is reversed when the heat is removed. Due to the regulation in temperature, PCMs store 5 to 14 times more heat per unit volume than sensible storage materials such as water, masonry, or rock (Atul Sharma, 2009). Tay *et al.* (2012) recently formulated a new measure called the effectiveness-NTU model to calculate the efficiency of PCM and claim it can be as high as 18 times more than ordinary building materials. Figure 2-5 illustrates sensible and latent heat in respect to stored heat and temperature.

Latent heat thermal energy storage is principally attractive due to its ability to provide high-energy storage density and its characteristics to store heat at a small volume change, usually less than 10%. If the container can fit this volume change, then pressure remains constant and consequently the phase change proceeds at a constant temperature corresponding to the phase-transition temperature of PCM (Mehling *et al.*, 2008; Atul Sharma, 2009). They can either capture solar energy directly or thermal energy through natural convection.

2.3.2.2 Transition temperature

Transition temperature ranks 1st in thermo-physical properties studied in PCM literature. As a mark of the importance of this variable, Farid *et al.* (2004) advises that PCMs should be selected, first based on their transition temperature. It is the study of the temperature at which PCMs change state.

Mehling *et al.* (2008b) reports that use of PCM in building applications may be for storage and supply or temperature control. A different transition temperature needs to be

optimized for storage compared to temperature control. The focus for storage and supply is the amount of heat or cool stored and supplied when needed with small temperature change. In applications for temperature control, the focus is on temperature regulation. Two forms of regulation exist in the specification of transition temperature of the PCM to be used for temperature control:

1. The PCM with a melting range at the average room temperature generally buffers temperature fluctuations. This view is corroborated by Xu *et al.* (2005).
2. The PCM with a higher transition temperature than the average temperature reduces temperature peaks. In this case the PCM disallows the temperature increase or drop above a specified mark.

In a hot climate like Nigeria the latter option is preferable to reduce high temperatures. Xiao *et al.* (2009) optimized PCM for energy storage in a passive solar room using a simplified analytic model. The variables examined are the optimal transition temperature, the latent heat capacity to estimate the benefit of the interior PCM for energy storage in Beijing- a humid continental climate. PCM panels were incorporated into the interior surfaces of partition walls, floor and ceiling. The following conclusions are made:

- The equation of the optimal transition temperature, T_m of interior PCM in a lightweight passive solar room is obtained as Equation 2-1:

$$T_m = T_a + \frac{(Q_r + Q_{r\ in})}{h_{in} \cdot P \cdot A} \quad \text{Equation 2-1}$$

Where T_a is the average room temperature, Q_r is the transmitted solar radiation on the interior surfaces (W), $Q_{r,in}$ is the radiation heat transfer rate from indoor heat sources (W), h_{in} is the heat transfer coefficient of interior surface ($\text{W m}^{-2} \text{ } ^\circ\text{C}^{-1}$), P are the duration (s) and A_{in} is the area of interior PCM panel (m^2)

This formulae indicates that the optimal transition temperature depends on the average indoor air temperature and the amount of radiant energy absorbed by the PCM panels from solar and casual gains.

2.3.2.3 Thickness

The thickness of a chosen PCM product affects heat flux through the PCM. This is important because the performance of PCMs are based on effective melting and

solidification (Kuznik *et al.*, 2008a). This indicates that the thickness and conductivity are closely linked in the optimization of performance of a given PCM.

The study of the thickness of PCM is based on thermal capacity. Thermal capacity is the ability of a material to store sensible heat depending on the density, specific heat capacity and thermal conductivity of the material. Based on thermal capacity, building construction may be classified into:

- I. Lightweight
- II. Heavyweight

I. Lightweight buildings: Generally, lightweight buildings are made with timber frame and similar light in-fill panels. Conventional wallboard provides little thermal mass (Richardson and Woods, 2008) however when PCM is added to it, the large latent heat attributed to adding PCM to walls is sufficient to reduce interior wall surface temperature fluctuations to just 8% of that of the exterior air.

II. Heavyweight building: On the extreme end heavyweight buildings are made of dense concrete block inner leaf and partitions, with precast concrete and stone tiles to the solid concrete ground floor that supply thermal mass. The structural thermal performance of buildings with thermal mass walls would dominate, and PCM needs to be applied only in a thin interior facing layer to achieve the thermal benefits

Richardson and Woods (2008) analytically show the relationship between PCM performance and amount of PCM or thickness of PCM product. They held the temperature at a constant comfort level thereby establishing a useful basis for comparing the performance of thermal mass with different amounts of PCMs in walls. The study shows that as the amount of PCM increases, PCM performance improves. To be effective the surface of the PCM must be sufficiently exposed to allow heat transfer. The larger the amount of these materials that are exposed to the internal environment in a building, the greater the benefits in thermal mass. However, there exists a limit beyond which the structural integrity of the wall fails. PCM thickness that achieves only partial melting at the interior side is more effective at anchoring surface temperatures to the building thermal capacity rather than the interior air temperature of the building. The study concludes that thickness for both PCM should be sufficiently large, such that heat movement cannot reach the interior side of the wall. PCM latent heat and thickness

should be as high as structural integrity and cost permit; until it reaches a critical point where as more of the latent heat cannot be accessed.

In another study, Xu *et al.* (2005) using analytic calculations validated, with an experimental cabin the PCM built in Tsinghua University of Beijing concludes that the thickness of PCM used for floor temperature regulations should not be larger than 20mm . The heat of fusion and the thermal conductivity of PCM should be larger than 120 kJ kg and 0.5 W/m K, respectively. The values for heat of fusion and conductivity are in agreement with the work of Zhang *et al.* (2006).

Zalba *et al.* (2004) design, construct and run an experimental air-conditioning system to study PCMs and report that PCM of 25 mm thickness is suitable with solidification average time of 6.5 hours, and melting average time of 9 hours. An increase of thickness means an increase in the duration of the solidification process, but the effect of the temperature is higher when the thickness of the PCM is also higher. This means that in climatic areas with a night temperature of about 16 °C an increase in thickness would be more efficient, while in areas with an average night temperature of 18 °C, an increase in the thickness of the PCM could endanger the viability of the system. In the melting process, an increase of PCM thickness is more critical at low temperatures, and an increase in temperature is more critical with higher thickness of the PCM. This means, that with applications where the inlet temperature of the air is about 28 °C, an increase in PCM thickness could delay substantially the melting process, while in situations where the inlet temperature is about 30 °C, the increase in time of the melting process would be not so important.

It is apparent from the works by Xu *et al.* (2005) and Zalba *et al.* (2004) that the optimal thickness of any PCM wall depends variables such as the properties of the PCM, the type of construction, application and the climate.

2.3.2.4 Conductivity

Generally, PCMs have low levels of thermal conductivity (Atul Sharma, 2009). Due to their low heat conductivity, PCM in thick layers within the building fabrics may not melt or solidify completely by diurnal temperature variations alone. Thus, there can be sufficient energy stored but insufficient capacity to dispose of this energy quickly enough (Belen Zalba, 2003). To counteract this negative feature, the systems are enhanced with mostly metallic fins, matrices, tubes, encapsulation, carbon brushes, graphite flakes; and placed in a combination of tube and shell or rectangular

containment systems (Agyenim *et al.*, 2011). However, in some cases of thermal protection or insulation, it is appropriate to have low conductivity values.

On-going research is being conducted to evaluate the performance of copper foam enhanced PCM building fabric of a model of terrace houses in hot and humid Malaysia in a climatic laboratory chamber (Isa *et al.*, 2010). The integration of copper foam with microencapsulated PCM is hypothesized to cause an increase in heat transfer that will increase heat storage capacity and reduce internal temperature fluctuations compared with other materials. This is because the diurnal temperatures in such climates have little variation and is assumed that night temperatures will not be low enough to solidify the PCMs passively. The distribution of the small PCM microcapsules in a wall offers a larger heat exchange surface where the heat transfer rate to store and release heat is raised significantly. PCM in copper coating is utilized in this study (see Figure 2-6) because the PCM melts faster than with coatings such as acrylic and aluminium.

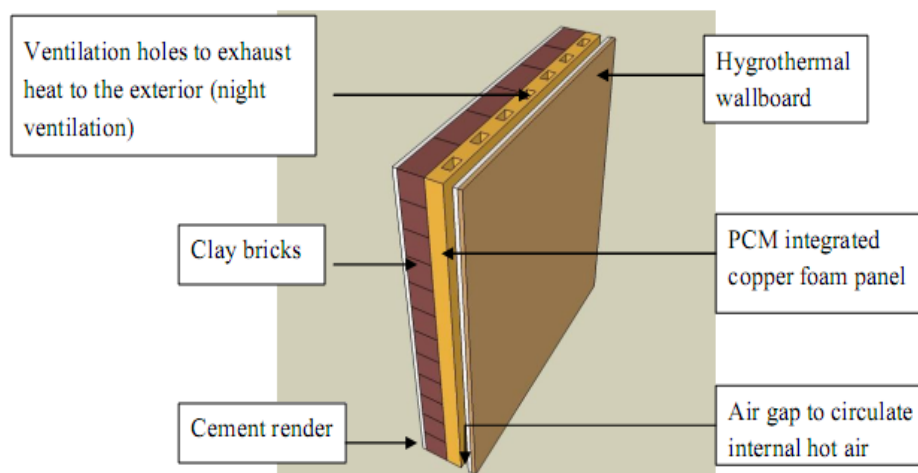


Figure 2-6 Walling system with copper foam integrated PCM panelling and ventilation holes (Isa *et al.*, 2010)

A building model measuring 3.0 m in depth, width, and height was built and the panel installed directly onto the interior surface of the brick wall, in a climate chamber. All the materials used are the exact same materials of a typical terrace house. One side of the wall was installed with copper foam integrated panels and the other three walls with insulation material to imitate connected terrace houses; and the façades installed with insulation materials will be considered as internal partitions of the house as shown in Figure 2-7.

Two ventilation strategies are explored and shown in Figure 2-8. The ventilation systems are:

- To circulate air, warmed and raised to the top part of the interior into the air gap between the copper foam integrated PCM panels and the wallboard using a ventilation fan, to reduce the air temperature. This cooler air will be ventilated back to the internal space through openings at the bottom of the internal wallboard



Figure 2-7 Walling system - wallboard finishing (Isa *et al.*, 2010)

- To use night cooling, by circulating air into the ventilation openings at the bottom of the external wall. The air then moves into the ventilation holes of the copper foam integrated PCM panel and out through the ventilation holes and openings located in the top part of the external wall. Heat stored during the day will be discharged back into the environment that will reduce the temperature of the copper foam integrated PCM panels rapidly, and the PCM will reverse the phase transition from liquid back to a solid ready to store heat the next day

The preliminary results showed:

- Smaller PCM encapsulates, leading to larger surface areas, in the wall perform better than that of bigger ones

- Force ventilation is required in tropical climates due to a low diurnal variance in temperature
- A panel-type installation is better than direct integration of PCM into the building structure

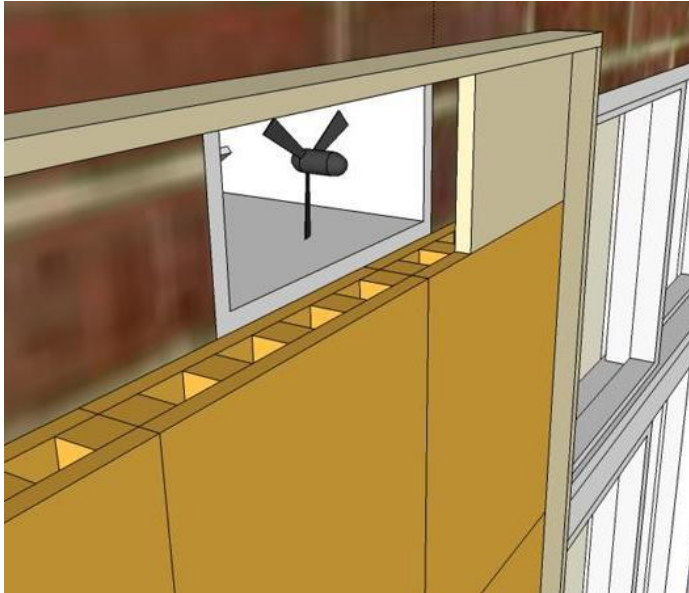


Figure 2-8 Forced ventilation for PCM layer (Isa *et al.*, 2010)

It should be noted that this study is on-going so measured or predicted results are yet to be published.

Zhou *et al.*(2007), also examine the effects on room air temperature of conductivity, and results show that conductivity has an effect on indoor temperature only in the solidification process. Above $0.5\text{Wm}^{\circ}\text{C}$, the conductivity has no obvious influence for both melting and solidification processes. Therefore, in hypothetical studies, the use of $0.5\text{Wm}^{\circ}\text{C}$ conductivity is adequate for successful PCM performance. This value is agreed on by Xu *et al.* (2005).

2.3.2.5 Other thermo-physical variables

Combinations of other thermo-physical properties have been extensively reviewed in literature. They include:

- Enthalpy/temperature relationship
- Latent heat
- Position

- Transition time
- Density

The thermo-physical properties of PCM are significantly correlated to one another. For instance the performance of a certain thickness of PCM product is affected by its latent heat capacity, conductivity and climate. A large surface area increases the melting and solidification rate of PCM panels. The temperature amplitude decreases with the increase of heat transfer coefficient and surface area of the PCM panels. Human thermal comfort decreases with increase in temperature amplitude. (Zhou *et al.*, 2008; Xiao *et al.*, 2009; Isa *et al.*, 2010).

The thermo-physical properties of PCM are therefore complex variables that need to be optimized depending on other variables. The need for a critical examination of the effect of the thermo-physical properties of the PCM based on application is apparent for its successful performance.

2.3.3 Chemical classification of PCM

Chemically, PCM are classified as organic, inorganic and a combination of the two, known as eutectic compounds (Farid *et al.*, 2004). Figure 2-9 shows the different types of organic, inorganic and eutectic PCMs. The properties of inorganic and organic PCMs are shown in Table 2-5.

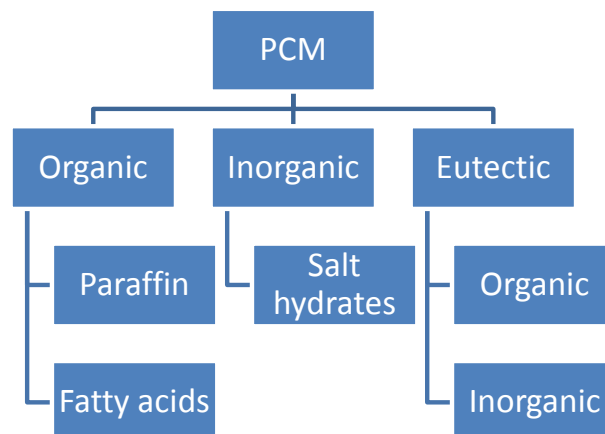


Figure 2-9 Chemical classification of PCM (Pasupathy *et al.*, 2008a)

Although PCMs are made of different chemical content, two studies (Ahmet, 2005 and Diaconu and Cruceru, 2010) found in literature indicate the possibility of combining

different PCMs to achieve the properties of a required PCM product. This is desirable for hypothetical studies or computer simulations aimed at optimizing the properties of PCMs in a given context. Such studies will not be limited to existing PCM products as any combination of thermo-physical properties can be created.

Classification	Inorganic	Organic
Category	Crystalline hydrate, molten salt, metal or alloy	Paraffin wax, non-paraffin wax, high aliphatic carbon, acid/esters or salts, alcohols, aromatic hydrocarbons, aromatic ketone, lactam, Freon, multicarbonated category, polymers
Advantages	Higher energy density storage, higher thermal conductivity, non-flammable, inexpensive	Physical and chemical stability, good thermal behaviour, adjustable transmission zone
Disadvantages	Super-cooling, incongruent melting, corrosion	Low thermal conductivity, low density, low melting point, volatile, flammable, volume change
Improvement	Mixed with nucleating and thickening additives for super-cooling, thin layers for conductivity, mechanical stir for incongruent melting	Conductivity enhancements, fire-retardant additives

Table 2-5 Properties of organic and inorganic PCMs

2.3.3.1 Organic materials

Organic PCMs have a number of characteristics which render them useful for latent heat storage in building elements. They are more chemically stable than inorganic PCM, they do not exhibit incongruently melting or super-cooling Although the initial cost of

organic PCMs is higher than that of the inorganic type, the life cycle cost is competitive (Kelly, 2010). However, organic materials have significant disadvantageous characteristics; they are flammable and they may generate harmful fumes on combustion. Table 2-6 shows the melting point and heat of fusion of some organic PCMs.

PCM	Melting Point (°C)	Heat of Fusion (kJ/kg)
CH ₃ (CH ₂) ₁₆ COO(CH ₂) ₃ CH ₃ Butyl stearate	19	140
CH ₃ (CH ₂) ₁₁ OH 1-dodecanol	26	200
CH ₃ (CH ₂) ₁₂ OH 1-tetradecanol	38	205
CH ₃ (CH ₂) _n (CH ₃ .. Paraffin	20-60	200
45% CH ₃ (CH ₂) ₈ COOH, 55% CH ₃ (CH ₂) ₁₀ COOH, 45/55 capric-lauric acid	21	143
CH ₃ (CH ₂) ₁₂ COOC ₃ H ₇ Propyl palmitate	19	186

Table 2-6 Organic PCM and properties Feldman et al. 1993 in (Kelly, 2010)

Other problems, which can arise are adverse reaction of PCM with concrete, thermal oxidative ageing, odour and an appreciable volume change. Appropriate selection and modification have now eliminated many of these undesirable characteristics. It has been found that the thermal oxidative ageing of PCMs concerned can be inhibited by the use of a proper antioxidant. Organic materials are further classified into:

- I. Paraffin
 - II. Non-paraffin
- I. Paraffin:** Paraffin wax consists of a mixture of mostly straight chain *n*-alkanes CH₃–(CH₂)–CH₃ (Kelly, 2010). The crystallization of the (CH₂)-chain release a large amount of latent heat. Both the melting point and latent heat of fusion increase with chain length. Paraffin is safe, reliable, predictable, less expensive and non-corrosive. They are chemically inert and stable below 500°C. They show little volume changes on melting and have low vapour pressure in the melt form. Systems using paraffin usually have very long freeze–melt cycle. Other

favourable characteristics of paraffin are congruent melting and good nucleating properties.

Paraffin PCMs show some undesirable properties such as low thermal conductivity, incompatibility with plastic containers and are moderately flammable. All these undesirable effects can be partly eliminated by slightly modifying the wax and the storage unit.

Paraffin PCMs exhibit a wider melting range compared to inorganic PCMs which have a narrow phase change zone conclude Kuznik and Virgone (2009b) when testing the commercial product, Energain by the Dupont de Nemours Society. It is constituted of 60% of microencapsulated paraffin within a copolymer. Three different external climates are tested to evaluate the potential of the PCM wallboards in summer, mid-season and winter cases. Including the PCM wallboard reduces the air temperature fluctuations in the room. The wall surface temperatures fluctuations are also reduced. The wall surface temperature is lower when using PCM wallboard, then the thermal comfort is enhanced by radiative heat transfer. The natural convection mixing of the air is also enhanced by PCM material, avoiding uncomfortable thermal stratifications.

- II.** Non-paraffin: Each of the non-paraffin organic materials has differing properties unlike the paraffin. A number of esters, fatty acids, alcohols and glycols are suitable for energy storage. These materials are flammable, have high heat of fusion, low thermal conductivity, low flash points, varying level of toxicity, and instability at high temperatures.

2.3.3.2 Inorganic materials

Inorganic materials are further classified as salt hydrates and metallics. They cover a wide range of temperatures, and due to their high densities have similar melting enthalpies per mass but higher ones per volume than organic PCMs (Gunther *et al.*, 2007). Their heats of fusion do not degrade with cycling.

I. Salt hydrates

Salt hydrates are the most important group of PCMs, which have been extensively studied for their use in latent heat thermal energy storage systems in earlier studies (Gunther *et al.*, 2007). They are alloys of inorganic salts and water forming a typical crystalline solid of general formula $AB \cdot nH_2O$. The most attractive properties of salt hydrates are high latent heat of fusion per unit volume, relatively high thermal conductivity and subject to small volume changes on melting. Salt hydrates are

compatible with plastics. Many salt hydrates are sufficiently inexpensive for the use in storage and are only slightly toxic (Gunther *et al.*, 2007).

Limitations of most salt hydrates are incongruent melting and poor nucleating properties resulting in super-cooling of the liquid before crystallization begins. Their main disadvantage is material incompatibility with metals by corroding.

Voelker *et al.* (2008) conducts a study using both paraffin and salt hydrates. The integrated PCM is microencapsulated paraffin with a diameter of approximately 5 μm and has a transition range of between 25°C and 28°C. The salt hydrate is calcium chloride hexahydrate. Its transition range is reduced (with additives sodium chloride and potassium chloride) from 23°C and 27°C to 25.5°C and 27.0°C. Two identical test rooms were built in the temperate climate of Weimar, Germany using lightweight building construction. The rooms are plastered with the modified paraffin and conventional gypsum plaster respectively. The thickness of the plaster coating was 1 cm in the beginning and later increased to about 3 cm. Additional tubes filled with a modified calcium chloride hexahydrate were introduced to improve the thermal effect in the PCM-conditioned room. The salt mixture was filled in six PVC tubes with a diameter of 63 mm and a length of 1.0 m underneath the ceiling. A PVC plug sealed each end of the tubes. During warm days a reduction of the peak temperature of about 3°C in comparison to the room without PCM can be achieved. Insufficient night time cooling (solidification) of the PCM as a result of high indoor temperatures (melting) or high solar radiation during the day can limit the functionality of the PCM, see Figure 2-10. This phenomenon is known as hysteresis. The salt hydrate also shows a super-cooling of up to 10 K, so a nucleator was needed to produce an applicable PCM.

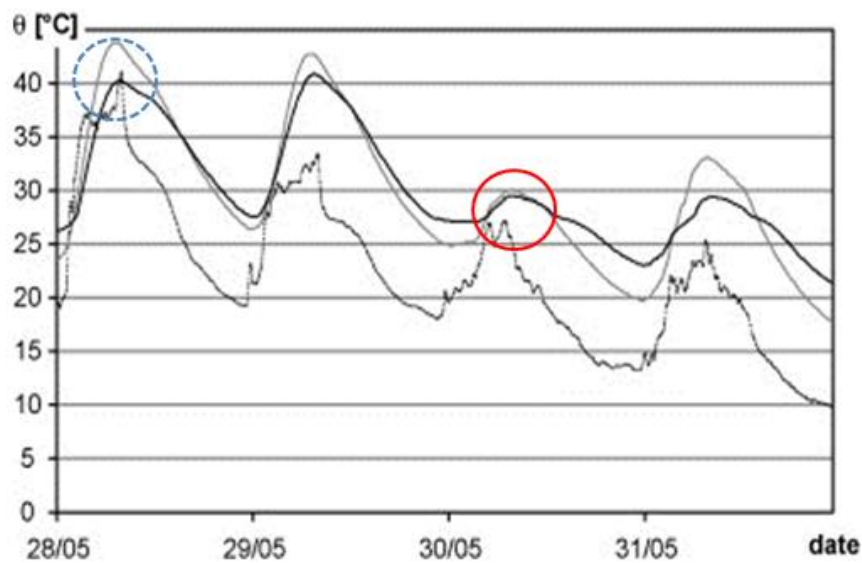


Figure 2-10 PCM limited by incomplete charge/discharge: air temperature (grey without PCM, black with PCM), ambient temperature (dotted) from Voelker. *et al* (2008). The dashed circle shows a functioning cycle, while the line circle shows the decrease in function due to hysteresis

A numerical study is conducted on a room with a heavyweight thermal storage wall (Khalifa and Abbas, 2009). The PCMs used are hydrated salt and paraffin wax. The room temperature fluctuation in the zone is evaluated for each material using different thickness for each wall. The west, east and north walls were constructed with brick and concrete, the floor was made of concrete, and the roof constructed of layers of concert, asphalt and soil. The hydrated salt and paraffin wax are encapsulated in copper capsules with length to diameter ratio of 0.76. The capsules were arranged in a staggered manner in the direction of wall thickness (i.e. the length of the capsule equals the thickness of the wall). It is found from the numerical simulation that a storage wall 0.08-m-thick made from the hydrated salt maintained the zone temperature close to the comfort temperature with the least room temperature fluctuation compared to the 0.02-m-thick concrete wall and the 0.05-m-thick wall made from paraffin wax. However, it is not clear why these wall thicknesses were chosen. The performance comparability of walls of different properties is questionable when thermo-physical variables including heat capacity, latent heat of fusion are different. The study concludes that an 8-cm-thick

storage wall made from the hydrated salt is capable of maintaining the comfort temperature in the zone with the least room temperature fluctuation.

2.3.3.2.1 *Metallic inorganic PCM*

Metals have not yet been seriously considered for PCM technology because of a weight penalty. However, when volume is a consideration, they are likely candidates because of the high heat of fusion per unit volume and high thermal conductivities. An example of metallic PCM used in satellites is germanium contained in modular graphite canisters (Lauf and Hamby, 1990). Another is sodium as used in (Bellettre *et al.*, 2004). The use of metals poses a number of unusual engineering problems. A major difference between the metals and other PCMs is their high thermal conductivity. Some of the features of metallic materials include low heat of fusion per unit weight, high heat of fusion per unit volume, high thermal conductivity, low specific heat and relatively low vapour pressure.

2.3.3.3 *Eutectics*

A eutectic is a composition of two or more components, which melt and freeze congruently forming a mixture of component crystals during crystallization. Eutectics nearly always melt and freeze without segregation since they solidify to an intimate mixture of crystals, leaving little opportunity for the components to separate. A combination of organic PCM may be tailored as new PCMs, with almost any suitable melting point for specific climate requirements (Ahmet, 2005; Diaconu and Cruceru, 2010). As earlier mentioned, this is desirable in cases where hypothetical thermo-physical properties are being examined in the absence of suitable commercial products. Lauric acid (LA, 98% pure), palmitic acid (PA, 96% pure), stearic acid (SA, 97% pure) and myristic acid (MA, 97% pure) are used in preparation of eutectic mixtures while taking into consideration the advantageous characteristics of fatty acids by Ahmet, (2005). A series of combination of two systems of LA–MA, LA–PA, and MA–SA in different combinations were prepared from the liquid mixtures by slow cooling to room temperature in order to determine their eutectic mixture ratio. It can be concluded from the DSC thermal analysis that the LA–MA, LA–PA, and MA–SA eutectic mixtures are promising PCMs for heat storage in passive solar heating systems with melting temperatures of 34.2, 35.2, and 44.1 °C and the latent heats of fusion of 166.8, 166.3 and 182.4 J g⁻¹ respectively. With the increasing number of thermal cycle, the changes in the melting temperatures and the latent heats of fusion of these materials are

irregular, but are at a reasonable level for a four-year energy storage period, which corresponds to 1460 thermal cycles.

2.4 Application of PCMs

The literature on applications of PCMs examines the ways PCM are incorporated into the fabric and the components of buildings. Zhu *et al.* (2010) report that the successful use of PCMs in buildings depends on amount of PCM, the encapsulation method, the location of PCMs in building structure, equipment design and selection, utility rate policy, occupancy schedule, system control and operation, design, orientation of the construction of the building and cost.

It should be noted that cost is a factor limiting the uptake of PCMs (Mehling *et al.*, 2008a and Kelly, 2010). Although cost is a variable in applications of PCMs (Mehling *et al.*, 2008a and Kelly, 2010), it has been overlooked in this research. The effect of cost in hypothetical studies aimed at optimizing thermo-physical properties may be considered negligible. The importance of cost increases as the PCM study moves towards field or commercial applications.

As earlier established, PCM performance requires the complex balance of the PCMs' properties and application. Within the studies reviewed, PCMs application is studied twice as much as its properties. The most highly ranked variables studied are methods of containment, building incorporation, climate and building energy calculations.

2.4.1 Method of containment and incorporation of PCM

PCM are contained and/or incorporated into building fabric in the following ways:

- Immersion
- Direct incorporation
- Encapsulation
- Shape-stabilized PCM

The nature of incorporation affects the amount of PCM that can be added to the building. However, the impact of the nature of PCM incorporation on a hypothetical evaluation is negligible as long as the thermo-physical properties required are achieved.

2.4.1.1 Immersion

Immersion is a basic method of incorporating PCM in building facades (Feldman *et al.*, 1995). It is the process of impregnating PCMs by dipping a porous building finishing product into liquid PCM. This is possible at practically any time and place. Immersion

technique however decreases the permeability of the wall, thus creating indoor humidity problems (Zhang *et al.*, 2005). Furthermore, PCMs drip when they melt and are flammable.

2.4.1.2 Direct incorporation

PCM composite walling material such as PCM-gypsum board and PCM-concrete are prepared by direct incorporation. This process is similar to immersion except that the impregnation occurs at the mixing stage of industrial production. This is a progression from immersion technique and its great advantage is that it enables conversion of ordinary materials such as wallboard to PCM wallboard. Conventional wallboards require very little additional process equipment; almost no additional labour is involved; and existing production facilities can be easily modified to produce PCM wallboards. By this method, PCM wallboard production can also enjoy the economic benefits of continuous processing. The same is true for PCM concrete. However, Zhu *et al.*, (2010) reports that to maintain the fabrics' structural integrity, only 20-30% by mass percentage of PCM only should be added.

If the external wall of the building is constructed from PCM concrete blocks, a thermal storage capacity approximately four times that of the energy-storing wallboard can be achieved (Kelly, 2010). In certain applications, the circumstances of climate, application and temperature of thermal energy acquisition could warrant the combined use of PCM wallboard and PCM concrete. An example of this would be PCM wallboard for short-term diurnal storage to reduce equipment cycling and peak energy demand while PCM concrete could be used in conjunction with an alternative energy source to reduce fuel consumption and sustain the more even time-load characteristic.

Placing the PCM in contact with the interior face of the interior sheathing improves the rate of solidification of the PCM compared to when the pipes were placed in the middle of the insulation or in contact with the outer sheathing layer (Zhang, 2004).

Over a long period of time, leakage may become a problem for immersion and direct incorporation methods; which then further reduces the amount of PCM in the wallboard. Direct incorporation methods negatively affect heat transfer during energy recovery and reduction in overall thermal conductivities (Zhou *et al.*, 2007). To check these limitations, encapsulation is required.

2.4.1.3 Encapsulation

Encapsulation is the containment of PCM within a capsule of various materials, forms and sizes prior to incorporation so that it may be introduced to the mix more conveniently than immersion and direct corporation. PCM must be encapsulated so that it does not adversely affect the function of the construction material. There are three principal means of encapsulation:

- I. Macro- encapsulation
- II. Micro – encapsulation
- III. Shape stabilized PCM (SSPCM)

I. Macro-encapsulation

This is the containment of PCMs in such forms of packaging as tubes, pouches, spheres and panels. These containers can serve directly as heat exchangers or they can be incorporated in building products (Pasupathy *et al.*, 2008b; Khalifa and Abbas, 2009). In a study by Zhang *et al.*(2005), PCMs are contained in pipes capped at both ends to prevent leakage. The containers are assembled within the wall and held in place by brackets attached to the sides of the studs preventing the drilling of holes which could otherwise reduce their structural integrity. Macro encapsulation eliminated PCM dripping when the PCMs melted in the case of immersion and direct incorporation; reduced the flammability of the wall; eliminated the moisture transfer problem across the envelope; eliminated problems associated with contact between PCM and wall finishes and between PCM and people. In addition, problems associated with PCM volume changes during the phase change process were eliminated because the pipes are never completely filled with PCM.

A field experiment (Castell *et al.*, 2010) was conducted to test PCM with two heavyweight construction materials; conventional and alveolar brick for Mediterranean construction in Spain in real conditions. For each construction material, macro-encapsulated PCM is added in one cubicle (RT-27 and SP-25 A8) and a domestic heat pump is added as a cooling system. The results show lower peak temperatures of up to 1°C in both constructive typologies, but especially in the alveolar brick cubicle. Energy consumption during summer in cubicles with PCM was reduced by about 15% compared to the cubicles without PCM. Further research is required to see if recorded savings can be achieved in occupied buildings.

de Gracia *et al.* (2012) experimentally test the thermal performance of a ventilated double skin facade with PCM in its air channel, during the heating season in the Mediterranean climate under mechanical or natural ventilation mode. The experimental set-up consists of two identical cubicles differing by the incorporating of macro-encapsulated PCM in the fabric of one cubicle. The PCM used in this application is the macro-encapsulated salt hydrate SP-22 from Rubitherm. The ventilated double façade fabric acts as a solar collector during the solar absorption period, until the solar energy is demanded and can be discharged to the indoor environment. Results show that the use of the ventilated facade with PCM increases the temperature every day from 9°C to 18°C under severe winter conditions. It also reduces significantly the electrical energy consumptions of the installed HVAC systems. These savings depend strongly on the mode of operation and the weather conditions. The energy savings registered during the experiments under severe winter, being 19% and 26% depending on the HVAC set point (21°C and 19°C, respectively). Moreover, the passive experiments demonstrate that the use of HVAC system is almost not necessary during the mild winter period. The use of SP-22 as PCM provides less than desired thermal benefits in this system, since its transition temperature is too low for the season and climate being studied (20°C). Only a part of the stored latent heat is injected to the indoor environment in some of the operational strategies. Hence, the system may have a higher thermal capacity if the transition temperature were lower.

Some previous experiments with macro-encapsulated PCM in the building fabric failed due to the poor conductivity of the PCM (Castellón *et al.*, 2010). When it was time to regain the heat from the liquid phase, the PCM solidified around the edges and prevented effective heat transfer. The dimensions are so small in micro encapsulation that this effect is controlled.

II. Micro encapsulation

Micro encapsulation is a technology whereby small, spherical or rod-shaped particles are enclosed in a thin and high molecular weight polymeric film to produce capsules in the micrometer to millimeter range, known as microcapsules (see Figure 2-11). Plastic or metallic encapsulation of the PCM is expensive but safe, as the PCM is not in contact with the concrete. PCM in copper coating melts faster than with coatings such as acrylic and aluminium. All three states of matter (solids, liquids, and gases) may be microencapsulated.

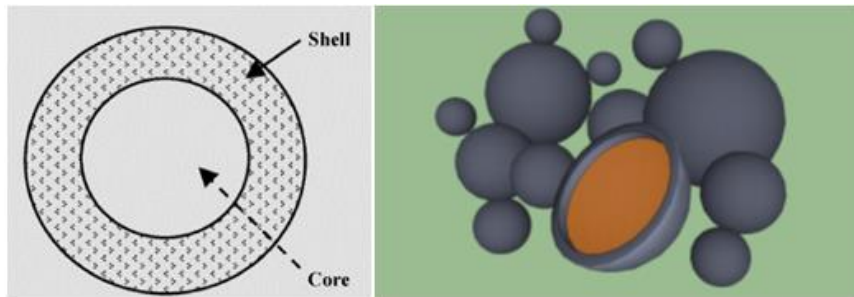


Figure 2-11 Microcapsule (Tyagi *et al.*, 2011) and sphere shaped microencapsulated PCM with polymer coating (Isa *et al.*, 2010).

Tyagi *et al.* (2011) reviewed PCM micro-encapsulation and concluded that it allows the PCM to be incorporated simply and economically into conventional construction materials, as liquid and gas phase materials can be handled more easily as solids. The most often used micro-encapsulation methods are:

1. Physical methods
 - a. Pan coating
 - b. Air-suspension coating
 - c. Centrifugal extrusion
 - d. Vibrational nozzle
 - e. Spray drying
2. Chemical methods
 - a. Interfacial polymerization,
 - b. In situ polymerization,
 - c. Matrix polymerization

The types of microcapsules as shown in Figure 2-12 are:

1. Mononuclear (core-shell) microcapsules contain the shell around the core
2. Polynuclear capsules have many cores enclosed within the shell
3. Matrix encapsulation in which the core material is distributed homogeneously into the shell material

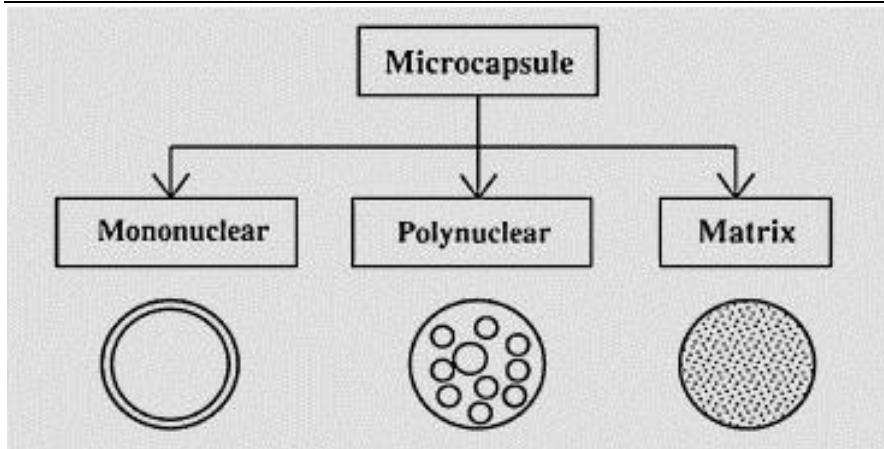


Figure 2-12 Types of microencapsulation (Tyagi *et al.*, 2011)

Micro encapsulation (Figure 2-11) by impregnating the PCM in the concrete is very effective, but may affect the mechanical strength of the concrete. Most of microencapsulated PCMs can undergo more than 10,000 phase transition cycles that make the product life span last for more than 30 years (Isa *et al.*, 2010). Nevertheless, the potential use of microencapsulated PCMs in various thermal control applications is limited, to some extent, by cost (Zalba *et al.*, 2003).

The possibility of using microencapsulated PCM in concrete is demonstrated without losing any of the concrete's initial characteristics while achieving high energy savings in cooling power (Cabeza *et al.*, 2007). An experiment consisting of two identically shaped cubicles of concrete, one with conventional concrete, and the other one with the modified concrete, called the Mopcon concrete was setup in the locality of Puigverd of Lleida, Spain as shown in Figure 2-13. The south, west and roof walls of the Mopcon cubicle contains about 5% in weight of phase change material mixed with the concrete. The dimensions of the cubicles are 2 m × 2 m × 3 m. The panels have a thickness of 0.0012m; the distribution of the windows is the following: one window of 1.7 m × 0.6 m at the east and west wall, four windows of 0.75 m × 0.4 m at the south wall and the door in the north wall. Since the effect of the PCM alone is tested, the cubicles are not insulated.



Figure 2-13 Cubicles testing Mopcon concrete

Results obtained during summer show that while the maximum ambient temperature was 31°C, the west wall of the cubicle without PCM reached 39°C, while that of PCM reached only 36°C, showing a difference of 3°C. The maximum temperature in the wall with PCM also shows a time-lag of 2 hours later when compared with the wall without PCM. This shows the thermal inertia of the PCM wall is higher. The minimum temperatures show a 2°C difference also, from 22°C to 20°C

III. Shape stabilized PCM (SSPCM)

Shape-stabilized PCM, SSPCM (also called form-stabilized PCM) are made of dispersed PCM encapsulated in macromolecule material, such as high-density polyethylene (HDPE) allowing the PCM to keep its shape when it undergoes phase change (Zalba *et al.*, 2003). The mass percentage of PCM in SSPCM can be as much as 80%. This is a significant difference from immersion and direct incorporation which can take only 20-30% mass percentage of PCM, to maintain the structural integrity of the building component. Also compared with conventional PCM, SSPCM reduce the danger of leakage. As long as the operating temperature of the PCM is below the melting point of the supporting material, the supporting material keeps its shape as PCM changes state. This allows the SSPCM to be used for thermal storage in buildings without encapsulation (Zhu *et al.*, 2010).

This material can be shaped into plates or added into concrete to be directly applied as floor or wallboard (Xu *et al.*, 2005). SSPCM plates respond more rapidly than the mixed type PCM impregnated gypsum and prove to be thermally more effective in terms of utilizing the latent heat.

Encapsulation, as highlighted earlier, is required to effectively store and release the latent heat of PCM. However, this increases not only the thermal resistance between PCM and the heat transfer fluid but also the capital cost of the system.

Li *et al.* (2009) also attempts to solve PCM leakage problems by micro-encapsulating paraffin and then blending with different supporting materials to prepare shape-stabilized Phase Change Materials, the encapsulation and low thermal conductivity problems of paraffin or other organic solid-liquid PCMs are expected to be well resolved simultaneously. High-density polyethylene HDPE/Wood Flour composite is a common wood-plastic composite that comprises mainly High Density Polyethylene (HDPE), Wood Flour (WF) and addition agents. In the study, six novel SSPCMs, which comprise micro-encapsulated paraffin as the latent heat storage medium and HDPE/WF composite as the matrix, were prepared by blending and compression molding method. To enhance the thermal conductivity, some Micro-mist Graphite (MMG), a kind of inorganic material with high thermal conductivity and good adhesive property, was added to the micro-encapsulated paraffin/HDPE/WF composite PCM. Micrographs taken on scanning electron microscope revealed that the SSPCMs have homogeneous constitution and most of micro-encapsulated paraffin particles in the composite PCMs were undamaged. Both the shell of micro-encapsulated paraffin and the matrix prevent molten paraffin from leaking. DSC results showed that the melting and freezing temperatures as well as latent heats of the prepared SSPCM are suitable for potential Latent Heat Thermal Energy Storage (LHTES) applications. Thermal cycling test showed that the shape stabilized composite PCMs are of good thermal stability although it was subjected to only a 100 melt-freeze cycling. The thermal conductivity of the composite PCM without MMG was increased by 17.7% by introducing 8.8 % in weight micro mist graphite. The results of mechanical property test indicated that the addition of MMG has no negative influence on the mechanical properties of form-stable composite PCMs.

2.4.2 Building component

During the 1980s, the first research on PCM integrated into building materials to solve the problems of thermal protection in summer was conducted (Hawes *et al.*, 1990). The building components in which PCMs can be incorporated include concrete walls, wallboard, floors, roofing and ceilings. PCMs incorporated within the building fabrics of a building affects indoor air and mean radiant surface temperatures.

2.4.2.1 PCM in Walls

Thermal energy storage requires large surface areas (Ortiz *et al.*, 2010). Walls provide the largest surface area compared to ceilings and floors. In the literature reviewed, the incorporation of PCM in walls ranks 1st out of floor, ceiling, roof and mechanical cooling system. However, some studies incorporate PCMs in a combination of the building components.

Kuznik and Virgone (2009a) argue that use of PCM are more advantageous in wall boards as opposed to dispersing them within concrete due to higher rates of impregnation in the former case. In the laboratory experiment, two identical test cells called MICROBAT are used to investigate the effects of the PCM wallboards.

MICROBAT boxes are named PCM and witness boxes respectively. PCM material, Energain1 manufactured by the Dupont de Nemours Society (2012) constituted of 60% of microencapsulated paraffin within a copolymer is used. The investigation concludes that an optimal use of the PCM requires a wall temperature above 22.3°C for energy storage process, and a wall temperature below 17.8°C for energy release process. The effects of PCM wallboard causes time lag between indoor and outdoor temperature evolutions and to reduce the internal temperature amplitude in the cell. A comparison between the cases with and without PCM shows that the more the thermal excitation is rapid, the more the PCM is efficient. The effect of hysteresis phenomenon has been clearly exhibited with the experimental data: the melting process rises at a temperature higher than for the solidification process. In retrofit situations, use of wall boards and other PCM enhanced finishes are the only options. This has been demonstrated to be beneficial for reducing peak loads as well as regulating temperature.

Zhou *et al.* (2007) compare the performance between mixed PCM-gypsum type composite and SSPCM plate on passive solar thermal storage and results, through simulation show they can reduce the indoor temperature swing by 46% and 56%, respectively. A south-facing middle room in a multi-layer building in Beijing, China, is

studied, which has only one exterior wall (the south wall). The exterior wall is externally insulated with 60mm-thick expanded polystyrene (EPS) board. There is a 2.1m × 1.5m double-glazed window in the south wall and a 0.9m × 2m wood door in the north wall which is adjacent to another room or the corridor. The floor is a wood floor with an air layer. PCM composite plates are attached to inner surfaces of four walls and the ceiling as linings. The two PCM composites considered are:

- 30 mm-thick mixed type PCM-gypsum, which is made up of one layer of gypsum and 25% by weight of PCM mixed together
- 30 mm-thick separate layers of 19 mm-thick gypsum and 11 mm-thick SSPCM (80% by weight of PCM)

Both samples contain the same amount of PCM and have the same thickness. The heat of fusion of the PCM is 150kJ/kg and the room air change per hour (ACH) is assumed to be 1.0 h⁻¹. The total indoor heat generation rate produced per day by; the equipment; lighting; and occupants etc. is assumed to be 50 W. The winter climate data is generated by the software Medpha (Meteorological Data producer for HVAC Analysis). The study further claims that SSPCM plates in storing and recovering heat respond in a more controlled temperature range than the mixed type PCM-gypsum - the surface temperature history for the case of SSPCM plates is flatter and controlled within the range of phase transition (20.5°C–21.5°C). At night, during heat recovery process the heat flux variation of the SSPCM plates respond faster and presents higher heat flux than the mixed type PCM-gypsum.

According to their findings, PCM composites with a narrow transition zone of 1 °C best reduce the indoor temperature swing and improve the thermal comfort. A wider phase transition zone provides poorer thermal performance due to the less energy storage. Zhou *et al.*(2007), also examine the effects on room air temperature of melting temperature, heat of fusion, thermal conductivity, inner surface convective heat transfer coefficient, location, thickness and wall structure of SSPCM. In each parametric analysis, only one specific parameter is changed, whereas others are kept constant when the simulation is carried out.

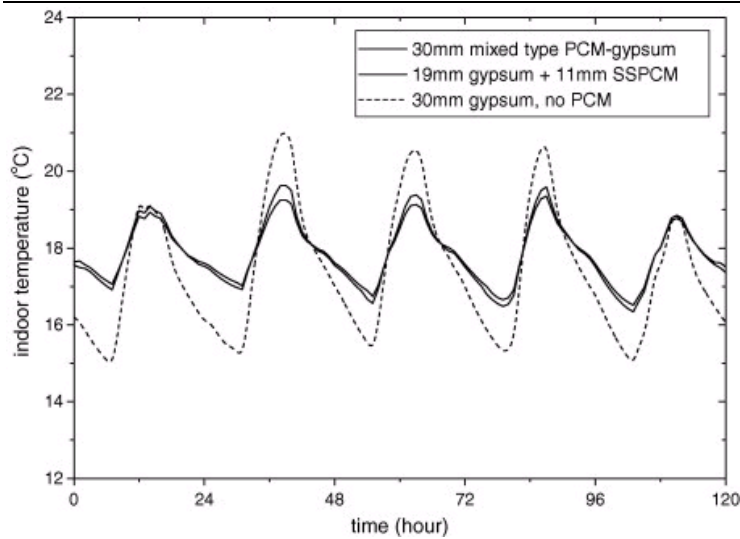


Figure 2-14 Effect of PCM of different transition temperature on indoor air temperature 14-16 November in Beijing, China (Zhou *et al.* 2007)

The results show that:

1. For the given conditions, the optimal melting temperature is about 20°C and the heat of fusion should be more than 90 kJ/kg
2. The inner surface convection, rather than the internal conduction resistance of SSPCM, limits the latent thermal storage. Higher convective heat transfer coefficient improves the indoor temperature level due to the fact that the increased convection enhances the exchange of energy between the SSPCM plates and the air
3. Thermal conductivity has an effect PCM performance only in the solidification process. In both the melting and solidification process, once thermal conductivity is above 0.5Wm^oC, no obvious influence appears on PCM performance
4. The effect of PCM plates located at the inner surface of interior wall is superior to that of exterior wall. It is seen that SSPCM plates located on the south wall or the floor are unfavourable in the context of this experiment. This is because south wall is the exterior wall for which the inner surface temperature is lower than that of interior walls such as the west, east, north and ceiling. Also, the net area of the south wall is smaller due to the large window included. These two aspects decreased the heat flow rate from the SSPCM plates to the indoor air at

- night time. For the case of the floor, the heat resistance of the wood board and the air layer may account for the lower value of temperature difference since the SSPCM plates can only be placed under the wood board for practical consideration
5. Insulating the exterior wall influences the performance of the SSPCM plates and the indoor temperature in winter. If the wall is not externally insulated, the indoor temperature during the considered period would be too low and that would keep the PCM plate in full solid state without phase transition functioning just as insulation. This confirms the importance of external thermal insulation
 6. The SSPCM plates create a heavyweight response to lightweight constructions with an increase of the minimum room temperature at night as shown in Figure 2-14. SSPCM plates attached to the wall inner surfaces shaves indoor temperature swing for both lightweight and heavyweight wall fabric materials and there is no obvious difference between their minimum daily temperatures. However, heavyweight buildings have been shown to store more energy than lightweight buildings in the first place
 7. The SSPCM plates really absorb and store the solar energy during the daytime and discharge it later and improve the indoor thermal comfort degree at night time

The feasibility of using the microencapsulated PCM (Micronal BASF) in sandwich panels to increase their thermal inertia and to reduce the energy demand of buildings was studied (Castellón *et al.*, 2010): Only preliminary results are available, showing the industrialization of the process to improve the results.

2.4.2.2 PCM in ceilings and roofing systems

Prototype variants of newly developed passive PCM ‘Sails’ were tested in an occupied central London office and modelled with computational fluid dynamics (CFD) (Susman *et al.*, 2010). These sails are units located below the ceiling that passively absorb excess room heat. They are made of flexible sheets containing PCM which absorb excess room heat throughout the day as shown in Figure 2-15. At night the sails are either left in the space to discharge to ventilated cool night air or taken outside to discharge directly to the night air and sky. System advantages include:

- Optimal location for absorbing naturally convected heat.

- Potentially greater surface area than that afforded by fabric-integrated systems
- Simple design suitable for new-build or retrofit applications

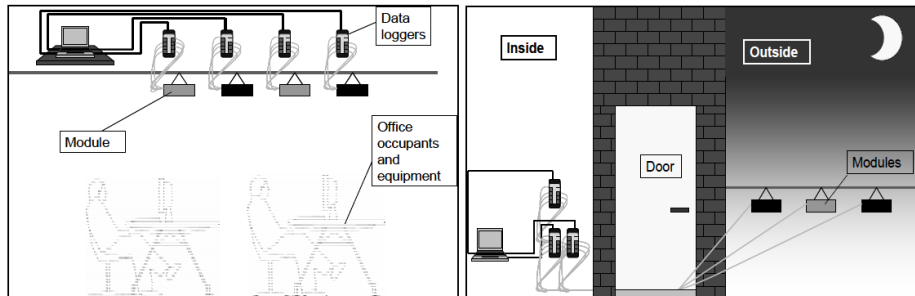


Figure 2-15 Passive sail with night time cooling

Computer simulation software FLUENT(ANSYS, 2012) is used to optimize the PCM system. Firstly, results show that a PCM with a narrowly defined phase transition zone centred on the thermal comfort zone is preferable; which is an important point for PCM selection. Secondly, that external night time cooling is much more effective than simple night ventilation. Thirdly, radiant heat transfer has a significant effect on surface heat flux and therefore cooling capacity. Fourthly, the surface heat flux decreases at a high rate, reaching zero at the end of the charge period. With these conclusions in mind, an active PCM Sail system was developed as shown in Figure 2-16. It operates in the same way as the passive sail but contains a chilled water circuit for the option of active heat discharge to the night air or a dedicated cooling system. The system's cuboid container is modelled in FLUENT as 2mm thick aluminium and contains a compound formulation of aluminium foam, of relative density 17%, and pure paraffin A22. Not being combined with LDPE means the paraffin has a much more defined transition zone and also effectively doubles its energy density. The system operation initially tends towards passive operation and when the night time air temperatures are found to be inadequately high, free cooling will be initiated by circulating water through the cooling system's condenser. The dedicated cooling system will finally provide the necessary supplementary cooling when flow temperatures from free cooling are also found to be inadequate. This kind of control will minimize the energy used by the system. The results show the stabilization of temperature during phase change is highly defined, with a sharp rise upon transition to fully liquid state; this is due to the purity of the paraffin. Also, temperatures at all locations remain extremely close to each other throughout, indicating

that the metal foam has a strong influence in dispersing accumulated heat throughout the PCM.

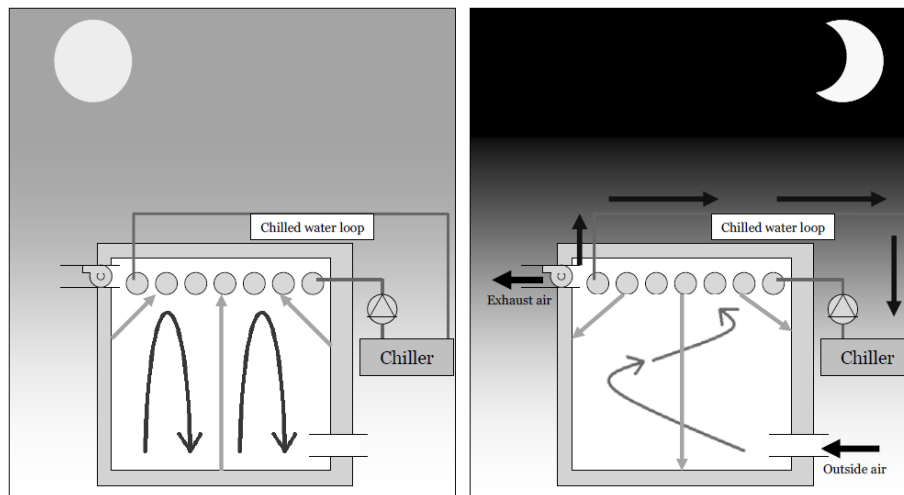


Figure 2-16 Operation of active sail (Susman *et al.*, 2010)

2.4.2.3 PCM in floors

Xu *et al.* (2005), using a computer model validated a PCM floor heating system with an experimental set-up built in Tsinghua University of Beijing. The objective is to study the influences of various factors on the thermal performance of the system.

The dimensions of the cabin are 3 m (depth) \times 2 m (width) \times 2 m (height). There is a double-glazed window facing south. The roof and walls are made of 100 mm-thick polystyrene boards. The floor is composed of 8 mm-thick SSPCM layer and a 50 mm-thick polystyrene layer and the experiments were performed from October 15th to December 15th, 2003. It was found that for the context, the suitable melting temperature of PCM is roughly equal to the average indoor air temperature for the purpose of regulating temperature. The heat of fusion and the thermal conductivity of PCM should be larger than 120 kJ kg and 0.5 W/m K, respectively. This is in agreement with the work of Zhang *et al.* (2006).

The limitation of this paper lies in the methodology adopted to optimize the variables; transition temperature; thermal conductivity; and heat of fusion. The results have been validated based on three options of each variable that the paper does not justify. Therefore the variables have been optimized only for the proposed options. For instance, in terms of transition temperature for Beijing, the range of temperatures examined for optimization is 15 to 23°C. Bearing in mind that transition temperature

should be about average indoor temperature, which for Beijing is between 8.5 and 37.2°C, the justification for the range optimized is unclear.

The above application of PCM is advantageous in climates requiring heating. There is no study of PCM floor-boards used for cooling within the literature reviewed.

2.4.2.4 PCM in HVAC for Free-cooling

Besides smoothing temperature variations with thermal mass added by PCM in the building fabric, it may be necessary to have systems supplying extra heat or cold and storage. This is advantageous in optimizing the performance of the system in case of fluctuating supply and demand.

An experimental system (Agyenim and Hewitt, 2010) consisting of a longitudinally finned RT58 PCM in a horizontal cylinder has been conducted to investigate a suitable PCM to take advantage of off-peak electricity tariff. The system consisted of a 1.2 m long copper cylinder filled with 93 kg of RT58. The potential implication of integrating this PCM storage system to an air source heat pump to meet 100% residential heating energy load for common buildings in UK has demonstrated that heat storage size can be reduced by up to 30%.

Zhang *et al.* (2006) investigate the thermal performance an under-floor electric heating system with SSPCM plates. The same experimental house as Xu *et al.* (2005), set up in Tsinghua University, Beijing, China is used as shown in Figure 2-17. The PCM consists of paraffin with a transition temperature of 20°C to 60°C, and high-density polyethylene HDPE as supporting material. The under-floor heating system included 120 mm-thick polystyrene insulation, electric heaters, 15 mm-thick PCM, some wooden supporters, 10 mm-thick air layer and 8 mm-thick wood floor. Results show that if the melting temperature is too high, the quantity of solar radiation heat stored by SSPCM reduced in the daytime and; if the melting temperature is too low, it is difficult to maintain the indoor air temperature under a comfortable level at night time. The following conclusions were obtained. The transition temperature of SSPCM can be adjusted by using different paraffin and up to 80% of the material can be made of PCM without it losing its structural integrity. The shape-stabilized material can be mixed with concrete material to shape building component. However, a PCM floor or wallboard can narrow the temperature swing in a day in winter with a suitable transition temperature of 2°C higher than the average indoor air temperature of the room without PCM. For the electric under-floor space heating system, the optimal melting temperature is about 40°C and should not be thicker than 20mm.

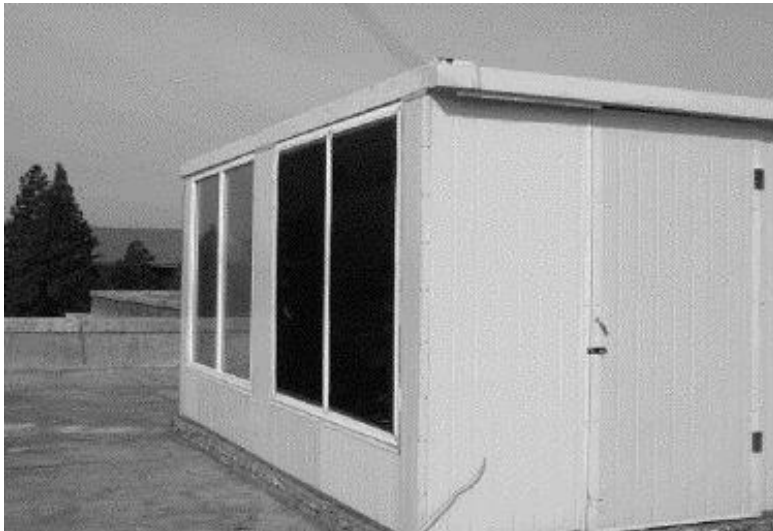


Figure 2-17 Experimental house Tsinghua University, Beijing, China (Zhang *et al.*, 2006)

The study conducted by Agyenim and Hewitt, (2010) and Zhang *et al.* (2006) are examples showing PCM in an active heating system. This is only of benefit to climates that require heating. There are two free cooling approaches in building applications. They are water side free cooling and air side free cooling (Zhu *et al.*, 2009). The water side free cooling often uses evaporative cooling towers to cool down the chilled water directly without resort to the mechanical cooling while the air side free cooling is to use fresh air and/or re-circulated indoor air to cool down a building. Contrary to the name free-cooling, auxiliary components such as water pumps and cooling tower fans are used in water side to provide the circulation force. Ventilation fans and/or heat pipes or water piping are used in air side to provide enhanced heat transfer between air and PCM storages.

In the UK, Francis Agyenim *et al.*,(2007) investigate the possibility of integrating PCMs to a water-side absorption free-cooling system to cover 100% of peak cooling load for a three bedroom house on the hottest summer day in Cardiff, Wales. A macro-encapsulated PCM system was designed using erythritol with melting point 117.7°C as a PCM. Results show that 100 litres of erythritol would provide 4.4 hours of cooling at peak load based on the optimum COP of 0.7 for LiBr/H₂O absorption cooling system.

Zalba *et al.* (2004) design, construct and run an experimental installation to study PCMs with a transition temperature around 20–25 °C to study the feasibility of an air-side free-cooling installation. They conclude that the concept is feasible in climates where the temperature difference between day and night in summer is larger than 15 °C. This is demonstrated studying the main influence variables, such as air inlet temperature, air flow and material used. RT 25, a trade mark from Rubitherm (2012) with a wide phase change temperature interval of 20–24 °C is a good PCM for free-cooling application given its relatively low price than for instance a molecular alloy with 34% C₁₆ and 66% C₁₈ and a melting temperature of 19.5–22.2 °C. The two PCMs were chosen as the best for free-cooling. Five flat-plate encapsulates of 15 mm of interior thickness and another of three encapsulates of 25 mm interior thickness were compared. Results show that the 15 mm encapsulate would be ideal for a free-cooling application because of solidification average time of 4 hours, and melting average time of 6 hours. On the other hand, an encapsulate of 25 mm thickness seems more suitable for an application such as temperature security with solidification average time of 6.5 hours, and melting average time of 9 hours. Other conclusions reached are:

1. An increase in air flow decreases the average time of the solidification process for about 0.86 h
2. An increase of both air temperature and thickness means an increase in the duration of the solidification process, but the effect of the temperature is higher when the thickness of the encapsulate is also higher. This means that in climatic areas with a night temperature of about 16 °C an increase in thickness would be more efficient, while in areas with an average night temperature of 18 °C, an increase in the thickness of the encapsulate could endanger the viability of the free-cooling system
3. An increase on air flow decreases the average melting time in about 1 h.
4. The most significant effect in melting phase is the temperature of the air, while in the solidification process, it is the thickness of the PCM
5. In the melting process, an increase of encapsulate thickness is more critical at low temperatures, and an increase in temperature is more critical with higher thickness of the encapsulate. This means, that with applications where the inlet temperature of the air is about 28 °C, an increase in encapsulate thickness could delay substantially the melting process, while in situations where the inlet

temperature is about 30 °C, the increase in time of the melting process would be not so important

Furthermore, a viability analysis of the system was performed comparing the storage system with a conventional split refrigeration system with similar power. The comparison between the two systems shows that the storage system needs an additional investment of 9%, has a pay-off period of 3–4 years, and an electric power 9.4 times lower than the conventional one.

To improve the system the following need to be addressed. Overnight cooling is required for the effective solidification of PCMs for seasons when the daily temperature fluctuation is not adequate. PCM are used in heat exchangers but due to poor thermal conductivity of PCM, the value of overall heat transfer coefficients is low.

2.5 Conclusions

In Chapter 1, the need for energy conservation in Nigerian office buildings is made. In this chapter, PCM literature is reviewed for their benefit in energy conservation while maintaining thermal comfort in building applications.

From literature:

1. Diaconu and Cruceru (2010) predict peak cooling/heating load reduction of 35.4% and reduction of the total cooling load of 1% by simulating the performance of a PCM wallboard in Algeria- a continental temperate climate
2. In Castell *et al.*, (2010b), total energy consumption was reduced by 15% in an experimental cubicle made of micro-encapsulated PCM enhanced brick in the Mediterranean
3. Also in the Mediterranean, maximum and minimum temperatures were reduced by 1°C and 2°C respectively by the passive use of PCM in concrete (Cabeza *et al.*, 2007)
4. A reduction of about 3°C has been recorded with the use of PCM in an active system by Voelker *et al.* (2008)

Such varying results in the application of PCMs are due to the complex classes of variables affecting their performance. These variables are broadly classified into properties and applications of the PCM. The properties of PCM may be further classified into thermo-physical and chemical properties; whereas the application of PCMs examines the ways PCM are incorporated into the fabric and the components of buildings.

From the literature reviewed, the conclusions in the following parameters are further discussed:

- Thermo-physical properties of PCM
- Chemical properties of PCM Surface area of PCM
- PCMs for Nigerian climate

2.5.1 *Thermo-physical properties of PCM*

After reviewing studies by Zalba et al. (2004), Xu et al.(2005), Zhang et al. (2006), Zhou et al. (2007), Pasupathy et al. (2008b), Richardson and Woods (2008), Zhou et al., (2008) etc., the following points on thermo-physical properties of PCM are adopted for this study:

- Thermal energy storage by a combination of sensible and latent heat energy shows promising results for energy conservation and thermal comfort
- For latent heat storage, solid–liquid transitions have proved to be economically attractive for use in thermal energy storage systems
- Materials to be used for phase change thermal energy storage should have a transition temperature lying in the practical range of operation
- The most significant effect in melting phase is the transition temperature, while in the solidification process; it is the thickness of the PCM
- The optimal transition temperature depends on the average indoor air temperature and is proportional to radiation absorbed by the PCM system in place
- It has been shown that a narrow transition temperature of 1°C is best to reduce the indoor temperature swing and improve the thermal comfort
- PCM thickness should be sufficiently large, such that heat movement cannot reach the interior side of the wall and should be as high as structural integrity and cost permit; until it reaches a critical point where as more of the latent heat cannot be accessed. PCM used for temperature regulation in active PCM floor heating systems should not be larger than 20mm and 25 mm thickness for an air-conditioning system. It is concluded from the literature reviewed that there is a need to optimize PCM thickness based on the context and application.
- The latent heat of fusion of PCMs should be in the range of 120–160 kJ kg⁻¹

- The conductivity of PCM should be as high as 0.5 W/mK, above which the conductivity of the PCM does not affect the PCMs thermal performance.

2.5.2 *PCM can be chemically tailored to fit different contexts*

The following chemical properties of PCMs as highlighted by Farid *et al.* (2004), Ahmet (2005) and Diaconu and Cruceru (2010) are considered as a backdrop of this study:

- A combination of PCM may be tailored as new PCMs, with almost any suitable melting point and latent heat of fusion for specific climate requirements
- Solid-liquid PCM, primarily used in building applications are classified as organic, inorganic and a combination of compounds known as eutectic compounds. Eutectics are combination compounds that can be designed to achieve required specifications
- PCM should melt congruently with minimum sub-cooling and be chemically stable, low in cost, non-toxic and non-corrosive

2.5.3 *PCMs perform better with a large surface area*

Generally, PCMs require large surface areas for optimal performance (Ortiz *et al.*, 2010). Walls provide the largest surface area compared to ceilings and floors. In the literature reviewed, the incorporation of PCM in walls ranks 1st out of floor, ceiling, roof and in HVAC systems.

Historically, PCM have been incorporated into buildings by immersing porous materials such as wallboards; direct incorporation; macro and micro- encapsulation; and most recently as shape stabilized PCM (SSPCM) components. The following are the type of PCM containment in the building fabric which affects the surface area according to Zalba *et al.* (2003), Zhou *et al.* (2007), Zhu *et al.* (2010):

- Immersion and direct incorporation have failed due to leaking, flammability and structural problems. Structurally, immersion technique is limited because only 20-30% of PCM should be incorporated in elements to be able to keep their structural integrity
- Macro-encapsulation is affected by the nature of containment which disrupts phase change due to severely reduced surface area of the PCM within the containers

- Micro-encapsulation while increasing the surface area and thereby the efficiency of the PCM to melt and solidify as required is still limited by the 20-30% limit of PCM incorporated in elements to keep their structural integrity
- SSPCM are made of dispersed PCM encapsulated in macromolecule material, such as high-density polyethylene (HDPE) allowing the PCM to keep its shape when it undergoes phase change
- A comparison of micro-encapsulated PCM and SSPCM indicates that percentage of PCM achieved by SSPCM is superior to that of microencapsulated PCM directly incorporated in building fabric- up to 80% as compared with 30% for micro-encapsulated PCM
- However, for computer studies examining the thermo-physical performance of PCMs such as this one, the actual containment method is not significant as long as the thermo-physical properties are suitable for the context.

2.5.4 PCMs suitable for the Nigerian climate have not been studied

Considering that PCM performance is heavily dependent on transition temperature (Xiao *et al.* 2009), which in turn is dependent on climate, there is a conspicuous gap in literature covering the effect of climate on PCM performance across different climatic zones. The following points are gathered from the literature review (Voelker *et al.*, 2008; Isa *et al.*, 2010; Susman *et al.*, 2010):

- None of the climates studied fall within a composite of hot and humid and hot and dry as experienced in a large swathe of Nigeria
- None of the studies cover West Africa and the only hot and humid climate studied is a preliminary one (Isa *et al.*, 2010) in Malaysia which is yet to publish measured or predicted results
- In warm climates where night time temperatures are not low enough to charge the PCM, an active night time cooling process is required to prevent hysteresis.

3 CHAPTER 3

METHODOLOGY

Contents
3.1 Overview
3.2 Context
3.3 Research aim
3.4 Research objectives
3.5 Research strategy
3.6 Research design
3.7 Research methods
3.8 Analysis
3.9 Computer simulation software packages
3.10 Limitations
3.11 Reliability, Replicability and Validity
3.12 Ethical issues
3.13 Conclusion

Problem	Chapter one: Introduction- 'Nigerian buildings and Energy use'		
Theoretical framework	Chapter two: Literature review- 'Phase change materials as energy conservation mechanisms in buildings'		
Methodology	Chapter three: 'Methodology'	Chapter four : 'Validation study'	
Results	Chapter five: 'Disaggregating primary electricity consumption for office buildings in Nigeria'	Chapter six: 'Optimizing thermal and energy performance of buildings'	Chapter seven: 'PCM performance in office buildings'
Conclusion	Chapter eight: Conclusion		

3.1 Overview

This chapter provides information on how the research was conducted in order to achieve the research aim and objectives presented section 3.2. It covers the sampling selection, research strategy, design and method adopted for this thesis thereby contextualizing the methodology and justifying their use as compared to alternative ones. Other issues discussed in this chapter include reliability, replicability, validity, ethical issues, limitations and a reflection on how the negative effect of these are minimized on the research process. Issues related to modelling and simulation of PCMs are discussed.

Figure 3-1 shows the overall research methodology adopted for the thesis. It show the context, research aim, research strategy, research design, research methods and analysis adopted for the study.

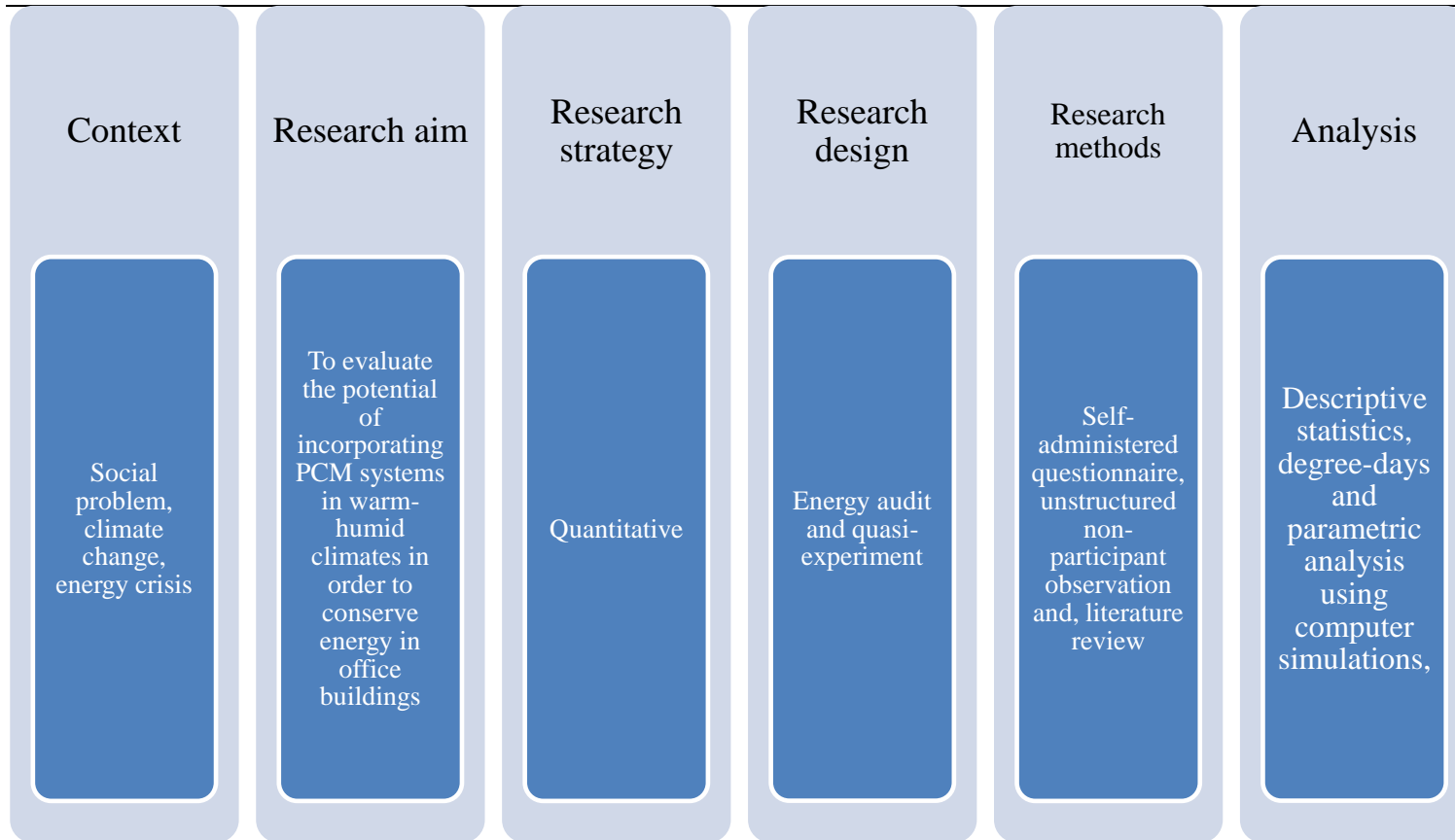


Figure 3-1 Overall research methodology

3.2 Context

As discussed in Chapter 1, Nigeria is faced with an electricity crisis and so the basis of this research is a personal experience of an important socio-economic problem facing the Nigerian public. Chapter 1 presents literature on the magnitude of the crisis and how people react to it. It also sheds light on the significant impact it is having on the built environment. Frequent and erratic power outages are common, driving the provision for back-up power generators fuelled by petrol and diesel.

A paucity of information on energy consumption, efficiency and conservation steers the research into an exploratory field.

3.3 Research aim

The aim of this investigation is to evaluate the potential of incorporating PCMs in office buildings in Abuja in order to conserve energy within the context of an overburdened and failing central power utility in Nigeria.

3.4 Research objectives

The objectives of the study are:

1. To examine the need for energy conservation within the context of the electricity shortage supply in Nigeria
2. To search for the knowledge gap within literature for PCMs used for energy conservation and thermal comfort within the composite hot and dry/hot and humid climate of Abuja
1. To validate the computer software's and user's ability to simulate PCMs in buildings
2. To develop a method for collecting electricity consumption data in places suffering from power shortages
3. To investigate electricity consumption within office buildings in Nigeria
4. To determine the potential for energy savings within the cooling load
5. To create a base-case for testing the performance of PCMs
6. To optimize a model for a PCM suitable for office buildings in Abuja
7. To evaluate the potential effect of incorporating PCMs in the building fabric on thermal comfort and energy consumption

The research objectives are discussed in relation to chapters as shown in Table 3-1.

Research objective	Chapter	Chapter progression
To build a context behind the need for a study into energy conservation	1	The basis of the research
To search for the knowledge gap within literature for PCM used for energy conservation and thermal comfort within warm-humid climates	2	The context from Chapter 1 leads to a search for energy conservation in Nigerian office buildings using PCMs
To validate the computer software's and user's ability to simulate PCMs in buildings	4	The use of computer models is based on an abstraction of reality which leads to a need for validating the method
To develop a method for collecting electricity consumption data in places suffering from power shortages	3 and 5	The erratic nature of power supply highlighted in Chapter 1 leads to the development of a data collection technique; presented in Chapter 3 and analysed in Chapter 4
To investigate the electricity consumption within office buildings in Abuja	5	The paucity of data highlighted in Chapter 1 necessitated the need to investigate electricity consumption in a field exercise
To determine the potential for energy savings within the cooling load	5	The information from the field exercise is evaluated for the potential of energy savings in the cooling load
To create a base-case for testing the performance of PCMs	6	Data from Chapters 2 and 4 are used to create a base-case building
To optimize the model for a PCM system for office buildings in warm climates	7	The base-case building in Chapter 5 is used to optimize the properties of PCM for the given context in Chapter 1.
Evaluate the potential effect of incorporating PCMs in the building fabric on thermal comfort and energy consumption	7	The performance potential of optimized PCM is evaluated on the base-case designed in Chapter 5

Table 3-1 Mapping research objectives to chapters and their progression

3.5 Research strategy

A quantitative research strategy is used. The research strategy adopted for this research is informed by the basis and design of the research. The basis is exploratory and the design is

quasi-experimental. As the basis of the research is a fact finding and exploratory one, the nature of quantitative studies gives it the ability to objectively prove a given hypothesis. The results from a quantitative study are tangible and reliable (Naoum, 2012). This study may be the foundation for more studies on the subject of electricity conservation in Nigeria using PCM.

The process of evaluating electricity conservation in buildings quantitatively is illustrated in Figure 3-2 and shown below:

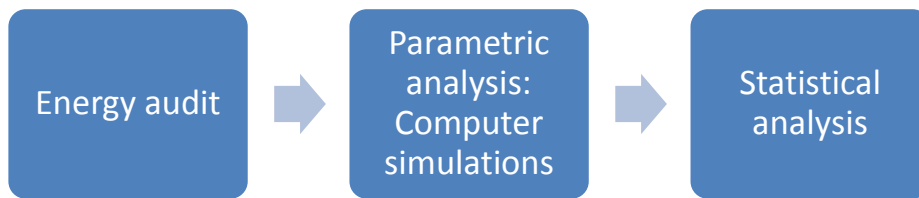


Figure 3-2 Method of calculation of building energy consumption

1. Energy audit: A sample of single-purpose office buildings is energy audited and analysed
2. Parametric analysis: This is the process of using computer simulation models based on the data from the energy audit to examine variables one at a time. This process follows a quasi-experimental design
3. Analysis: These analyses are conducted to illustrate the energy saving potential of energy conservation measures in a base-case building by considering discrete changes in the key variable identified

The procedure and analysis adopted in this research is based on Lam et al (2008) and Pedrini et al (2002). In Lam et al (2008), the methodology also involves a 4 phase process. A similar method is employed by Pedrini et al (2002) with a slight variation in sequence of actions. The research was initiated with intelligent computer simulation, then an audit in this case.

Caudana. *et al.*(1995) highlight the need for standard methodologies in the field of building energy auditing. Of the many new energy conservation tools and environmental protection determined by conducting energy audits, a very high percentage is applicable to both new and retrofit buildings (Caudana *et al.*, 1995; Santamouris and Dascalaki, 2002; Poel *et al.*, 2007). The proposed PCM optimized in this research is intended for retrofit buildings.

3.6 Research design

This research adopts a descriptive, and quasi-experimental approach to frame the answers to its research aim and objectives. These approaches are classified by Gliner, Morgan. et al. (2000) who divided research design into:

- Individual differences (non-experimental)
- Descriptive
- Experimental

3.6.1 Descriptive research design

Descriptive approach is used for exploratory studies with little or no interest in finding out the relationships between identified variables. For the objective to investigate how electricity is used in mix-mode Nigerian office buildings, a descriptive approach is adopted. Using the descriptive approach, energy audits are adopted because different strains of inquiry are possible concerning energy use in buildings. The energy audit process is further discussed in 3.7.2.1.

3.6.2 Quasi-experimental research design

The evaluation of the potential of using PCMs is based on a quasi-experimental approach. The hypothesis is that 'Use of PCMs can save energy'.

Experimental approach has what is known as an active independent variable and is further divided into randomised and quasi-experimental approach. A randomised approach is adopted to *determine* causality whereas quasi-experiment approach can *examine* causality which is the aim of this research.

As an exploratory study, the aim is to examine causality. By identifying key variables, computer simulations are used to examine their effects on PCM performance. Computer simulations are a simplification of energy flows and real life events. Computer simulations are limited in their ability to predict actual outcomes. The predicted results indicate possible changes from a base-case.

Quasi-experimental design is accepted in social sciences as a design lacking control in certain sampling factors such as random assignment. Randomisation and random assignment in sampling were difficult due to accessibility issues as discussed in Section 3.7.1. However, quasi-experiment provides statistically accepted reliable and valid results.

The control group is the base-case which is used as the basis from which differences are measured while the experimental group is the same building but with the inclusion of an independent variable being examined.

3.6.2.1 Dependent and independent variables

The dependent variables predicted are electricity consumption and thermal comfort. Electricity consumption is measured in Watt-hours whereas thermal comfort is measured in terms of indoor dry bulb air temperature and operative temperature, both measured in degree Celsius. As discussed in Chapter 1, dry bulb temperature is the most common index for the specification of comfort (Macpherson, 1962; Nicol *et al.*, 2012). However operative indoor air temperature combines the effect of surface temperature of the PCM wall surface as well as air temperature an is considered more accurate.

Comment [A5]: Addition

The independent variables examined are classified into two groups. The groups are bio-climatic design variables and PCM design variables as shown in Figure 3-3. Bio-climatic design variables examined are orientation, glazing, shading, airtightness and insulation. These variables are examined as part of the process of creating a suitable base-case on which to test the performance of PCMs.

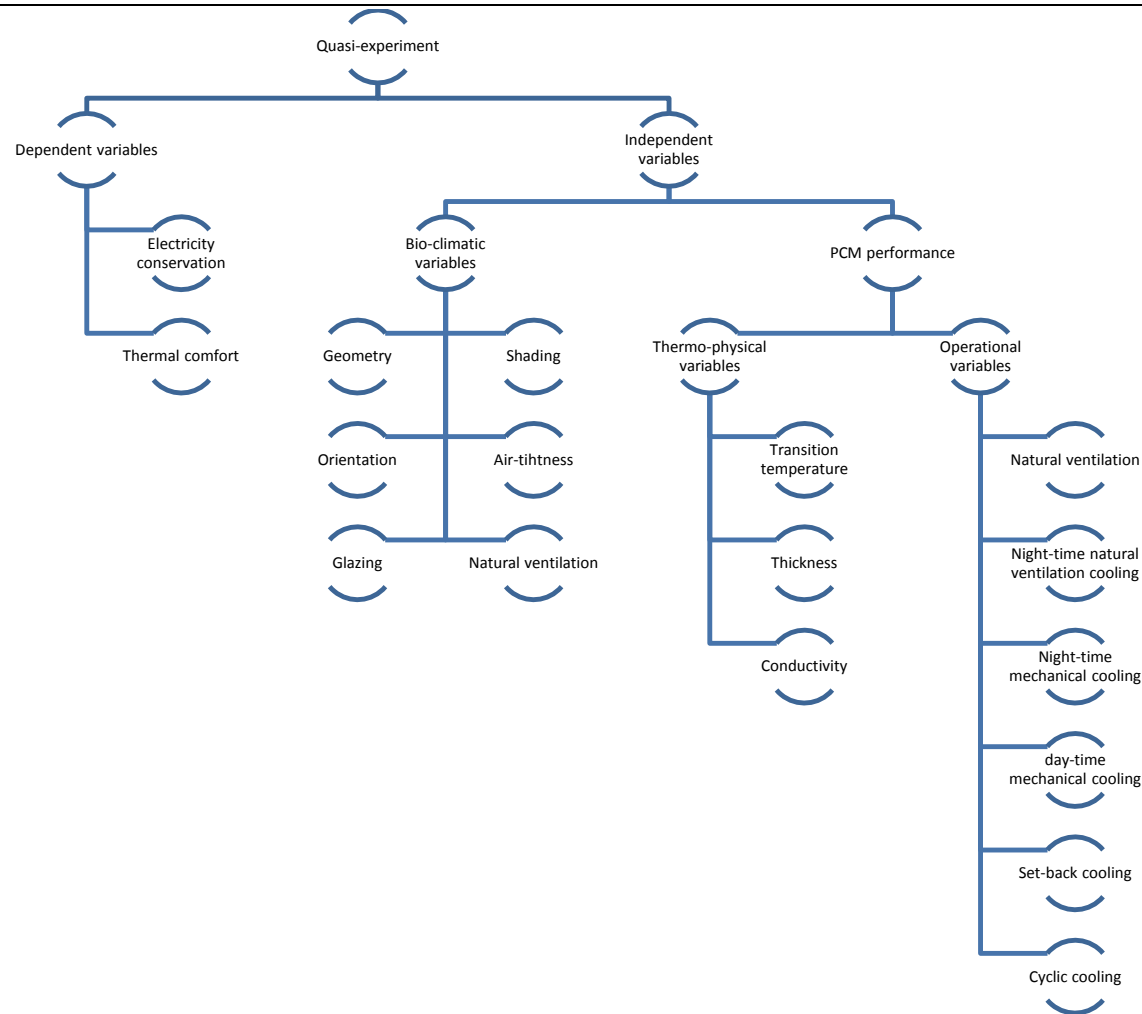


Figure 3-3 Dependent and independent variables

PCM design variables are further classified into thermo-physical properties and cooling operational strategies. Thermo-physical properties examined are transition temperature, conductivity and thickness of the PCM. Operational strategies examined are natural ventilation, night-time natural ventilation, mechanical cooling night-time mechanical cooling, set-back cooling and cyclic cooling. Further discussions are found in Chapters 5 and 6.

3.7 Research methods

Buildings are made of different energy flows running simultaneously and dynamically. The flows may be lighting, cooling or appliance usage by occupants or machinery. These are complex systems that require a cross-sectional approach.

The rest of this section covers sampling and data collection methods.

The energy audit procedure encompasses not only data collection but also the analysis process. The energy audit is initiated by a walk-through then an analysis exercise. The walk-through is a field visit through a building enabling data collection by observing or measuring objects of interest. The research instruments utilised for the energy auditing each building include:

- Self-administered questionnaires
- Unstructured non-participant observation
- Literature review of national statistics, building regulations, and climatic data

The analysis is conducted parametrically using computer simulations in an experimental research design. The analysis conducted is discussed in detail in Section 3.8.

3.7.1 Sampling

Selected sampling is used to capture the data required for the study. The process begins with a list of possible buildings to audit. The list is based on outlined characteristics that fit the scope of the research. These include single use occupancy status, mix-mode cooling, site electricity metering etc.

Twenty-four office building were identified as having the attributes suitable to participate in the research. Seven buildings out of those were omitted as political and security instability made visiting the Nigerian Niger delta unsafe. Another 2 buildings had insufficient data such as log of back-up generator used, and were discarded. In total, 15 buildings were fully audited.

The buildings are chosen based on the following factors:

- Design climates in Nigeria
- Building selection

A random sampling method is more suited for a scientific study such as this; however steps were taken to reduce the impact of such a sampling methods as further discussed in section 3.6.2

3.7.1.1 Design climates in Nigeria

Nigeria experiences a variation of climate as one moves from the coast to the northern parts of the country. The climate of a particular location also varies with the time of the year, latitude of the location and landscape (Ajibola, 2001). Nigeria is classified based on indices such as geo-political zones, vegetative belts and design climates. Electricity consumption and thermal comfort are directly affected by climate rather than vegetation or politics therefore the classification based on design climates is adopted.

Komolafe and Agarwal ((1987) in (Ajibola, 2001)), (Ogunsote, 1991) and UNEP/GRID, (2002) have classified Nigerian climates as shown in Table 3-2.

Researchers design climate classification	Komolafe in Ajibola (2001)	Design climates in Ogunsote (1991)	Vegetative climate in Ogunsote (1991)	Climatic classification in Africa (UNEP/GRID, 2002)
-Hot and dry	-Hot dry	-Hot and dry	-Coastal	-Humid
-Hot and humid	-Temperate	-Warm and humid	-Forest	-Moist humid
-Composite of 1 and 2	dry	humid	-Transitional	-Dry sub-humid
	-Temperate humid	-Composite of 1 and 2	-Highland	-Semi-arid
	-Hot humid		-Savannah	-Arid
			-Semi-desert	-Hyper arid

Table 3-2 Climate classification by different authors

Figure 3-4 shows the climatic classification in Africa by United Nations Environment Programme (UNEP) and Global Resource Information Database (GRID) (2002).

The climatic profiles of three cities namely Lagos, Kaduna and Abuja are shown in Table 3-3 and Figure 3-5. The cities represent the design climate for hot and humid, hot and dry

3-Methodology

and a composite of hot and humid and hot and dry respectively. These are major cities within broad climatic classification that house a large number of office buildings suitable for the energy audits. The fieldwork was originally designed to audit buildings in four major cities however, it was not possible to visit Port Harcourt because of political and security issues experienced at the time.

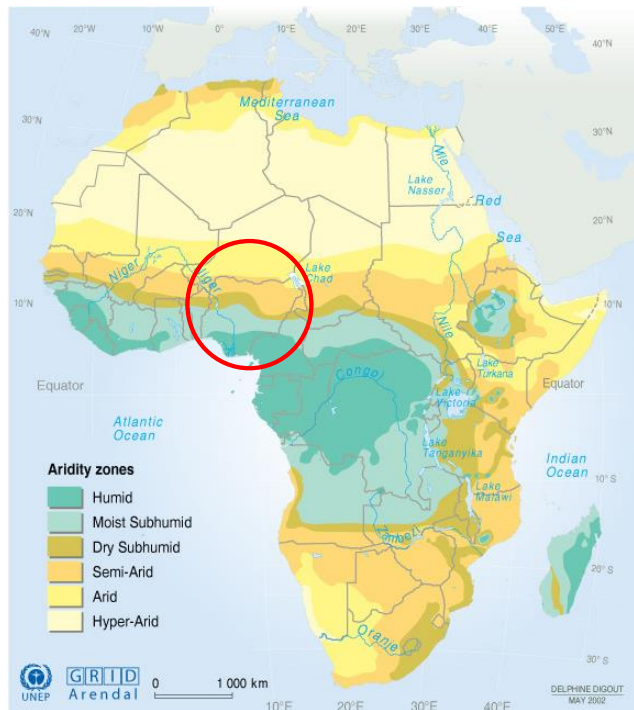


Figure 3-4 Climatic classification in Africa (UNEP/GRID, 2002)

3-Methodology

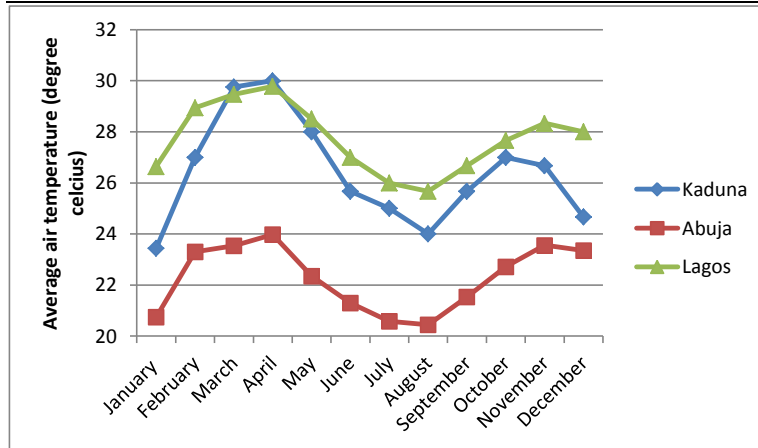


Figure 3-5 Air temperature profiles for some Nigerian cities (Nigerian meteorological agency)

Monthly temperature (°C)	Kaduna		Abuja		Lagos	
	Max	Min	Max	Min	Max	Min
	30	23.5	30.9	25.1	29.6	25.5
Ave annual air temperature (°C)	26		28		28	
Precipitation (mm)	1192		1221		1538	
Humidity (%)	5-95		20-91		34-99	
Daylight hours	12		12		12	
Wet season	5 months, May-Sept		7 months, Apr-Oct		6 months, Apr-Jul and Oct-Nov	
Dry season	7 months, Oct- Apr		5 months, Nov-Mar (Harmattan in Dec)		6 months, Aug-Sep and Dec-Mar	
Neutrality temperature, T_n (°C)	26		26.3		26.4	
Comfort band (+/-2 of T_n °C)	24-28		24.3-28.3		24.4- 28.4	
Cooling Degree Days/annum	213		291		303	

Table 3-3 Climatic data of some Nigerian cities

Measures of comfort such as average, minimum and maximum temperatures are presented in Table 3-3. Others are precipitation and mean daylight hours. Figure 3-6 to Figure 3-8 show average monthly ambient air temperature and two comfort bands. One is calculated from the Neutrality temperature T_n . Neutrality temperature is calculated using the formula shown in Equation 3-1 by de Dear and Brager (1998).

$$T_n = 17.8 + 0.38(T_{ave}) \quad \text{Equation 3-1}$$

Where T_n is Neutrality temperature, and T_{ave} is mean monthly temperature. It should be noted that this equation is adopted for use as the equation for Neutrality temperature in this research

The other comfort band is proposed by European standards (15251:2007-08, 2007) for mechanically cooled buildings in the summer.

Lagos: There are two wet seasons in Lagos, with the heaviest rains falling from April to July and a weaker rainy season in October and November. There is a brief relatively dry spell in August and September and a longer dry season from December to March. Monthly rainfall between May and July averages over 300mm, while in August and September it is down to 75 mm and in January as low as 35 mm. The main dry season is accompanied by harmattan winds between December and early February. The average temperature in January is 28.5°C and for July it is 25.5°C as shown in Figure 3-6. On average the hottest month is February with a mean temperature of 29.6°C; while July is the coolest month. The average annual temperature is 28°C. Average annual precipitations is 1538mm, and mean daylight hours is 12hrs.

Kaduna: There are two marked seasons in Kaduna; the dry, windy harmattan which is a northeast trade wind, characterized by dust, intensified coldness and dryness and the wet seasons. On the average, the city experiences a rainy season from May to September. Night temperatures in the cooler months may dip to 10°C and day temperatures in hot months rise to 31.6°C. The average annual temperature is 26°C and average annual precipitation is 1192mm. Mean daylight hours is 12hrs. Monthly average temperatures are shown in Figure 3-7. Also shown are thermal comfort bands based on the neutrality temperature and EN15251 (Olesen, 2010) comfort conditions.

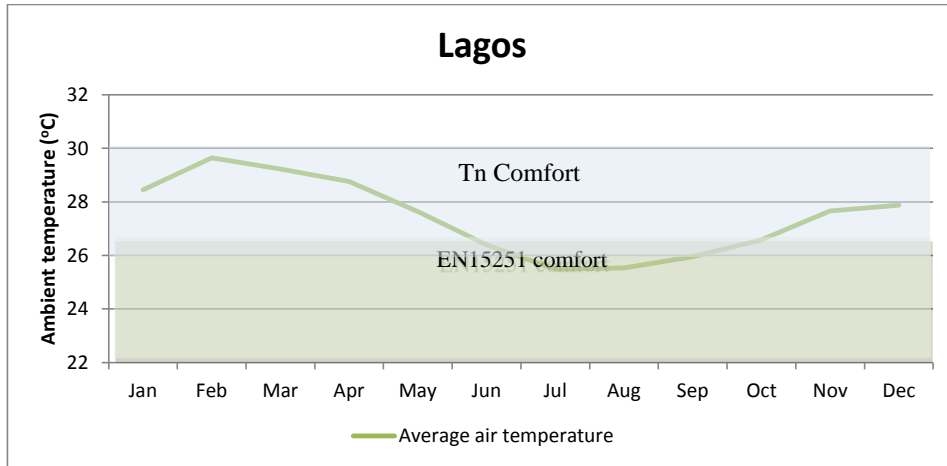


Figure 3-6 Air temperature profiles for Lagos (Nigerian meteorological agency) and thermal comfort band based on the neutrality temperature and EN15251

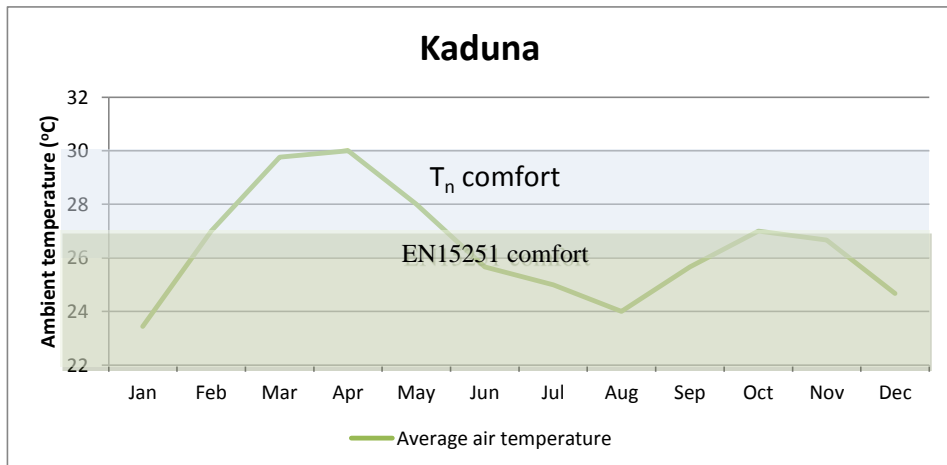


Figure 3-7 Air temperature profiles for Kaduna (Nigerian meteorological agency) and thermal comfort band based on the neutrality temperature and EN15251

3-Methodology

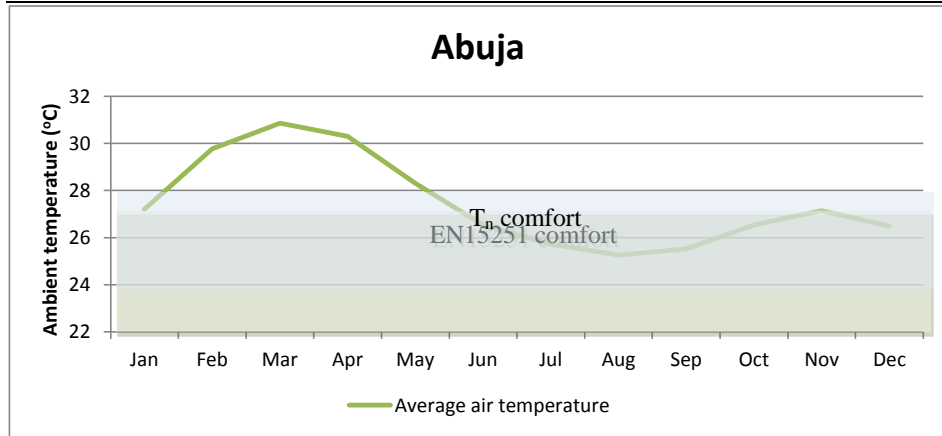


Figure 3-8 Air temperature profiles for Abuja (Nigerian meteorological agency) and thermal comfort band based on the neutrality temperature and EN15251

Abuja: Abuja experiences three weather conditions annually. This includes; a warm, humid wet season beginning from April and ends in October; and a dry season from November to March. In between the two, there is a brief interlude of harmattan. Daytime temperatures reach as high as 30°C and night time lows can dip to 12°C. The high altitudes and undulating terrain of the Abuja act as a moderating influence on the weather of the territory. The average annual temperature is 28°C and monthly average air temperatures are shown in Figure 3-8. Average annual precipitation is 1221mm and average daylight hours are 12hrs. Out of the three cities studied, Abuja, which experiences a composite hot and dry and hot and humid climates is used to test PCM performance. Abuja is chosen because it experiences both hot and dry and hot and humid climates. This type of composite climate is representative of a significant part of Nigeria. Abuja as the capital city also has a large amount of purpose built and single-use office buildings suitable for the test. This is further discussed in Chapters 5 and 6

3.7.1.2 Building selection

Twenty-four buildings were earmarked for energy audits across 4 major cities in Nigeria. Seven buildings out of the initial 24 were omitted as political and security instability made visiting Port-Harcourt in the Nigerian Niger delta unsafe. The selection of buildings audited is based on the following criteria;

- Design climate

- Access to the building
- HVAC system
- Availability of electricity consumption data

Design climate: The design climate has been discussed in Section 3.7.1.1.

Access to the building: Willingness of office buildings' management to participate in the investigation imposed access as criteria for selection based on security, bureaucracy or privacy. Access into the office buildings was approved only by the head of the organizations, which then referred the activity to the appropriate department.

HVAC system: The scope of this research covers only mixed mode buildings. These are buildings that use both mechanical and natural means to provide thermal comfort. However, these buildings are a combination of open and cellular plan configurations. Natural ventilation during work hours is difficult due to occupancy, peak internal load, casual internal gains, and peak solar radiation coincidence, leading to a reliance on mechanical cooling.

Availability of electricity consumption data: Electricity consumption data for a minimum of a year is crucial to investigate the performance of the building over different seasons. The performance over three years is optimal to compare within seasons in different yearly cycles. With the paucity of consumption data, only office buildings having adequate records were chosen.

The provision of an on-site electricity meter means the building electricity consumption records from the utility company are more accurate as the meter records are checked by the management against electricity bills.

3.7.2 *Data collection*

A cross sectional survey method of data collection using a process of energy auditing is used. A cross sectional method of data collection enables the examination of different strains of inquiry affecting building energy consumption. Both primary and secondary methods of data collection are used to examine these different strains as shown in Table 3-4. The table also justifies the use of the methods.

3-Methodology

Data	Source	Use
Monthly electricity bills	Primary quantitative data	Electricity consumption data provided by the state utility based on private electricity metering devices installed.
Alternative power (generator) log books and observation	Primary quantitative data	Back-up electricity consumption data and pictures provided by the building managers based on log usage.
Building characteristics	Primary quantitative data	Observation, pictures, diagrams and questionnaire used for accurate modelling.
Aggregate end use	Primary quantitative data	Physical inventory recorded for analysis such as lighting, cooling, and appliances loads.
Occupancy and schedules	Primary quantitative data	Data recorded in questionnaire for analysis; comparison of modelled with recorded (calibrating of software) and calculation of savings.
Climatic data	Qualitative and quantitative based on literature	Retrieved from Nigerian national archives, synthetic data from Meteonorm. Data required for modelling, simulations and climate description.
National building codes and frameworks	Secondary quantitative data	Data required for analysis and simulations such as minimum fresh air quantity/person

Table 3-4 Justification of collected data

3.7.2.1 Primary sources

Primary data collected include a physical inventory of all electrical equipment, pictures of building components and finishes, observation of building user behaviour and the self-administered questionnaire covering a minimum period of 1-3 years of electricity consumption. For such calculations, a minimum of a year's data is required and 3 years is optimal.

Questionnaires are used because they allow ease of comparability which is desirable in this analysis. Interviews and focus group data collection methods were considered and discarded due to the objectives of research. Also collection of electricity consumption data through the use of data loggers and other field instruments became unnecessary due to the availability of smart meters at the buildings. Electricity consumption data required is for a year at least for significant analysis. This issue made on-site electricity collection

unfeasible for this research. Monthly bills from the central utility supplier showing payment and actual consumption records were used instead.

The self-administered questionnaire consists of nine sections and an introduction/consent form at the beginning. The nine sections are divided into:

1. Building characteristics
2. Occupancy schedule
3. Site sketch
4. Electricity from utility use
5. Electricity from alternative source use
6. Heating ventilation and air conditioning
7. Cooling load
8. Lighting load
9. Appliances

The fieldwork was conducted from November 2009 till March 2010 to record, calculate and estimate the input variables for the modelling and simulation. The classes of data are shown in Figure 3-9.

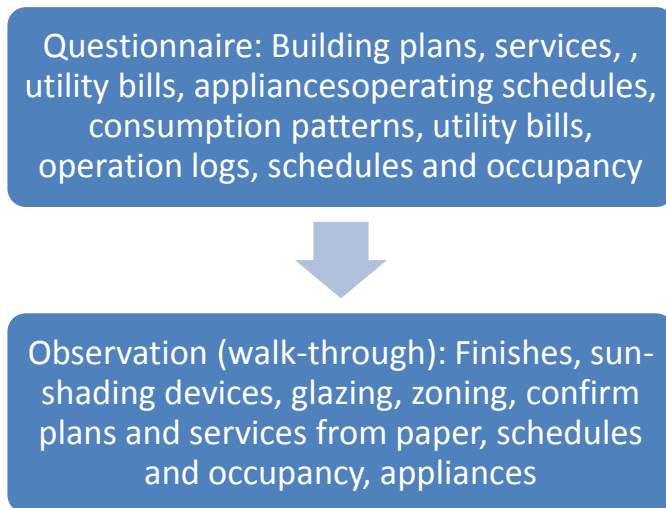


Figure 3-9 Data collection procedure

3.7.2.2 Secondary sources

Secondary data sources used include official literature and statistics mainly from the National Building Code (Federal Republic of Nigeria, 2006), climatic data from Nigeria meteorological agency (NIMET), electricity bills, electricity reports and alternative power (generator) log books.

As discussed in Chapter 1, there is a problem of erratic power supply which made collecting electricity consumption records complex. The total supply per annum is made up by a combination of; supply recorded by the smart meter provided by the Utility Company and also recorded on electricity bills; and the supply from the back-up power generators. The supply from back-up power generators, even though significant due to the frequency of black-outs is estimated. It is estimated based on recorded hours of use per annum by the buildings' management for fuel accounting purposes. The difference in total working hours from hours of back-up power recorded is the total supply hours by the central utility suppliers. These hours are converted to percentages and compared with that of back-up power to calculate the electricity supplied by the back-up generators. This estimation method proved more accurate than working out the power supplied from diesel consumption and the efficiency of the machine. This technique also minimises the errors due to inefficiency and sizing. This process is further discussed in Chapter 5.

3.8 Analysis

The analysis conducted in this research is by the following methods:

- Statistical analysis
- Degree-day method
- Parametric analysis

The three techniques commonly used for electricity consumption analysis are statistical (parametric and non-parametric), artificial neural networks and intelligent computer systems techniques (Parti and Parti, 1980; Day *et al.*, 2003; O'Sullivan and Keane, 2005; Swan and Ugursal, 2009).

3.8.1 Statistical analysis

The fieldwork provided data on independent variables such as lighting load, cooling load, building appliance load, occupancy, schedules, and building characteristics. Analysing the

data from the fieldwork is based on a combination of two approaches namely descriptive and inferential statistical analyses. The two statistical methods are used to:

1. Explore and describe the existing energy performance of the buildings investigated
2. Explore associations between the variables

Descriptive statistics employed are used in calculating means, normalization and electricity consumption by aggregate end-use. Inferential statistics are used during degree-day calculations to examine the relationship between electricity consumption and climate.

3.8.2 Degree-day

Degree-day calculations are employed to study the alignment of the cooling dominated consumption with ambient air temperature. This is a way to examine if there is an opportunity for energy savings in cooling demand. Degree-days are the summation over time, of the difference between a base temperature and ambient temperature. Degree-days capture both extremity and duration of ambient temperature. It is given by Equation 3-2.

$$(T_{ave} - T_{max}) * F_{day} * F_{hour} \quad \text{Equation 3-2}$$

Where T_{ave} is the average ambient temperature for the day, and T_{max} is the upper temperature of the comfort band. F_{day} is a function indicating that the day is a work-day and F_{hour} indicates if the hour being examined falls within work-hours. F_{day} and F_{hour} return a value of 1 denoting work-days and work-hours.

Neutrality temperature is adopted as the base line temperature to calculate degree-days in this work using degree-day's technique due to its robustness in adapting to ambient conditions.

Day et al (2003) use degree day analysis methods to disaggregate primary electricity consumption and check the opportunity for energy savings. The degree-days are correlated to electricity consumption as an indication of the buildings performance. In this research, the objective is to examine the general performance of the buildings audited. A poorly performing building indicates the opportunity for energy conservation thereby making the case for incorporating PCMs in the building fabric.

3.8.3 *Parametric analysis with computer simulations*

The aim of the parametric analysis is to observe the response following a modification in a variable. Parametric analyses are conducted for reasons including the need to determine (Hamby, 1994):

1. Which parameters require additional research for strengthening the knowledge base, thereby reducing output uncertainty
2. Which parameters are insignificant and can be eliminated from the final model
3. Which inputs contribute most to output variability
4. Which parameters are most highly correlated with the output
5. The consequence of changing a given input parameter

This investigation is concerned with point 5. Points 1-3 have already been established within the literature review and point 4 is outside the scope of this investigation.

The parametric analysis is used to examine the consequence of changing a given independent variable on electricity consumption and thermal comfort using computer simulations. Figure 3-10 describes the process of parametric analysis conducted. The steps are:

1. Define the model, its independent and dependent variables. This includes defining the climatic profile as discussed in Section 3.8.3.1.
2. Vary the values of each independent variable one at a time, in a rational and incremental manner using the whole building energy calculation software EnergyPlus
3. Record the corresponding value of the dependent variable
4. Assess and compare the influences of each input/output relationship through statistical methods

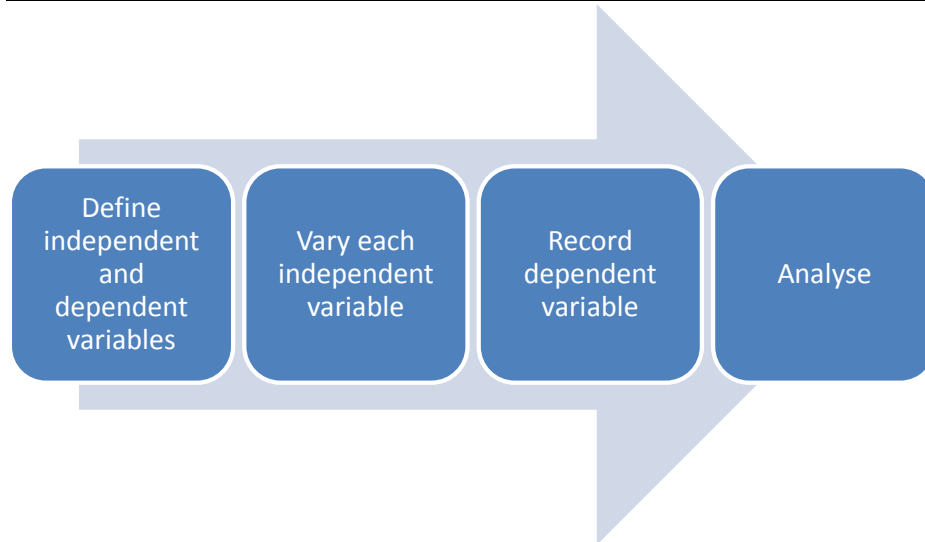


Figure 3-10 Parametric analysis procedure

3.8.3.1 Climatic data

EnergyPlus requires climatic data to run valid simulations based in a given location. These climatic data are added as separate weather file input before running the simulations as shown in Figure 3-11. The weather file used in this research has been synthesized by Meteonorm (2012) for Abuja, Nigeria in hourly timesteps over a year. Meteonorm synthesizes climatic values into a format called Typical Meteorological Years (TMY). Values such as ground temperatures, average temperature, solar azimuth and elevation, global, diffuse and beam (direct normal) radiation as well as radiation on inclined planes, longwave radiation, luminance, precipitation, and humidity parameters are available. The weather file has been added to a downloadable Yahoo Groups database for weather files. Weather files available for input include Test Reference Year (TRY), Typical Meteorological Year (TMY) 1 and 2, and Weather Year for Energy Calculations (WYEC) 1 and 2. Crawley (1998) claims that either the TMY2 or WYEC2 data sets provide energy simulation results that most closely represent typical weather patterns after he contrasted the different hourly weather data sets.

3-Methodology

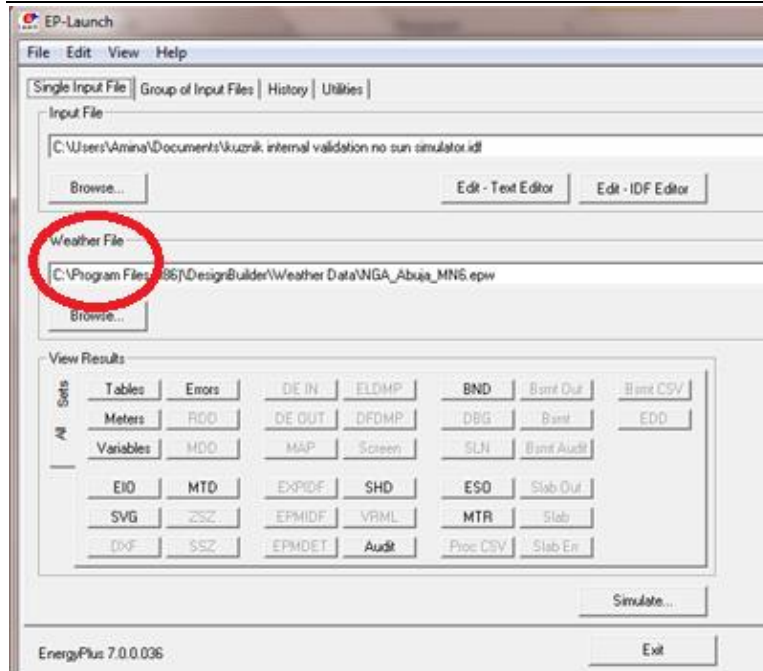


Figure 3-11 Weather file input in EnergyPlus

The TRY data (NCDC 1976) comprises actual historic year of weather, selected between years 1948 and 1975. Years in this period which had months with extremely high or low mean temperatures were progressively eliminated until only one year remained. This type of dataset is limited to a small number of locations in the United States of America and neglects total horizontal and direct normal solar radiation data.

In addition to the data making up TRY, total horizontal and direct normal solar radiation data for 234 United States of America locations make up TMY (NCDC 1981). For TMY, individual months are selected as compared to the long-term distribution of significant criteria over the year making up TRY. The resulting TMY data files each contain months from a number of different years.

Another approach created the Weather Year for Energy Calculations (WYEC). It is a typical weather file that has three years: typical (average), cold/cloudy, and hot/sunny. This approach captured more than the average or typical conditions and provide simulation results that identify some of the uncertainty and variability inherent in weather.

More comprehensive methods that attempt to produce a synthetic year to represent the temperature, solar radiation, and other variables within the period of record are more appropriate and will result in predicted energy consumption and energy costs that are closer to the long-term average (Crawley, 1998). Both TMY2 and WYEC2 use this type of method. They are based on improved solar models, and more closely match the long-term average climatic conditions.

METEONORM 6.x (2012) is a 'comprehensive meteorological reference gives you access to meteorological data'. It uses sophisticated interpolation models that allow a reliable calculation of solar radiation, temperature and additional parameters at any site in the world. From the monthly values (station data, interpolated data or imported data), Meteonorm calculates hourly values of all parameters using a stochastic model. The resulting time series correspond to "typical years" which have been determined to present valid simulation results (Crawley, 1998).

The generation of temperature is based on global radiation and measured distribution of daily temperature values of approx. 5000 sites. Meteonorm generates also additional parameters like precipitation, wind speed or radiation parameters like diffuse and direct normal irradiance (Remund *et al.*, 2010).

The accuracy of Meteonorm predictions is statistically examined by Desnica *et al.* (2006). The predicted results from Meteonorm are compared with all available long-term averaged measured values for each month from Croatian stations and other geographically close stations in neighbouring countries. The results showed a very good agreement generally, with correlation coefficient ranging from 0.992 to 0.999.

3.9 Computer simulation software packages

Numeric building energy calculation comes in computer software packages that perform several functions as specified by the developers. They may be able to calculate cooling or heating loads, simulate atmospheric conditions within the building, costing, feasibility analysis of different retrofits including renewable energy and low- energy technologies etc. Building energy simulation may be divided in two phases; geometric modelling and energy calculation phases.

Modelling implies a simplification of the real physical processes in real buildings. These simplifications are made by software designers through the use of assumptions that allow the problem to be solved more easily within practical constraints such as; the core capacity

and run-time of computer hardware; generally accepted mathematical expressions for certain physical processes.

Building energy simulations are used to predict energy flows by examining variables such as temperatures, envelope losses, system performance, and electrical loads in buildings. Computer simulation as a numerical method of analysis was chosen as a preferred method of prediction compared to analytical ones due to the inflexibility and incomplete nature of analytical methods as indicated in Judkoff and Wortman (2008a). Due to the complexity of a building model, time and finances, computer simulations can analyse the effects of different energy conservation mechanisms and their complex interactions more efficiently, comprehensively and accurately than any other available method (Kaplan and Caner, 1992) in (Ibarra and Reinhart, 2009).

Most building energy simulation programs come with a graphical user interface (GUI) as well as the actual simulation engine. GUIs are used to model input files and display results for the simulation engines. Usually, the developers of simulation engines are public organizations such as government laboratories and universities whereas GUIs are more often developed by commercial vendors. As a result there can be several GUIs for the same simulation engine. While the choice of GUI determines the ease of use if a simulation program, it is ultimately the engine that determines how reliable simulation results are (Ibarra and Reinhart, 2009).

The modelling and simulation is conducted by building energy simulation software Energyplus which requires a modelling plug-in. Designbuilder was used as the plug-in for this research. Some other examples of software packages used for building energy simulations are TRANSYS, Esp-r and SUNREL as shown in Table 3-5.

Software	Study
TRANSYS	(Ibáñez <i>et al.</i> , 2005; Ahmad <i>et al.</i> , 2006; Oyeleke, 2011)
Esp-r	(Heim and Clarke, 2004; Fang and Medina, 2009)
SUNREL	Khudhair and Farid, 2007

Table 3-5 Examples of simulation software

The combination of Energyplus and Designbuilder does the following:

1. Categorize heating/cooling loads, ventilation, lighting (Henninger *et al.*, 2004), wasted energy through glazing, infiltration and operation (Wang *et al.*, 2009)
2. Modelling and prediction of performance with energy conservation mechanism (Pedersen, 2007)
3. Analysis of total consumption of different loads against climate and costs (Crawley, 2005)
4. Benchmarking and compliance (Jentsch *et al.*, 2008)
5. Statistical analysis of data for associations and correlations (Buchanan and King, 1987)

The selection of which software to use is based on the following reasons:

- Capability of the software in modelling and energy calculations
- User's skill and sophistication of the software
- Cost

3.9.1 Modelling with DesignBuilder

Designbuilder performs the following functions; building energy simulation based on real weather, visualization, CO₂ emissions, solar shading, natural ventilation, day-lighting, comfort studies, computational fluid dynamics, pre- and early stage design, building energy code compliance checking HVAC simulation and building stock modelling. Output is based on detailed sub-hourly simulation time steps using the EnergyPlus simulation engine. However, it should be noted that the simulation in DesignBuilder is performed by an internal simulation engine provided by EnergyPlus. DesignBuilder is therefore a graphical user interface (GUI) for EnergyPlus.

DesignBuilder models are organised in a simple hierarchy as shown in Figure 3-12.

Building model data is laid out on the following tabs in the DesignBuilder interface:

- Activity
- Construction
- Openings
- Lighting
- HVAC
- Options

- CFD

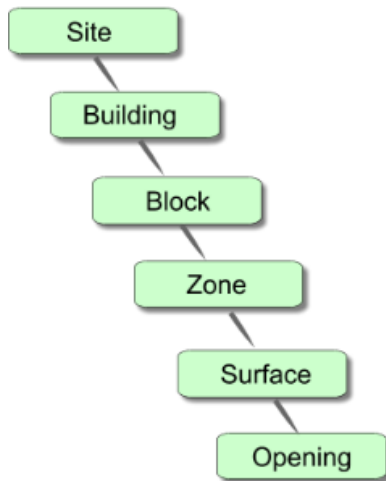


Figure 3-12 DesignBuilder model design hierarchy

The process for creating a new building model typically follows the following sequence (DesignBuilder, 2011):

- Create new site
- Create new building
- Create building geometry
- Partition building into thermal zones
- Set Model Data
- Add any 'custom openings' (windows, doors etc) by drawing up the surface level
- Size heating and cooling systems
- Check design by carrying out summer and winter simulations displaying hourly data
- Run annual simulations

3.9.2 Simulations with EnergyPlus

The simulations form part of the procedure of conducting a parametric analysis to optimize bio-climatic design variables on a hypothetical base-case building. This is fundamental to optimizing the thermo-physical and operational strategies behind a proposed PCM model as

discussed in section 3.3. Chapters 6 and 7 discuss bio-climatic and PCM optimization respectively using computer simulations respectively.

The inclusion of the whole building energy analysis software, EnergyPlus allows all energy flows to be examined in a dynamic and integrated manner. Thus one limitation of the parametric technique is offset by the whole building energy calculation in the process. The limitation is the inability of the technique to capture the effect of changing an independent variable on more than one dependent variable.

Some advanced EnergyPlus simulation capabilities are limited in the DesignBuilder software (Ibarra and Reinhart, 2009) creating the need to export DesignBuilder models files into more powerful simulation engines. For instance it is currently not possible to model or simulate PCMs in DesignBuilder; but possible in the external version of EnergyPlus.

EnergyPlus is a 'Qualified Computer Software' for calculating energy savings for purposes of the energy-efficient commercial building in the USA (Pedersen, 2007). Expert users can get access to the source code allowing for third-party validation which adds to the software's credibility and long term reliability. EnergyPlus has been validated under the comparative Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs BESTEST/ASHRAE STD 140. It accurately predicts space temperatures which is crucial to energy efficient system engineering, occupant comfort, occupant health, system size, plant size (Ibarra and Reinhart, 2009).

EnergyPlus is an integrated simulation. This means that all three of the major parts, building, system, and plant, are solved simultaneously. The program is a collection of many program modules that work together to calculate the energy required for heating and cooling a building using a variety of systems and energy sources. The core of the simulation is a model of the building that is based on fundamental heat balance principles

(EnergyPlus, 2011). See schematic in Figure 3-13

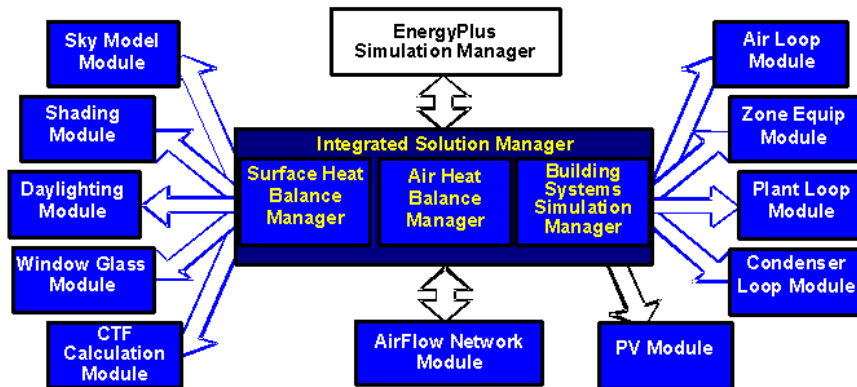


Figure 3-13 EnergyPlus energy calculation schematic (EnergyPlus 2010)

In this context, the energy flows investigated are the effects on electricity consumption and thermal comfort of:

- Bio-climatic design principles
- Incorporating PCMs into the building fabric

Originally, EnergyPlus simulate PCM performance using an enthalpy formulation called the Conduction transfer function (CTF) (Clarke, 2001). The algorithm models temperature dependent thermal conductivity, so simulations can be done with the PCM in any location within the surface structure. Because of the short time steps used in the finite difference solution algorithm, the zone time step can be reduced to correspond with the one minute minimum time step, small enough to produce adequate predictions.

More recently, EnergyPlus added a new solution algorithm that utilizes an implicit finite difference procedure called conduction finite difference (CFD). Computer models are mainly based on response functions or numerical finite differencing. Response function is good for solving linear equations that are time invariant while numerical finite differencing is good for simultaneous solution of complex non-linear problems while taking into consideration variant time steps. This level of accuracy for finite differencing aids spatial and temporal integrity of real energy systems (Clarke, 2001).

EnergyPlus software is most suitable tool for the simulation of PCMs incorporated in the building fabric (Tetlow *et al.*, 2011). EnergyPlus has been demonstrated to simulate PCM

performance in buildings by Pedersen (2007); and validated for simulating PCM systems in buildings by Chan (2011).

According to Castell, *et al.* (2009) who compare the capabilities of a commercial software EnergyPlus to calculate energy performance of PCM incorporated cubicle; the simulations in EnergyPlus do not reflect the effect of the PCM in the thermal behaviour of the cubicles. This difference is especially important for the simulations with controlled temperature, where the improvements in the energy consumption are not observed in the simulations. Some additional work must be done to consider the experimental weather data and to modify other parameters (such as infiltrations) to better represent the real behaviour of the cubicles and match better with the experimental results.

Chan (2011) uses statistical indices namely mean bias error (MBE) and root-mean-square error (RMSE) for error analysis to validate his simulated results from EnergyPlus and experimental results from Kuznik and Virgone (2009a). Kuznik and Virgone (2009a) conducted an experiment to examine the thermal performances of a PCM copolymer composite wallboard using a full scale test room. They presented the variables and results in detail to provide an opportunity for comparative validation for other researchers. The results from Chan (2011) show that all the cases slightly underestimate the surface temperatures with MBE ranging from -0.68% (northern wall on summer day) to -1.07% (western wall on winter day); and RMSE values range from 2.07% to 3.9% . On the whole, it shows that the computer simulated results are in good agreement with the experimental data presented by Kuznik and Virgone (2009a).

Neto and Fiorelli (2008) compare a simple model using EnergyPlus and artificial neural network to simulate PCM performance. EnergyPlus consumption predictions presented an error range of $\pm 13\%$ for 80% of the tested database. Even though the error for EnergyPlus is higher than that of ANN, the algorithm used an implicit finite difference scheme coupled with an enthalpy-temperature function accounts for phase change energy accurately.

3.10 Limitations

Several limitations affected the research problems. They classified into:

- Fieldwork stage limitations
- Simulation stage limitations

3.10.1 Fieldwork stage

The limitations experienced when conducting the fieldwork include:

1. Access to buildings and building documents
2. Unreliable feedback from questionnaires
3. Inadequate records
4. Confidentiality for some companies
5. Insecurity
6. Sampling issues
7. Electricity consumption data

Access to the selected buildings was gained through different category of gatekeepers. Gatekeepers could be an associate who works in the building, or through an introduction to one. The gatekeeper could also be the head of the organization itself. The latter proved to be the best type of gatekeeper because approval is sought from the head before the audit could commence in the first place. Plans to audit some suitable buildings failed due to a lack of approval from the head.

However, unreliable feedback was recorded from some of the buildings where the liaison officer in charge of assisting with the data collection was reluctant to help.

Another source of unreliable feedback was due to poor record keeping due to lacking management practices or negligence or lack of knowledge by the person in charge.

Some of the buildings housed sensitive offices or businesses facing confidentiality and even legal difficulties and so refused to participate in the audit exercise. However, a few agreed with the provision that they remain anonymous within the thesis.

Political insecurity was an issue that prevented the audit of buildings in a whole design climate; that covering Port-Harcourt city. An attempt to audit the building by proxy failed due to the complex nature of the data required.

There were limited resources to cover more data than the author collected in the 3 months it took for the fieldwork. This means that the period for data collection has to be rationalized.

Sources of error during the data collection stage include:

1. Poor records due:
 - To poor management
 - To ability of the person in charge

- To erroneous data recorded in the questionnaire due to fraudulent activity in the company. For instance, to cover up for fraudulent purchase of diesel to power the back-up generators, the respondent may doctor the amount of diesel consumed

Gatekeeper access related issues directed the sampling style adopted in this study. Being a quantitative study, ideally sampling should be a random process that became impossible due to a lack of database-type information on suitable buildings, but also access into identified buildings.

Gatekeeper issues are attributed but not limited to privacy, security, market competition, and bureaucracy and administrative culture. As mentioned earlier, a whole region was rendered insecure due to political activity. Another issue was that the researcher could not access a list of mix-mode buildings in these cities to enable a random selected of these buildings to make it indeed a true experiment. For the buildings identified to be mix-mode, access to the type of data required was considered sensitive to some organisations and thus required approval from key management personnel that were inaccessible or simply declined to participate. In other instances, the key personnel may have given access but for bureaucratic and administrative culture, the staff member tasked with filling the questionnaire will simply fail to do so. This may be due to incompetence, poor record-keeping, and power dynamics or simply to protect against the exposure of illegal activity within the organisation.

In the event that the energy audit was successful, some of the documents filled and submitted proved to be erroneous or had missing data in the computing stage. This problem in some cases proved so poor that the cases had to be discarded.

3.10.2 Simulation stage

The methods of analyses adopted, as discussed earlier have their inherent drawbacks (Judkoff *et al.*, 2008b). The following are limitations encountered during the simulation stage:

1. Climatic data
2. Occupant behaviour
3. Erratic power supply
4. Thermal calculations
5. Validation of software

6. Cost of software and training

7. Researcher's inexperience and other human error

All the above limitations are acknowledged and all effort has been made to minimize their effect on the validity of results. There is naturally a difference between climatic data experienced over the time the data was collected and that used during simulations as discussed in section 3.8. However, the weather file and software adopted for this research have been used successfully in other investigations and validated by Desnica *et al.* (2006) and Remund *et al.* (2010).

Occupant behaviour is difficult to capture, especially in the limited timeframe. However its effect on the results has been limited by the nature of electricity consumption recorded through a smart meter, rather than estimated based on the occupancy schedules. Its effect and the steps taken to reduce the impact when the primary energy users in the fieldwork are disaggregated in Chapter 5 are discussed.

Erratic power supply made electricity supply data collection complex. A technique of estimating electricity supply taking both the central utility supply, and back-up privately generated power into consideration in Chapter 5.

Difference between thermo-physical properties of building elements existing and modelled for simulations have been considered and limited by using different software for different materials as discussed in section 3.3. However errors still remain due to simplifications of already mentioned complex energy flows in a building. Heat transfer assumptions are made in the software and have been duly noted and its effect on the results have been reported in literature and discussed further in Chapters 4 and 7. The validation exercises described in Chapter 4 are considerations to limiting the impacts of these errors. The results of the validation indicate the error is within acceptable levels.

The cost of commercial software was a consideration for the option to adopt. Even though student discounts are available, the discounted prices and any training for a novice user can still be prohibitive.

From the initial fieldwork stage to the simulation stage, the researcher's human error is naturally a limitation. To check this, building input was enhanced through careful observation, pictures and building plans supplied in the energy audit. Analytic calculations in the second analysis chapter were done and compared with the default values supplied in the library of DesignBuilder. Inconsistent values are recalculated and substituted with more practicable ones calculated. This analytical validation also improved errors due to

differences between actual thermal and physical properties of the building. Proper records of field and simulation notes are stored physically and electronically in Microsoft Excel sheets. Care was taken when naming and dating the relevant files.

It should also be noted that the researcher had no prior experience in using the software DesignBuilder or EnergyPlus. Being an architect, the text input required by EnergyPlus for the modelling of PCMs proved complex. It was designed for practitioners with engineering backgrounds. However, a large effort was made to learn how to use both software by attending paid training and workshops, online tutorials, joining online support forums and asking other experienced users for one-on-one help.

3.11 Reliability, Replicability and Validity

Reliability is concerned with the stability of tests measuring dependable variables. The dependent variables in this research are electricity consumption and thermal comfort. The issue is testing if re-subjecting the independent variables to the same measuring test will yield the same results for the dependent variables. For instance, will acceptable values of total electricity consumption be predicted if another author used my independent variables and software?

In recognition of reliability of results, EnergyPlus, a tool that is a highly sophisticated and validated is used to run the simulations. External validation of the software has been discussed in the literature review chapter. An internal validation has been conducted by the author as discussed in Chapter 4. In addition, an attempt is made to place all results presented in theory in the analysis chapters (5-6).

Replicability is based on researchers' intrinsic inclination to question their own and other peers' findings. It is concerned with establishing a well-documented and verifiable methodology of research. This is a check especially important to quantitative research. The aim is to reduce the impact of researchers' bias and subjectivity on the research process, and conclusions generated.

The methodology laid out in this and result Chapters 5 to 7 reflect on the principles of replicability. The methodology presented provides the steps to test the energy conservation and thermal comfort performance of PCMs in office buildings in Nigeria.

Validity is concerned with the integrity of the conclusions generated from a research (Bryman, 2008). Measurement, internal, external and ecological validity are forms of establishing the validity of research. Measurement validity is concerned with the

performance of the measurement instrument in relation to the concept being examined.

Internal validity is concerned with achieving the aim of inferring causality, which is vital to most experiments. External validity questions the generalizability of the results to the population; and ecological validity questions if it has enough practical value as to be applied in real life.

The different methodological criteria adopted in this research are associated with one or more forms of validity issues. That of simulation has been discussed within the literature review and this chapter already.

Internal validity in experiment design is important in experiment research designs and is limited by random assignment of sampling and having a control group. This research is exploratory and has the aim of indicating if the choice of building material has an effect on electricity consumption. It is testing within subjects, but running the simulations with different variables. The control and experimental groups are described in Chapters 6 and 7 accordingly. Consideration has been given to describing the control groups, called base-case, and the experimental groups in order to achieve internal validity.

Sampling selection issues affect external validity related to representative samples and ability to generalize findings to the target population. The exploratory nature of this research and sampling issues limit its scope for generalization. Due to the aim of the study, to evaluate the potential for energy savings, the context has been reflected on. The results may be generalized only to commercial buildings with similar climates and construction. Ecological validity is the feature of research to be useful in real-life settings. It is strong for fieldwork studies. The data collection and analysis is based on field data. The measurement instruments used for data-collection are self-administered questionnaire and unstructured, non-participant observation with analysis provided by sophisticated and dynamic software. The effort in collecting primary data from the fieldwork is a consideration on ecological validity.

3.12 Ethical issues

Ethical issues worthy of note include:

1. Deception: True representation of aims of investigation was given to the respondents, building occupiers and business management team
2. Response rates: True response rates of the questionnaire are reflected in the reduction of sample size as shown in Chapter 5. The sample size decreased from 24

to 15 buildings during the field data collection stage. The sample size further decreased to 5 buildings during the analysis of field data stage

3. Cooperation: Only organisations that gave consent were considered for the research. The consent form is attached to the questionnaire. Approval was also given to use or publish privately owned data
4. Confidentiality and anonymity: These have been sought by some organisations and respondents. The issues are reflected by numerically labelling the buildings in Chapter 5. None of the respondents have been mentioned by name
5. Funding body: Satisfying the funding body's mandate for energy related topics, in this instance energy conservation in Nigeria has been adhered to as evidenced by the thesis itself
6. Bias: Presentation of data and results without bias was achieved principally due to the objective nature of the study, but also the researcher's effort to make it so.
7. Plagiarism: Plagiarism was guarded against at all time during the writing up of this thesis by properly referencing other authors acknowledging their ideas

3.13 Conclusions

In Chapter 2, the case for PCMs as an energy conservation mechanism in Nigerian office buildings is made. This chapter provides information on how the study is conducted in order to achieve the aim of evaluating the potential of incorporating PCMs in a composite hot and humid/hot and dry climate in order to conserve energy in office buildings within the context of an overburdened and failing central power utility in Nigeria.

A novel contribution is made for collecting electricity data for the contextual case existing in Nigeria; where there is an erratic power supply and back-up power generator are employed for a significant duration. The technique involves calculating the difference in total working hours from hours of back-up power recorded as the utility supply hours. Then the supply from the back-up generator is estimated from the percentage of time it is switched on.

A quantitative research strategy using cross-sectional method of data collection is used using an energy audit process to collect data in the field. The research instruments utilised for the energy audits include:

- Self-administered questionnaires
- Unstructured non-participant observation

- Literature review of national statistics, building regulations, and climatic data

Selected sampling was adopted for this research. The buildings are chosen based on the design climates in Nigeria and building selection.

The analyses conducted on the collected data include degree day calculations which are based on correlation techniques and descriptive statistics. Parametric analyses are also employed to holistically study the effect of PCMs on thermal comfort and electricity conservation. Quasi-experiments using computer simulations by building energy simulation software Energyplus are conducted on the 5 buildings that had adequately filled the questionnaires from the fieldwork.

EnergyPlus (Pedersen, 2007; Neto and Fiorelli, 2008) combined with a modelling plug-in called DesignBuilder (Ibarra and Reinhart, 2009) is used to construct a bio-climatically optimized base-case model for the proposed PCM. The same process is also used to optimize the performance of PCM thermo-physical and cooling operational strategies. Other issues discussed in the methodology chapter include reliability, replicability, validity, ethical issues, limitations and a reflection on how the negative effect of these are minimized on the research process. EnergyPlus has been validated for simulating PCM systems in buildings by Chan (2011).

4 CHAPTER 4

VALIDATION STUDY

Contents
4.1 Overview
4.2 Building energy calculations: PCM thermal performance testing
4.3 Limitations of analysing PCMs with computer simulations
4.4 Validation
4.5 Conclusion

Problem	Chapter one: Introduction- 'Nigerian buildings and Energy use'		
Theoretical framework	Chapter two: Literature review- 'Phase change materials as energy conservation mechanisms in buildings'		
Methodology	Chapter three: 'Methodology'	Chapter four : 'Validation study'	
Results	Chapter five: 'Disaggregating primary electricity consumption for office buildings in Nigeria'	Chapter six: 'Optimizing thermal and energy performance of buildings'	Chapter seven: 'PCM performance in office buildings'
Conclusion	Chapter eight: Conclusion		

4.1 Overview

The calculation of the effect of PCMs on thermal comfort and energy conservation are conducted by Analytical (Theoretical) testing, Laboratory, Field experimentation and Computer simulation (Numerical testing). A discussion of the benefit and limitations of each method is conducted in this chapter and computer simulations are shown to be more suitable for this study.

Validation of the simulations is required to ascertain that the software chosen and user are able to adequately model the buildings and climate. As mentioned in the Methodology chapter, different versions of EnergyPlus are used to run the simulations with PCM and without. DesignBuilder- which uses EnergyPlus v6 is used to model the base-case building without PCM and is then imported into an external version of EnergyPlus v7 to model and simulate PCMs. In the case where two software are used, there is a need to:

- Validate the two set of results
- Validate the user's ability and the capability of the software

4.2 Building energy calculations: PCM thermal performance testing

Building energy calculation process involves predicting thermal performance and energy requirements of buildings (Ayres and Stamper, 1995). Existing methods to calculate building energy are:

- Analytical (Theoretical) testing
- Experimentation in laboratories and in the field
- Computer simulation (Numerical testing)

4.2.1 Analytic testing

Analytic tests simply refer to heat balance formulation and solutions of problems but are of limited applicability due to their ability to calculate only static parameters as shown in studies by Durmayaz, Kadioglu *et al.* (2000); Li and Lam (2000); Lam *et al.* (2004); Kanda, Kawai *et al.*(2005); and Xiao *et al.* (2009).

Latent heat transfer problems for PCMs are complex and challenging for analytical calculations. Analytic calculations require a simplification of complex energy flows in buildings. However, building energy flows are dynamic and complex. These assumptions and simplifications, in addition to the non-dynamic nature of analytic calculations of complex and dynamic building energy flows limit them from being used for detailed PCM performance examinations.

4 Validation study

Neural network (NN) models or neuromorphic systems are examples of analytic building energy calculating techniques based on operational principles similar to those of the human brain. A neural network can be considered, in general, as a set of linked units able to connect an input phenomenon (Caudana *et al.*, 1995). In their work, Neto and Fiorelli (2008) model a simple problem based on artificial neural network as an auditing and predicting tool in order to forecast building energy consumption. The results for the neural networks showed a fair agreement between energy consumption forecasts and actual values, with an average error of about 10% when different networks for working days and weekends are modelled.

Degree-days, another analytic method calculated through regression techniques has been used to model predictions for energy performance indicators (Chung and Hui, 2009) and thermal performance of PCM (Zalba *et al.*, 2004).

Of particular importance to this research, Darkwa and O'Callaghan (2006) gave a formulation for calculating effective heat capacity, C_{eff} , of PCMs as shown in Equation 4-1 as:

$$C_{eff} = C_s + ae^{-0.5\left(\frac{T-T_m}{b}\right)^2} \quad \text{Equation 4-1}$$

Where C_s is specific heat capacity, a is the total amount of latent heat, T is the coefficient of solar radiation, T_m is transition temperature and b is the width of phase change zone. The use of such an equation is further illustrated in Chapter 7.

In a study, Xiao *et al.* (2009) analytically calculated the optimal transition temperature and the total amount of latent heat capacity. The equation of the optimal transition temperature, T_m of interior PCM in a lightweight passive solar room is obtained as Equation 4-2:

$$T_m = T_a + \frac{(Q_r + Q_{r, in})}{h_{in} \cdot P \cdot A} \quad \text{Equation 4-2}$$

Where T_a is the average room temperature, Q_r is the transmitted solar radiation on the interior surfaces (W), $Q_{r, in}$ is the radiation heat transfer rate from indoor heat sources (W), h_{in} is the heat transfer coefficient of interior surface ($\text{W m}^{-2} \text{ } ^\circ\text{C}^{-1}$), P are the duration (s) and A_{in} is the area of interior PCM panel (m^2)

4.2.2 Experimentation

Experimentation is usually conducted for problems that are difficult to analytically solve or simulate. There are two types:

- Laboratory testing
- Field testing

4.2.2.1 Laboratory testing

Laboratory techniques for examining PCM performance are classified broadly into its properties and applications. Laboratory techniques used for calculating the thermo-physical microstructures of PCMs are usually by scanning electron microscope SEM. Latent heat of fusion and melting temperature of PCMs are measured by differential thermal analysis (DTA), and differential scanning calorimeter (DSC) (Atul Sharma, 2009). In DSC and DTA techniques, sample and reference materials are heated at constant rate. The temperature difference between them is proportional to the difference in heat flow between the two materials and the record is the DSC curve. The recommended reference material is alumina (Al_2O_3). Latent heat of fusion is calculated using the area under the peak and melting temperature is estimated by the tangent at the point of greatest slope on the face portion of the peak.

Atul Sharma (2009) argues that DSC fails to provide correct information; due to a temperature gradient inside the PCM and depends on the heating/cooling rate and sample mass; or meaningful information on super-cooling. Latent heat and melting point are better determined by thermal analysis.

Castello et al. (2008) investigate different measurement procedures of DSC to determine enthalpy temperature relationship of PCM and claims to increase the DSC performance to a satisfactory level.

Other tests performed on the PCM include the thermal stability by a melt–freeze cycle test and thermal conductivity with ready-made measuring apparatus.

A thermal performance test was conducted on PCM plates (Li et al., 2009). They were put into the constant temperature drying oven for the melting process then immediately subjected to the solidification process in the refrigerator performed consecutively up to 100 thermal cycling. The surface temperature variations of the samples during these processes were automatically recorded to a computer via a data-logger. This method is adequate for assessing just the thermal performance of the plate for preliminary studies on PCM products rather than buildings.

4 Validation study

Alawadhi (2008) presents the thermal analysis of a building brick containing PCM in a laboratory test. The model consists of bricks with cylindrical holes filled with PCM. The thermal effectiveness of the proposed brick-PCM system is evaluated by comparing the heat flux at the indoor surface to a wall without the PCM during typical working hours. A parametric study is conducted to assess the effect of different design parameters, such as the PCM's quantity, type, and location in the brick. Four different cases are investigated, bricks with one, two, and three PCM cylinders, as well as, a brick without PCM. Three type of paraffin PCMs are examined: n-octadecane, n-eicosane, and P116. PCM transition temperature is within the operating temperature of the system- a statement that fails to show optimization of the transition temperature. The P116 and noctadecane are ineffective in reducing the heat flux to the indoor space because transition temperature is too low and too high respectively. However, when n-eicosane is introduced, the rate of change of the heat flux is substantially reduced during the period from 10 a.m. to 5 p.m., with a maximum heat flux reduction of 24.2% because its transition temperature is optimum. Having a minimum quantity of the PCM is desirable to maintain the strength of the brick. Results indicate that with only one cylinder the maximum heat flux is reduced by about 11.5%, and 17.9% with two cylinders. When three cylinders are used, the reduction reaches 24.2%. The results indicates that having PCMs in the building fabric increases the heat capacity of the fabric and reduces heat gain by absorbing the heat before it reaches the interior. The limitations of laboratory testing is evident in the study. These include oversimplifying such processes such as solar incidence and heat flux through construction materials.

4.2.2.2 Field testing

Field experiments present the most realistic results because they have been shown to work in practice if successful report Cabeza *et al.* (2007).

PCM performance has been evaluated in the field by Kuznik *et al.* (2011). The investigation studies building component, method of incorporation, human comfort, and PCM thermo-physical properties. The PCM material used is *Energain* by the Dupont de Nemours Society (2012). It is composed of 60% of micro-encapsulated paraffin, which has a melting temperature of about 22 °C. The final form of the PCM material is a flexible sheet with a density of 1019 kg/m³. In order to assess the potential of PCM wallboards, two offices in a renovated office building are monitored over a year. One has PCM wallboards in the lateral walls and in the ceiling, while the other room,

4 Validation study

identical to the first one, was not equipped. The first set of experimental data analysed was for a week-end (17th and 18th) in November in an effort to limit the effects of building occupants to the two occupants of the offices behaving in a similar manner. The maximum temperature of the room with PCM is lower than the maximum temperature of the room without PCM of about 2.2 °C conforming to earlier works reviewed. The week-end of March 28th/29th had temperature of the rooms rise to about 40°C. The PCM was completely in the liquid phase and the two rooms had very close air temperature indicating no latent storage effect in the wallboard. For the period between February and December, the difference between the room with PCM and the room without PCM is about 98 h for the number of hours for which the globe temperature is above 29 °C. In conclusion, the thermal comfort is enhanced due to both the air temperature and the walls surface temperature. This particular effect is efficient if the building before renovation is of low inertia and if the temperature variations are around the phase change temperature of the PCM.

4.2.3 Computer Simulating PCM applications

Simulations in buildings are used to predict energy flows in internal temperature profiles, envelope losses, system performance, and electrical loads (Ibarra and Reinhart, 2009). The building in question may be an existing structure, a retrofit of an existing structure, or a new design. Building energy flows are complex, hence the need for a complete simulation of the thermal behaviour of the designed space in the conditions of use established beforehand (Ibáñez et al., 2005).

Computer simulations and experimental methods are more suited to the non-linear nature of PCM problems and the thermo-physical properties of the phases (Agyenim *et al.*, 2011). Computer simulations involve the use of software programs to predict building energy performance. A common hypothesis for all computer models is that the input variables are based on realistic data when they are available, otherwise the evaluation of energy consumption might be unreliable (Neto and Fiorelli, 2008). Computer simulation of PCM is suitable because of the ability to manage the complexity of the phenomena involved by changing one factor at a time. However, due to the many factors affecting ability and effectiveness of PCMs in buildings to achieve the practical application, computer simulation is only possible with experimental data (Kuznik and Virgone, 2009b).

A computer model is developed by Pasupathy *et al.* (2008a) to validate the field measurement of a PCM roofing system; assuming the heat conduction in the composite

4 Validation study

wall is one-dimensional. The aim is to study the effect of having PCM panels on the roof for thermal management of a residential building. The study was conducted on two identical test rooms. One room is constructed without PCM and the other with a stainless steel panel filled with PCM placed in between the roof top slab and the bottom concrete slab, to evaluate the thermal performance of an in-organic eutectic PCM. The eutectic has a transition temperature in the range of 26°C to 28°C. Cold water from the tank is allowed to pass through the heat exchanger as and when required. This water is used to cool the PCM when the complete freezing of PCM is not possible in the night hours during the summer. In addition, during peak summer in daytime when the temperature of the PCM starts increasing above its melting temperature, cold water is to be circulated to maintain constant temperature around PCM melting temperature. It is observed from the study that the quantity of water required is very large which is not easily available during the summer months. Experiments are conducted in the PCM room during the months of January and February in Chennai, India. Experiments are also conducted for the room with and without PCM panel and results are validated with simulated ones.

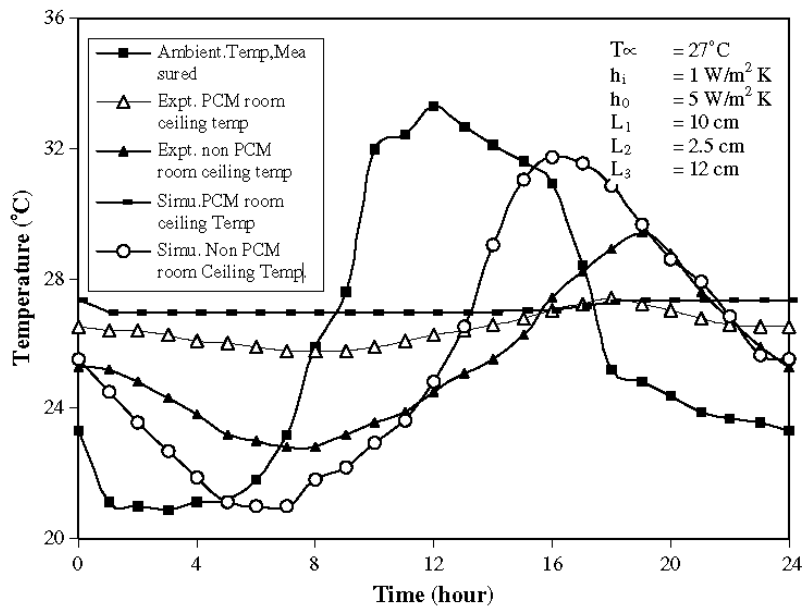


Figure 4-1 Results of experiment compared to simulation by Pasupathy *et al.* (2008a)

There is a significant difference between the results predicted by the simulation and experiment (see Figure 4-1) because building energy simulation is always an abstraction of reality. Certain assumptions and simplifications are made in the modelling process in

4 Validation study

order to represent the actual building in a way which the software will understand. A difficult choice between oversimplifying in order to save time and trying to be overly precise have to be delicately balanced between the two extremes (Patrick Arnold *et al.*, 2005).

The results by Pasupathy *et al.* (2008a) emphasize the difficulty of using numerical tests to study PCM behaviour. During the modelling phase, the thermal conductivity of the concrete slab and the roof top slab are considered constant and not varying with respect to temperature. The convection effect in the molten PCM is neglected. A uniform specific heat capacity is considered during phase change process, though in reality, there is variation within this small temperature range. In the experimentation, the measured air temperatures vary approximately ± 3 of 27 C whereas in the simulations, the air temperature of the PCM room was kept a constant value of 27 °C throughout the day. Furthermore, it is observed that the temperature difference of the ceiling in the PCM and non-PCM rooms is not very appreciable as in the theoretical results. The differences in temperature value between the theoretical and experimental results are due to the following reasons. However, a similar pattern exists between the theoretical and experimental results.

Other differences the theoretical and experimental results may be due to the following reasons:

1. The effective thermal conductivity of the PCM in the experiment is higher due to the presence of uniformly distributed high conductivity heat exchanger material in the PCM panel
2. The actual phase change may not occur during the phase change temperature prescribed in the theoretical analysis

The above study by Pasupathy *et al.* (2008a) highlights the importance of validation of results. Validation process ensures that the predictions from computer simulations are acceptable. Validation is further discussed in Chapters 3 and 6.

4.3 Limitations of analysing PCMs with computer simulations

Computer simulations are an abstraction of reality and therefore contain simplifications and assumptions on the energy flows in any building thereby increasing the possibility of errors. Due to these errors, in this research the predictions from the simulations are used to qualitatively assess the effect of a given independent variable on electricity conservation and thermal comfort.

4 Validation study

The main factors that affect the accuracy of simulated predictions according to Zalba *et al.*, (2003) and (Clarke, 1993) include:

1. Accuracy of the input data depending on the accuracy to which the building properties are known, user's skill, experience, and time
2. Applicability of the tool to the building and climate being analysed
3. Ability of the tool to predict real building performance when given perfect input data
4. The absence of a validation methodology

However, the main drawback of simulating Phase Change Materials is caused by difficulty in representing the phase change interface (Lamberg *et al.*, 2004; Pedersen, 2007b; Fang and Medina, 2009). It was found that sometimes PCMs would begin the phase change process from partially melted states which makes them difficult to model the heat energy flux in the material. Currently used simulation models are the enthalpy and effective heat capacity methods (Fang and Medina, 2009).

The enthalpy method assumes that the total energy is composed of sensible and latent parts. The effective heat capacity method on the other hand, in the phase change temperature range, increases the specific heat of the PCM to simulate the delayed effect of the phase change on the heat transfer process. In numerical simulation, the new effective heat capacity value is constantly updated according to the temperature of each node in the simulation.

Mathematically, the two methods are adequate, but their main shortcoming arises from how they handle the absorption or release of heat over the phase change temperature range in the phase change process which may lead to two problems (Fang and Medina, 2009):

1. Inaccurate estimation of the thermal storage capacity: During the phase change process of the PCM, the heat is not evenly absorbed or released along the phase change temperature range. It is observed that there was always a single large heat flow peak that occurred at a certain temperature in the phase change temperature range. Therefore, it is likely that the heat absorbed or released in the phase change process could be overestimated or underestimated if incorrect heat absorption or release distribution assumption were made.
2. Incorrect prediction of the phase change temperature: Inaccurate temperature predictions will be produced if incorrect heat absorption/release distributions are assumed. When the phase change process takes place at a fast rate, however, these details are less relevant.

4 Validation study

The effective heat capacity method, using a narrow temperature range is a more precise numerical method when numerical results were compared to the experimental results (Lamberg *et al.*, 2004; Fang and Medina, 2009).

Difficulty in modelling the phase transition using the older calculation technique called Conduction Transfer Function (CTF) in EnergyPlus is limited by the development the Conduction Finite Difference (CFD) calculation technique which has been discussed in the Literature review (Chapter 2) and Methodology (Chapter 3). Apart from the difficulty in modelling phase transition, natural convection, which exists in the liquid–solid interface of PCM due to the temperature difference in the liquid PCM, is ignored in some calculations. This is because the main heat transfer mode in PCM systems is conduction, which some studies assumed to mean that convection has a negligible effect on the solid–liquid interface position compared to the effect of heat conduction in solid PCM. Lamberg *et al.* (2004) show that when the effect of natural convection is neglected in the calculation, the PCM heats up to the maximum specified temperature twice as slowly as it actually takes in reality increasing the error in the liquid PCM during the melting process.

Discrepancies also occur due to the three-dimensional(3D) heat transfer nature of walls (Alawadhi, 2008). Numerical models adopt one-dimensional (1D), two-dimensional (2D) or three-dimensional (3D) models to solve energy formulated equation. The use of 2D formulation is more advantageous than 1D models and so forth as the latter leads to more errors (Zalba *et al.*, 2003).

Other difficulties of conducting computer simulations of building energy are a lack or difficulty of sourcing weather files for input during simulation (Patrick Arnold *et al.*, 2005). This is further discussed in Chapter 3.

In light of all the limitations, an effort has been made in this research to improve the performance of building energy simulations through the choice of software, methodology adopted and data input through validation.

Validating building energy calculation models is difficult as there is no defined methodology in the construction industry for how certain aspects of construction are represented in a building model beyond the use of sound professional judgment (Patrick Arnold *et al.*, 2005). Absence of methodologies for problem definition, appraisal and evolution also makes generalization and practical applicability complicated.

4.4 Validation

Validation of simulated against actual results may be comparative, analytic or empirical (Judkoff *et al.*, 2008b) as shown in Table 4-1. Comparative analysis is employed to validate the results predicted by EnergyPlus. The work of Kuznik, *et al.* (2009) presented the variables and performance of a laboratory tested model having PCM in the building fabric. The variables are used to create a validation model and the results compared.

A comparative study involves a direct comparison of two or more building performance simulation results using equivalent input. It is a useful technique because buildings can be created and placed in a real or imagined environment such that various heat transfer mechanisms are stressed as desired. The investigator has complete control over the accuracy of the input, and all external errors are easily eliminated.

The great disadvantage of the comparative technique is the absence of a truth model. For this reason the comparative study is best done using software with very different modelling and solution approaches.

The comparative technique is used before empirical validation studies are done to identify the need for empirical validation and to define the level of empirical validation needed.

The power of analytic technique is that major errors in the thermal solution algorithms of a simulation may readily be identified and isolated. The analytical solution is the truth model, and all the uncertainty of simultaneous error sources is eliminated. The disadvantage of this technique is the limited number of configurations and combined mechanisms for which analytical solutions may be derived. Additionally, analytical verification can only test the correctness of the numerical solution portion of some internal error sources. It cannot test the correctness of the model itself. However, the power of analytical verification is increased when used with the comparative study technique. In empirical validation a real building or test cell is instrumented and the calculated results from simulations are compared to the measured results obtained from the instrumentation. The comparison variables are uncertain because of direct measurement error. Measurement error also causes a degree of input uncertainty that when propagated through simulation leads to some output uncertainty. For purposes of validation, deviations between measured and calculated values significantly beyond these uncertainty bands are attributed to either the modelling or numerical solution component of some error sources, given that all inputs have been measured. Empirical

4 Validation study

validation is time consuming and expensive that the empirical test cases must be chosen with great care.

Technique	Advantages	Disadvantages
Comparative Relative test of model and solution process	<ul style="list-style-type: none"> • No input uncertainty • Any level of complexity • Inexpensive • Quick: many comparisons possible 	<ul style="list-style-type: none"> • No truth standard
Analytical Test of numerical solution	<ul style="list-style-type: none"> • No input uncertainty • Exact truth standard given the simplicity of the model • Inexpensive 	<ul style="list-style-type: none"> • No test of model • Limited to cases for which analytical solutions can be derived
Empirical Test of model and solution process	<ul style="list-style-type: none"> • Approximate truth standard within accuracy of measurements • Any level of complexity 	<ul style="list-style-type: none"> • Measurement involves some degree of input uncertainty • Detailed measurements of high quality are expensive and time consuming • A limited number of data sites are economically practical

Table 4-1 Comparison of validation techniques Judkoff et al., 2008b

4.4.1 Validating the two sets of results

A validation is conducted between the results predicted by:

1. DesignBuilder modelling and EnergyPlus 6 internal simulation engine
2. EnergyPlus 7 simulation engine alone

The two engines predicted the same results thereby validating the two versions of EnergyPlus software.

4.4.2 Validating the user's ability and the capability of the software

Another validation exercise is conducted for modelling PCM in EnergyPlus to validate the user's ability and the capability of the software. This section describes how the

4 Validation study

researcher used variables from a published experiment and predicted results. The results of the experiment and that predicted by the researcher are compared.

The work of Kuznik *et.al.* (2009b) presents details of an investigation into the performance of PCM wallboards in a scaled model using a climatic chamber. The results and variables used in the study are presented and used by the researcher to create a model and simulations are run using EnergyPlus. The difference in the predicted results and those presented for the experiment indicate the validity of simulations generated by the user and EnergyPlus.

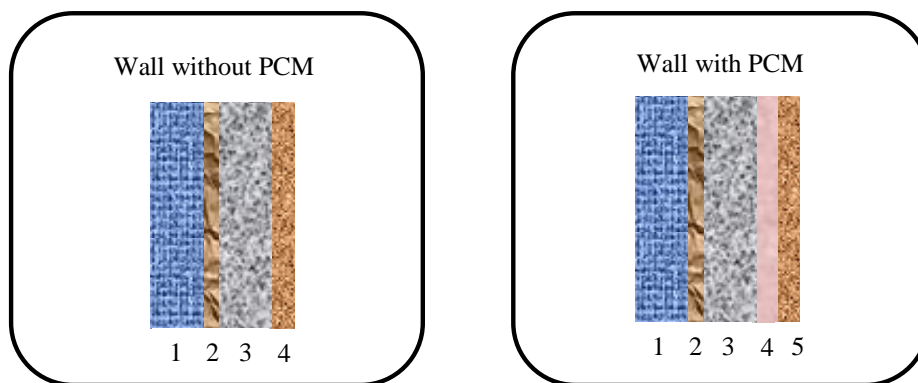


Figure 4-2 Configuration of building construction 1) 50 mm wood plate (outer layer), 2) 10 mm plaster, 3) 50 mm polystyrene, 4) 13 mm plaster, 5) 5 mm Energain® PCM from Kuznik *et.al.* (2009b)

Building component	Material	Thickness (mm)
Floor	Concrete	200
Vertical wall	Plaster	10
	Polystyrene	50
	plaster	10
	wood plate	50
Ceiling	Plaster	10
	wood plate	8
	insulating material	55
	wood plate	25
Glazing	Glass	10

Table 4-2 Building materials used in Kuznik *et.al.* (2009b)

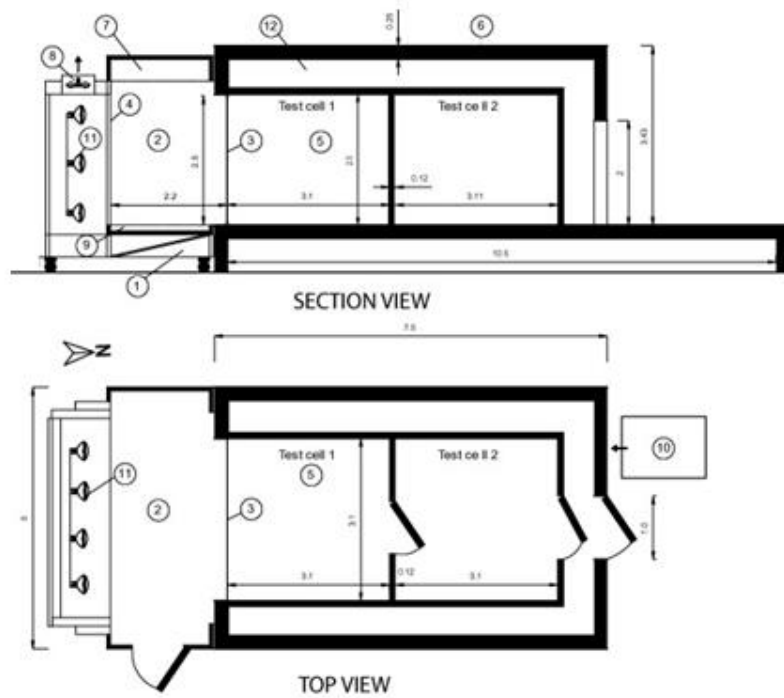
4 Validation study

In France, Kuznik *et.al.* (2009b) set up a test room to investigate the thermal performance of a PCM composite wallboard experimentally and to provide data for validation. They used a commercial PCM product, *Energain*[®] produced by DuPont de Nemours (2012).

It constitutes of 60% microencapsulated paraffin within an ethylene based copolymer. The PCM is a flexible sheet of 5mm thickness which density is about 900kgm^{-3} . It has an area weight of 4.5 kg/m^2 , melting and freezing temperatures are 13.6°C and 23.5°C respectively. The thermal conductivity is 0.22 W/m K in solid phase and decreases to 0.18 W/m K in liquid phase. The distribution of the specific heat at different temperatures is close to a Gaussian distribution, ranging from 3.6kJ/kg K to 15.2kJ/kg K .

The experimental full-scale test room called MINIBAT is located in CETHIL-INSA de Lyon, France and is illustrated in Figure 4-3. The test room is $3.1\text{ m} \times 3.1\text{ m}$ square meters and 2.5 m high and bounded on five sides by a climatic chamber regulated at constant temperature. The glazed south façade isolates the cell 1 from a climatic chamber whose temperature is controlled at 20.5°C by the means of an air-treatment system. Three vertical walls of this test room, facing North, East and West, are incorporated with PCM *Energain*[®] with configurations 50 mm wood plate (outer layer), 10 mm plaster, 50 mm polystyrene, 5 mm *Energain*[®] PCM layer and 13 mm plaster (inner layer), as shown in Figure 4-2 and Table 4-2. A thermal guard allows the five other exterior faces walls to maintain a uniform value of 20.5°C .

In order to have a light source that reproduces best the solar effect, a solar simulator is installed for the test room, as shown in Figure 4-3. Gas discharge lamps with metal halide (CSI lamp) are used to generate short-wave radiation which is close to the solar spectrum. The radiative flux thus created penetrates into the test room through the glazed wall.



1 cooling unit; 2 climatic chamber; 3 simple glazing; 4 protection glass of the solar simulator; 5 test cell; 6 concrete; 7 air blowing plenum; 8 solar simulator's heat removal ventilators; 9 air extraction plenum; 10 HVAC unit of the thermal guard; 11 solar simulator; 12 thermal guard. (Metric units)

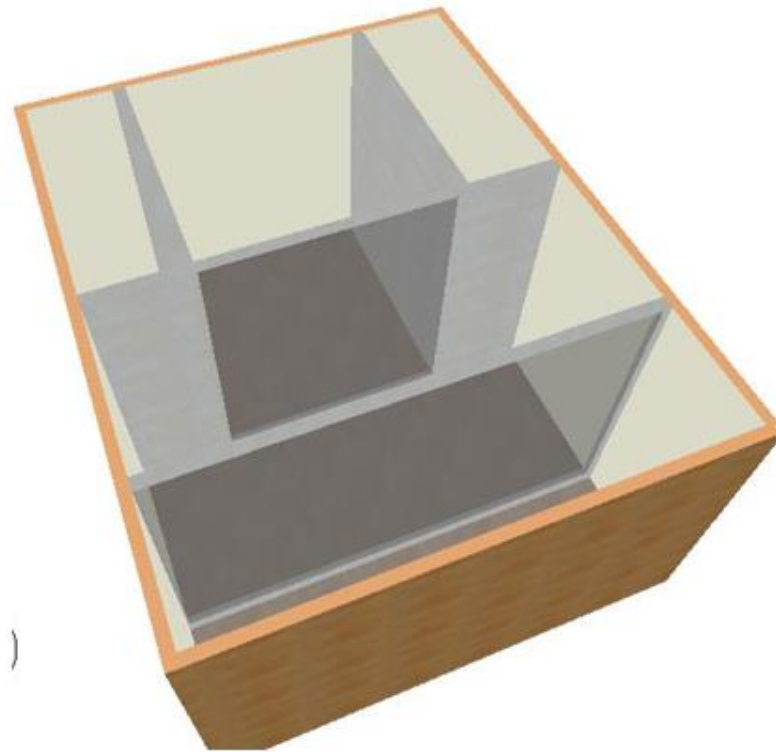


Figure 4-3 Test room for validation as presented in experiment (left) and Model by researcher using Designbuilder visualization plug-in (right)

4 Validation study

Experiments are conducted for the test room for a summer day, for which the temperature of the climatic chamber varies between 15°C and 30°C. Night -cooling is employed to improve the PCM storage and release effects. For the purpose of night-cooling, ventilation is switched-on between 6 and 18 hours, and 30 and 42 hours. To conduct the validation exercise, the test room was modelled by using a combination of DesignBuilder and EnergyPlus. The thermo-physical properties of the PCM *Energain*[®] were input to simulate its thermal process in the composite wall of the test room, as shown in Table 4-3.

4.4.2.1 Modelling by researcher

In EnergyPlus, the test is run as the calculation for a cooling design day in the summer for a hypothetical day and night air temperature profile. The air temperature swings between a maximum of 30°C to 15°C during the course of 24hrs. This option allows the weather input over a day as opposed to the annual hourly data necessary for a full simulation in EnergyPlus. The variables used in the test modelled by Kuznik (2009b), shown in Table 4-2 and Table 4-3 are used to make the model.

Material	Density (kg/m³)	Heat capacity (J/kgK)	Thermal conductivity (W/mK)
Concrete	400	919.5	0.16
Plaster	817	1620	0.35
Wood plate	544	1640	0.136
Polystyrene	35	1210	0.04
Insulating material	200	362.8	0.06
Glass	2500	770	1

Table 4-3 Thermo-physical properties of building materials from Kuznik *et.al.* (2009b)

4.4.2.2 Sources of variation between the two tests

Some sources of variation between the experimental test and computer modelling used by the researcher include:

- A. Sun simulation
- B. Weather profile in EnergyPlus
- C. Cooling and heating supplied to mimic day and night temperatures

A-Sun simulation: In the experiment, the sun was simulated by a set of discharge lamps to achieve a radiative heat flux shown in Figure 4-4.

4 Validation study

The highest radiant density shown in Figure 4-4 is 170W/m^2 . Therefore, in the computer simulation, the heat component attributed to the sun is introduced to the test room as a light source of 170W/m^2 in the space called solar simulator, see Figure 4-5.

Figure 4-4 also shows the component of the energy given by the solar simulator at different times which is estimated as 0 till 2hrs, 0.09 till 16hrs, 0.59 till 18hrs, 1 until 22hrs and 0.47 till 24hrs- and the pattern is repeated for the second day.

The lights in the computer model are operated using the schedule shown in Figure 4-6. The schedule used in the modelling mimics the fraction of the radiant energy as a function of time as shown in Figure 4-4.

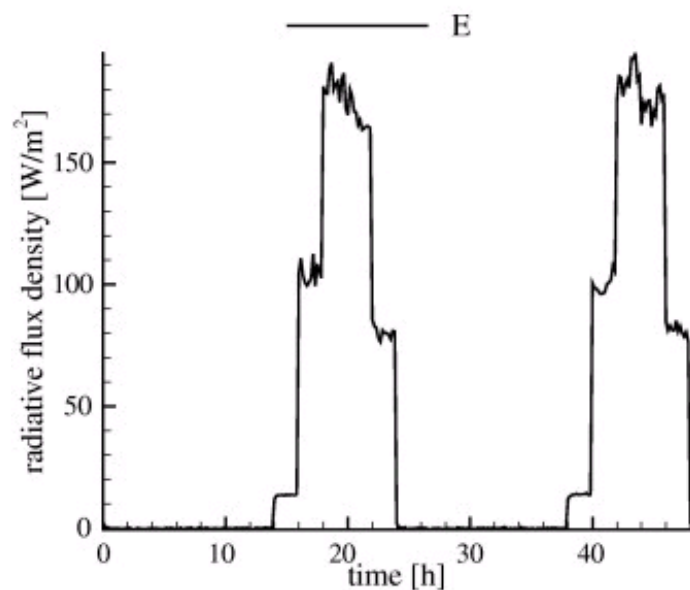


Figure 4-4 Radiative heat flux achieved by the solar simulator in experiment

4 Validation study

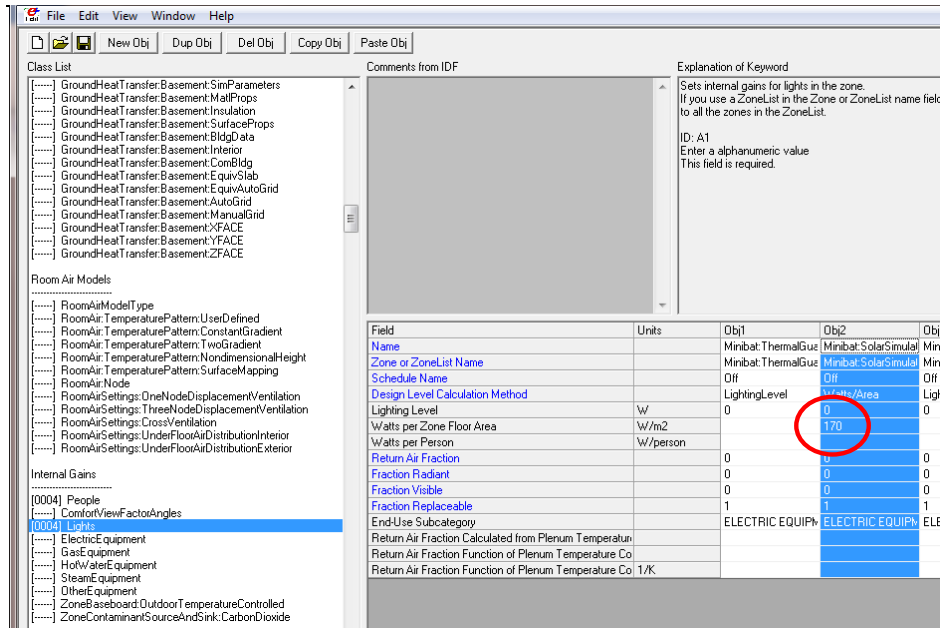


Figure 4-5 Modelling the solar simulator in EnergyPlus

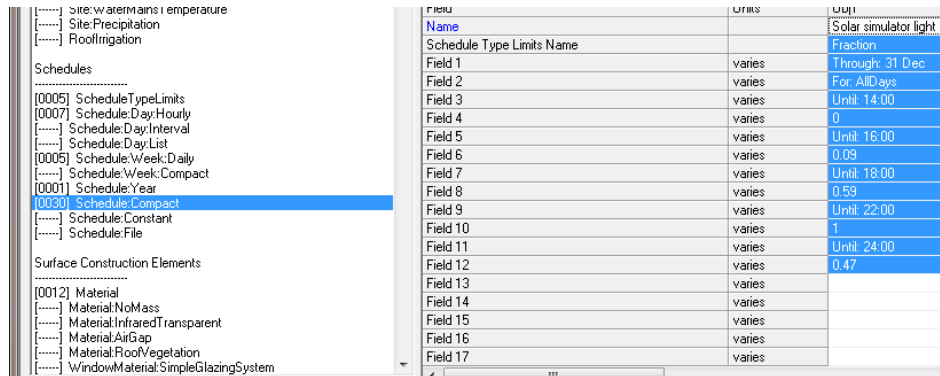


Figure 4-6 Schedule operating the solar simulator

These variations in the way the sun is simulated in the experiment and in the model may cause a variation in results.

B- Weather profile in EnergyPlus

EnergyPlus requires a weather file before it can run a simulation. However, the experiment has a specific schedule for two days running in the same pattern which cannot be duplicated by the researcher in a weather file. Instead the test case is treated as a box within a box. The outer box is modelled to remove the effect of the weather file on the test case.

4 Validation study

C- Cooling and heating supplied to mimic day and night temperatures: In the experiment, the air conditioning is achieved by supplying air through an inlet at the top of the test room as shown in Figure 4-7. The inlet air temperature follows the profile in Figure 4-9. In EnergyPlus the inlet air temperature is set as a single temperature, a maximum and minimum but not as schedule which is ideal to model the profile achieved in the experiment.

To model the air temperature in EnergyPlus, the cooling and heating in the test-room is set in a schedule as shown in Figure 4-7. This however, affects the air temperature predicted in the room as a result of setting a maximum and minimum inlet air temperature.

```
! Modified schedule: office_openoff_Heat
Schedule:Compact,
  Minibat:Testroom Heating SP Sch,  !- Name
  Temperature,                    !- Schedule Type Limits Name
  Through: 31 Dec,                 !- Field 1
  For: AllDays,                    !- Field 2
  Until: 02:00, 27.5,              !- Field 4
  Until: 04:00, 25,                !- Field 6
  Until: 06:00, 22.5,              !- Field 8
  Until: 08:00, 20,                !- Field 10
  Until: 10:00, 17.5,              !- Field 12
  Until: 12:00, 15,                !- Field 14
  Until: 14:00, 17.5,              !- Field 16
  Until: 16:00, 20,                !- Field 18
  Until: 18:00, 22.5,              !- Field 20
  Until: 20:00, 25,                !- Field 22
  Until: 22:00, 27.5,              !- Field 24
  Until: 24:00, 30;                !- Field 26

! Modified schedule: office_openoff_Cool
Schedule:Compact,
  Minibat:Testroom Cooling SP Sch, !- Name
  Temperature,                    !- Schedule Type Limits Name
  Through: 31 Dec,                 !- Field 1
  For: AllDays,                    !- Field 2
  Until: 02:00, 27.5,              !- Field 4
  Until: 04:00, 25,                !- Field 6
  Until: 06:00, 22.5,              !- Field 8
  Until: 08:00, 20,                !- Field 10
  Until: 10:00, 17.5,              !- Field 12
  Until: 12:00, 15,                !- Field 14
  Until: 14:00, 17.5,              !- Field 16
  Until: 16:00, 20,                !- Field 18
  Until: 18:00, 22.5,              !- Field 20
  Until: 20:00, 25,                !- Field 22
  Until: 22:00, 27.5,              !- Field 24
  Until: 24:00, 30;                !- Field 26
```

Figure 4-7 Schedule for cooling and heating in EnergyPlus

4.4.2.3 Results

The times of occurrence of highest temperature between measured and simulated test case are 0hr, 24 hrs, and 48 hrs as shown in Figure 4-8 and Figure 4-9. The times of occurrence of lowest temperature between measured and simulated test case are 12hr and 36 hrs. The temperatures in the thermal guard is also achieved and maintained at 20.5°C throughout the experiment, see Figure 4-9.

4 Validation study

The measured result is compared with simulated results as shown in Figure 4-10 and Figure 4-11. With PCM wallboards in the study by Kuznik *et al.* (2009b), the air temperature is between a minimum of 20°C and a maximum of 32°C. That of the simulated predictions from this study is a minimum of 23°C and a maximum of 30°C. It should be noted that the maximum air temperature of 30°C is capped as a result of the cooling and heating profile described in 4.4.2.2. The profile makes it impossible to go above 30°C or below 15°C. This limitation affects only such a case that requires varying inlet air temperatures which is unusual in practical settings.

However, an acceptable agreement of results is achieved within a root mean square error of 10.4%. This is a significant agreement considering the limitations in modelling and experimental errors in the study by Kuznik *et.al.* (2009b).

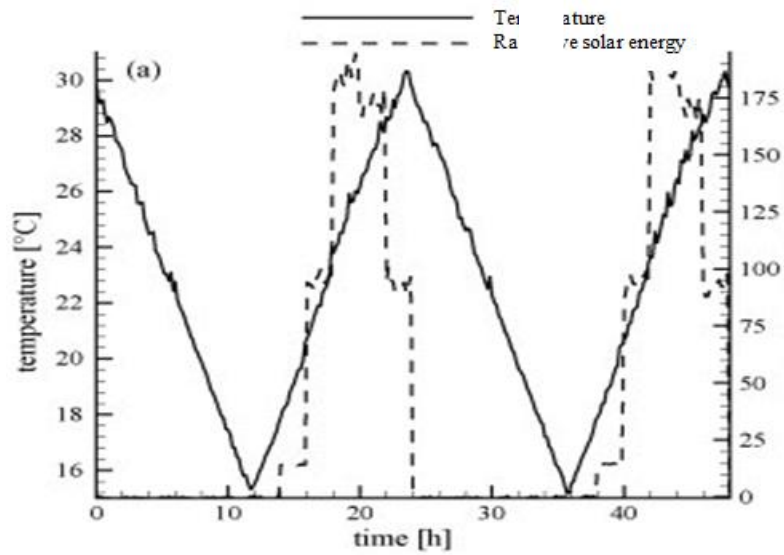


Figure 4-8 Synthetic air inlet temperature profile mimicking day and night temperature by Kuznik *et.al.* (2009b)

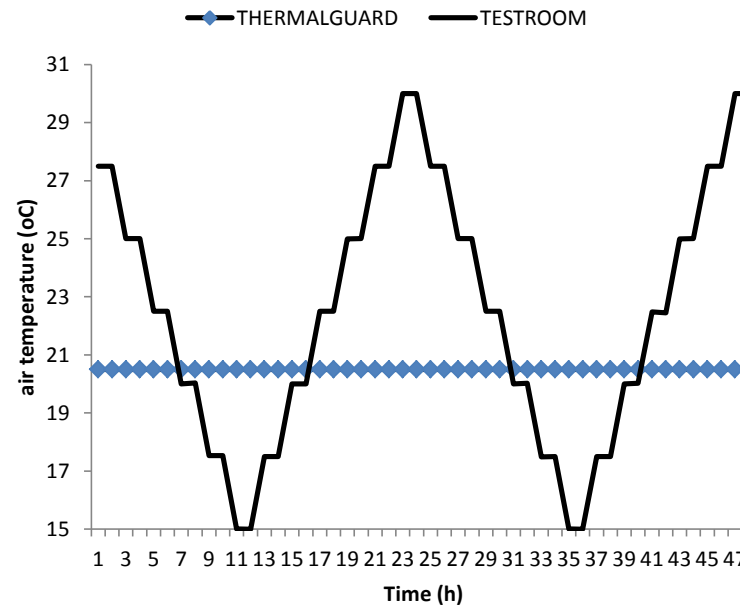


Figure 4-9 Inlet air temperature profile achieved in the testroom by researcher, thermal guard air temperature showing temperature in climatic chamber maintained at 20.5°C

4 Validation study

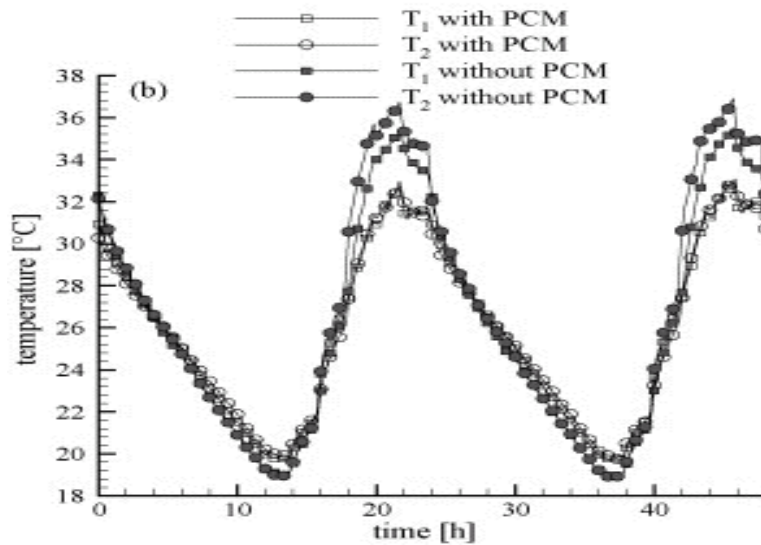


Figure 4-10 Measured air temperature for the testrooms with and without PCM by Kuznik *et al.* (2009b). T₁ and T₂ are probes at two different heights in the same room.

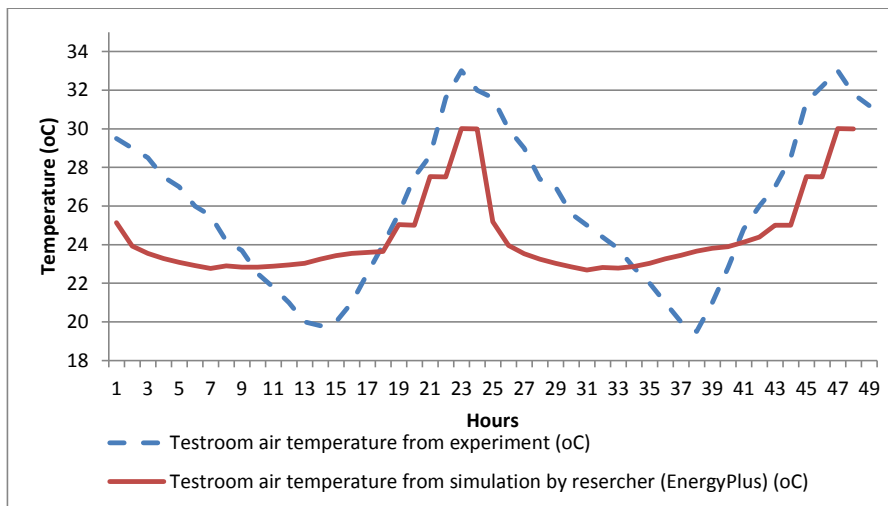


Figure 4-11 Comparison of result of simulated PCM effect predicted by EnergyPlus and experiment

4.5 Conclusion

Simulations are suited to the non-linear nature of PCM problems and the thermo-physical properties of the liquid-solid phases when compared to analytic calculations (Ibáñez *et al.*,

4 Validation study

2005; Kuznik and Virgone, 2009b; Agyenim *et al.*, 2011). Computer simulations are shown to be suited to the non-linear nature of PCM problems and the thermo-physical properties of PCM phases (Agyenim *et al.*, 2011). They also allow for cost effective and timely examination of multiple variables when compared with experiments. However, validation is required to limit the difficulties in modelling and simulating complex energy flows in buildings. Two rounds of validations are conducted on the computer simulations presented. Comparative type of validation of the results between the:

- Two versions of EnergyPlus used for the PCM simulations
- User's ability and the capability of the software

Comparing the two versions showed no differences between the results of the simulation of a base-case without PCM. It should be noted that only the simulation of the base-case without PCM is compared due to EnergyPlus version 6's inability to model or simulate PCM.

User's ability and the capability of the software are tested by comparing the results from the Kuznik *et al.* (2009b) experimental test room investigating the thermal performance of a PCM composite wallboard; and those predicted by EnergyPlus. The comparison shows an acceptable root mean square error of 10.4% between the two sets of results. This is an indication of the user's ability to model PCMs and EnergyPlus's ability to simulate PCM performance.

5 CHAPTER 5
DISAGGREGATING PRIMARY ELECTRICITY CONSUMPTION FOR
OFFICE BUILDINGS IN NIGERIA

Contents

5.1 Overview

5.2 Introduction

5.3 Walk-through

5.4 Analysis- Degree-days

5.5 Results

5.6 Building descriptions

5.7 Normalized End-uses

5.8 Degree-day calculations

5.9 Conclusion

Problem	Chapter one: Introduction- 'Nigerian buildings and Energy use'		
Theoretical framework	Chapter two: Literature review- 'Phase change materials as energy conservation mechanisms in buildings'		
Methodology	Chapter three: 'Methodology'	Chapter four : 'Validation study'	
Results	Chapter five: 'Disaggregating primary electricity consumption for office buildings in Nigeria'	Chapter six: 'Optimizing thermal and energy performance of buildings'	Chapter seven: 'PCM performance in office buildings'
Conclusion	Chapter eight: Conclusion		

5.1 Overview

In chapter one, electricity generation, distribution and consumption are discussed and it was concluded that a more rational approach to consumption is required to reduce reliance on a failing central utility supply. A paucity of information on the consumption patterns by different sectors was also documented. A data collection field exercise is required to get valid and reliable data. The data collection exercise is conducted via an energy audit; surveying and analysing energy flows in a building. This exercise is beneficial to prepare a primary dataset for validating building performance simulation results and bridge part of the building energy knowledge gap in Nigeria. The results provide a platform for evaluating the effects of energy conservation mechanisms (ECMs) such as PCMs on total electricity consumption through the use of computer simulations.

This chapter presents the findings of the energy audit field exercise. A quantitative survey into 15 office buildings in varying Nigerian climates is conducted using questionnaire and observation techniques. Analysing the 15 buildings showed the quality of data from 10 of the buildings to be poor. Therefore only the results of 5 buildings are presented here. Data collected during the fieldwork, combined with variables from the National building code are used to generate a base-case. The data include building characteristics, work schedules, lighting, cooling and appliances loads etc.

5.2 Introduction

The information recovered from this stage will serve as data input for the generation of the base-case on which to model and simulate alternative energy conservation mechanisms including PCMs. As established, Nigerian literature on electricity consumption suffers from a paucity of information. This necessitated the fieldwork exercise to enable data collection through an energy audit.

An energy audit of each building is conducted using a uniform data collection process and tools. They are self-administered questionnaire and observation as shown in Figure 5-1. The objective is to investigate the electricity consumption in mix-mode Nigerian office buildings resulting in the disaggregation of total consumption into cooling, lighting and appliances. The use of PCM as an energy conservation mechanism affects the cooling load directly therefore a significant cooling aggregate is an indication that targeting this end-use will provide substantial savings.

Another objective is to test the alignment of recorded monthly electricity consumption against the weather profile of the location where the building is located. Electricity consumption in buildings in warm climates is dominated by cooling the interior of the buildings. Therefore, the hypothesis is that electricity consumption is strongly correlated to ambient air temperature. In the case that the two variables are misaligned, it indicates an opportunity for energy savings. These savings, in particular are in cooling consumption by modifying the building construction in an attempt to attain and maintain thermal comfort.

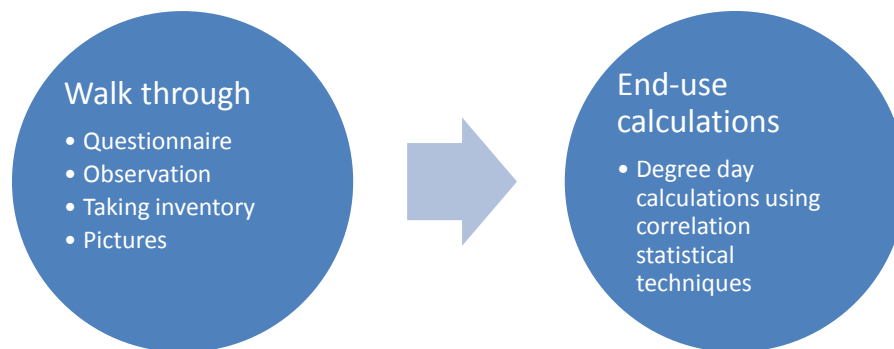


Figure 5-1 Methodology of energy audit

This stage of the research covers the following:

1. Walk-through
2. Analysis (Degree-days)

5.3 Walk-through

The audit required key personnel such as the facility manager, energy manager or estate manager, depending on the management structure, in collaboration with information and communication technology departments, and even finance departments to produce and calculate required data. A self-administered questionnaire was used to collect essential data. It consists of nine sections and an introduction/consent form at the beginning. The nine sections are:

1. Building characteristics
2. Occupancy schedule
3. Site sketch
4. Electricity from utility use
5. Electricity from alternative source use
6. Heating ventilation and air conditioning
7. Cooling load
8. Lighting load
9. Appliances

The building characteristics section covers the gross and conditioned floor areas and building envelope characteristics. It also treats general aspect of architecture of the building. The occupancy schedule section covers the number of building users and the pattern of usage. The site sketch section was used only in buildings where the building plans were unavailable. Electricity from utility covers quantity consumed per month as recorded from utility bills in the electricity from utility use section. The electricity from alternative use section treats electricity consumption from back-up power generators used during power failure. The section looks at fuel, power factor, maintenance factor, capacity and hours or amount of fuel used by the engine per month; to allow measurability with the monthly consumption from the utility. The last four sections comprising of cooling, HVAC, lighting and appliances load sections deal with aggregate loading of each end-use in the building. It questions the quantity, energy rating from manufacturer and annual hours of use of each brand of product within each section.

The main sources of data used to calculate building energy consumption are:

1. Architectural specifications: Used to identify geometries and layouts, construction components, window areas and others, derived from site and floor plans, sections and construction details such as roof, wall, windows and exterior shading
2. Electric lighting system: The data collected are the quantity and nameplate energy rating
3. Air conditioning system: The data include cooling and heating set points, supply air and exterior air flows for each zone, total and sensible cooling capacity, coefficient of performance (COP) and energy efficiency ratio (EER), characteristics such as model and year, and schedule report
4. Occupancy and operational schedules: The data is used for evaluating occupants' behaviour and end-uses
5. Equipment inventory: The data includes number of computers and other relevant equipment with considerable energy consumption
6. Billing history: Monthly energy consumption for at least a year are collected as indicated by utility bills
7. Building component properties: Special features must be characterized in detail (such as windows in buildings with large window/wall ratio), which generally is available in catalogues and manuals published by the supplier
8. Back-up generator usage reports will aid utility bills in its function due to usage of back-up generator in Nigeria as a result of erratic power supply

5.3.1 Electricity usage

Total electricity consumption is disaggregated into end-uses. End-use consumptions are the aggregate loads such as Heating Ventilation and Air-Conditioning (HVAC), lighting and appliances. Figure 5-2 illustrates the demand and supply load distribution for the total electricity consumption.

HVAC requires the determination of how much energy is used for heating and cooling and electricity use for associated equipment, such as fans and pumps. However, only cooling associated electricity consumption is considered as Nigeria is a tropical climate requiring minimal heating for thermal comfort. Lighting and appliances cover the electricity required to power the lighting system and the electrical appliances that the building users utilise

respectively. Baseload is the combination the non-weather related energy use e.g. artificial lighting, office equipment, electrical appliances and the lifts and escalators.

The aggregate end-uses are normalised by floor area. Normalised consumption values take into account building size, climatic variations or occupiers to eliminate the effects of these in comparing different buildings.

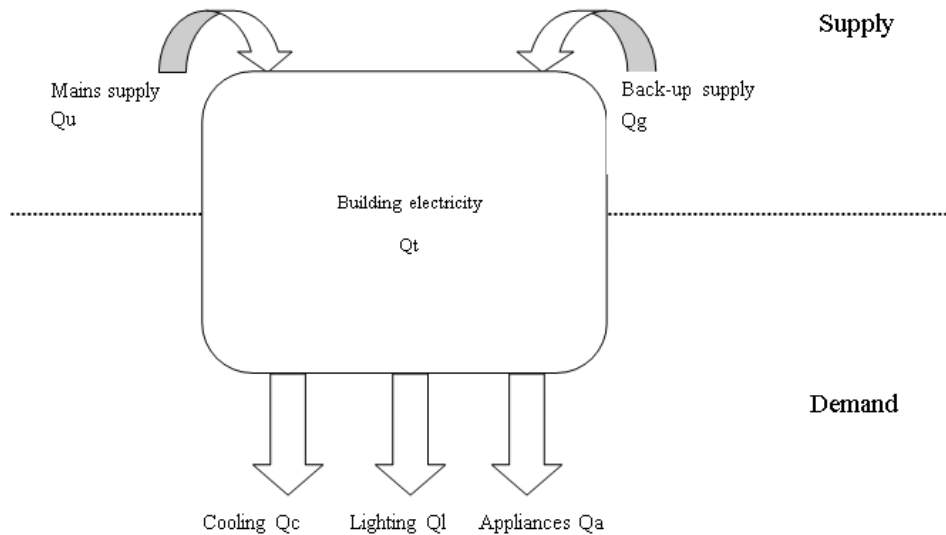


Figure 5-2 Demand versus supply

5.3.1.1 Total electricity demand

$$Q_t = Q_c + Q_l + Q_a \quad \text{Equation 5-1}$$

All Q are in (kWh); Q_t is the total electricity demand per annum. Q_c , Q_l and Q_a are cooling, lighting, and appliances demand respectively as shown in Equation 5-1. Aggregate demand calculations are based on the formulae presented below.

Cooling demand as shown in Equation 5-2 is:

$$Q_c = Q_{c1} + Q_{c2} + Q_{c3} \dots \dots + Q_{cn} \quad \text{Equation 5-2}$$

Where $Q_{c(1-n)}$ represent the variations in type and specifications of the different cooling equipment.

Lighting demand as shown in Equation 5-3 is:

$$Q_l = Q_{l1} + Q_{l2} + Q_{l3} \dots \dots + Q_{ln} \quad \text{Equation 5-3}$$

Where $Q_{l(1-n)}$ represent the variations in type and specifications of light fixtures.

Appliances demand as shown in Equation 5-4 is:

$$Q_a = Q_{a1} + Q_{a2} + Q_{a3} \dots \dots + Q_{an} \quad \text{Equation 5-4}$$

Where $Q_{a(1-n)}$ represent the variations in type and specifications of appliances.

The demand load is calculated by the equation for each type and specification as shown in Equation 5-5:

$$\text{Energy rating} \times \text{Quantity} \times \text{Hours of use} \quad \text{Equation 5-5}$$

The hours of use were estimated based on the answers supplied by the respondents and limited observation. A significant effort was made to reduce the sources of such error by recording the variance in working hours on the different classes of appliances by the researcher. A physical count of all electrical equipment, including that of cooling and lighting was made. Then a record of its usage was collected.

Cooling load is the demand from the cooling systems installed estimated from an inventory of the units in the building and is similar to the lighting load, which is done from the light fixtures.

Appliances loads encompass all other aggregate end-uses that do not fall under cooling and lighting. The appliance demand load is calculated by energy rating as provided by the manufacturer or recorded from the nameplate of the electric consuming appliances and the quantity of appliances. In the case that the energy rating was not available from the appliance, a search on the product detail on the internet was conducted. If that also failed, the rating of a similar appliance was used. The assumption that the appliances run at the specified rating may lead to errors related to inefficiency of the appliances; other errors may arise from the assumption of hours of use by appliances. The difficulty therefore in using the same method of calculation as with cooling and lighting loads lies in accurate estimation of hours of use for the multiple types of appliances that constitute this end use. A better formula, shown in Equation 5-6 is:

$$Q_a = Q_t - (Q_c + Q_l) \quad \text{Equation 5-6}$$

Using Equation 5-7 allows the electricity consumption for loads like elevators, escalators and water pumps to be examined without the difficulty of

5.3.1.2 Total electricity supply

$$Q_t = Q_u + Q_g \quad \text{Equation 5-7}$$

Q_t , as shown in Equation 5-7 is the total supply per annum. Q_u is consumption recorded by the smart meter provided by the utility Company. It is also recorded on electricity bills. Q_g is the supply from the back-up power generator.

The electricity supplied by the back-up power generator Q_g is significant due to the frequency of black-outs, but the method adopted to quantify the supply is estimated. The estimation is based on recorded hours of supply per annum conducted by the buildings' management to track their fuel consumption. The difference in total working hours from hours of back-up power recorded is the hours the building enjoys electricity supplied by the central utility company. These hours are converted to percentages of the total working hours and compared with that of electricity supplied by the back-up generators. This estimation method proved more accurate than calculating the electricity supplied based on quantity of diesel consumed and the efficiency factor of the power generators. This way the errors due to inefficiency and sizing are minimised. The formula used, shown as Equation 5-8 is:

$$Q_g = (Q_u \times G)/U \quad \text{Equation 5-8}$$

Where U and G are percentage of time that utility and back-up generators are in use respectively.

5.4 Analysis- Degree-days

The degree day calculation technique is adopted to study the alignment of the cooling dominated consumption with ambient air temperature. Degree-days are the summation of temperature differences over time, capturing both extremity and duration of ambient temperature. The temperature difference is between a reference temperature and the ambient temperature. The reference temperature is known as the base temperature which, for buildings, is a balance point temperature at which the heating or cooling is not required to maintain comfort conditions. The degree day method therefore sums up the duration of

time that occupants are feeling discomfort. The level of discomfort is measured by dry bulb air temperature. The two main uses for degree-days in buildings are:

- To estimate energy consumption and carbon dioxide emissions due to space conditioning for new build and major refurbishments
- For on-going energy monitoring and analysis of existing buildings based on historical data

Both reasons enable the study of PCM as a building energy conservation mechanism design strategy.

Degree-day technique is calculated with underlying simplified assumptions relating to the use of interior temperatures, casual gains, and air infiltration rates etc. to provide a good approximation of building thermal performance. A cooling degree-day is a day requiring cooling to achieve comfort and a heating degree-day is vice versa. Cooling degree-days are used in this research as Nigeria is in the tropics and generally requires only cooling.

The concept of degree-days is used by correlating electricity consumption with cooling degree days which produces a scatterplot and a performance line (CIBSE, 2004). Poor performance lines are those with a wide scatter of points. This is invariably due to a failing of the system controls or if cooling accounts for only a small proportion of the fuel requirement.

However a good performance line merely means that its performance is consistent but not necessarily efficient. Once established, the performance line can be used as a 'performance target' for the future operation of the building. Where poor correlation exists it is unlikely that degree-days can be used for useful analysis until further investigations into the building have been made. Curved lines may indicate that constant temperature is not maintained throughout the year whereas broken/horizontal lines might indicate that consumption does not depend on weather over that period e.g. due to large distribution losses.

This approach is heavily dependent on the accuracy of the base temperature, degree day and consumption data.

5.4.1 Base temperature

Neutrality temperature is adopted as the base line temperature to calculate thermal comfort in this work using degree-day's technique due to its robustness in adapting to ambient

conditions. According to Day *et al.* (2003), using the correct building base temperature can improve performance line.

A test to validate the robustness of using neutrality temperature as the base-temperature was conducted comparing it with base temperatures of 20 °C, 22 °C, 24 °C, 25 °C. The suitability of using the test base temperatures as denoted by R^2 of 0.005, 0.003, 0.005, 0.29 respectively for the test base temperatures. The R^2 for neutrality temperature was 0.36 indicating the superiority of using the neutrality temperatures having the highest correlation.

An example of a good performance between electricity consumption and monthly cooling degree days shown in Figure 5-3 is gotten from the work conducted by Day *et al.* (2003). Figure 5-4 shows an example of a poor performance line. It is gotten from the correlation of electricity consumption recorded during the fieldwork and ambient temperature. It should be noted that there are no published design degree days for Nigerian cities except those calculated by Ajibola (2001).

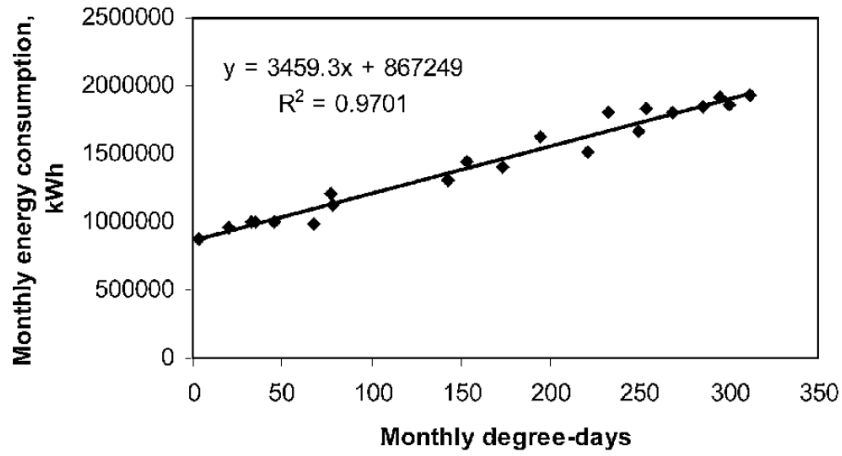


Figure 5-3 Example of a good performance line (Day et al., 2003)

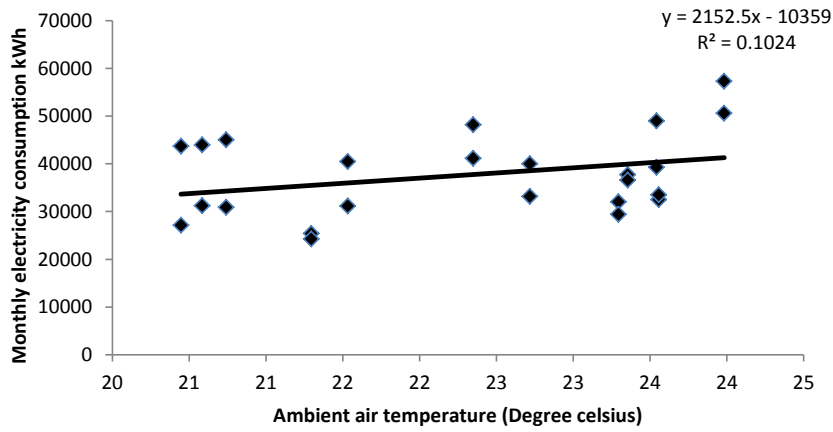


Figure 5-4 Example of a bad performance line illustrated in this research

5.4.2 Base-load

Baseload is defined as the non-weather related energy use such as artificial lighting, office appliances, lifts and escalators. The cooling load therefore is the difference between the total electricity consumption and the baseload.

Mathematically, the equation of a straight line such as the performance line generated by the scatterplot in Figure 5-3 and Figure 5-4 is given as Equation 5-9:

$$y = mx + c \quad \text{Equation 5-9}$$

y and x are points on the line, y is the value on the y axis and x is the value on the x axis respectively. m is the slope or gradient of the line and c is the Y Intercept or where the line crosses the Y-axis.

From the scatter plot of electricity consumption against ambient air temperature, the intercept c is also the baseload.

5.5 Results

The following sections present the results of the analyses conducted on the data recorded in the energy audit. The results presented here are for 5 buildings that had adequate data out of 15 buildings audited. Some of the problems encountered that caused the discarding of the buildings include poor accounting practices and lack of data. The results are classified into:

- Building descriptions
- Electricity demand and supply
- Normalized End-uses
- Degree-day calculations

Due to confidentiality issues, the 5 buildings presented here will be referred to as buildings 1-5.

5.6 Building descriptions

These results, described in Table 5-1 are recorded during the walk-through stage of the energy audit. The walk-through enabled observation of:

- Physical building characteristics such as construction, glazing, occupant behaviour
- Electricity consumption by taking an inventory of electrical appliances

5-Disaggregating primary electricity consumption for office buildings in Nigeria

Climate zone	Hot and dry	Composite of hot and dry/hot and humid			Hot and humid
Buildings	Building 1	Building 2	Building 3	Building 4	Building 5
Calculated cooling degree days/yr	246	267	267	267	301
Occupants	20	130	125	600	137
Week-day work hours/ yr	8am-5pm (2340 hrs)	8am-5pm (2340 hrs)	8am-6pm Sat: 8am-12pm (2818 hrs)	8am-5pm (2340 hrs)	8am-5pm (2340 hrs)
Gross floor Area (m²)	250	1200	3218	8184	2944
Occupancy (m²/person)	12.5	9.23	25.8	13.6	21.5
Wall/window ratio (%)	16	18	73	10	20
All single pane glazing	clear	Tinted, internal blinds	Tinted, reflective, internal blinds	clear	Tinted, internal blinds
Annual back-up consumption (kWh)	5,713	48,399	127,186	1,777,929	717,505
Consumption/yr (kWh)	40,807	189,799	317,965	2,435,519	875,006
Back-up power (%)	14	26	40	73	82
Cooling load (kW)	5,625	99,563	225,548	749,925	427,950
Lighting load (kW)	6,387	59,542	46,328	81,326	60,197
Office appliance load (kW)	28,795	30,694	46,089	1,604,268	386,859

Table 5-1 Energy audit buildings' descriptions

5.6.1 Physical building characteristics

All the buildings are made of the same wall construction method most common in Nigeria of hollow sandcrete blocks with standard mix proportion of 1:6 cement-sand ratios. The size of the block used is 225 x 225 x 450 mm for external walls or 225 x 225 x 150 mm for internal walls with one-third of the volume as cavity (Baiden and Tuuli,

2003; Baiden and Asante, 2004). These are heavy-weight walling units made from coarse natural sand or crushed stone dust mixed with cement and water and pressed to shape, see Figure 5-5.



Figure 5-5 Sandcrete block unit (Nigerian building code)

The blocks are produced hollow having a much more obvious cavity right through the block. The total volume of the cavity is, however, restricted to 50% of the gross volume of the block. Sandcrete blocks are used for single leaf wall construction, the blocks are laid in running or stretcher course in which the units of successive courses overlap half their length. Joints in between the blocks are filled with cement: sand mortar of mix not richer than 1:4. The wall construction is considered in the heavyweight category with a calculated U-value of $1.4 \text{ W/m}^2\text{K}$ based on the CIBSE calculation method (CIBSE, 2007).



Figure 5-6 Internal venetian blinds

5-Disaggregating primary electricity consumption for office buildings in Nigeria

All the buildings have internal venetian blinds and single pane glazing as shown in Figure 5-6 and Figure 5-7. There is no wall insulation in any of the buildings. The setting for all buildings is urban. It was observed that with the exception of Building 5, all the other buildings have mechanical cooling but rely on natural means and infiltration for ventilation. See Figure 5-11 for a sample of widespread cooling system in Nigeria.



Figure 5-7 Single glazed, bronze tinted, aluminium framed windows and doors

5.6.1.1 Building 1 (Kaduna)

Building 1 is a small single story bank branch in the northern city of Kaduna. It is cellular and open plan with clear single pane glazing. There are security bars across the windows, internal blinds and, external overhangs for shading. Wall to window ratio is 16%, and the Gross floor area (GFA) is 250m². There are 20 occupants in the building, giving occupancy of 12.5 m² per person. Operational hours are week days: 8am-5pm (2340 annual hours).

5.6.1.2 Building 2 (Abuja)

Building 2 is a 4 story government office in the central city of Abuja. It is cellular and open plan with security bars; tinted glazing, and internal blinds for shading. Wall to window ratio is 18% and the GFA is 1200 m². There are 130 occupants in the building, giving occupancy of 9.23 m² per person. Operational hours are week days: 8am-5pm (2340 annual hours).

5.6.1.3 Building 3 (Abuja)

Building 3 is also a 4 story government office in the central city of Abuja. It has a combination of open and closed plan layout of offices. Windows are tinted and reflective, with internal blinds in some areas, external overhangs and window hoods for shading. Wall to window ratio is 73%. And the GFA is 3218 m². There are 125 occupants in the building, giving occupancy of 25.8 m² per person. Operational schedule is week days: 8am-6pm; and Saturdays: 8am-12pm (2818 annual hours)

5.6.1.4 Building 4 (Abuja)

Building 4 is the 13 story head office of a bank in Abuja. It is serviced by 3 elevators. These factors account for higher consumption values. It is cellular and open plan. Windows are clear and recessed with, security bars. Wall to window ratio is 10% and the GFA is 8184 m². There are 600 occupants giving occupancy of 13.6. m² per person. Operational schedule is week days: 8am-5pm (2340 annual hours). Building 5

5.6.1.5 Building 5 (Lagos)

Building 5 is a 4 storey regional branch of a bank in the southern city of Lagos. It is cellular and open plan. Windows are tinted with internal blinds, and iron security bars. Wall to window ratio is 20%.and GFA is 2944 m². There are 130 occupants giving occupancy of 21.5 m² per person. Operational schedule is week days: 8am-5pm (2340 annual hours). This is the only building where a form of mechanical ventilation is

provided. The other buildings audited relied on natural means and infiltration for ventilation.

5.6.2 Electricity demand and supply in the buildings

The buildings have generally similar appliances in use such as photocopiers, information computer ICT systems, lighting fixtures and cooling systems. All the buildings also have provision of back-up power generators. The following sections discuss:

- Electricity demand
- Electricity supply

5.6.2.1 Electricity demand

The inventory of type, quantity and estimation of usage pattern is recorded for the different end-uses. The different end-uses were classified under appliances, cooling and lighting. The consumption of each appliance was estimated using Equation 5-10.

Energy rating × Quantity × Hours of use Equation 5-10

The demand for each class is simply a summation of the demand for the appliances in the class. For instance the summation of the consumption of cooling was calculated using Equation 5-11.

$$Q_c = Q_{c1} + Q_{c2} + Q_{c3} \dots \dots + Q_{cn} \quad \text{Equation 5-11}$$

This section presents some example of appliances inventoried during the walk-through and their estimated hours of use:

1. Fridge: In all the buildings, fridges are left on all the time, even over weekends and holidays
2. Water pumps, see Figure 5-8: A sample of an estimated pattern of use was for 3 periods of 30 minutes over the course of a day to pump water into overhead tanks
3. ICT equipment: In a bank audited, their ICT equipment was never turned off, whereas in another quantity surveying office building, ICT was on only during working hours. See Figure 5-9 for a sample of power back-up for ICT in building 3. This is required due to the 24 hour need for powering the IT system installed. It is however, a somewhat disordered assembly which may negatively affect the performance of the system. It also is kept outside and subject to adverse weather conditions

4. Printers/photocopiers: The record for this category also accounted for the type of action taken and an estimation of how many hours or percentage time used
5. Water dispensers: These are generally left on all the time according to the respondents



Figure 5-8 Water pump to back-up central water supply which also is scarce



Figure 5-9 Makeshift battery storage for ICT showing poor positioning in the heat of the mechanical cooling system's exhaust and weather elements



Figure 5-10 Lighting systems showing the range of available lighting from inefficient tungsten lamps to more efficient fluorescent lamps

6. Security lighting, see Figure 5-10: These are mostly turned on by the night guards when they come on their shifts at 7pm and are turned off by the day shifts at 7am
7. Interior lights: It was observed that it was common practice for the building users to close the venetian blinds shading exterior windows and leave the lights on. This may be due to poorly designed buildings allowing glare discomfort on the building users. Figure 5-10 shows examples of observed lighting systems during the energy audit. Generally there was an awareness and appreciation of efficient light bulbs. There were some incandescent light bulbs and mercury halide security lamps also
8. Cooling system: Cooling systems in all five buildings are split direct expansion (DX) units ranging in energy rating from 750 -1450 kW; a few dual hosed DX packaged units ranging from 5000-6000kW; wall units ranging from 750-1450kW, and a precision unit specifically installed to cool a data centre. Figure 5-11 shows some cooling systems operating in the buildings energy audited. None of the buildings have heating systems. It is common practice to put on the

cooling once there is electric supply whether it is required or not. It was observed that on especially cool days, the building users wore cold protection clothes rather than use natural ventilation

This behaviour maybe as a result of dust in the air during harmattan or for rodent and insect control. Further research is required to examine the cause of this observed occupant behaviour which is not covered in the scope of this research.



Figure 5-11 Split unit cooling system

5.6.2.2 Electricity supply

In the field work, back-up power generation is used for up to 78% of the time in a Lagos office building as shown in Table 5-2. On average, 53% of electricity is supplied by back-up power across all three climates. In the hot and dry climate, a building records the lowest electricity supplied by back-up generator at 14%.

The electricity supplied by back-up generator is estimated by Equation 5-12 which has been generated by the author to deal with erratic power supply in buildings being energy audited:

$$Q_g = (Q_u \times G)/U \quad \text{Equation 5-12}$$

Where U and G are percentage of time that utility and back-up generators are in use respectively. Q_g is the supply from the back-up power generator. Q_u is consumption recorded by the smart meter provided by the utility Company. It is also recorded on electricity bills.

This result is comparable to the results of Adenikinju (2005) who claims that power failure or voltage fluctuations occur about seven times per week, each lasting for about two hours, without the benefit of prior warning as y. On the other hand, the results vary from that of Agho *et al.* (2009) who claim that 99% of 150 respondents randomly selected in Lagos, Benin City and Abuja do not get electricity supply for up to 24 hours without interruption. However, the results may be affected by location and timing of data collection

5-Disaggregating primary electricity consumption for office buildings in Nigeria

Climatic Zone	Buildings	Electricity supplied by Generator (%)	Average generator usage/month (hours)
Hot and dry	1	NA	NA
	2	27%	65
	3	NA	NA
	4	14%	33
Composite of hot and dry/hot and humid	5	17%	40
	6	74%	177
	7	56%	134
Hot and humid	8	74%	177
	9	NA	800
	10	NA	NA
	11	NA	NA
	12	78%	187
	13	NA	NA
	14	NA	NA
	15	NA	NA

Table 5-2 Electricity supplied by back-up power generator in the 15 buildings audited (NA indicates lack of data)

5.7 Normalized End-uses

Disaggregating electricity consumption into end-uses is required to examine the source of significant electricity demand. These are an indication of potential energy saving opportunity. Cooling, lighting and appliance loads are calculated to account for 40%, 12% and 48% respectively as shown in Figure 5-12. The substantial contribution by cooling is an indication that targeting this end-use will provide significant energy

savings. Table 5-3 shows the normalized electricity consumption by area, of each disaggregated end-use and the average across the 15 buildings audited.

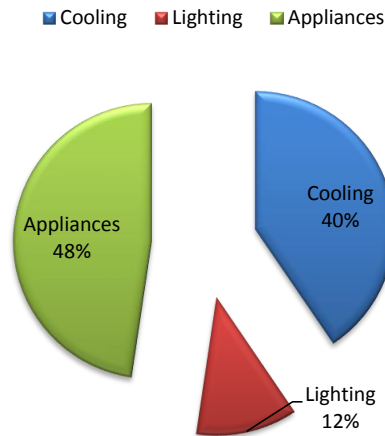


Figure 5-12 Electricity consumption disaggregated by end uses

Electricity consumption, be it total or aggregate end-use values may be normalized with thermal comfort variables such as gross floor area, occupants, or cooling degree days; to enable comparability of electricity consumption in different scenarios. When examining buildings of varying activities or sizes, the results may have errors due to the different scales of sizing in different building types. Existing HVAC systems may cause the energy use in specific buildings to be different than in similar buildings, hence the need to normalize these other factors that may affect energy consumption. For instance, the energy consumption of a small factory building is incomparable to that of a large industrial estate; normalizing the consumption with gross floor area allows the consumption to be relatively fairly compared and/or benchmarked. There are no previous records to compare the results presented here; as none of the buildings visited had ever been audited before. Furthermore, Nigeria is yet to develop energy benchmarks.

Average electricity consumption normalized by gross floor area and by building users are 15.9kWh/m² and 3062.2kWh/person respectively. Normalization based on gross floor area is adopted in this investigation. This is due to the author's architectural bias and the unit of measurement being buildings, rather than people.

The good and typical practice benchmarks per conditioned floor area for mechanically cooled buildings are 128 kWh/m² and 226kWh/m² respectively (CIBSE, 2004). Those for naturally ventilated buildings are 33kWh/m² and 54kWh/m² respectively.

5-Disaggregating primary electricity consumption for office buildings in Nigeria

Buildings	Cooling		Lighting		Appliances	
	Normalised consumption (kWh/M2)	Demand (kWh)	Normalised consumption (kWh/M2)	Demand (kWh)	Normalised consumption (kWh/M2)	Demand (kWh)
Building 1	23	5,625	26	6,387	115	28,795
Building 2	83	99,563	50	59,542	26	30,694
Building 3	70	225,548	14	48,328	14	48,089
Building 4	92	749,925	10	81,326	196	1,604,268
Building 5	145	425,950	20	60,197	131	386,859
Average	83	301,322	24	51,156	96	419,741
Aggregate %	40%	39%	12%	7%	48%	54%

Table 5-3 Electricity consumption by aggregate end-use

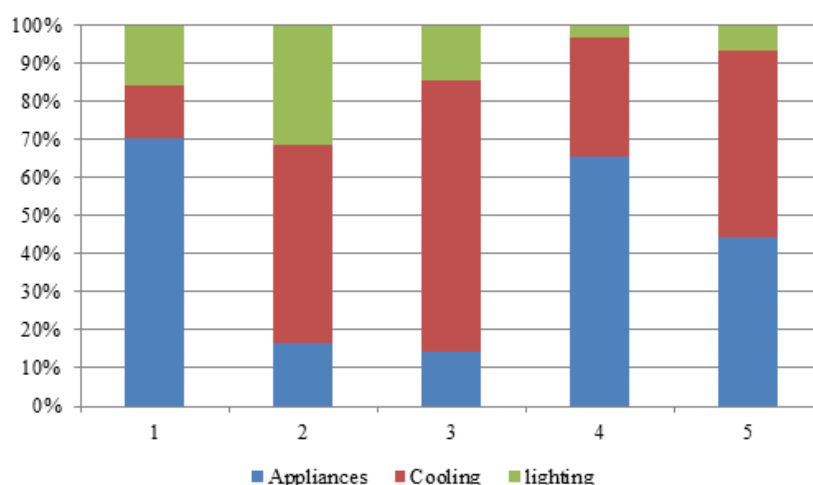


Figure 5-13 End-use electricity consumption in 5 buildings audited

Building 1-5 have their normalized electricity at 163kWh/m², 158kWh/m², 99kWh/m², 298kWh/m², and 203kWh/m² respectively as shown in Table 5-3.

Figure 5-13 shows the aggregate consumption in percentage across the five buildings. Compared to the benchmarks for all the building classes by CIBSE, (2004), the average normalised consumption recorded during the fieldwork is exceptionally low. This is may be due to the difference in climate under which the CIBSE bases its benchmarks on

and the warm climate experienced in Nigeria. Technological advancements in a developed country such as the UK as compared to a developing country such as Nigeria may affect the suitability of the benchmark for Nigerian office buildings. However, even the benchmark for naturally ventilated office buildings is higher than the average recorded for the fieldwork, signifying that buildings in Nigeria generally use less energy than in the UK. This may indicate a prevailing condition of thermal discomfort that may also affect productivity.

5.7.1 Cooling

The cooling load is the difference between the total electricity consumption and the combined consumption of lighting and appliances. The combined consumption of lighting and appliances per annum for buildings 1 to 5 are 35,182kWh, 90,236 kWh, 96,417kWh, 1,685,594kWh, and 447,056kWh respectively. Building 4 consumes the most baseload electricity, being the national headquarters of a commercial bank. Building 1 is a small bank branch and consumes the least.

Cooling loads for buildings 1-5 are 5,625kWh, 99,563kWh, 225,548kWh, 749,925kWh, and 425,950kWh respectively. Cooling normalized consumption for buildings 1-5 are 23kWh/m², 83kWh/m², 70kWh/m², 92kWh/m², and 145kWh/m² respectively. The cooling load accounts for an average of 40% of electricity consumption in the buildings. It is the second largest consumer.

5.7.2 Appliances

The consumption of each appliance was estimated using Equation 5-10. Appliance loads for buildings 1-5 are 28,795kWh, 30,694 kWh, 46,089 kWh, 1,604,268 kWh, and 386,859 kWh respectively. Appliances load normalized per square meter consumption for buildings 1-5 are; 115kWh/m², 26kWh/m², 14kWh/m², 196kWh/m² and 131kWh/m² respectively. The average is 83kWh/m². This accounts for 48% of consumption, the largest consumer.

5.7.3 Lighting

The consumption of each lighting fixture was estimated using Equation 5-10. A variety of lighting fixtures such as incandescent, fluorescent, sodium and mercury lamps are installed in the buildings ranging from as little as 18w to 500w. Lighting loads for buildings 1-5 are 6,387 kWh, 59,542 kWh, 48328 kWh, 81,326 kWh and 60,197 kWh

respectively. Lighting normalized consumption for buildings 1-5 are 26kWh/m², 50kWh/m², 14kWh/m², 10kWh/m², and 20kWh/m². This load accounts for 12% of electricity consumption, the least end-use consumer.

5.8 Degree day calculations

In this work, degree day calculations were based on a 3 year (2005-2007) daily average dry bulb air temperature profile provided by the Nigerian national meteorological agency (NIMET). It has been established that cooling dominates the HVAC load for Nigerian buildings and therefore, only cooling degree days are considered. A cooling degree day is calculated as that which the average air temperature for that day is more than the neutrality temperature. Assumptions for degree day calculations are:

1. Only cooling is required for comfort in all buildings, therefore HVAC is synonymous to cooling within the document
2. Operational schedules used are based on the building managements' specifications and not actual measured use
3. Nigeria has no public holidays annually

Cooling degree days are calculated with base temperatures corresponding to neutrality temperatures of 26°C, 26.3°C, and 26.4°C for Kaduna, Abuja and Lagos respectively. As discussed in Section 5.4, degree day approach is heavily dependent on the accuracy of the base temperature and consumption data. It should also be noted that degree-day calculations is limited by its inability to consider direct solar radiation in its evaluation of indoor thermal comfort.

5.8.1 Building 1

Building 1 is a small single story bank branch in the northern city of Kaduna. Similar to all the buildings investigated, the correlation between consumption and monthly cooling degree days (MCDD) is poor. The R² recorded is 0.007, and the line suggests that the more the discomfort due to high temperatures, the less electricity is consumed rather than the opposite. The consumption trend shows the misalignment between consumption and monthly cooling degree day (CDD) also, as shown in Figure 5-14 and Figure 5-15.

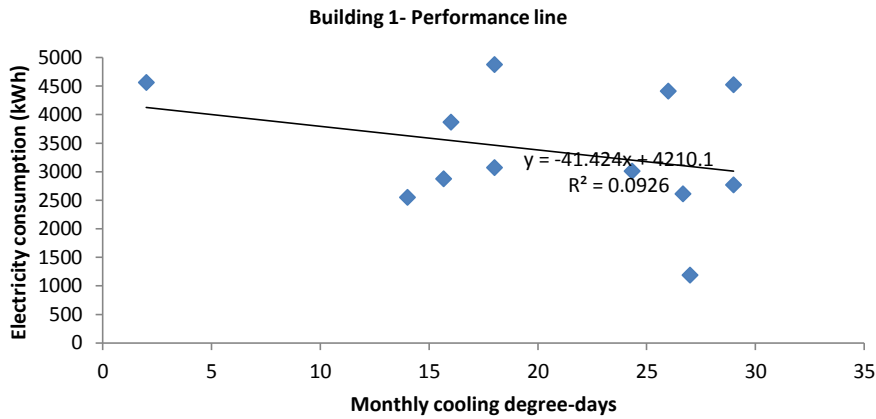


Figure 5-14 Building 1 Performance line

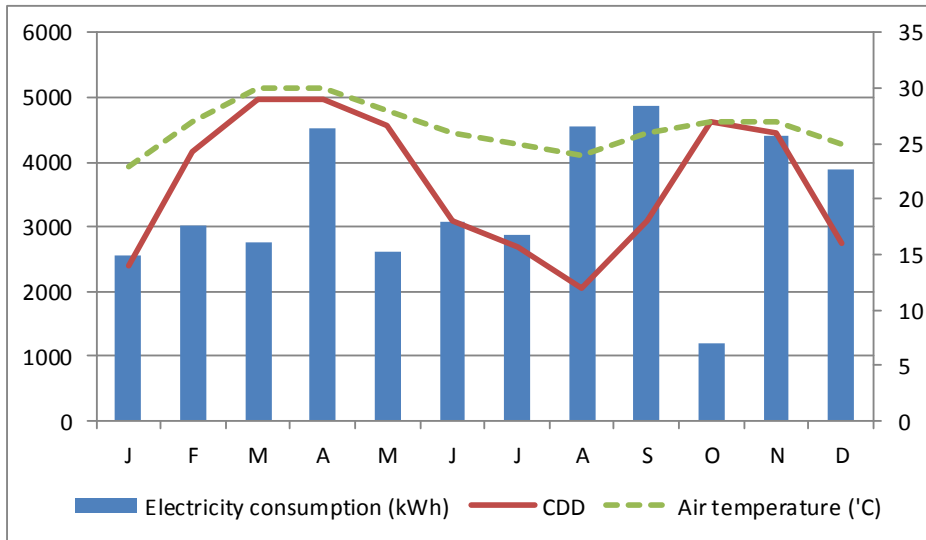


Figure 5-15 Building 1 Combination chart

5.8.2 Building 2

Building 2 is a 4 story government office in the central city of Abuja. The correlation between consumption and monthly cooling degree days is poor. The R^2 in Figure 5-16 is 0.1235, and the line indicates that the hotter the day, the less electricity consumption in the building. This should be the opposite, thus showing an opportunity for energy savings. The consumption trend as shown in shows this misalignment also, see Figure 5-17.

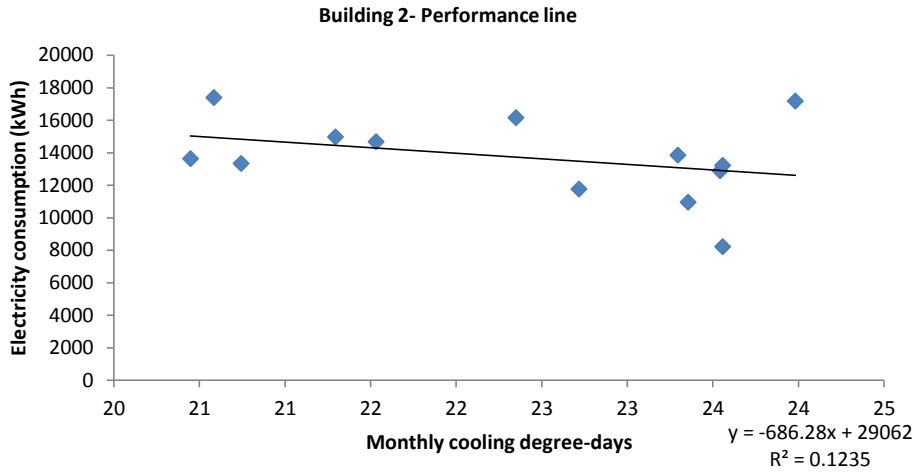


Figure 5-16 Building 2 performance line

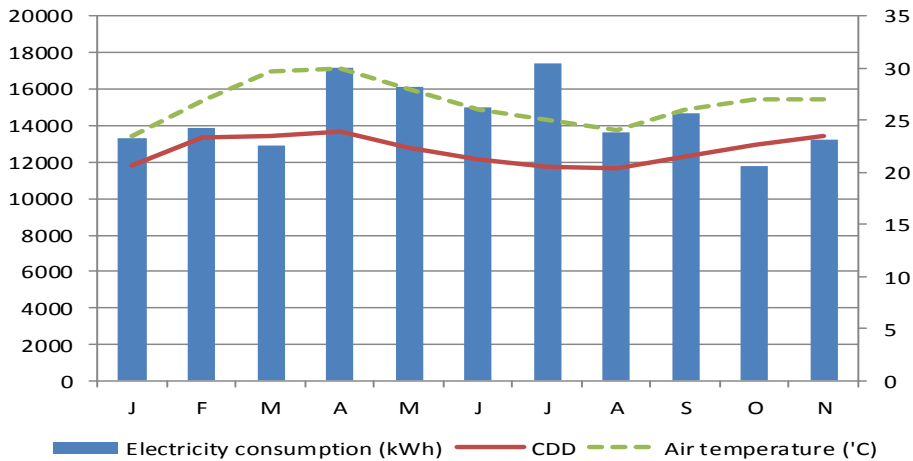


Figure 5-17 Building 2 combination chart

5.8.3 Building 3

Building 3 is also a 4 story government office in the central city of Abuja. The correlation between consumption and monthly cooling degree days is better than all the buildings but still poor with R^2 at 0.3361 as shown in Figure 5-18. The line indicates that the hotter the day, the more the electricity consumption in the building. Even

though this should be the normal trend, the consumption shown in Figure 5-19 show the misalignment between consumption and monthly cooling degree days.

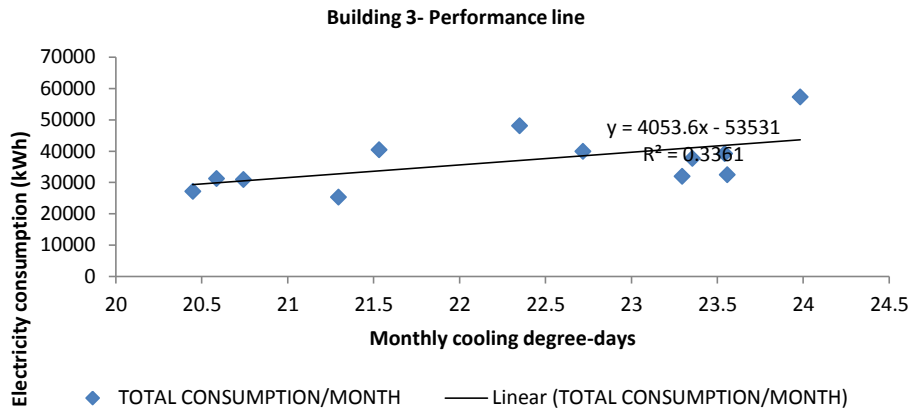


Figure 5-18 Building 3 performance line

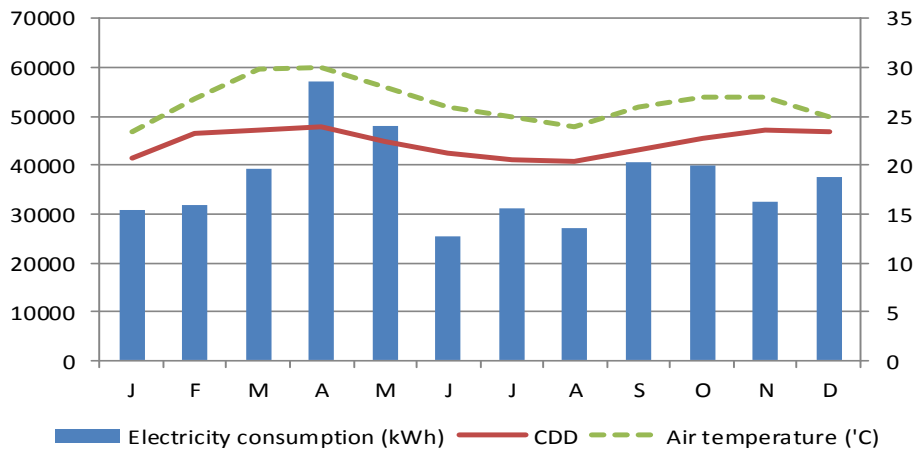


Figure 5-19 Building 3 combination chart

5.8.4 Building 4

Building 4 is the 13 story head office of a bank. It is serviced by 3 elevators. These factors account for higher consumption values. The correlation between consumption and monthly cooling degree days is poor. The R^2 in Figure 5-20 is 0.144. The line indicates that the hotter the day, the more the electricity consumption in the building.

Even though this should be the normal trend, the consumption shown in shows Figure 5-21 the misalignment between consumption and MCDD.

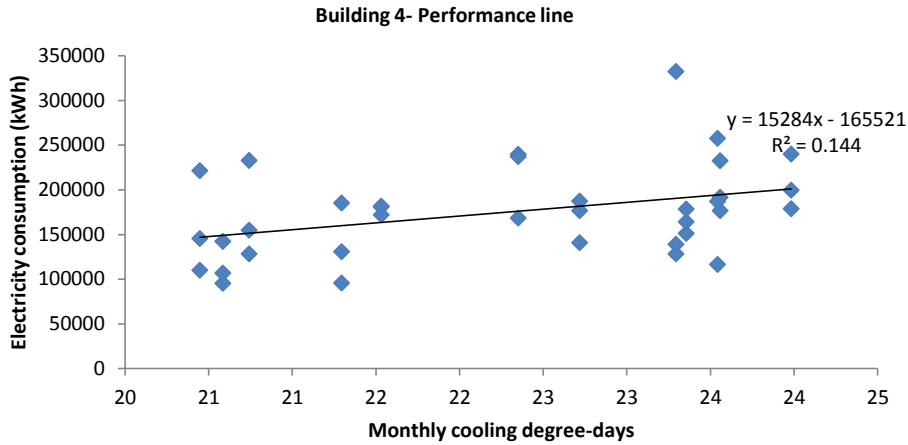


Figure 5-20 Building 4 performance line

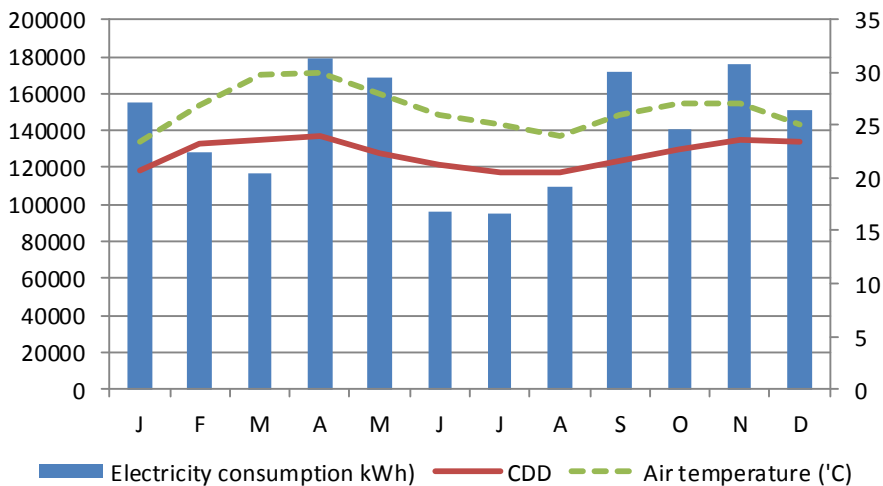


Figure 5-21 Building 4 combination chart

5.8.5 Building 5

Building 5 is a 4 story regional branch of a bank in the southern city of Lagos. The correlation between consumption and monthly cooling degree days is poor. The R² in Figure 5-22 is 0.0238, and the line indicates that the hotter the day, the less electricity consumption in the building. This should be the opposite, thus showing an opportunity

for energy savings. The consumption trend as shown in shows this misalignment also, see Figure 5-23.

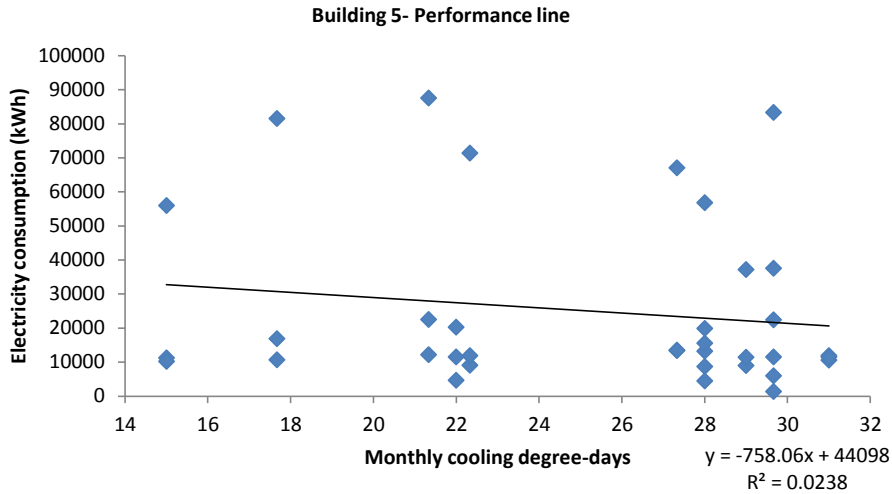


Figure 5-22 Building 5 performance line

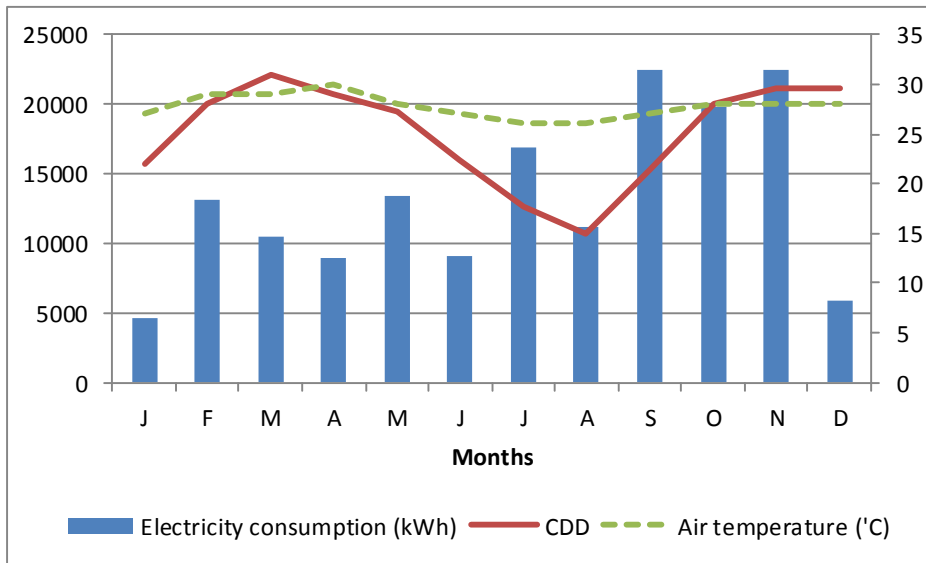


Figure 5-23 Building 5 combination chart

5.9 Conclusion

In Chapter 1, a paucity of electricity consumption data is highlighted necessitating the need for a field data collection exercise. In this chapter, the data collected is studied to

investigate the electricity consumption within office buildings in Abuja and determine the potential for energy savings within the cooling load

Total electricity consumption is aggregated to end-uses; cooling, lighting and appliances. Cooling, lighting and appliance loads account for 40%, 12% and 48% respectively. The substantial contribution by cooling is an indication that targeting this end-use will provide significant energy savings.

Degree day calculations are used to test the correlation between electricity consumption and cooling degree-days. The method is shown to be beneficial for building energy calculations, especially at the early stage. Neutrality temperature is tested and adopted as base temperature required to calculate degree-days.

The monthly electricity consumption in of buildings audited in three cities in Nigeria is tested for the alignment to the weather profile. Inferential statistical analysis shows major discrepancies. The R^2 , an indication of correlation in the buildings 1-5 are 0.06, 0.026, 0.022, 0.129, and 0.136 respectively. For Buildings 1-5 there was little correlation between energy consumption and climate. The climate accounts for only a maximum of 13.6% of electricity consumption in building 5. This result indicates that other factors affecting consumption include building fabric, poor user controls, poor system or building design and inadequate data.

However, the disaggregated values show climate-related cooling to be a significant end-use at 40% consumption.. Therefore there is an opportunity for energy savings in cooling consumption; in terms of modifying the building construction, the cooling system, and occupants behaviour. An opportunity for PCM energy conservation exists. Due to erratic power supply, electricity consumption data collection in Nigeria needs a complex approach. Electricity consumption is a combination of utility and back-up generator consumptions. A method of estimation is presented that accounts for consumption covered for both utility and back-up power supply given by Equation 5-12. Electricity consumption data recorded is used in modelling and simulating the performance of PCM in Abuja office buildings in the following chapters (5 and 6). The information recorded during the energy audit includes data on occupancy, schedules, construction, and glazing.

6 CHAPTER 6
OPTIMIZING THERMAL AND ENERGY PERFORMANCE OF
BUILDINGS

Contents
6.1 Overview
6.2 Context- Abuja city
6.3 The base-case modelling
6.4 Result and discussion
6.5 Bioclimatic model
6.6 Conclusion

Problem	Chapter one: Introduction- 'Nigerian buildings and Energy use'	
Theoretical framework	Chapter two: Literature review- 'Phase change materials as energy conservation mechanisms in buildings'	
Methodology	Chapter three: 'Methodology'	Chapter four : 'Validation study'
Results	Chapter five: 'Disaggregating primary electricity consumption for office buildings in Nigeria'	Chapter six: 'Optimizing thermal and energy performance of buildings' Chapter seven: 'PCM performance in office buildings'
Conclusion	Chapter eight: Conclusion	

6.1 Overview

Following the investigation into the electricity consumed in Nigerian office buildings, the cooling load which accounts for 40% of total consumption, provides an opportunity for energy savings.

This chapter looks into the variables and their sources required to construct a base-case. A base case is required because testing PCM systems on a poorly designed building might give mistakenly superior results for energy savings. Testing PCM systems on a thermally optimized base-case building on the other hand is a better indicator of its effect. The effect of the bio-climatic variables is examined using computer simulation and analysed parametrically. The analysis is conducted quasi-experimentally by holding all variables except the variable being examined.

The context is Abuja mix-mode office buildings. The modelling and simulation is conducted by the software DesignBuilder and an internal EnergyPlus simulation engine respectively (DesignBuilder, 2011; EnergyPlus, 2011). The end result is a hypothetical base-case building that is used to test the performance of PCMs in office buildings in Abuja.

6.2 Context- Abuja city

Abuja is the capital city of Nigeria. Located in the centre of Nigeria within the Federal capital territory (FCT), it was built mainly in the 1980s. The creation of a new capital was in light of the ethnic and religious divisions of the country, in a location deemed neutral to all parties. In addition, the old capital, Lagos is overwhelmed by a population boom that makes the city overcrowded and conditions squalid. The Federal capital territory has a land area of 8,000km², which is two and halftimes the size of Lagos.

Abuja is divided into 3 phases ranging from central to suburban. Bearing in mind the context of this thesis is office buildings, the research is limited to the central Phase 1 district of the city which is divided into five districts:

1. Central District
2. Garki
3. Wuse
4. Asokoro
5. Maitama

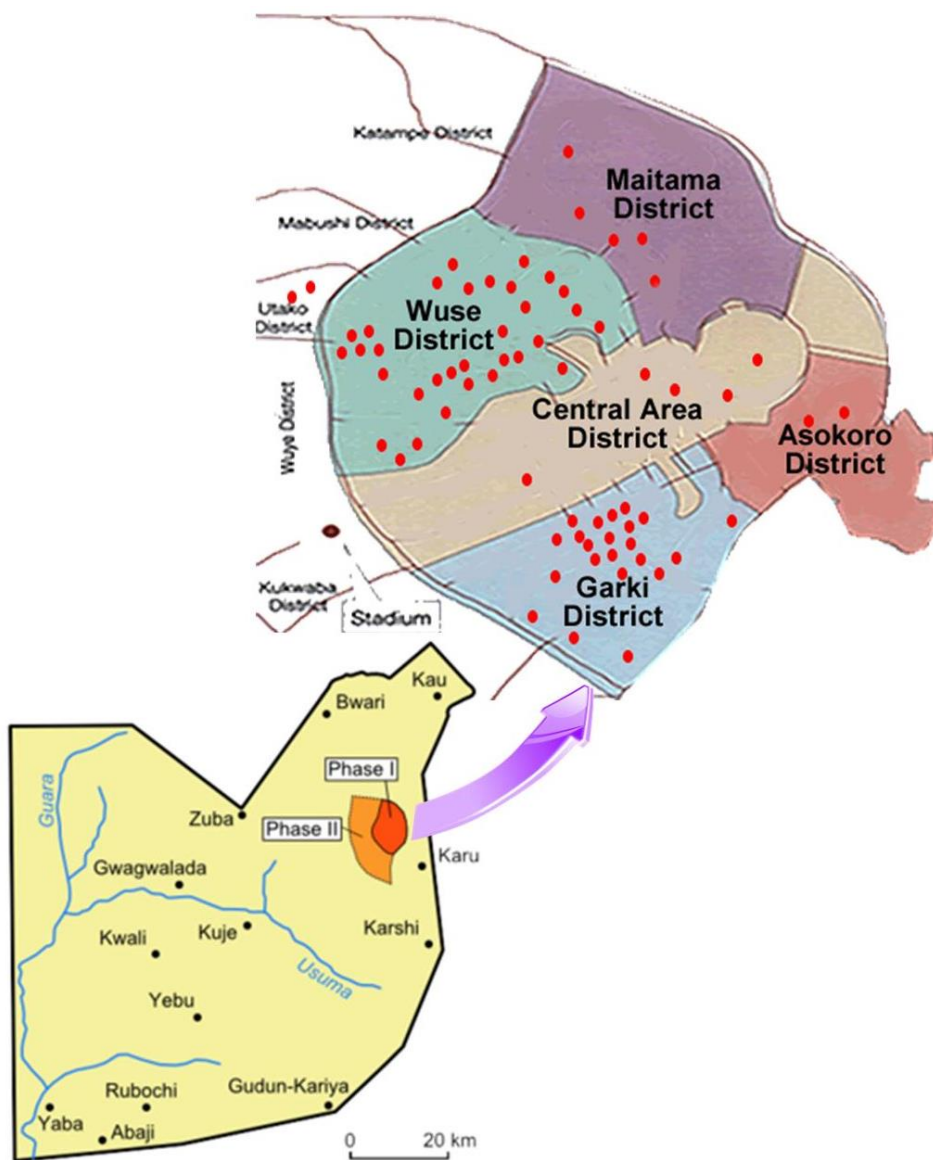


Figure 6-1 Abuja city districts- highlighting Phase 1

The central Phase 1 district is the city's principal business zone, where most national and multinational corporations have their offices. This is the area in Abuja that all the buildings investigated in the research are located, see Figure 6-1. Abuja is chosen because of the overall superior calibre of data collected from the buildings in the energy audit exercise covered in chapter four.

6.2.1 Abuja climate

Abuja experiences a composite of hot and humid, and hot and dry climate. The city experiences three weather conditions annually. This includes; a warm, humid wet season beginning from April and ends in October; and a dry season from November to March. In between the two, there is a brief interlude of harmattan.

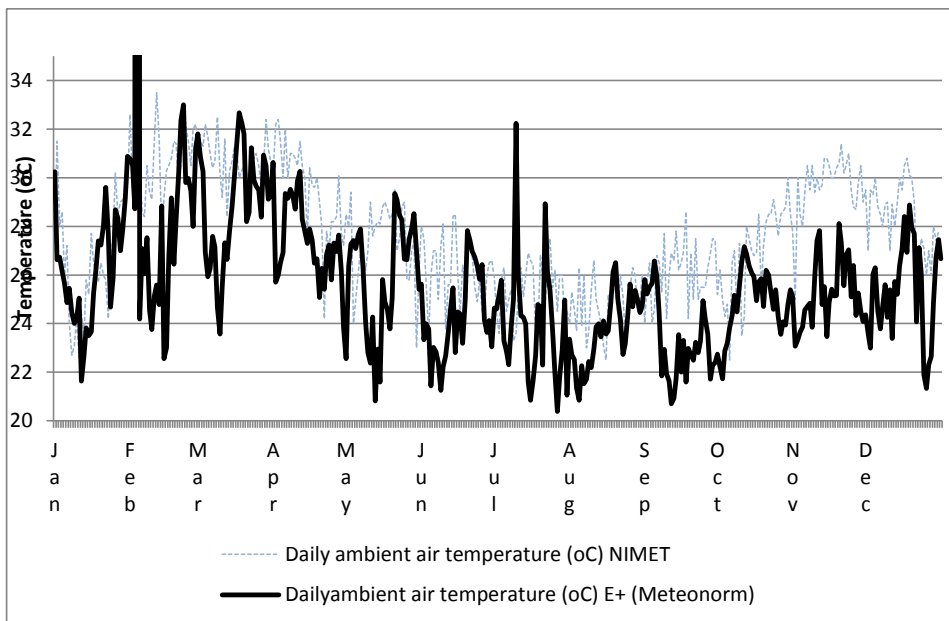


Figure 6-2 Abuja ambient air temperature (°C) comparing weather data from Metenorm (used in EnergyPlus) and Nigerian meteorological agency (NIMET)

The average ambient air temperatures synthetically provided (Meteonorm, 2012) for Abuja over a year are shown Figure 6-2. These are compared with values supplied by Nigerian meteorological agency (NIMET) for the year 2005. The average difference between the two sets of values is 1.436089 and the Root Mean Square Error (RMSE) is 20%. This is acceptable considering natural variance in local weather conditions in different years. EnergyPlus requires climatic data to run valid simulations based in a given location. These climatic data are added as separate weather file input before running the simulations as shown in Chapter 3. The weather file used in this research has been synthesized by Meteonorm (2012) for Abuja, Nigeria, in hourly timesteps over a year. Values such as ground temperatures, average temperature, solar azimuth and elevation, global, diffuse and beam

(direct normal) radiation as well as radiation on inclined planes, long-wave radiation, luminance, precipitation, and humidity parameters are available. However, only air temperature- used to calculate Neutrality temperature is used to analyse comfort in this research.

From the synthetic weather data from Meteonorm, the Neutrality temperature using Equation 6-1 by de Dear and Brager (1998) is 26.3°C. Szokolay (2004) has defined the comfort range as a band 4°C wide centred on the Neutrality temperature. Therefore the thermal comfort range for Abuja city may be regarded as 24.3°C to 28.3°C.

$$T_n = 17.8 + 0.38(T_{ave}) \quad \text{Equation 6-1}$$

Where T_n is Neutrality temperature, and T_{ave} is mean monthly temperature.

The comfort limits as calculated by Ogunsote (1991) based on the Effective temperature index (ET) has day and night comfort operative temperatures at 23°C -29°C and 17°C -23°C respectively. A comparison between the result using ET by Ogunsote (1991) and that calculated with Neutrality temperature comfort band between 28.3°C to 24.3°C for day and night shows the limitation of the ET index. The ET prediction for day comfort temperature shows fairly good agreement but that of night-time falls outside the predicted range.

6.3 The base-case modelling

The base-case model is a hypothetical building constructed with variables extracted from primary and secondary sources. Section 6.3 describes the sources of the variables. A more detailed description of the actual values used to construct the base-case is provided in the Sections 6.3.4.

These variables are bio-climatically optimized for thermal comfort and energy conservation in the context of Abuja office building. Such a base case is required because testing PCM systems on a poorly designed building might give erroneously superior results simply because there is so much room for energy savings. Testing PCM systems on a thermally optimized base-case building on the other hand indicates only its effect.

The process of bio-climatic optimization is illustrated in Figure 6-3. A bio-climatic system uses design features such as shading, orientation, insulation and thermal mass of the building to reduce or eliminate the heating and cooling requirements of the climatic zone (Khalifa and Abbas, 2009). Bioclimatic principles affect the energy flows within a building, such as heat

transfer through building fabric or from internal gains. Adopting bioclimatic design principles saves energy as buildings are designed based responding to natural ventilation, local climate and materials, and using renewable or clean technologies. In this instance, PCM performance is examined in the next chapter, and the base-case model constructed here is used.

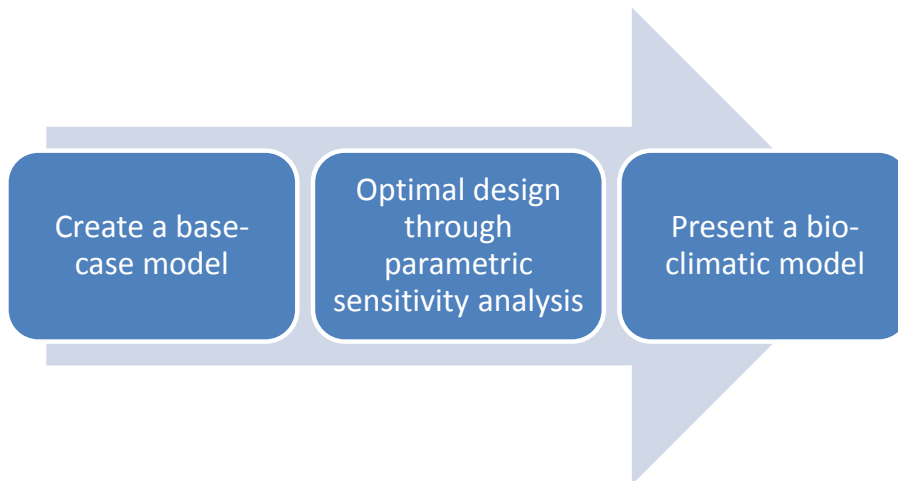


Figure 6-3 Optimizing procedure for bio-climatic model

The modelling and simulation in this study is done by the software DesignBuilder and an internal EnergyPlus simulation engine respectively (DesignBuilder, 2011; EnergyPlus, 2011). DesignBuilder is a tool for checking building energy, carbon emissions, lighting and comfort performance. In this instance, it is used as a graphical user interface for the text based simulation engine of EnergyPlus. EnergyPlus is a whole building energy simulation program used to model energy and water use in buildings. In this instance, it is used as a predictive tool; to parametrically evaluate the thermal and energy performance of the whole building. The process for creating the base-case follows this sequence (DesignBuilder, (2011):

1. Create new site
2. Create new building
3. Create building geometry
4. Partition building into thermal zones
5. Set Model Data
6. Add any 'custom openings' (windows, doors etc) by drawing up the surface level
7. Size heating and cooling systems
8. Check design by carrying out summer and winter simulations displaying hourly data
9. Run annual simulations

Sources of variables making the base-case are shown in Figure 6-4 and Table 6-1. The primary source is the data collected from the field during the energy audit. The secondary sources are through Nigerian building code (Federal Republic of Nigeria, 2006) and a literature search of a bio-climatic approach to building design in hot climates.

Fieldwork data	Nigerian building code	Bio-climatic design literature
Spatial planning	Lighting	Geometry
External wall	Ventilation	Orientation
Partition wall	Room dimensions	Glazing
Glazing	Occupancy	Shading
Roofing		Airtightness
Ground floor		Insulation
Other floors		
Schedules		

Table 6-1 Sources of base-case variables

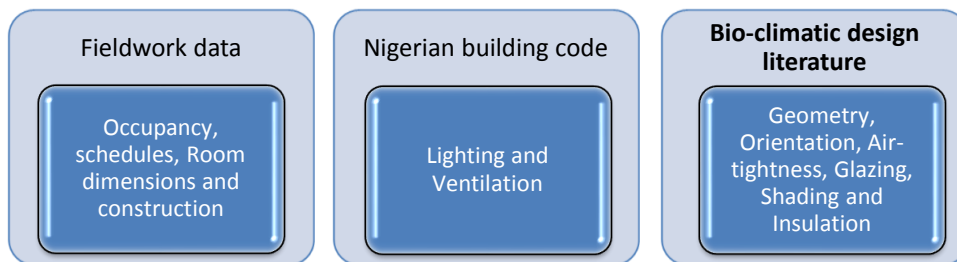


Figure 6-4 Base-case morphology

6.3.1 Fieldwork data

A discussion on data collected from the field has been done in Chapter 5, but the variables presented here are those required to create a base-case model as close to existing structures in the Abuja office building context as possible. The variables include external walls, partition walls, glazing, ground floor, other floors, and schedules as shown in Table 6-2.

6-Optimizing thermal and energy performance of buildings

Building	Climatic Zone	Glazing	Employees	Space/person (m ² /person)	Gross floor area (m ²)	Conditioned floor area (m ²)	Total exterior glass (m ²)	Total exterior wall area (m ²)	Total exterior roof area (m ²)	Floors	Wall: Window (%)
1	Hot and dry	clear	12	19	232	200	37	239	112	2	15%
2		clear	200	5	850	700	115	1,400	900	2	8%
3		reflective clear	20	13	250	250	33	209	250	1	16%
4	Composite of hot and dry/	reflective brown tint	130	9	1,200	1,000	270	1,500	1,200	4	18%
5	hot and humid	reflective brown tint	125	26	3,218	2,700	745	13,042	320	4	6%
6		reflective clear	600	14	8,184	6,704	480	4,600	672	13	10%
7	Hot and	clear	297	14	4,034	4,034		464	792	4	0%
8	humid	reflective brown tint	9	18	4,034	3460	39	280	226	3	14%
9		reflective brown tint	85	11	1120	962	38	720	350	3	5%
10		reflective brown tint	137	21	2,944	2,609	301	1,488	960	4	20%
Average			162	15	2606.6	2261.9	229	2394	578	4	11%

Table 6-2 Building characteristics recorded during energy audits in the field- used in constructing the base-case

6.3.1.1 Building fabric characteristics

It should be noted that U-values of the components making up the building fabric are calculated from the data of building construction recorded in the field (see Table 6-4). As discussed in Chapter 4, all the buildings investigated had 225* 225* 450mm external sandcrete walling units joined with mortar and plastered on both sides with 25mm sand:cement mixture. U-values of the sandcrete walls and the other building components observed in the field and shown in Table 6-3 are calculated by Chartered Institute of Building Service Engineers methodology (CIBSE, 2007).

Building component	U-value (W/m ² K)
Sandcrete wall	1.4
Ground floor	4.4
Floor	6.7
Roof	0.4

Table 6-3 Calculated U-values of building components using CIBSE (2007) methodology

The formula used is Equation 6-2:

$$U = \frac{l}{R_{os} + R_a + R_{is} + R_t} \quad \text{Equation 6-2}$$

Where

U= U-value (W/m² K)

R_{is} = Inside surface resistance (m² K /W)

R_{os} = Outside surface resistance (m² K /W)

R_a = Air gap resistance (m² K /W)

l = Thickness (m)

k= thermal conductivity of layer (m)

1/k = R_t= Fabric resistance

The resistance values of the building components and layers are also from the default CIBSE (2007) guidelines existing in EnergyPlus. Some of the values are shown in Table 6-3.

Layers	Thickness (l)	Conductivity, k (W/mK)	Resistance, R (m ² K /W)
Ceramic tiles	0.01	0.8	0.01
Screed	0.025	0.4	0.06
Concrete	0.3	2	0.15
Aluminum cladding	0.01	45	0.000222
Air	0.6	0.23	2.6
Ceiling tiles	0.01	0.4	0.03
Asphalt	0.045	0.75	0.06
Screed	0.025	0.4	0.1
External wall external surface			0.04
External plaster	0.025	0.18	0.14
Sandcrete layer 1	0.0875	1.7	0.05
Airspace			0.18
Internal plaster	0.025	0.18	0.14
External wall internal surface			0.13

Table 6-4 Building thermo-physical characteristics used to calculate u-values from CIBSE (2007) guidelines

Descriptions of the building components observed in the field are:

1. **Partition wall:** All the buildings investigated had 150* 225* 450mm internal sandcrete walling units joined with mortar and plastered on both sides with 25mm sand:cement mixture. The calculated U-value of such a wall is 1.4 W/m² K
2. **Glazing:** All the buildings investigated had 3mm single glazing with internal blinds; 21% had clear glazing, and 79% had tinted bronze glazing
3. **Roofing:** All the buildings investigated had aluminum clad gable roofs with dropped ceilings made of chip wood. The calculated U-value is 0.38 W/m² K
4. **Ground floor:** Ground floors are solid concrete slabs laid directly on the soil and finished with tile made of fired and unfired ceramic and granite. The average U-value of such floors is calculated to be 4.4 W/m² K
5. **Other floors:** Other floors are solid concrete slabs with dropped ceilings made by wood fibers on wooden joists and finished with tile made of fired and unfired ceramic and granite. The average U-value of such floors is calculated to be 6.7 W/m² K

6. **Building schedule:** Average daily working hours are estimated at 9 hours from 8am-5pm. None of the buildings operated on week-ends, however some staff members work for an average of 4hrs on Saturday, once a month

6.3.1.2 Spatial planning

From fieldwork measurements, air-conditioned floor area is averagely 23% of gross floor area of 10 buildings audited as shown in Table 6-5. The average gross and conditioned floor area is 2607m² and 2262m² respectively. The average number of employees is 162. These data are used to calculate the spatial configuration for the base-case in Section 1936.3.4.

Building	Climatic Zone	GFA (m ²)	CFA (m ²)	Difference	Difference (%)	Employees
1	Hot and dry	232	200	32	14%	12
2		850	700	150	18%	200
3		250	250	0	0%	20
4	Composite of hot and dry/ hot and humid	1,200	1,000	200	17%	130
5		3,218	2,700	518	16%	125
6		8,184	6,704	1480	18%	600
7	Hot and humid	4,034	4,034	0	0%	297
8		4,034	3460	574	14%	9
9		1120	962	158	14%	85
10		2,944	2,609	335	11%	137
	Average	2607	2262	345	12%	162

Table 6-5 Spatial plan development showing GFA- Gross floor area, CFA- Conditioned floor area and number of employees across 10 buildings audited having adequate data

6.3.2 Nigerian building code

Nigerian building requirements are mainly from a single source called the National building code (Federal Republic of Nigeria, 2006). The specifications that affect the scope of this study and are covered in designing the base-case are:

- Lighting
- Ventilation
- Room dimensions
- Occupancy

6.3.2.1 Lighting

The Nigerian building code specifies that all rooms with external glazing must exceed 65 lux for natural daylighting. For rooms adjoining and requiring access to natural daylighting from said external glazing, there needs be an unobstructed opening of more than 8% of the floor area but not less than 2.4m². Stairways must have external glazing also. Natural lighting lower than the 65lux level requires artificial lighting. Lighting level for office buildings specify about 500 lux (CIBSE, 2007) and (Ogunsote, 1991).

6.3.2.2 Ventilation

Naturally ventilated rooms require more than 4% of floor area external openings. For rooms adjoining and requiring access to natural ventilation from said external glazing, there needs be an unobstructed opening of more than 8% of the floor area but not less than 2.4m². Mechanical ventilation must supply 10 L/s/person.

6.3.2.3 Room dimensions

Ceiling height must exceed 2.4m unless; it's a sloping roof and dropped ceiling in which case it may as low as 1.5m and 2.2m respectively.

A habitable room must have any one dimension exceeding 3m and 10.8m²; except toilets and kitchens respectively. Distance from property line to building should be 6m or above.

6.3.2.4 Occupancy

Standard occupancy is 0.65m²/occupant but should not exceed 10.3m²/occupant. For occupant load less than 500 people, exits are required; for 501-1000 people 3 exits; and more than 1000 people 4 exits are required.

6.3.3 Bio-climatic design literature

The ultimate aim of the bioclimatic approach to building design is to attain a certain comfort level for the occupants in the buildings (Olgyay and Olgyay, 1953).

The climate is a major influence on the amount of energy that is used for heating and cooling and also the amount of energy that is used for lighting. In energy terms, the building features that affect energy consumption the most is the building façade. It contributes to both the embodied energy and operating energy of a building. The magnitude of heat loss is low in hot climates, so building energy conservation strategies are based primarily on heat gain component analysis.

As discussed in section 6.1, there is a need for a bio-climatically optimized base-case building. A successful intelligent building needs to be a product of a design process that incorporates intelligence in all its stages while taking advantage of technological innovations (Ochoa and Capeluto, 2008).

Therefore, using bioclimatic design principles to conserve energy is ideal. However, some environments may not achieve comfort solely with bio-climatic design principles and may require mechanical means to condition the interiors of buildings. Using mechanical means should also however be 'intelligent' and optimized in terms of design, operation and control to conserve the most energy.

The Abuja climate as mentioned earlier is characterized by high temperatures, high rainfall intensity and large diurnal temperature swings during harmattan. The cooling degree days in Abuja are 267 days out of 365 days making a year. This means that 73% of the time, the temperature is too hot for comfort.

Kim and Moon (2009) conducted computer simulations to quantify the impact of some bioclimatic variables in the building fabric of a building on cooling energy consumption in the hot humid climate of Miami, Florida. The various heat gain components are ranked according to impact as:

1. Solar radiation through windows is the highest (34.2%)
2. Conduction through windows (12.3%)
3. Infiltration (11.5%)
4. Conduction through walls (5.6%)

Climate	Element and requirement	Purpose
Hot and dry	<ul style="list-style-type: none"> Minimise south and west walls Minimise surface area Maximise building depth Minimize window wall 	<ul style="list-style-type: none"> Reduce heat gain Reduce heat gain and loss Increase thermal capacity Control ventilation heat gain and solar gains
Hot and humid	<ul style="list-style-type: none"> Minimise building depth Minimize west facing wall Maximise south and north walls Maximise surface area Maximize window wall 	<ul style="list-style-type: none"> Ventilation Reduce heat gain Reduce heat gain Night cooling Ventilation
Composite	<ul style="list-style-type: none"> Controlled building depth Minimise west wall Limited south wall Medium area of window 	<ul style="list-style-type: none"> Thermal capacity Reduce heat gain Ventilation and some heating Controlled ventilation

Table 6-6 Nigerian climate classification and bioclimatic options based on (Ogunsote, 1991; Haase and Amato, 2006; Mustafa, 2008)- showing highlighted composite climate suitable for Abuja.

The results indicate that shading is an essential variable for building energy conservation in hot climates. The single largest heat gain component is conduction through the building fabric, followed by infiltration.

Therefore, the general design guidelines for comfort for this type of climate in literature (Ogunsote, 1991; Haase and Amato, 2006; Mustafa, 2008) as shown in Table 6-6. Looking at Table 6-6, the variables recommended for a composite climate include:

- Shading
- Geometry
- Orientation
- Glazing
- Thermal mass

- Internal gains minimization
- Outdoor living
- Insulation

6.3.3.1 *Shading*

Shading of the building during the day against solar heat gains by placing long axis east-west. Al-Tamimi, Fadzil et al. (2011) reports that any opening in east or west direction should be avoided, unless there is need in which case intensive consideration should be taken to use thermal insulation for the exterior walls. The insulation involves selecting proper shading devices or a type of glass that has low U-value. Solar Control and Shading devices should consider lighting standards for offices at 500 lux (Action Energy, 2003)

6.3.3.2 *Geometry*

Open and single banking of spaces are encouraged within the building to encourage ventilation (Ogunsote, 1991). A compacted building depth allows for control in thermal capacity and reduced surface area. Kim and Moon (2009) claim that the single largest heat gain component is conduction through the building fabric, therefore a compact building is able to regulate comfort temperatures through a reduction in surface area.

6.3.3.3 *Orientation and Glazing*

Orienting and planning buildings considering the topography of the site and sun-path. From the sun path diagram in Figure 6-5, the sun in Abuja rises more in the south east than north east over the year. This indicates that for a design aimed to exclude insolation, the wall with the most glazing should be facing the north.

There are contradicting opinions as to the effect of multiple glazing of buildings in hot climates. Kim and Moon (2008) claim that multiple glazing of windows in hot climates does not provide any significant heating and cooling energy benefits, and thus, are unnecessary. Rilling and Al-Shalabi (2008) on the other hand say solar heat gains decrease drastically by double layers glazing and triple layers glazing setup. An examination of the effect of multiple glazing is conducted in this research.

Many factors in glazing are important when thermal performance is evaluated. For a given glazing type, the critical variable determining the solar heat gains and the amount of daylight entering a building is the glazing area and direction. In general, thermal comfort can be improved by applying natural ventilation and wall/window ratio should be 20-35% with

openings well planned to catch comfortable breezes if naturally ventilated (Rilling and Al-Shalabi, 2008).

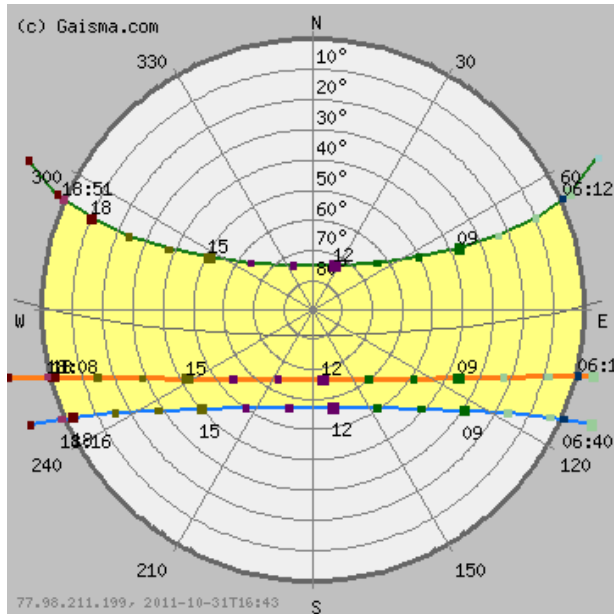


Figure 6-5 Sun path diagram for Abuja (www.gaisma.com/en/location/abuja.html)

6.3.3.4 Insulation

Suitable roofing is required to protect the building against intense rainfall and solar radiation. However, the benefit of insulation in both climates has been questioned by Kim and Moon (2009). They report that wall insulation does not influence energy consumption, roof insulation renders minimal energy benefits, window insulation has virtually no influence in heating and cooling energy consumption and envelope insulation provides little significant energy savings. This is due the small temperature difference between indoor and outdoor temperatures in hot and humid climates. While a minimal level of insulation may be beneficial, any additional insulation would not contribute to proportionate savings in heating or cooling energy. Rilling and Siang (2007) agree that adding insulation to building fabric in warm climates improves performance of environmental temperature only to keep hot air enclosed inside leading to a higher temperature level. The inclusion of air-conditioning is recommended to improve the overall thermal comfort of the building.

6.3.3.5 *Thermal mass*

The use of appropriate properties of materials should consider a building's thermal capacity and ventilation. Walls, floors and roofs should have high thermal capacity and time lag. The building envelope is a major variable in determining the peak demands and energy consumption. According to Lam and Li (1999) and Heim and Clarke (2004) the heat capacity of the building fabric and glazing have the most effect within the building envelope respectively.

6.3.3.6 *Internal gains minimization*

This is possible through reducing heat from occupants, equipment and artificial lighting.

6.3.3.7 *Outdoor living*

Shaded and partly enclosed outdoor areas are encouraged for outdoor sleeping, ventilation, and visual pleasure.

Based on the literature covered here, the following bio-climatic variables are examined as energy conservation mechanisms: geometry, orientation, glazing, shading, airtightness and insulation. The examination of increase of thermal mass is covered in the next chapter with the inclusion of PCM in the building fabric.

Internal gains minimization by building occupants is outside the scope of this study and outdoor living is ill-suited to office workers. They are therefore not studied as independent variables in this work.

6.3.4 *Optimal design variables for parametric analysis*

The aim of the parametric analysis is to observe the response following a modification in a given variable. This is required for the optimization of the system performance through proper selection of design variables. Computer simulations are adopted for this process. Degree-days can also be used as a method of examining energy conservation potential of a building. However, compared to full thermal computer simulation, degree-day's disadvantage lies in the basis of overly simplified assumptions and erroneous base temperature adoption (Day *et al.* (2003). However, degree-day calculations are easily carried out manually or within computer spread sheets. They have a transparency and repeatability that computer simulations may not provide.

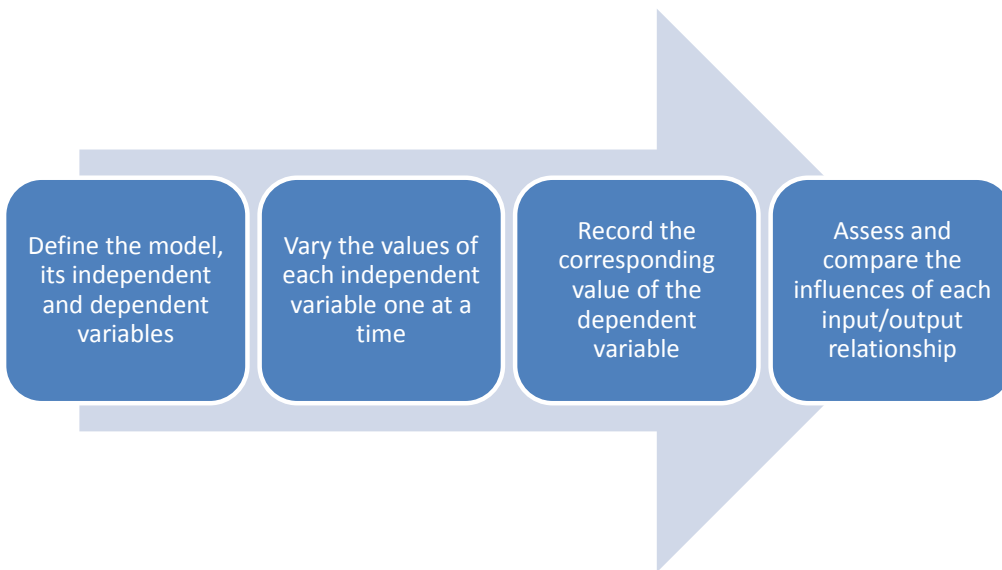


Figure 6-6 Parametric analysis procedure

The parametric analysis follows the procedure in Figure 6-6. Table 6-7 shows the different classes of variables used to construct the base-case. They are classified based on their sources; fieldwork data, Nigerian building code and bio-climatic design literature already discussed in Section 6.3. The following sections provide the actual values used to construct the model in DesignBuilder, with the exception of the class of independent variables extracted from bio-climatic design literature. These are examined and optimized for energy conservation and thermal comfort for office buildings in Abuja. They are:

- Geometry
- Orientation
- Glazing
- Shading
- Airtightness
- Insulation

Fieldwork data	Nigerian building code	Bio-climatic literature
<p>Spatial planning: Area is 417m², the unconditioned space is 52 m²; conditioned space is 91 m² (21m x 7m x 7m). Height is 3.5m.</p> <p>External wall: 225* 225* 450mm external sandcrete walling units, U-value 1.4 W/m² K.</p> <p>Partition wall: 150* 225* 450mm internal sandcrete walling units, U-value 1.4 W/m² K.</p> <p>Glazing: 3mm single glazing with internal blinds; 21% had clear glazing, and 79% had tinted bronze glazing,</p> <p>Roofing: Aluminum clad gable roofs with dropped ceilings made of chip wood. U-value is 0.38 W/m² K.</p> <p>Ground floor: Solid concrete slabs, U-value 4.4 W/m² K.</p> <p>Other floors: Solid concrete slabs with dropped ceilings made by wood fibers on wooden joists and finished with tile made of fired and unfired ceramic and granite, U-value 6.7 W/m² K.</p> <p>Schedules: 9 hours from 8am-5pm, some 4hrs on Saturday, once a month.</p>	<p>Lighting Rooms with external glazing must exceed 65 lux for natural daylighting.. Lighting level for office buildings specify about 500 lux (CIBSE, 2007) and (Ogunsote, 1991).</p> <p>Ventilation Naturally ventilated rooms require more than 4% o floor area external access. Mechanical ventilation must supply 10 L/s/person.</p> <p>Room dimensions Ceiling height must exceed 2.4m unless; it's a sloping roof and dropped ceiling in which case it may as low as 1.5m and 2.2m respectively. A habitable room must have any one dimension exceeding 3m and 10.8m²; Distance from property line to building should be 6m or above.</p> <p>Occupancy 0.65m²- 10.3m²/occupant.</p>	<p>Geometry Orientation Glazing Shading Airtightness Insulation</p>

Table 6-7 Design variables for parametric analysis

6.3.4.1 Base-case independent variables examined

The following independent variables, shown in Table 6-8 are examined for their effect on energy conservation and thermal comfort for office buildings in Abuja.

Description	Variable
Geometry	rectangular and square
Orientation	north-south, east-west
Air tightness	poor and good
Glazing	Single glazing with analysis between; clear; bronze tinted; reflective and bronze tinted; and double glazing.
Shading	No shading, venetian internal shading and external window hoods
Insulation	north-south, east-west, all sides

Table 6-8 Examined independent variables

1. Geometry: The analysis is the comparison of total electricity consumption between square and rectangle plan mechanically cooled office buildings. In the fieldwork, the average space per occupant is 15m²/occupant. The national recommended value is 0.65m²/occupant and maximum is 10.3m²/occupant. For the construction of the base-case, 10.3m²/occupant is used.

The average number of employees is 162 as shown in Table 6-5. Therefore gross floor area for 162 employees is 1620 m². The average height of a floor is 3.5m and the average number of floors making up the purpose-made office buildings audited is 4. This gives a total building height of 14m. Dimensions for the square model is thus given as (21*21*14)m; and that of the rectangular model is (12*37*14)m. The sources of these values are discussed in Section 6.3.

2. Orientation: The analysis on orientation is between cases when the building lies along the east-west and north-south axes for the rectangular plan base-case.
3. Glazing: The analysis is between single and double glazing, with some variants. Single glazing analysis is conducted with clear, bronze tinted, and lowE glass; and double glazing. The DesignBuilder default U-value of clear glazing is 5.8 W/m² K. That of single brown tinted clear, and lowE glazing are, 5W/m² K, and 3.8W/m² K respectively (see Table 6-9). The U-value of double glazing is 3W/m² K.

Glazing	Single 6mm		Double 6mm	
Description	Clear	Bronze-tinted	Brown tinted and lowE	Clear with air between
U-values	5.8W/m ² K	5W/m ² K	3.8W/m ² K	3W/m ² K

Table 6-9 Default glazing U-values from DesignBuilder

4. Shading: Analysis is made between No shading, venetian internal shading (A) and external window hoods (B+C) as shown in Figure 6-7. The depth of B and C is 1m. A snapshot of the some of the modelling input for venetian shading options in DesignBuilder is shown in Figure 6-8.

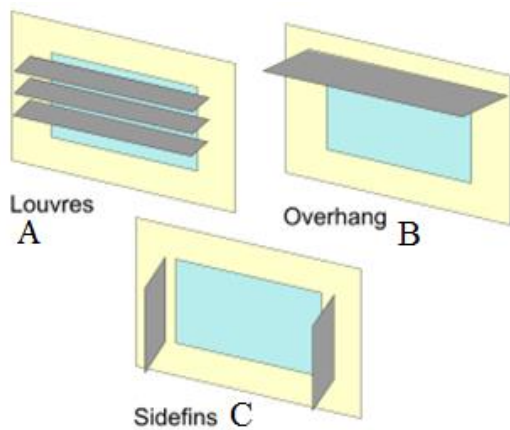


Figure 6-7 Illustration of default shading options in DesignBuilder (2011)

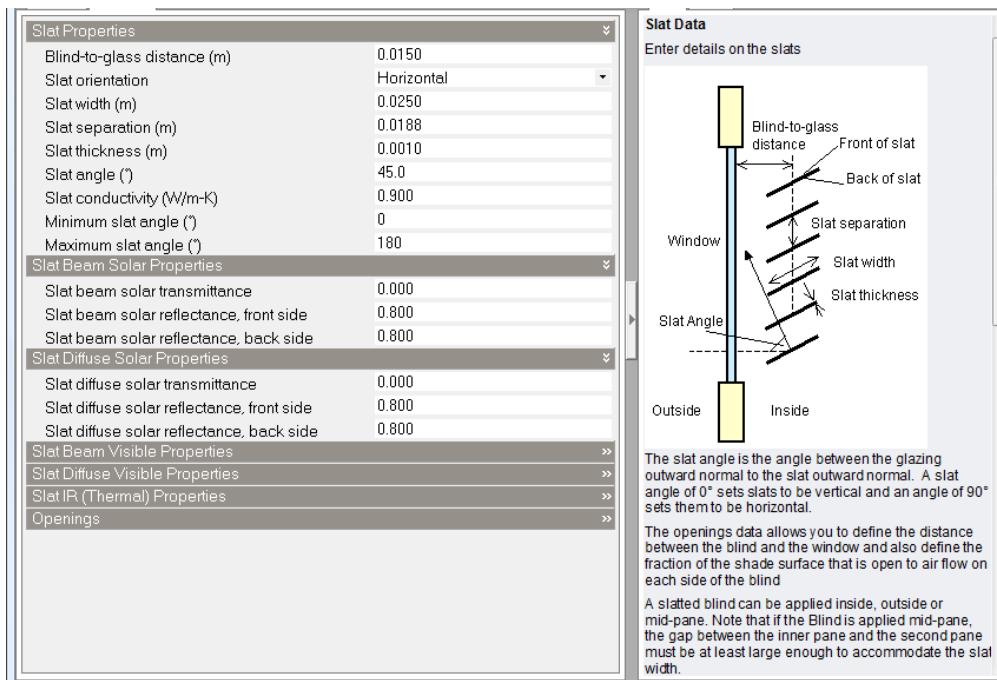


Figure 6-8 Modelling shading with default DesignBuilder values (2011)

5. Air-tightness: The analysis is between poor and good level of infiltration as default in DesignBuilder as shown in Figure 6-9 and Figure 6-10.
6. Insulation: The analysis is between the installation of wall insulation in the north-south, east-west and on all sides at once. Expanded polystyrene (EPS) of 10mm, conductivity 0.04 W/m K, specific heat 1400J/Kg K and density 15 Kg/m³ is used.

<u>General</u>	
<i>Good</i>	
Category	<i>Airtightness</i>
<u>Windows</u>	
External	
Flow coefficient (kg/ m ² crack @1Pa	0.00006
Flow exponent	0.7
Internal	
Flow coefficient (kg/ m ² crack @1Pa	0.00006
Flow exponent	0.7
<u>Doors</u>	
External	
Flow coefficient (kg/ m ² crack @1Pa	0.00006
Flow exponent	0.7
Internal	
Flow coefficient (kg/ m ² crack @1Pa	0.02
Flow exponent	0.7
<u>Vents</u>	
External	
Flow coefficient (kg/ m ² crack @1Pa	0.004
Flow exponent	0.66
Internal	
Flow coefficient (kg/ m ² crack @1Pa	0.003
Flow exponent	0.6
<u>Walls</u>	
External	
Flow coefficient (kg/ m ² crack @1Pa	0.00004
Flow exponent	0.7
Internal	
Flow coefficient (kg/ m ² crack @1Pa	0.002
Flow exponent	0.75
<u>Floors</u>	
External	
Flow coefficient (kg/ m ² crack @1Pa	0.00003
Flow exponent	1
Internal	
Flow coefficient (kg/ m ² crack @1Pa	0.00003
Flow exponent	0.7
<u>Roof</u>	
Flow coefficient (kg/ m ² crack @1Pa	0.00003
Flow exponent	0.7

Figure 6-9 Good infiltration default by DesignBuilder

<u>General</u>	
<i>Poor</i>	
Category	<i>Airtightness</i>
<u>Windows</u>	
External	
Flow coefficient (kg/m² crack @1Pa	<i>0.001</i>
Flow exponent	<i>0.6</i>
Internal	
Flow coefficient (kg/ m²crack @1Pa	<i>0.0018</i>
Flow exponent	<i>0.6</i>
<u>Doors</u>	
External	
Flow coefficient (kg/ m²crack @1Pa	<i>0.0018</i>
Flow exponent	<i>0.66</i>
Internal	
Flow coefficient (kg/ m²crack @1Pa	<i>0.02</i>
Flow exponent	<i>0.6</i>
<u>Vents</u>	
External	
Flow coefficient (kg/ m²crack @1Pa	<i>0.01</i>
Flow exponent	<i>0.66</i>
Internal	
Flow coefficient (kg/ m²crack @1Pa	<i>0.009</i>
Flow exponent	<i>0.6</i>
<u>Walls</u>	
External	
Flow coefficient (kg/ m² crack @1Pa	<i>0.0002</i>
Flow exponent	<i>0.7</i>
Internal	
Flow coefficient (kg/ m²crack @1Pa	<i>0.005</i>
Flow exponent	<i>0.75</i>
<u>Floors</u>	
External	
Flow coefficient (kg/ m²crack @1Pa	<i>0.001</i>
Flow exponent	<i>1</i>
Internal	
Flow coefficient (kg/ m²crack @1Pa	<i>0.0002</i>
Flow exponent	<i>0.7</i>
<u>Roof</u>	
Flow coefficient (kg/ m²crack @1Pa	<i>0.00015</i>
Flow exponent	<i>0.7</i>

Figure 6-10 Poor infiltration default by DesignBuilder

6.3.4.2 Base-case dependent variable

To examine energy conservation in an adequately cooled base-case, the dependent variable used is total annual electricity consumption (kWh). The values of each independent variable are varied parametrically in 4 timesteps per hour using the whole building energy calculation software EnergyPlus. Then the corresponding value of the total annual electricity consumption is recorded and the influences of each input/output relationship are compared through descriptive statistical methods.

6.3.4.3 Base-case independent variables kept constant

A number of variables were kept constant throughout the simulations, namely location/climate (Abuja, Nigeria), building use (office), building volume (6174 m^3), internal heat gains, occupancy density ($10.3 \text{ m}^2/\text{occupant}$), window to wall ratio (25%), floors (4) and lighting intensity ($4 \text{ W}/\text{m}^2$). Others are occupancy, external and partition walling, floors, roofing and schedules as further discussed below, see Table 6-10.

Climate: Abuja-type climate is chosen as it is the most prevalent climate classification in Nigeria (Ogunsote, 1991). It is a composite of hot and humid and hot and dry climate. Furthermore, Abuja being the capital city has a significant amount of office buildings. The weather file used in this research has been synthesized by Meteonorm (2012) for Abuja, Nigeria, in hourly time-steps over a year.

Occupancy and spatial planning: Average number of occupants is 162; thus number of occupants adopted is 160. At a rate of $10.3 \text{ m}^2/\text{occupant}$; gross floor area is 1648 m^2 . Therefore for a floor of area of 417 m^2 , the unconditioned space is 52 m^2 .

Each conditioned space is 91 m^2 with the longer side spanning 21m and the shorter 7m. The breadth is also 7m. All the sides of the unconditioned space span approximately 7m. The spatial plan and elevation is shown in Figure 6-11. The height of each storey is 3.5m. Average number of floors from fieldwork is 4 floors and this number is used for the base case; each floor 412 m^2 .

Description	Variable	Source
Location	Abuja	Fieldwork
Climate	Composite of warm and dry	Fieldwork
Employees	162 employees	Fieldwork
Occupancy	10.3m ² /occupant	Nigerian Building code
Average number of floors	4	Fieldwork
Wall to window ratio	25%	Bio-climatic design literature
Internal heat gains	18W/m ²	Fieldwork
Lighting intensity	4W/ m ²	Fieldwork
Building volume	5840 m ³ (162 employees x 10.3m ² x 14m building height)	Combination
Roofing	Aluminum clad gable roof	Fieldwork
Ground floor	Solid concrete ground floor with U-value of 4.4 W/m ² K.	Fieldwork
Other floors	Solid concrete slabs with dropped ceilings	Fieldwork
External wall	225* 225* 450mm external sandcrete walling units	Fieldwork
Partition wall	150* 225* 450mm internal sandcrete walling units	Fieldwork
Ground floor	Concrete slabs	Fieldwork
Other floors	Concrete slabs with dropped ceilings	Fieldwork

Table 6-10 Base-case common variables and their sources

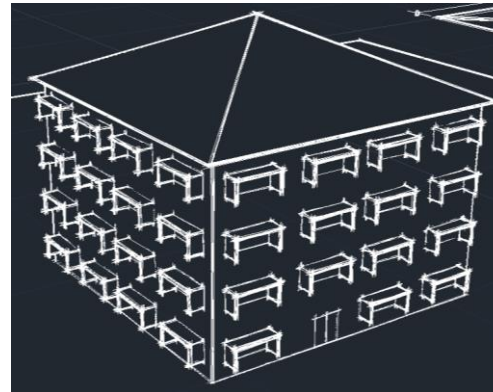
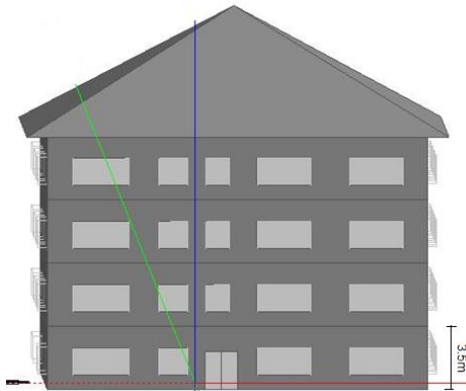
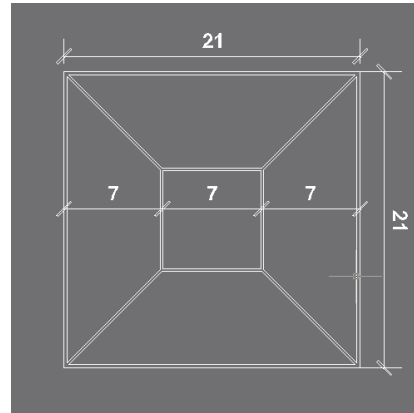
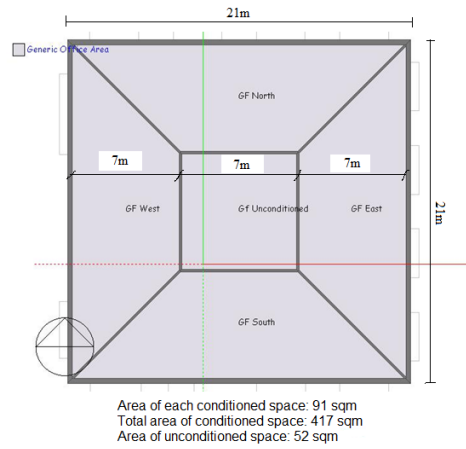


Figure 6-11 Visuals of the base-case model Designbuilder model on the left and CAD drawing on the right. All dimensions in meters.

Comment [A6]: addition

External wall: 225* 225* 450mm external sandcrete walling units joined with mortar and plastered on both sides with 25mm sand:cement mixture. The calculated U-value of such a wall is 1.4 W/m² K.

Partition wall: 150* 225* 450mm internal sandcrete walling units joined with mortar and plastered on both sides with 25mm sand:cement mixture. The calculated U-value of such a wall is 1.4 W/m² K.

Roofing: Aluminum cladding gable roofs with calculated U-value of 0.34 W/m² K.

Ground floor: Ground floors are solid concrete slabs laid directly on the soil and finished with tile made of fired and unfired ceramic and granite. The average U-value of such floors is calculated to be 4.4 W/m² K.

Other floors: Other floors are solid concrete slabs with dropped ceilings made by wood fibres on wooden joists and finished with tile made of fired and unfired ceramic and granite. The average U-value of such floors is calculated to be 6.7 W/m² K.

Schedules: Average daily working hours are estimated at 9 hours from 8am-5pm. None of the buildings operated on weekends, however some staff members work for an average of 4hrs per Saturday, once per month.

It should be noted that the spatial planning used for the spaces within the base case is informed by the need to analyse thermal comfort. The core portrays the unconditioned floor area, whose percentage is estimated from the data recorded in the fieldwork. The geometry of the spaces is to enable the normalization of the floor area so that the effect of size and shape can be eliminated during the experiments between spaces.

Comment [A7]: addition

6.4 Results and discussion

The results presented here are for a base-case with the mechanical cooling set to adequate. The indoor temperature is therefore maintained about an average of 24°C. The dependent variable used to examine the thermal performance of the variables is total annual electricity consumption.

6.4.1 Geometry and Orientation

The analysis on geometry is between rectangular and square-plan, while that of orientation is between cases when the building lies along the east-west and north-south axes of a mechanically cooled base-case. The two variables are examined together because the hypothesis is that electricity consumption of the square-plan base-case is not effect by the orientation of a building with uniform window/wall ratio. On the other hand, electricity

consumption of the rectangular plan base-case is entirely dependent on the orientation, therefore examining the two variables together yields more reliable results.

The results showed that total electricity consumed for the square plan building is 228MWh per annum for all the orientations as shown in Table 6-11. This proves the hypothesis that the orientation of a square plan building with uniform wall/window ratio does not affect its electricity consumption because the walls of a square shaped building have the same surface area, and thus the solar insolation on the building fabric remains equal on all sides.

The results also show that the best geometry is for the square planned base-case, saving upto 12% of electricity consumption.

However, a further look at the rectangular shaped building (Figure 6-12) shows the electricity consumption of a rectangular planned base-case with the principal axis lying along the east-west axis is 240MWh. That of the north-south axis is 260MWh. This indicates that the best case is when the principal axis lies on the east-west axis saving a possible 8%.

The sun rises in the north-east and sets in the south-west in Abuja as shown in the sun-path diagram in Figure 6-5. Therefore, if the building is positioned so that its principal axis is lying along the east-west axis, the sun's rays has a greater effect on the shorter sides of the building thereby reducing heat transfer into the interior of the building through the building façade.

Based on these geometrically and orientation optimized results, the more bio-climatically suitable square-plan building will be used for further analysis, see Figure 6-13. It is worthy of note that optimizing for naturally ventilated or mixed mode buildings may differ.

Open facades should face north or south as much as possible to avoid direct radiation from a low sun and the consequent intensive concentration of heat. In hot and dry or arid zones, screening of openings in mostly closed wall surfaces is indispensable. In hot-humid zones it is necessary to screen all openings and in some circumstances, complete facades against direct and indirect radiation from overcast skies.

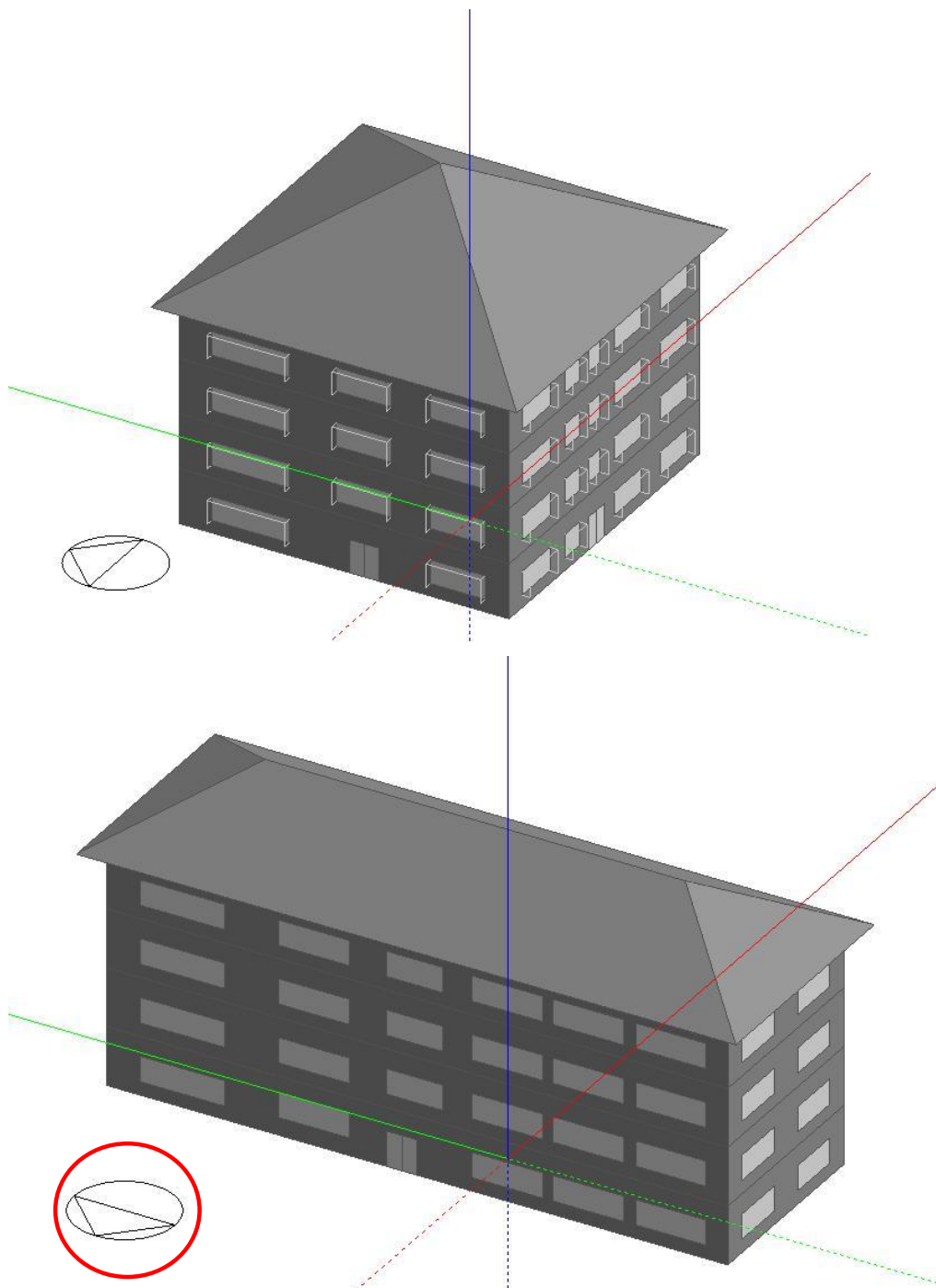


Figure 6-12 Comparison between square and rectangle planned base-case- Arrow showing best orientation for rectangular plan with principal axis lying along east-west

Geometry (plan)	Square	Square	Square	Square	Rectangle	Rectangle	Rectangle	Rectangle
Orientation	0	90	180	270	0	90	180	360
Airtightness	poor	poor	poor	poor	poor	poor	poor	poor
Insulation	none	none	none	none	none	none	none	none
Shading	none	none	none	none	none	none	none	none
Glazing	single clear 6mm	single clear 6mm	single clear 6mm	single clear 6mm	single clear 6mm	single clear 6mm	single clear 6mm	single clear 6mm
Volume: Surface area ratio	2.5	2.5	2.5	2.5	2.8	2.8	2.8	2.8
Cooling load (MWh)	142.3	141.9	142.2	141.9	172.4	153.0	147.9	148.3
Lighting load (MWh)	17	17	17	17	15.56	15.56	15.56	15.56
Appliances load (MWh)	70	70	70	70	70	70	70	70
Dry bulb temperature (°C)	25.53	25.52	25.56	25.52	26.19	25.72	26.07	26.16
<u>Electricity load</u> (MWh)	<u>228.7</u>	<u>228.0</u>	<u>228.6</u>	<u>228.0</u>	<u>259.2</u>	<u>239.8</u>	<u>259.7</u>	<u>238.6</u>

Table 6-11 Testing geometry and orientation

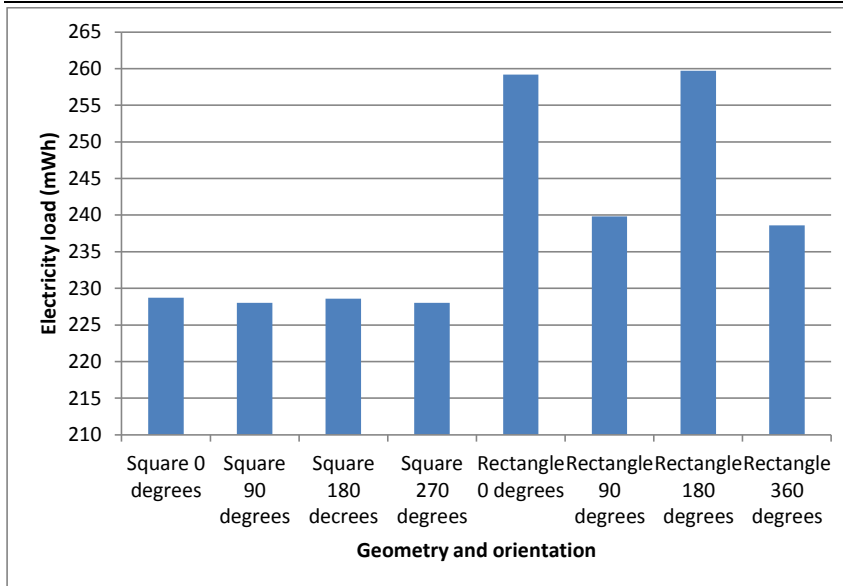


Figure 6-13 Electricity consumption across geometries and orientations

6.4.2 Glazing

The analysis conducted for glazing is for single glazing with; clear, bronze tinted, and LowE glass; and double glazing. The difference is in the amount of heat flux they allow determined by their U-values.

Geometry (plan)	Square	Square	Square	Square
Orientation	0	0	0	0
Airtightness	poor	poor	poor	poor
Insulation	none	none	none	none
Shading	none	none	none	none
Glazing 6mm	single clear	single bronze tinted	single lowE	double
Volume:Surface area ratio	2.5	2.5	2.5	2.5
Cooling load (MWh)	141.9	134.2	139.1	135.6
Lighting load (MWh)	17	17	17	17
Appliances load (MWh)	70	70	70	70
Dry bulb temperature (°C)	25.52	25.21	25.44	25.36
<u>Total Electricity load</u>(MWh)	228	<u>221</u>	<u>226</u>	<u>222</u>

Table 6-12 Testing glazing

The total consumption for single glazing with; clear, bronze tinted, and LowE glass; and double glazing is 228MWh, 221MWh, 226MWh and 222MWh per annum respectively. The best case is that of single but bronze tinted glazing with 221MWh per annum as shown in Table 6-12. This has the significant potential to save up to 7MWh of electricity in a year, making the cumulative savings of 15% of electricity compared to the base-case that consumes 260MWh.

Bronze tint stops a portion of the sun's rays from penetrating; making the bronze tint perform better than clear single glazing. Double glazing allows the sun's rays to penetrate to the interiors, but then traps a portion inside which gets reradiated. This worsens the already uncomfortable interior temperature. This greenhouse-like effect is also the case with the LowE glazing. Direct solar insolation into the interior should be avoided in tropical climates due to uncomfortably high temperatures.

6.4.3 Shading

The results for shading simulations are shown in Table 6-13. The total consumption for the case with no shading, venetian blinds and external window hoods is 228MWh, 219MWh and 208MWh per annum respectively. Furthermore, the consumption for a combination of bronze tinted single glazing and external window hoods is 204MWh. Therefore, a combination of the two is optimum, cumulatively saving up to 22% consumption compared to the base-case that consumed 260MWh per annum.

As discussed above shading walls and glazing especially is necessary for comfort in tropical climates, and direct solar insolation should be avoided (Ogunsote, 1991; Haase and Amato, 2006; Mustafa, 2008). Heat transfer through the building façade is through conduction, convection and radiation. Window hoods can shade windows totally against conduction, convection and radiation if designed properly. Venetian blinds on the other hand, perform worse than hoods due to their location in the interior. They fail to shade against conduction and convection. However, both window hoods and venetian blinds shade against glare, which is a significant factor affecting comfort.

Geometry (plan)e	Square	Square	Square	Square
Orientation	0	0	0	0
Airtightness	poor	poor	poor	poor
Insulation	none	none	none	none
Shading	none	internal blinds with low reflectivity	external overhang and fins 0.8m projection	external overhang and fins 0.8m projection
Glazing	single clear 6mm	single clear 6mm	single clear 6mm	single bronze tinted 6mm
Cooling load (MWh)	141.92	132.87	122	117.98
Lighting load (MWh)	17	17	17	17
Appliances load (MWh)	70	70	70	70
Dry bulb temperature (°C)	25.52	24.94	24.56	25.36
Total electricity load (MWh)	<u>228</u>	<u>219</u>	<u>208</u>	<u>204</u>

Table 6-13 Testing shading

6.4.4 Air-tightness

The analysis on air-tightness is between ‘good’ and ‘poor’ with specifications as shown in Table 6-14. The total consumptions for the building with good and poor air-tightness are 199 and 204 MWh per annum respectively.

For mechanically cooled and mix-mode buildings, air-tightness is essential to trap the conditioned air within the interior spaces and not leak the energy through cracks and infiltration. Air leakage should not be mistaken for ventilation. While ventilation is required, air leakage is not. Air-tightness may be achieved by the correct and proper construction of building elements such as insulation, windows, doors, roofs and other elements that have direct access to the exterior environment. Consequently condensation, mould, rot, damp and structural damage are also limited. This ensures a more viable protection against penetrating and unwanted air and moisture, thereby reducing the amount of energy use in the building by up to 23% when compared to the base-case that consumed 260MWh per annum.

Orientation	0	0
Airtightness	poor	good
Insulation	none	none
Shading	external overhang and fins 0.8m projection	external overhang and fins 0.8m projection
Glazing	single bronze tinted 6mm	single bronze tinted 6mm
Volume: Surface area ratio	2.5	2.5
Cooling load (MWh)	130.5	112.8
Lighting load (MWh)	17	17
Appliances load (MWh)	70	70
Dry bulb temperature (°C)	25.15	25.15
<u>Electricity load (MWh)</u>	<u>204</u>	<u>199</u>

Table 6-14 Testing air-tightness

6.4.5 Insulation

The results show the effects of insulation generally in warm humid climates to be minimal with no difference with and without insulation in the walls at 199 MWh total electricity consumption (see Table 6-15). Only insulation in lightweight roof materials affects its thermal performance reducing consumption to 193MWh, a 3% saving. The cumulative electricity savings is 26%.

Heavyweight elements such as flat roofs, walls and floors inherently use thermal mass to regulate interior temperature. Adding insulation to building fabric in warm climates keeps hot air enclosed inside leading to a higher temperature levels making the inclusion of air-conditioning necessary to improve the overall performance of the building.

Orientation	0	0	0
Airtightness	good	good	good
Insulation	none	walls	roof
Shading	external overhang and fins 0.8m projection	external overhang and fins 0.8m projection	external overhang and fins 0.8m projection
Glazing	single bronze tinted 6mm	single bronze tinted 6mm	single bronze tinted 6mm
Cooling load (MWh)	112.8	112.8	106
Lighting load (MWh)	17	17	17
Appliances load (MWh)	70	70	70
Dry bulb temperature (°C)	25.15	25.15	25.15
<u>Electricity load (MWh)</u>	<u>199</u>	<u>199</u>	<u>193</u>

Table 6-15 Testing insulation

6.4.6 Natural Ventilation

A saving of 67% is possible by switching from mechanical cooling to natural ventilation as shown by a reduction from 260MWh to 86MWh per annum for this base-case.

However, some environments may not achieve comfort solely with bio-climatic design principles and will require mechanical means to condition the interiors of buildings.

Using mechanical means should also however be optimized in terms of design, operation and control to conserve the most energy. These issues will be discussed in depth in Chapter 7.

Orientation	0	0
Airtightness	poor	good
Insulation	none	none
Shading	none	external overhang and fins 0.8m projection
Glazing	single clear 6mm	single bronze tinted 6mm
Cooling load (MWh)	172.4	0
Lighting load (MWh)	15.6	15.6
Appliances load (MWh)	70	70
Electricity load (MWh)	<u>259.2</u>	<u>86.4</u>

Table 6-16 Naturally ventilated base-case

6.5 Bioclimatic model

The bioclimatic model presented in Figure 6-14 shows the potential energy savings by adopting certain design principles both during the design and operation phases of a building.

A savings of 67% is possible by switching from mechanical cooling to natural ventilation as shown by a reduction from 260MWh to 86MWh per annum for this base-case. It should be noted that it may not be possible to achieve comfort with this solely natural ventilation. On the other hand, conducting preliminary simulations at the initial stage is beneficial for a mechanically cooled building as shown by a 26% reduction in total consumption from 260MWh to 193MWh. It should be noted that these savings exclude possible saving achievable by energy efficient practices by the building occupants. Uyigüe et al.(2009) claims that building occupants use double the amount of energy than is actually necessary for their needs. Therefore there is an opportunity reduce electricity use by half.

The conditioned floor area of the base-case is 1668m². Normalised electricity consumption by conditioned floor area for the mechanically cooled base-case is therefore 122kWh/m².

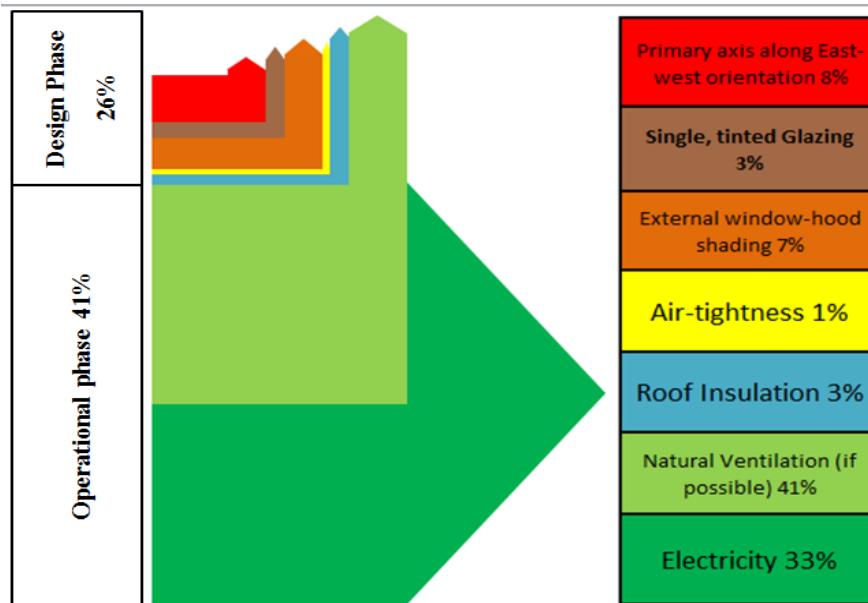


Figure 6-14 Bio-climatic model

The good and typical practice benchmarks per conditioned floor area for mechanically cooled buildings are 128 kWh/m² and 226kWh/m² respectively (CIBSE, 2004).

Compared to the value predicted for the base-case, the base-case performs better than the benchmark for good practice.

Proper orientation and shading the building's glazed areas provide the greatest energy savings at 8% and 7% reduction respectively. Improving air-tightness and insulating the roof provides the least at 1% and 3% reduction respectively. Optimizing geometry has the potential of up to 4% energy savings while and glazing has less potential at 3%. It should be noted that this process does not exhaust the bio-climatic design principles that may further conserving electricity.

6.6 Conclusion

A bio-climatically optimized base-case is constructed which will be used to test the performance of PCM in the next chapter. A base case is required because testing PCM systems on a poorly designed building might give erroneously superior results simply because there is so much room for energy savings. Testing PCM systems on an optimized thermally optimized base-case building on the other hand will provide reasonable results. Abuja the capital city of Nigeria is chosen as the location and climate for constructing the base-case. Abuja is a composite climate of hot and dry, and hot and humid climates.

In the process, a saving of 67% is shown to be possible by switching from mechanical cooling to natural ventilation as shown by a reduction from 260MWh to 86MWh per annum for this base-case. In the climates where thermal comfort is unachievable by using natural ventilation, conducting preliminary simulations at the initial stage is still beneficial for a mechanically cooled building as shown by a 26% reduction in total consumption from 260MWh to 204MWh. The base-case performs better than the benchmark for good practice by CIBSE (2004).

For mechanically cooled buildings in Abuja, more energy is conserved with a compact geometry, the principal axis lying along north-south, improving air-tightness, window hood shading and bronze tinting of glazed areas, and roof insulation. Some conservation techniques tested that have no significant effects on thermal performance are wall insulation, double glazing and lowE glazing. These results highlight the benefit of running dynamic simulations at any stage to compare thermal comfort and energy conservation potential of buildings.

Shading the building's glazed areas and making the building air-tight provide the greatest energy savings at 13% while insulating the roof provides the least at 3%. Optimizing geometry has the potential of up to 5% energy savings while orientation and glazing have more potential at 8%.

The modelling and simulation in this study is done by the software DesignBuilder and EnergyPlus respectively (DesignBuilder, 2011; EnergyPlus, 2011). The sources of variables making the base-case are:

1. The primary source is the data collected from field during the energy audit
2. The secondary sources are through a literature search of a bio-climatic approach to building design in warm climates
3. Nigerian building requirements

The optimally designed base-case is analysed through a parametric analysis to estimate the best bio-climatic design and construction principles for office buildings in warm tropical cities similar to Abuja. The independent variables examined are:

- Geometry
- Orientation
- Glazing
- Shading
- Airtightness
- Insulation

It should be noted that the spatial planning used for the spaces within the base case is informed by the need to analyse thermal comfort and further research is required to evaluate the generalizability of the results to other spatial planning types.

Comment [A8]: addition

Further savings may be achieved by changing HVAC systems to more efficient ones, improving building occupant behaviour, and introducing smart building materials within the building fabric, which is outside the scope of this presentation. It is worthy of note that occupant behaviour, and HVAC systems have not been examined, even though results in Chapter 5 indicate that they account for a large amount of inefficiency in building energy consumption. The two factors are outside the scope of this research.

7 CHAPTER 7

PCM PERFORMANCE IN OFFICE BUILDINGS

Contents
7.1 Overview
7.2 Modelling PCM in EnergyPlus
7.3 PCM thermo-physical properties
7.4 Testing for PCM optimum performance
7.5 Results and discussion
7.6 Optimizing PCM thermo-physical properties
7.7 Optimizing PCM operation strategies
7.8 Retrofit flexibility of PCMs in office buildings in Abuja
7.9 Thermal indices for evaluating PCM performance: Air and Operative temperature
7.10 Conclusion

Problem	Chapter one: Introduction- 'Nigerian buildings and Energy use'	
Theoretical framework	Chapter two: Literature review- 'Phase change materials as energy conservation mechanisms in buildings'	
Methodology	Chapter three: 'Methodology'	Chapter four : 'Validation study'
Results	Chapter five: 'Disaggregating primary electricity consumption for office buildings in Nigeria'	Chapter six: 'Optimizing thermal and energy performance of buildings' Chapter seven: 'PCM performance in office buildings'
Conclusion	Chapter eight: Conclusion	

7.1 Overview

In chapter 2, PCMs were discussed covering their history, containment method, applications, thermo-physical properties and how their energy can be calculated. In this chapter, a more in-depth discussion on the modelling, simulation and optimizing of a PCM suitable for the Abuja climate is presented as illustrated in Figure 7-1:

- Optimize thermo-physical properties and cooling strategies through parametric sensitivity analysis
- Degree day analysis
- Present a PCM model

Optimize thermo-physical properties through parametric sensitivity analysis in this chapter progresses to use the bio-climatic model presented in Chapter 6 and firstly, analyses the effect of varying thermo-physical properties of the PCM system on energy conservation and thermal comfort. The transition temperature is the principal property affecting the thermal performance of a system (Farid *et. al* 2004: Xiao *et al.* 2009). Further to transition temperature, the thickness and conductivity of the PCM are examined. Secondly, the cooling strategies that encourage the effective operation of the PCM are examined. The strategies include combinations of natural ventilation and mechanical cooling during the day and night.

The optimization process for both thermo-physical properties and cooling strategies is conducted as a parametric analysis like in Chapter 6. In the same manner, the simulations are conducted as quasi-experiments where all variables are held constant except the variable being examined.

The analysis is done using degree day and descriptive statistics to optimise a model PCM and cooling operational strategy for office buildings in Abuja.

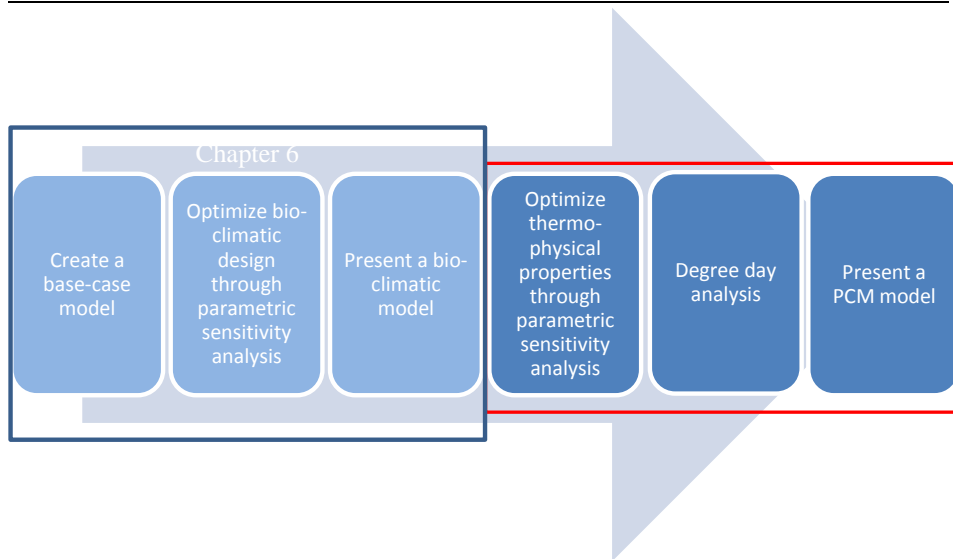


Figure 7-1 Optimizing procedure for PCM Model

7.2 Modelling PCM in EnergyPlus

In Chapter 6, the modelling and simulation of the base-case was conducted using DesignBuilder. In this chapter, the modelling and simulation of PCMs is conducted using EnergyPlus version 7. This is due to a limited algorithm employed for heat transfer for the modelling of PCM with DesignBuilder. It should be noted that all simulations in DesignBuilder are conducted by an internal EnergyPlus version 6 engine; it is *only* modelling PCMs that is conducted with the external EnergyPlus version 7 which is described further in this chapter.

A validation is conducted between the model without PCM generated by DesignBuilder modelling and EnergyPlus 6 internal simulation engine and the results predicted by EnergyPlus v7 simulation engine. The two engines predicted the same results thereby validating the two versions of EnergyPlus software.

The methodology of modelling PCMs used in this study is based on one presented by Oak Ridge National Laboratory (ORNL) after studying an existing test building and comparing the simulated and measured results (Shrestha *et al.*, 2011)..

First, the modelled base-case without PCMs in chapter 5 is imported as an .idf file generated with DesignBuilder. This import is necessary due to the algorithm available in DesignBuilder known as conduction transfer function (CTF) that is unable to effectively simulate of PCMs (Pedersen, (2007). EnergyPlus, on the other hand employs an algorithm called conduction finite difference (CFD) that has been proven to satisfactorily simulate PCM behaviour (Chan, 2011; Shrestha *et al.*, 2011).

Among the various algorithms available in EnergyPlus for surface modelling, “SimpleCombined” model and “CeilingDiffuser” model have been shown to best predict outside surface temperature and inside surface temperature respectively (Shrestha *et al.*, 2011). The two algorithms are used to simulate outside surface temperature and inside surface temperature respectively.

The minimum recommended number of time steps employed for using CFD in EnergyPlus is 20, and this value is adopted. This means that 20 iterations are run for each hour simulated. The larger the number of timesteps, the higher the accuracy of the simulation. On the other hand, a large number of timesteps increases the time taken to run simulations. A balance between accuracy and time to run a single simulation is required. Each PCM simulation runs for an average of 20 hours in this investigation.

7.2.1 The base-case

From fieldwork measurements, air-conditioned floor area is averagely 12% of gross floor area. Therefore for a floor of area of 417m², the unconditioned space is 52 m². The unconditioned floor area is represented as the inner core in the base case.

Each conditioned space is 91 m² with the longer side spanning 21m and the shorter 7m. The breadth is also 7m. All the sides of the unconditioned space span approximately 7m. The spatial plan and elevation is shown in Figure 7-2. The height of each storey is 3.5m. The other inputs of note making up the base-case are shown in Table 7-1.

The spaces are designed in this manner to enable the representation of variables recorded in the field such as the un-conditioned spaces, to evaluate the effect of orientation of the spaces and eliminate the effect of internal geometry and size of rooms. Due to the spatial planning of the base case, future research is required to evaluate the generalizability of the results to other office buildings.

Comment [A9]: addition

7-PCM performance in office buildings

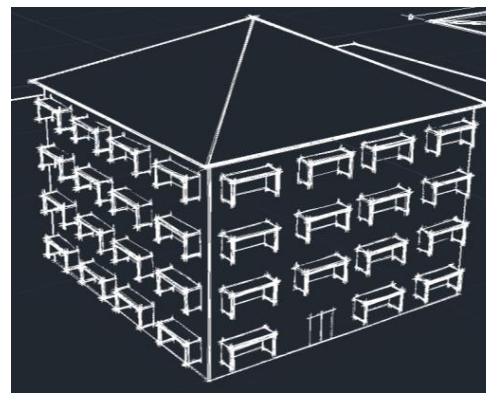
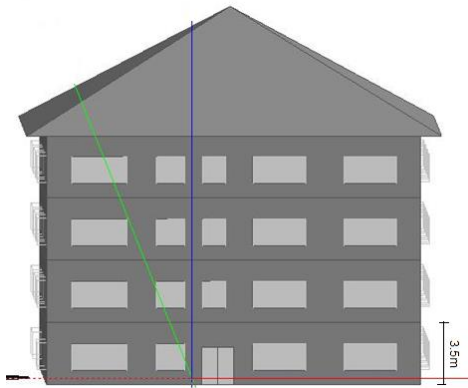
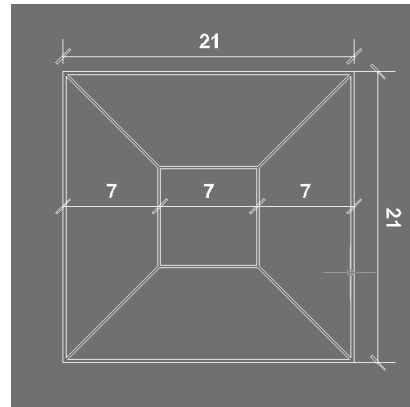
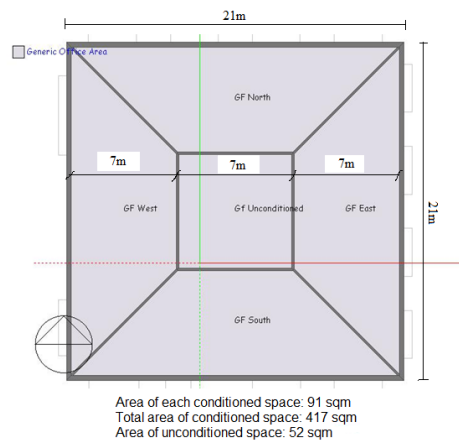


Figure 7-2 Visuals of the base-case model: DesignBuilder model on the left, CAD drawing on the right. All dimensions in meters.

Comment [A10]: addition

7-PCM performance in office buildings

Independent variable	Description	Impact on dependent variables	
		Thermal comfort	Electricity consumption
Schedules	These are daily, monthly, yearly or bespoke schedules options available in the software to model occupant behaviour or building operation.	Used to model switch on/off of HVAC.	Direct impact on electricity consumed by occupants and building services.
Surface construction elements	Used to specify finishes, construction elements, their thermal properties etc.	Thermal comfort is affected by the thermal properties of the construction elements.	Electricity consumption affected by the thermal properties of the construction elements.
Thermal zones and surfaces	Used to identify the thermal zones under examination	By identifying the thermal zones, it is possible to model different zones and measure the comfort level experienced in each type of zone.	By identifying the thermal zones, it is possible to model different zones and measure the consumption of each type of zone.
Internal gains	These are the modelling of occupants, activity, lighting, appliances etc. that affect the heat transfer within the interior	Internal gains mostly have a positive relationship with heat. As the internal gains increase, the warmer it gets.	They affect the amount of heat to be transferred by the chosen form of HVAC and thus affect the electricity consumed.
Natural ventilation and duct leakage	This is the modelling of the air movement through natural, mechanical or infiltration through the building fabric.	Infiltration causes unwanted air into an air-conditioned building thereby affecting the thermal comfort. Specifying natural or air-conditioning systems determines the comfort of occupants.	Infiltration causes unwanted air into an air-conditioned building thereby affecting the electricity consumed. Specifying natural or air-conditioning systems affect the cooling load in a building.

Table 7-1 PCM base-case input variables

7-PCM performance in office buildings

Independent variable	Description	Impact on dependent variables	
		Thermal comfort	Electricity consumption
HVAC equipment and design	This is the further specification of the HVAC system in place.	The type of HVAC determines the thermal comfort through the delivery method of air.	The efficiency of HVAC affects the electricity the system consumes.
Density of PCM 800kg/m³	This is a variable specific to the PCM used in the construction variable. The density of PCM needs to be high enough to store sufficient energy, but low enough to allow adequate heat transfer through the PCM.	A PCM that is not sufficiently utilized increases decreases thermal comfort by encouraging uncomfortable temperatures in the interior.	A PCM that is not sufficiently utilized increases the electricity consumed to condition the uncomfortable temperatures encouraged by the PCM system.
Latent heat of fusion: 120 kJ /kg	Latent heat of fusion is the amount of energy available for storage due to change in state	The bigger the latent heat of fusion, the more the capacity to regulate temperature over the course of a day	The more the capacity to regulate temperature, the less the electricity required for cooling.
Specific heat capacity 2000 J/kg K	This is the amount of heat required to change a unit mass of a substance by one degree in temperature	Due to latent energy during phase change the total energy required to raise the temperature is higher thereby affecting temperature	If temperature is regulated, it translates to a reduction in electricity consumption
Transition temperature T 22°C, 24°C, 31°C and 36°C are examined.	This is the temperature at which the PCM changes state. For temperature regulation, the transition temperature should be as low as the lowest average ambient air temperature. It should be lower than the average maximum temperature.	Optimum transition temperature ensures adequate regulation of temperature ensures occupant comfort	The more the capacity to regulate temperature, the less the electricity required for cooling.
Thickness t (mm)	Thickness 10mm, 50mm and 100mm are examined. The thickness should be just thick enough to store adequate energy to regulate temperature.	Optimum thickness ensures adequate regulation of temperature ensures occupant comfort	The more the capacity to regulate temperature, the less the electricity required for cooling.

Table 7-1 PCM base-case input variables

7-PCM performance in office buildings

Independent variable	Description	Impact on dependent variables	
		Thermal comfort	Electricity consumption
Conductivity (W/m K)	Conductivities 0.5W/m K, 1.0W/m K and 1.5W/m K are examined. The conductivity should be just high enough to ensure adequate heat transfer within the PCM.	Optimum thickness ensures adequate regulation of temperature ensures occupant comfort	The more the capacity to regulate temperature, the less the electricity required for cooling.
Operational Strategy	Natural ventilation, night-purge and mechanical cooling are examined as cooling mechanisms over the course of a working day	Thermal comfort is dependent on the operational strategy employed to ensure the effective utilization of the PCMs.	The electricity consumed for cooling is dependent on the length of time the occupants are kept in comfort passively.
Thermal absorptance (emissivity) 0.9	It is the fraction of incident long wavelength radiation that is absorbed by the material and affects the surface heat balances.	Values must be between 0.0 and 1.0- at 0.9, the PCM surface is highly absorptive therefore encouraging the effective performance of the PCM	
Solar absorptance 0.7	It is the fraction of incident solar radiation that is absorbed by the material.		
Visible absorptance 0.7	It is the fraction of incident visible wavelength radiation that is absorbed by the material.		

Table 7-1 PCM base-case input variables

7.2.2 PCM wall construction

In EnergyPlus, each type of envelope system is assigned one or more layers of materials based on the actual construction, and each surface is assigned its respective construction, outside boundary condition, and relative geometry. The PCM wall construction modelled for the base-case is adapted from the sandcrete block walling system generally used in Nigerian constructions. All the buildings investigated in the fieldwork are constructed with sandcrete blocks (Batagarawa et al., 2011).

For practical, it is beneficial to evaluate the incorporation of PCM as retrofit, a system that easily fits the sandcrete walling system. A panel type installation of PCM is better than direct integration according to Isa *et al.* (2010).

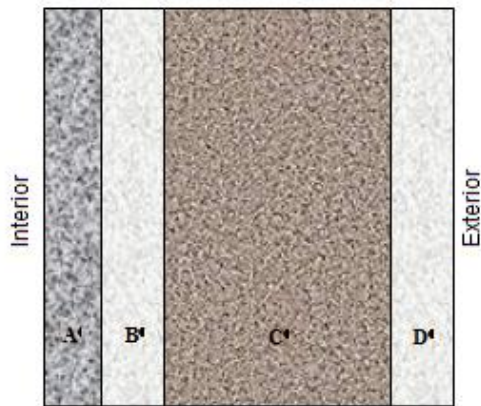


Figure 7-3 PCM wall system

The building wall proposed is made of four layers; starting from the interior with a layer of PCM, then a 25mm internal cement plaster rendering. This is followed by the 225mm hollow sandcrete blockwork that is finally rendered with a 25mm cement plaster on the exterior as shown in Figure 7-3 and Table 7-2.

	Layer	Thickness
A	PCM Layer	10mm
B	Internal render	25mm
C	Sandcrete block layer	225mm
D	External render	25mm

Table 7-2 PCM wall system

7.3 PCM thermo-physical properties

Some thermo-physical properties of PCM covered in literature are shown in Table 7-3. Density and specific heat capacities of PCM are given between 770-2907(kg/m³) and 740-2890(J/kg K) respectively (Darkwa and O'Callaghan, 2006; Kuznik *et al.*, 2008a; Agyenim *et al.*, 2011; Cabeza *et al.*, 2011; Zhou *et al.*, 2011). Density and specific heat capacity of 800 kg/m³ and 2000 J/kg K respectively are used in this study due to the frequency of use of these values by different researchers in literature.

Conductivity has been shown to have no effect on the performance of the PCM system above 0.5W/m K (Xu *et al.*, 2005; Zhou *et al.*, 2008; Zhou *et al.*, 2011). It has also been shown that a narrow transition temperature of 1 °C is best to reduce the indoor temperature swing and improve the thermal comfort (Zhou *et al.*, 2007; Pasupathy *et al.*, 2008b). A wider phase transition zone provides a worse thermal performance due to

the less energy storage. The latent heat of fusion of PCM should be in the range of 120–160 kJ/kg (Zhang *et al.*, 2006; Zhou *et al.*, 2008). 10mm thickness has been optimised for thermal performance of micro-encapsulated paraffin based PCM (Kuznik *et al.*, 2008a).

	Density (kg/m ³)	Conductivity, k (W/m K)	Transition temperature T (°C)	Specific heat capacity (J/kg K)	Latent heat of fusion (kJ/ kg)	Thickness (mm)
Model	770-	0.5	Around average	740-2890	120–	10-30
PCM	2907		indoor air temperature, 29.5		160	

Table 7-3 Thermo-physical properties of PCM from literature

From the literature review in Chapter 2, the following non-climate specific points have been recommended for optimum PCM performance:

1. Overnight cooling: This prevents hysteresis and enables effective phase change process (Voelker *et al.*, 2008)
2. Positioning: Placing PCM in contact with the interior face of the interior sheathing, the rate of recharging the PCM was superior to when placed in the middle of the insulation or in contact with the outer sheathing layer (Zhang, 2004)
3. Heat of fusion: Generally, for temperature regulation, the heat of fusion of the PCM should be higher than 120 kJ /kg, density is about 800 kg/m³ and the
4. Thermal conductivity should be 0.5 W/m K or higher (Xu *et al.*, 2005) and (Feldman *et al.*, 1995)
5. Transition temperature: PCM composites with a narrow transition zone of 1 °C best reduce the indoor temperature swing and improve the thermal comfort. A wider phase transition zone provides poorer thermal performance due to the less energy storage (Fang and Medina, 2009; Susman *et al.*, 2010). It is also shown that the optimal diurnal heat storage can be achieved when the PCM has a phase change temperature of 1–3 C above the average room temperature (Zhu *et al.*, 2009)

6. Surface area: A large surface area increases the heat melting/solidification rate of PCM panels (Zhou *et al.*, 2008; Xiao *et al.*, 2009; Isa *et al.*, 2010). The building components with the highest surface area are walls

7.4 Testing for PCM optimum performance

The analysis in Chapter 6 is conducted only for the dependent variable electricity consumption. Some environments however, may not achieve thermal comfort solely with bio-climatic design principles and will require mechanical means to condition the interiors of buildings. Mechanical means is optimized in terms of design, operation and control to conserve the most energy. This section studies the dependent variables and how a change in the independent variables affects the dependent variables.

The independent variables are of two classes. There are ones that remain constant and the ones that are optimised. They are shown in Table 7-1 and are further discussed in Sections 7.4.2 and 7.4.3.

7.4.1 Dependent variables

The dependent variables are:

- Total annual electricity consumption (kWh)
- Thermal comfort measured by dry bulb air temperature (°C)
- Thermal comfort measured by operative air temperature (°C)

Comment [A11]: addition

The values of each independent variable are varied one at a time, in an incremental manner using the whole building energy calculation software EnergyPlus. Then the corresponding value of the electricity consumption is recorded and the influences of each input/output relationship are compared through descriptive statistical methods. Building occupant comfort is measured in terms of dry-bulb air temperature, and hourly readings are recorded for a design day, month or year. The predictions covering working hours are extracted and are analysed together with electricity consumption figures. The operative air temperature is derived from dry bulb and mean radiant temperatures to analyse the effect of PCM on the temperature of the building surface.

Comment [A12]: Addition

7.4.2 Independent variables kept constant

The variables input into Energyplus that are kept constant include:

1. Schedules: This determines timings affecting such variables such as occupancy, disaggregated electricity consumption and ventilation

2. Surface construction elements: These elements have been discussed in chapter four with the exception of the PCM wall which has been described in page 220
3. Thermal zones and surfaces: Is the description of the thermal zones which in this case follow the spatial design described in Figure 7-2
4. Internal gains: This has been captured in the fieldwork results presented chapter four and the values adopted for the base-case are presented in chapter five
5. Natural ventilation: This is related to the modelling of surface construction elements, zoning and schedules. The values are picked by default from the values modelled in the two categories
6. HVAC equipment and design: This is the modelling of the prevailing HVAC system as against natural ventilation. The option of adequate mechanical cooling in EnergyPlus chosen is 'Ideal load air system' which is set to turn on when the temperature goes above 24°C- the lower band of Neutrality temperature. Air at 12°C is supplied to cool the interior. It is related to the modelled input of zoning and schedules
7. Outputs: These are the results generated based on the analysis required. The most important output for this investigation are electricity consumption and operational air temperature
8. Density: 800kg/m³
9. Latent heat of fusion: 120 kJ /kg
10. Effective heat capacity: Measuring the effective heat capacity of PCMs analytically is problematic due to the phase change. Darkwa and O'Callaghan (2006) gave a Gaussian formulation for effective heat capacity C_{eff} , shown in as Equation 7-1:

$$C_{eff} = C_s + ae^{-0.5\left(\frac{T-T_m}{b}\right)^2} \quad \text{Equation 7-1}$$

Where C_s is specific heat capacity, a is the total amount of latent heat, T is the coefficient of solar radiation, T_m is transition temperature and b is the width of phase change zone. This formulation is used in the absence of a real PCM material tested for actual effective heat capacity, C_{eff} .

For instance the proposed PCM used in the study, with thermo-physical properties as given in Table 7-4 and treated with Darkwa and O'Callaghan's

Gaussian formulation (2006) has the relative properties shown in Table 7-5 and Figure 7-4. The enthalpy is the amount of total (sensible and latent heat) energy of the PCM at a given temperature, the highest for the proposed PCM being 120kJ/kg. The cumulative enthalpy is the sum across of energy with a change in temperature

Variables 8-10 are held constant based on assumptions formed from literature (Darkwa and O’Callaghan, 2006; Kuznik *et al.*, 2008a; Agyenim *et al.*, 2011; Cabeza *et al.*, 2011; Zhou *et al.*, 2011).

Other variables such as Thermal absorbtance (emissivity), solar absorptance and visible absorptance of PCMs kept constant using default values in DesignBuilder, see Table 7-1.

PCM Specific Heat (Sensible) (J/kg K)	2000
PCM Latent Heat Capacity (Enthalpy) (J/kg)	120000
Melting Temperature (°C)	36

Table 7-4 Thermo-physical properties of PCM treated with Darkwa and O’Callaghan’s Gaussian formulation (2006)

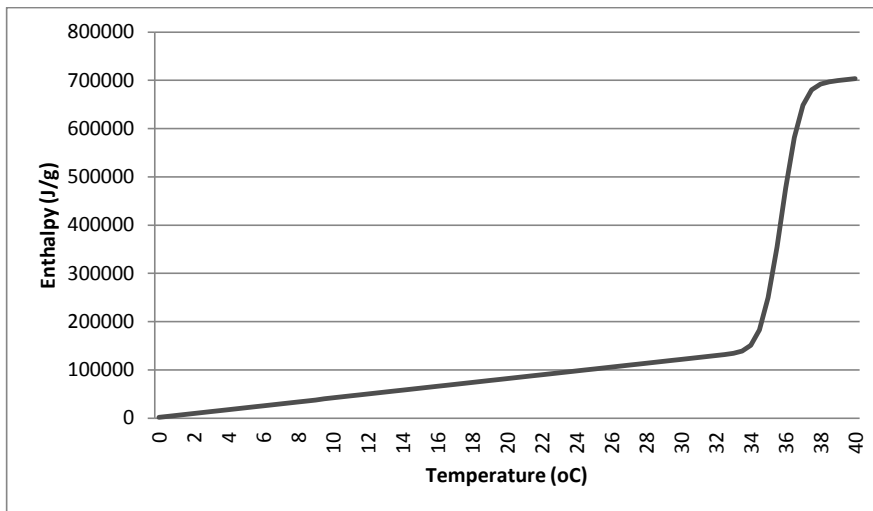


Figure 7-4 Graph showing enthalpy as a function of transition temperature

Temp (°C)	Enthalpy (J/kg)	PCM Cumulative Enthalpy(J/kg)
31	2000	126000
31.5	2000	128000
32	2006	130007
32.5	2062	132069
33	2464	134533
33.5	4533	139066
34	12159	151225
34.5	31922	183147
35	66729	249876
35.5	104840	354716
36	122000	476716
36.5	104840	581555
37	66729	648284
37.5	31922	680207
38	12159	692366
38.5	4533	696899
39	2464	699363
39.5	2062	701425
40	2006	703431

Table 7-5 PCM Enthalpy (Thermal Energy) based on Darkwa and O'Callaghan (2006)

7.4.3 Independent variables examined

The independent variables examined are of two classes; PCM thermo-physical properties and cooling strategies. The thermo-physical properties are:

- Transition temperature (°C)
- Thickness (m)
- Conductivity (W/m K)

The cooling strategies are:

- Natural ventilation
- Mechanical cooling
- Night-time cooling,
- Set-back cooling
- Cyclic cooling

These inputs are optimised for the application which in this case is energy conservation and improvement of thermal comfort in office buildings in Abuja.

7.4.4 Test case

In an attempt to isolate the effect of other building components such as solar insolation on the roof and heat transfer through the ground floor from the thermal assessments, the second floor in the model is chosen as the test floor. It is more suitably located in the middle of the four storey high model as recommended by Wang et al. (Wang *et al.*, 1999), see Figure 7-5.

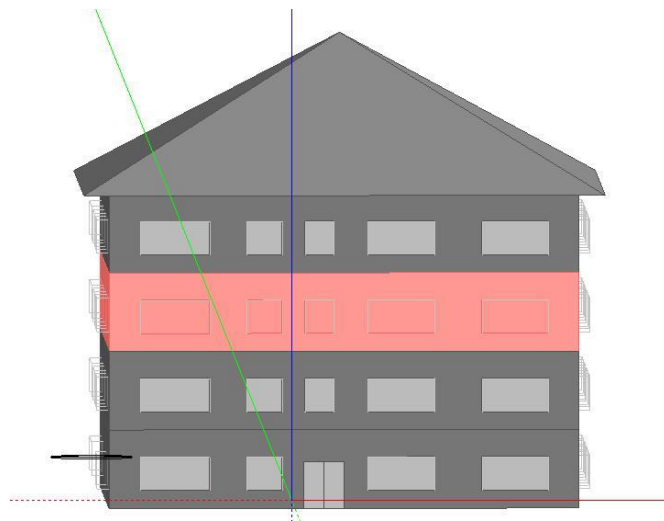


Figure 7-5 Test case modelled in DesignBuilder

7.4.5 Assumptions

The following assumptions are made concerning the operation and modelling of PCMs.

1. EnergyPlus assumes one-directional heat conduction
2. Density for PCM in both solid and liquid states is the same
3. Cumulative latent heat of PCM is derived from Equation 7-1 for lack of measured values which were input into EnergyPlus 7

With these points in mind - covering Sections 7.2 to 7.4- computer simulations are conducted using EnergyPlus version 7.

7.5 Results and discussion

Fifty-one simulations are presented in this chapter altogether as shown in Table 7-6 to Table 7-8. The simulations are classified into optimising:

- Thermo-physical properties

- PCM cooling strategies

It should be noted that other simulations were conducted which produced insignificant or inconclusive results. Due to a desire to improve the readability of this thesis, they were excluded.

Transition temperature: 12 simulations

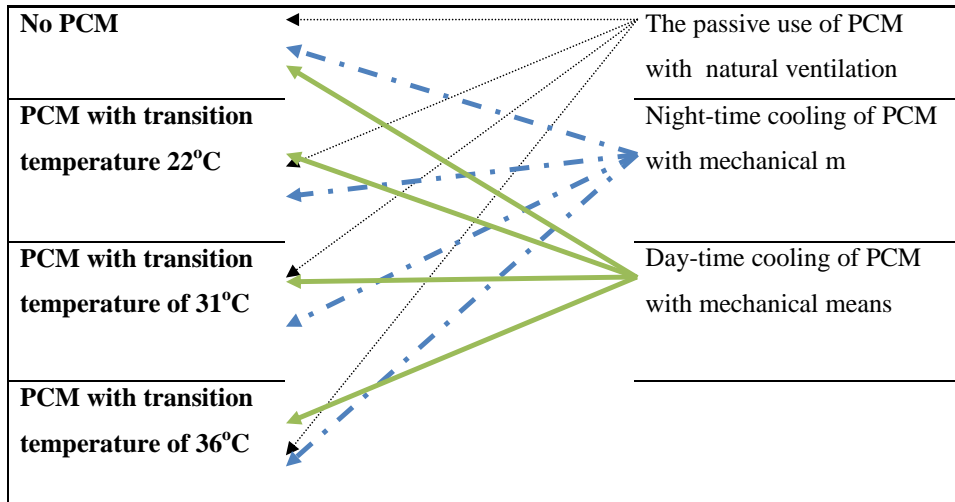


Table 7-6 Thermo-physical properties: Transition temperature simulations

The first twelve simulations look at transition temperature under three operational strategies. The cases are:

- No PCM
- PCM with transition temperature of 22°C
- PCM with transition temperature of 31°C
- PCM with transition temperature of 36°C

The three operational strategies examined to optimize the transition temperatures are:

1. The passive use of PCM with natural ventilation
2. Night-time cooling of PCM with mechanical means
3. Day-time cooling of PCM with mechanical means

Further discussion on PCM thermo-physical properties is found in Section 7.6.

The next 9 simulations look at a combination of thickness and conductivity as shown in Table 7-7. Three different thicknesses are examined for the optimized PCM system with transition temperature 36°C as base-case and adequate mechanical cooling. They are:

7-PCM performance in office buildings

1. 10mm
2. 50mm
3. 100mm

Three different conductivities are examined for the optimized PCM system with transition temperature 36°C. They are:

1. 0.5 W/m K
2. 1.0 W/m K
3. 1.5 W/m K

Thickness and conductivity: 9 simulations

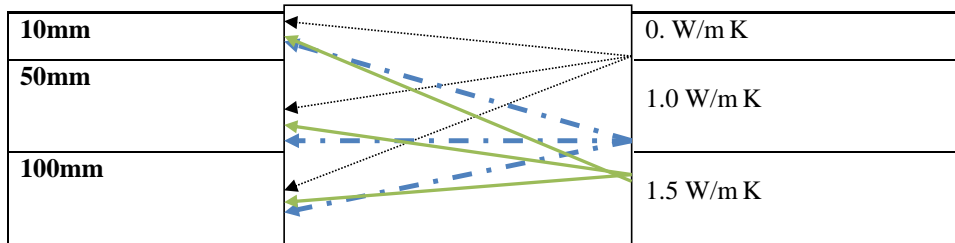


Table 7-7 Thickness and conductivity simulations

The last 33 simulations look at the best operational strategy for PCM in Abuja office buildings as shown in Table 7-8. They are natural ventilation, day-time mechanical cooling, night-purge, set-back cooling and cyclic cooling. These strategies are further discussed in section 7.6.2.2.

Operational strategies: 31 simulations

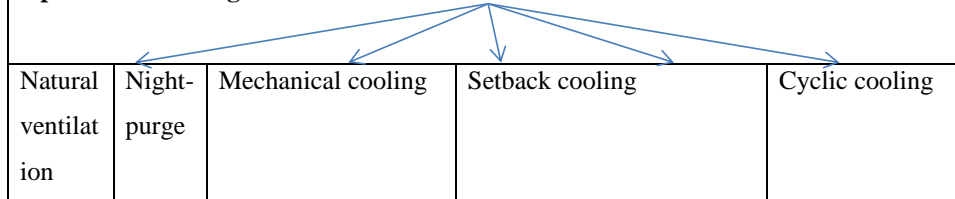


Table 7-8 Operational strategies simulations

Annual electricity consumption and hourly indoor air temperatures are recorded from each simulation. The thermal comfort is quantified against a total of 2340 work-hours per annum, which is an 8am-5pm weekday. In some simulations, yearly records are examined, while in others, monthly or design days are considered.

7.6 Optimizing PCM thermo-physical properties

It should be recalled in the literature review that transition temperature of PCMs should be about the average air temperature of the interior (Xiao *et al.*, 2009). To calculate the average air temperature in the test room, the base-case building presented in Chapter 6, Section 6.3.4 (without PCM) is modelled using natural ventilation. The following indoor air temperatures were predicted; average maximum temperature over the hot months is 36°C; and the average minimum over the cooler months is 22°C; while the average temperature is 31°C. The PCM transition temperatures examined for the proposed PCM are therefore 22°C, 31°C, and 36°C.

To study PCM performance, the predicted values of the simulations are compared to the bio-climatically optimised base-case model without PCM. The analyses use air temperature to optimize thermo-physical properties of PCMs. However in-depth analyses of cooling strategies are conducted in Section 7.7 using operative temperature in addition to air temperature.

Comment [A13]: addition

7.6.1 Transition Temperature analysis

The PCM cases examined are:

- No PCM
- PCM with transition temperature of 22°C
- PCM with transition temperature of 31°C
- PCM with transition temperature of 36°C

The three operational strategies examined to optimize the transition temperatures are:

1. The passive cooling of PCM with natural ventilation
2. Night-time cooling of PCM with mechanical means
3. Day-time cooling of PCM with mechanical means

Natural ventilation and day-time cooling have been observed to be the prevailing strategies in the fieldwork, whereas night-time cooling has been recommended for improvement of PCM performance (Voelker *et al.*, 2008; Isa *et al.*, 2010; Susman *et al.*, 2010).

Natural ventilation is the cooling of the interior during working hours using ambient temperatures by opening windows. Day-time mechanical cooling on the other hand is the cooling of the interior using adequate energy to keep the occupants in comfort. Based on the neutrality temperature 24°C is calculated as adequate set-point. The three strategies are recorded as the available cooling choices during the fieldwork and in literature. The combination of the four transition temperatures and the three operational

strategies are used to examine the optimum transition temperature for both energy and thermal comfort in Abuja, Nigeria.

7.6.1.1 *The passive cooling of PCM with natural ventilation*

As concluded in Chapter 6, it is ideal to use passive means to make the interiors of our buildings comfortable. PCM transition temperature of 22°C, 31°C and 36°C are examined through the modelling of 100% open windows- natural ventilation during working hours between 8am and 5pm. The variables making up the base-case with the exception of transition temperature are shown in Table 7-1. The base-case is the system with no PCM.

	No PCM (base-case)	PCM22tt	PCM31tt	PCM36tt
Hours of discomfort Yearly Summation (2340)	2,314	2,340	2,340	2,340
Electricity consumption kWh	86,390	86,390	86,390	86,390
Discomfort %	98.9	100	100	100

Table 7-9 Passive use of PCM with natural ventilation

The results show that the addition of PCM with natural ventilation, reduces thermal comfort compared to the base-case albeit insignificantly. There are 2340 working hours of discomfort for the building occupants with PCM in the fabric. This accounts for 100% of the time and is obviously a failed strategy. The electricity consumed is 86,390kWh and constitutes the baseload only- in the absence of any cooling. There are 2314 annual number of uncomfortable hours predicted for the simulation of the system without PCM as shown in Table 7-9 and Figure 7-6. This is also a failed strategy due to the unacceptable level of thermal discomfort.

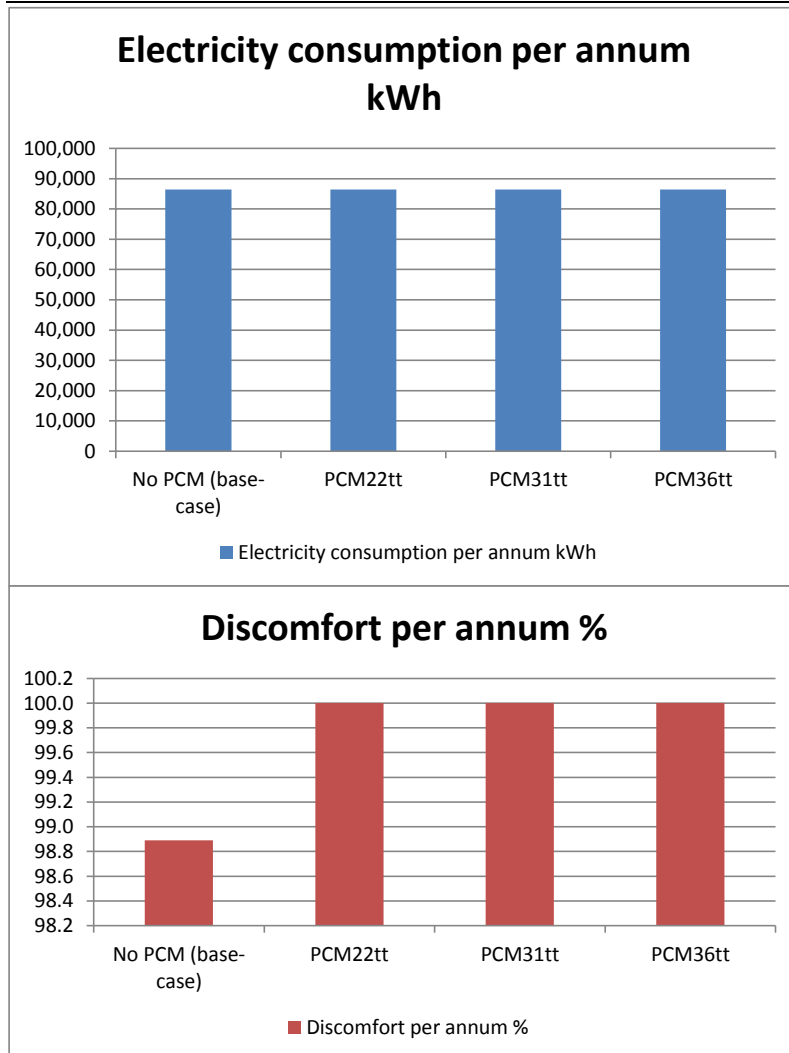


Figure 7-6 Passive use with natural ventilation

7.6.1.2 Night-time cooling of PCM with mechanical means

PCMs have been observed to decline in thermal performance due to hysteresis in chapter two. This phenomenon is caused by the failure of the PCM to completely melt or solidify in each respective cycle. One solution is night-time cooling. This strategy has been reported to more effective for overnight solidification of PCM in warm climates (Isa *et al.*, 2010; Susman *et al.*, 2010).

The strategy adopted is the mechanical cooling of the building to the lower bound comfort limit of 24°C from 6pm to 8am on working days, thereby ensuring that the PCM has fully solidified at the start of a working day. The variables making up the

base-case with the exception of transition temperature are shown in Table 7-1. The base-case is the system with no PCM.

	No PCM (base-case)	PCM22tt	PCM31tt	PCM36tt
Annual hours of discomfort (2340)	2,319	2,330	2,336	2,328
Discomfort (%)	99.1	99.6	99.8	99.5
Electricity consumption (kWh)	179,693	178,355	182,954	180,364
Difference in consumption from base-case	0	1,338	-3,261	-671
Difference in consumption from base-case (%)	0.00	0.007	-0.018	-0.004

Table 7-10 Night-time mechanical cooling

Results are shown in Table 7-10 and Figure 7-7. The night time only cooling strategy for a base-case with no PCM gives an annual total of 2319 uncomfortable working hours and a total electricity consumption of 179,693kWh. For PCM of transition temperatures of 22°C, the uncomfortable working hours and total electricity consumption are 2,330 and 178,355kWh. For PCM of transition temperatures of 31°C, the uncomfortable working hours and total electricity consumption are 2,336 and 182,954kWh. For PCM of transition temperatures of 36°C, the uncomfortable working hours and total electricity consumption are 2,328 and 180,364kWh.

The differences in consumption from the base-case for transition temperatures of 22°C, 31°C, and 36°C are little. Transition of 22°C showed a reduction in temperature of 0.007%, while transition temperatures of 31°C and 36°C showed an increase of 0.018% and 0.004%.

The results across all the strategies prove inconclusive. The uncomfortable work-hours across all four cases are 99.1%, 99.6%, 99.8% and 99.5% respectively making night-time mechanical cooling same as natural ventilation strategy, a failed one.

It is obviously of no use to combine night-time cooling and day-time cooling because day-time cooling alone is able to provide thermal comfort. Combining the two will only cause electricity consumption to rise while thermal comfort remains the same.

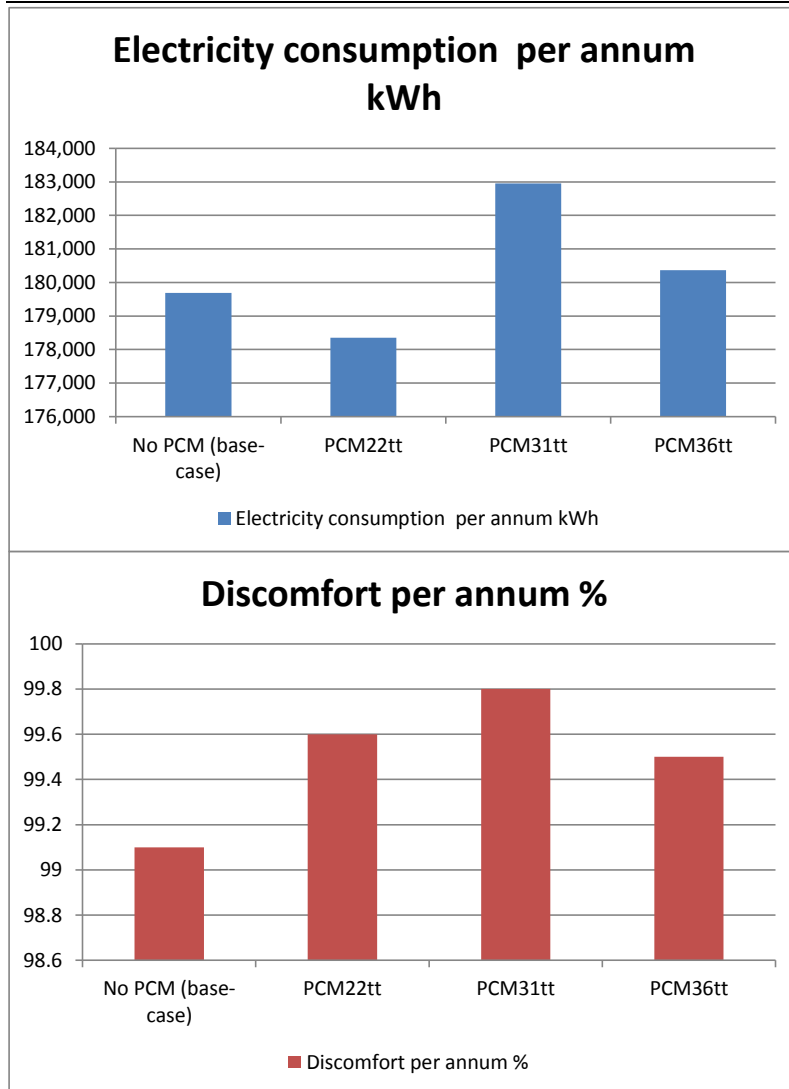


Figure 7-7 Night-time mechanical cooling

7.6.1.3 Day-time mechanical cooling of PCM

The strategy adopted is the mechanical cooling of the building to maintain the lower bound comfort limit of 24°C for working hours starting from 8am till 5pm on working days. This adequate cooling ensures that the PCM system is backed up by mechanical cooling to achieve comfort for the building occupants. In EnergyPlus, the chosen cooling strategy is ‘Ideal load air system’.

The variables making up the base-case with the exception of transition temperature are shown in Table 7-1. The base-case is the system with no PCM and there is a total of 2340 work-hours per annum.

	No PCM (base-case)	PCM22mt	PCM31mt	PCM36mt
Annual hours of discomfort (2340)	0	20	23	12
Discomfort per annum (%)	0.01	0.9	1	0.5
Annual electricity consumption kWh	193,000	191,577	184,454	181,277
Difference in consumption from base-case	0	1,423	8,546	11,723
Difference in consumption from base-case (%)	0.0%	0.7%	4.4%	6.1%

Table 7-11 Day-time mechanical cooling

Results are shown in Table 7-11 and Figure 7-8. The day-time mechanical cooling strategy gives an annual total of 0 uncomfortable working hours and a total electricity consumption of 193,000kWh for the base-case. For the case with PCM of transition temperature 22°C, there is an annual total of 20 uncomfortable working hours and a total electricity consumption of 191,577kWh. For the case with PCM of transition temperature 31°C, there is an annual total of 23 uncomfortable working hours and a total electricity consumption of 184,454kWh. For the case with PCM of transition temperature 36°C, there is an annual total of 12 uncomfortable working hours and a total electricity consumption of 181,277kWh. There is a general decrease in consumption as the transition temperature increases at 0.7% to 4.4%, then 6.1%. There is an increase of 13,307kWh in electricity consumption between overnight cooling and daytime cooling strategies with no PCM. However, this is of no benefit due to the unacceptable level of discomfort in the overnight cooling strategy as shown in Table 7-10.

The uncomfortable working hours are within acceptable levels of 0%, 0.9%, 1% and 0.5% of a total of 2340 work-hours. For no PCM system, all the working hours are comfortable yet the consumption is the highest. The system with the lowest consumption is PCM system with transition temperature 36°C and its corresponding uncomfortable hours is an acceptable 12 hours, the second lowest. This accounts for a maximum 6.1% decrease in consumption from the base-case with no PCM. From these comparisons, the best strategy in terms of comfort and electricity consumption is the PCM system with transition temperature 36°C. This transition temperature also corresponds to the average maximum interior air temperature of the building as Xiao *et al* (2009) recommended.

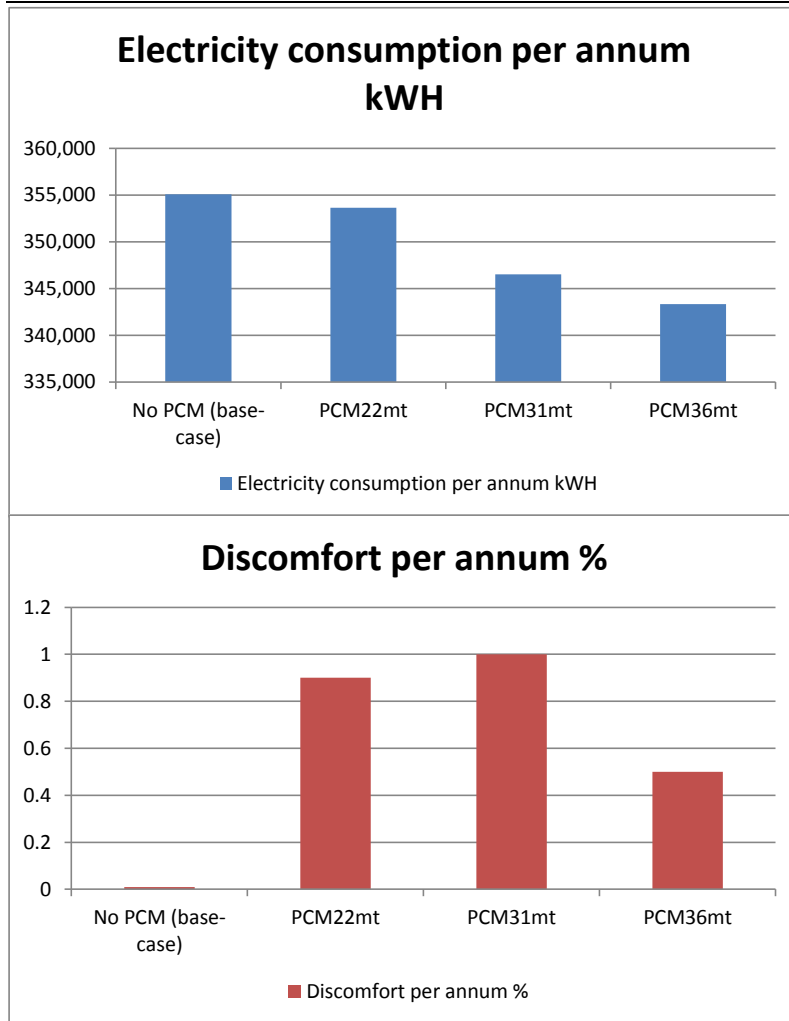


Figure 7-8 Day-time mechanical cooling

7.6.2 Thickness and conductivity analysis

The base-case adopted is the PCM with optimized transition temperature of 36°C and day-time mechanical cooling of the interior. The other variables making up the base-case are shown in Table 7-1.

Taking total annual electricity consumption and hourly indoor air temperature predictions over a year, the effect of varying the thickness and conductivity of the PCM is examined and optimised.

Some optimized values for thickness and conductivity have been extracted from literature. The ideal thickness has been reported to be 10mm, while the conductivity of

PCM does not affect its thermal performance as long as it is greater than 0.5W/m K (Feldman *et al.*, 1995; Xu *et al.*, 2005; Kuznik *et al.*, 2008b).

Three different thicknesses are examined for the proposed PCM with transition temperature 36°C. They are:

1. 10mm
2. 50mm
3. 100mm

Three different conductivities are examined for the optimized PCM system with transition temperature 36°C. They are:

1. 0.5 W/m K
2. 1.0 W/m K
3. 1.5 W/m K

Simulations	Transition temperature (°C)	Thickness (mm)	Conductivity (W/m K)
1 (Base-case)	36	10	0.5
2	36	10	1
3	36	10	1.5
4	36	50	0.5
5	36	50	1
6	36	50	1.5
7	36	100	0.5
8	36	100	1
9	36	100	1.5

Table 7-12 Variables for optimizing thickness and conductivity

7-PCM performance in office buildings

Simulations	1 (base-case)	2	3	4	5	6	7	8	9
Annual hours of discomfort (2340)	24	24	24	25	25	25	21	21	23
Discomfort per annum (%)	1	1	1	1.1	1.1	1.1	0.9	0.9	1
Annual electricity consumption per annum kWh	181,277	181,277	181,107	204,122	204,122	208,280	201,592	201,592	181,948
Difference in consumption from base-case	0	0	170	-22,845	-22,845	-27,003	-20,315	-20,315	-671
Difference in consumption from base-case (%)	0.0%	0.0%	0.1%	-12.6%	-12.6%	-14.9%	-11.2%	-11.2%	-0.4%

Table 7-13 Thickness and conductivity analysis

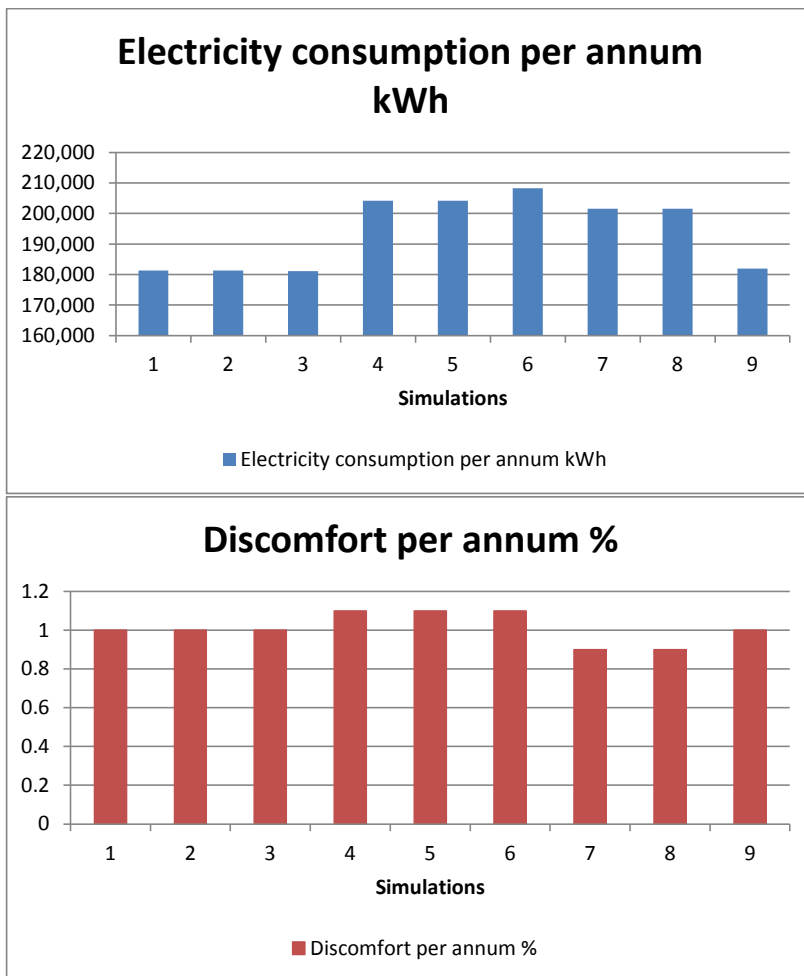


Figure 7-9 Thickness and conductivity analysis

While examining conductivities, results show that electricity consumed for PCM with conductivity of 0.5W/m K and thickness 10mm, 50mm and 100mm are 181,277kWh, 366197kWh and 201,592kWh respectively. Those of PCM with 1.0W/m K conductivity and thickness 10mm, 50mm and 100mm are 181,277kWh, 204,122kWh and 201,592kWh respectively. The final conductivity tested is 1.5W/m K and thickness of 10mm, 50mm, and 100mm resulted in consumptions of 343,182kWh, 208,280kWh and 181,948kWh respectively. See Table 7-12, Table 7-13 and Figure 7-9 for an illustration of the simulations conducted and results predicted.

The discomfort experienced in all 9 simulations is within accepted margins of 1.0%, 1.0%, 1.0%, 1.1%, 1.1%, 1.1%, 0.9%, 0.9% and 1.0% of the total working hours respectively.

Electricity consumed in simulation 1 to 3 is the same at 181,277kWh. There is a slight reduction in simulation 3 at 181,107kWh which increased by 12.6% for Simulation 4 and 5. Simulation 6 increased by 14.9%. Simulation 7 and 8 also experienced an increase in electricity consumption with a rise to 11.2%. Simulation 9 experienced a 0.4% increase. The highest consumption corresponds to PCM system with conductivity 1.5W/m K and thickness 50mm; whereas the lowest corresponds to PCM system with same conductivity of 1.5W/m K but thickness of 10mm- simulation 3. The results indicate that even though conductivity of greater than 0.5W/m K is adequate for effective melting and solidification of the PCM, increasing the conductivity above 0.5W/m K improves the performance. The base-case construction of the walling unit is heavyweight which in itself provides thermal mass. Adding a thick layer of PCM not only stops the PCM layer from fully melting, but the heavy-weight walls also trap the heat in the interiors. This is evidenced by the slight increase in consumption for the PCM with thickness 50mm and 100mm. The result agrees with Richardson and Woods (2008) who conclude that PCM thickness that achieves only partial melting at the interior side is more effective at anchoring surface temperatures to the building thermal capacity rather than the interior air temperature of the building. The thickness 100mm melts only partially thus its poor performance in terms of reducing high temperatures.

7.7 Optimizing PCM operation strategies

Based on the optimization of transition temperature, thickness and conductivity, the values producing optimum thermal comfort and energy conservation are 36°C, 10mm and 1.5W/m K respectively, see Table 7-14. These values in addition to those in Table 7-1 constitute the base-case for the following simulations.

Variables	Values
Transition temperature	36°C
Thickness	10mm
Conductivity	1.5W/m K

Table 7-14 Base-case variables for optimizing operational strategy

The following analyses examine the total annual electricity consumption and thermal comfort between the following operational strategies:

1. Day-time natural ventilation
2. Day-time natural ventilation and night purge
3. Day-time mechanical
4. Day-time mechanical cooling and night-purge
5. Set-back cooling
6. Cyclic cooling

Daytime natural ventilation, day-time mechanical cooling and night-time mechanical cooling have been discussed previously but will be revisited for more analyses.

The cooling of the building through natural ventilation overnight, in an effort to ensure that the PCM is fully solidified using cooler night time temperatures is known as night-purge. Set-back cooling is the adequate mechanical cooling supplied from the start of the working day at 8:00am till 12:00pm when it is switched off to simulate a power outage. It is evaluated to calculate the performance of PCM relative to the duration of mechanical cooling during working hours in Section 7.7.4. The results are used to evaluate the electricity consumption of the building using cyclic cooling. Cyclic cooling is a proposed strategy that allows the switching off of mechanical cooling of interiors in an attempt to save energy. In the Nigerian context, the analysis evaluates the length of time PCMs can maintain thermal comfort in a mechanically cooled building in the event of a power outage.

The energy and thermal performance of PCM with the above stated operational strategies are examined and the results are shown in Table 7-15 and Figure 7-11.

An analysis of comfort predicted in terms of annual hour of discomfort and electricity consumed is conducted for each operational strategy. A further analysis looking at the surface temperatures of the PCM walls for hot and cold design days. A design-day is a day that experiences an extreme in climatic condition that requires air-conditioning to achieve thermal comfort. The 21st of March and 4th of August are chosen as heating and cooling design-days.

The ambient air temperature experienced in Abuja is illustrated in Figure 7-10.

The surface temperature affects the radiant temperature and in the case where the surface temperature and air temperature are different, the operative temperature is adopted as a more valid thermal index (CIBSE, 2007). The Operative temperature is the average of the Zone Mean Air Temperature and Zone Mean Radiant Temperature (EnergyPlus, 2011).

Comment [A14]: Addition

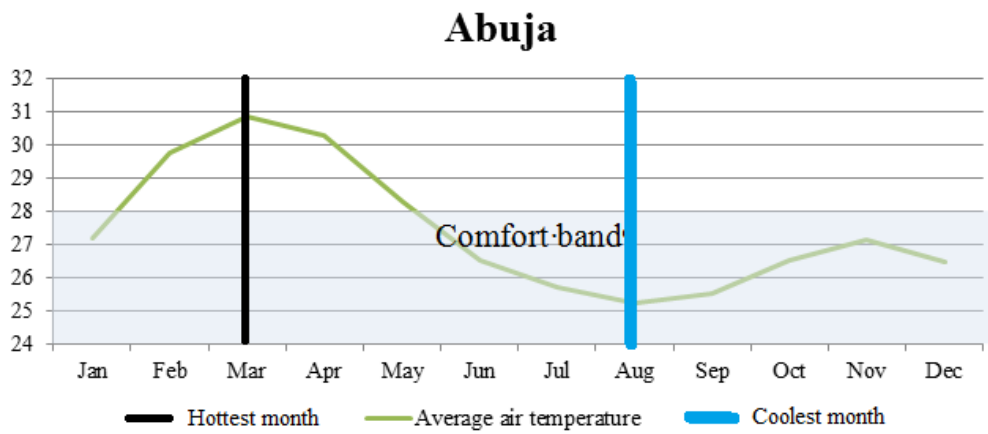


Figure 7-10 Abuja ambient air temperature- showing comfort band calculated by Neutrality temperature

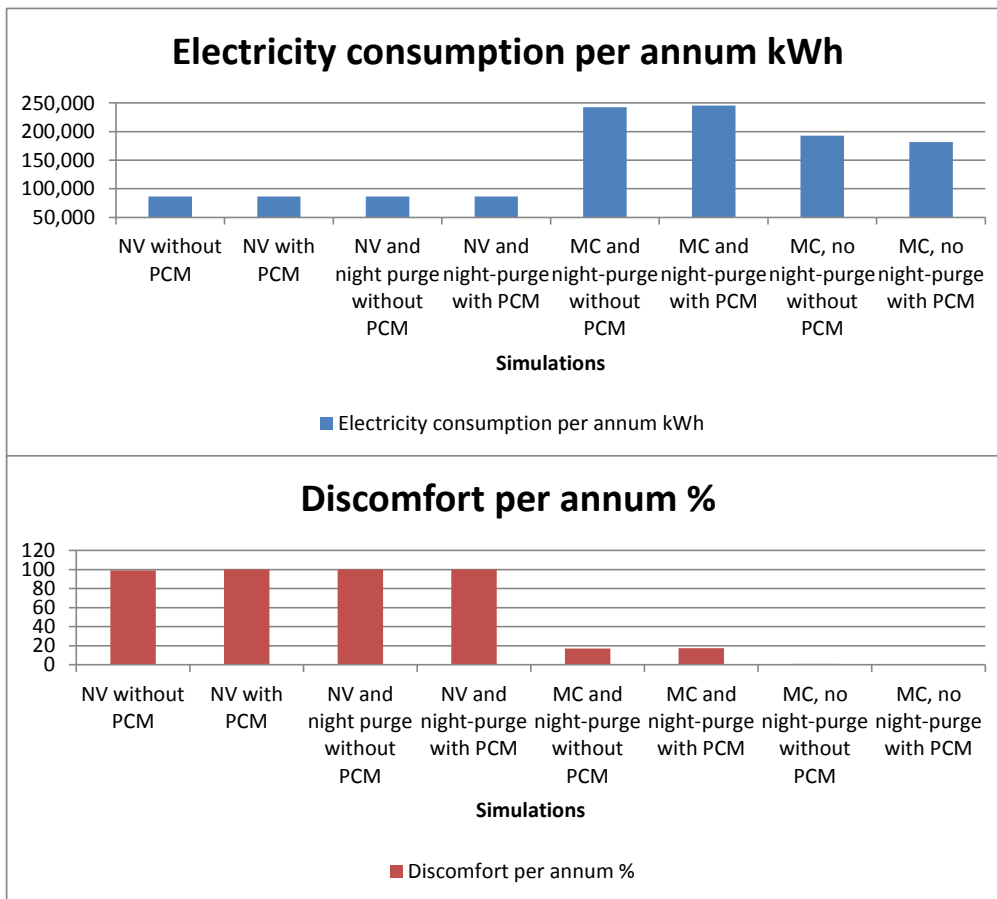


Figure 7-11 Optimizing operational strategies (NV=Natural ventilation, MC=Mechanical cooling)

7-PCM performance in office buildings

	NV without PCM	NV with PCM	NV and night purge without PCM	NV and night-purge with PCM	MC and night-purge without PCM	MC and night-purge with PCM	MC, no night-purge without PCM	MC, no night-purge with PCM
Annual discomfort hours (2340)	2,314	2,340	2,340	2,340	401	410	24	12
Thermal discomfort per annum %	98.9	100	100	100	17.1	17.5	1.0	0.5
Annual electricity consumption kWh	86,390	86,390	86,390	86,390	242,616	245,509	193,000	181,277
Difference in consumption from base-case	0	0	0	0	49,616	52,509	0	-11,723
Difference in consumption from base-case %	0	0	0	0	-181%	-184%	-123%	-110%

Table 7-15 Optimizing operational strategies (NV=Natural ventilation, MC=Mechanical cooling)

7.7.1 Day-time natural ventilation

The variables making up the base-case are shown in Table 7-1 and Table 7-14. Transition temperature of 36°C, conductivity of 1.5W/m K and thickness of 10mm are adopted. The base-case is the system with no PCM.

The results show that natural ventilation without PCM gives a yearly summation of discomfort hours of 2,314 and electricity consumption of 86,390 kWh. Natural ventilation with PCM gives a yearly summation of discomfort hours of 2,340 and electricity consumption of 86,390 kWh. As earlier concluded, the natural ventilation strategy provides inconclusive results as 98.9% and 100% discomfort is experienced for no PCM and PCM respectively. This is shown in Table 7-15 and Figure 7-11.

7.7.1.1 Design day analysis for Day-time natural ventilation using Operative temperature

The results of the analysis on the hottest and coldest day when the building is cooled with natural ventilation shows a small difference between air and surface temperatures of 0.4% and 0.5% for August and March respectively. The results, in Table 7-16, reflect the small difference in the maximum air and operative temperatures of 26.46°C and 26.46°C in August while in March they are 30.76°C and 30.71°C respectively. The minimum air and operative temperatures predicted are 25.6°C and 25.68°C in August while in March they are 28.9°C and 29.05°C respectively.

The operative temperatures are higher than air temperatures showing the need to consider surface temperatures when evaluating comfort. In August, the coldest month, the maximum operative temperature is within the comfort bands calculated from Neutrality temperature (24°C -28°C). In March, the hottest month, the operative temperatures fall out of the comfort band throughout the day.

Comment [A15]: Addition

Hr	MRT (°C) in Aug	MAT (°C) in Aug	MOT (°C) in Aug	Variance	MRT (°C) in Mar	MAT (°C) in Mar	MOT (°C) in Mar	Variance
1	26.1	25.9	26.0	0.0	30.1	29.9	30.0	0.0
2	26.0	25.9	26.0	0.0	30.0	29.7	29.9	0.0
3	26.0	25.8	25.9	0.0	29.9	29.6	29.7	0.0
4	25.9	25.8	25.8	0.0	29.7	29.4	29.6	0.0
5	25.9	25.7	25.8	0.0	29.6	29.3	29.4	0.0
6	25.8	25.6	25.7	0.0	29.4	29.1	29.3	0.0
7	25.8	25.6	25.7	0.0	29.3	29.0	29.1	0.0
8	25.8	25.6	25.7	0.0	29.2	28.9	29.1	0.0
9	25.8	25.7	25.7	0.0	29.2	28.9	29.1	0.0
10	25.9	25.7	25.8	0.0	29.3	29.0	29.2	0.0
11	26.0	25.8	25.9	0.0	29.4	29.2	29.3	0.0
12	26.1	26.0	26.0	0.0	29.5	29.3	29.4	0.0
13	26.2	26.1	26.1	0.0	29.7	29.5	29.6	0.0
14	26.3	26.2	26.2	0.0	29.9	29.8	29.8	0.0
15	26.4	26.3	26.3	0.0	30.0	30.0	30.0	0.0
16	26.4	26.4	26.4	0.0	30.3	30.3	30.3	0.0
17	26.5	26.5	26.5	0.0	30.5	30.6	30.6	0.0
18	26.5	26.5	26.5	0.0	30.7	30.8	30.7	0.0
19	26.4	26.4	26.4	0.0	30.6	30.6	30.6	0.0
10	26.4	26.4	26.4	0.0	30.5	30.6	30.5	0.0
21	26.4	26.4	26.4	0.0	30.5	30.6	30.5	0.0
22	26.4	26.3	26.3	0.0	30.5	30.5	30.5	0.0
23	26.3	26.2	26.3	0.0	30.4	30.4	30.4	0.0
24	26.3	26.1	26.2	0.0	30.3	30.2	30.3	0.0

Table 7-16 Day-time natural ventilation: Design day analysis for coldest and hottest days using operative air temperature (MRT-Mean Radiant Temperature, MAT- Mean Air Temperature and MOT- Mean Operative Temperature). Bold font denotes uncomfortable hours

7.7.1.2 Thermal comfort based on orientation

A test is conducted to examine the effect of orientation on PCM performance. Record of indoor mean air temperature is predicted on an hourly basis for a year. The operational strategy adopted is natural ventilation and results show all four orientations presented 100% discomfort during working hours. A look at the degree of discomfort shows the East suffers the most, closely followed by West as shown in Table 7-17. The North and finally South are shown to thermally perform better.

East	West	North	South
22,821	22,476	20,055	21,574

Table 7-17 Degree of discomfort calculation adapted from degree hour method

There is an average of 12 sunshine hours in Abuja, between 6am and 6pm daily. Work hours are between 8am and 5pm a therefore the eastern orientation receives more sunlight during working hours than the western orientation. The solar incidence in the southern orientation is greater than that in the north in Abuja due to the earth's tilt and how the tilt affects the sun's movement. Thus the worsened performance of the south orientation compared to the North orientation. The average sunshine hours and dominance of solar incidence is on the southern orientation in Nigeria.

The discomfort trend agrees with that of orientation optimization conducted in Chapter 6; the best orientation should place the principal axis along the east-west axis. This will limit openings and glazing on the east and west orientation, which receive direct sunlight in the mornings and evenings.

Further tests were conducted comparing the thermal performance of the rooms with and without PCM in the four orientations. Results show the degree of discomfort per hour for a year.

The system with no PCM performs better than with PCM as shown in Figure 7-12. The degree of discomfort for the system with PCM for East, West, North and South are 22,821, 22,476, 20,055 and 21,574 respectively per annum. The degree of discomfort for the system without PCM for east, west, north and south are 16,312, 15,591, 14,395 and 14,548 respectively per annum.

This further confirms that East-West thermally performs worse than the North-South as initially reported.

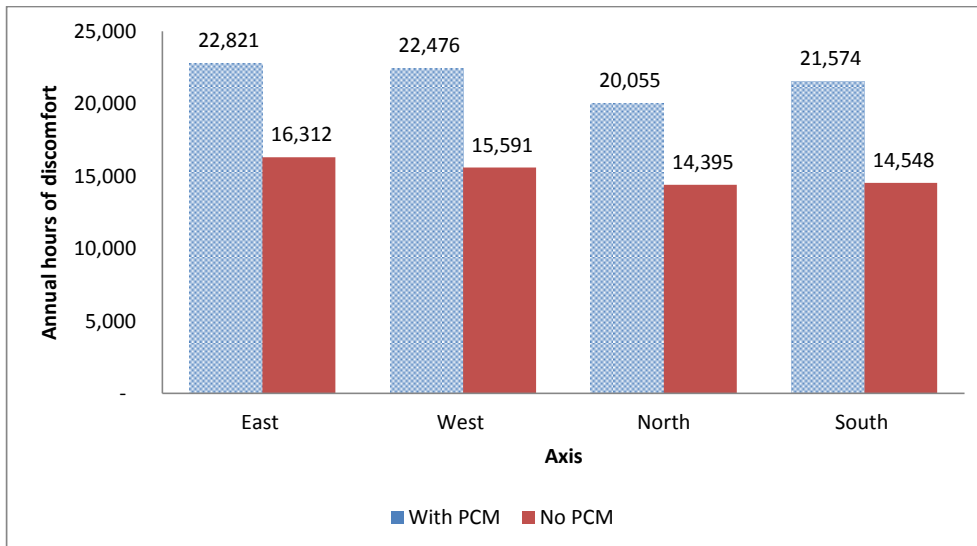


Figure 7-12 Degree of discomfort for rooms of different orientations and between PCM and plain walls

7.7.2 Day-time natural ventilation and night purge

The strategy adopted is the cooling of the building through natural ventilation during working hours and overnight and the base-case is the system with no PCM. The variables making up the base-case are shown in Table 7-1 and Table 7-14. For whatever transition temperature, conductivity of 1.5W/m K and thickness of 10mm are adopted.

Night-time cooling through ventilation is employed to ensure that the PCM is fully solidified using cooler night time temperatures without extra energy consumption. This process is called night-purge.

Results are shown in Table 7-15. Natural ventilation and night purge for the base-case without PCM gives a yearly sum of discomfort hours of 2,340 and electricity consumption of 86,390 kWh. Natural ventilation and night-purge with PCM also gives a yearly summation of discomfort hours of 2,340 and electricity consumption of 86,390 kWh.

An increase in degree of discomfort is experienced for naturally ventilated buildings using night-purge strategy in both March and August.

In March the intensity for the building with PCM is 2673 and that for without is 2631, see Table 7-18. In August, the intensity falls to 1552 and 1543 for building with and without

PCM respectively. The degree of discomfort is calculated based a combination of the degree-day and the temperature attained during the degree-day as shown in Equation 7-2:

$$(T_{ave} - T_{max}) * F_{day} * F_{hour} \quad \text{Equation 7-2}$$

Where F_{day} is a function showing if the day is a work-day and F_{hour} shows if the hour being examined falls within the work-hours. F_{day} and F_{hour} return a value of 1 denoting work-days and work-hours.

	NV and night purge without PCM		NV and night-purge with PCM	
Degree of discomfort	March	August	March	August
	2631	1543	2673	1552

Table 7-18 Degree of discomfort for night-purge (Natural ventilation=NV)

The results indicate the benefit of the cooler august night-time temperature for thermal comfort. The improvement occurs during the cold months when night temperatures are sufficiently cool. This indicates that the ambient air temperature in Abuja is inadequate for night-purge cooling of a passive PCM system except in the cooler months.

Furthermore, using night ventilation in Abuja practically presents its own set of problems such as; allowing in harmattan dust during the dry season; mosquitoes and rodents.

7.7.2.1 *Design day analysis for Day-time natural ventilation and night purge using Operative temperature*

The results of the analysis on the hottest and coldest day when the building is cooled with natural ventilation during the day and night purge at night shows a negative difference between air and surface temperatures of -5.1% and -1.1% for August and March respectively. The introduction of night purge increases air temperatures above surface temperatures, with August higher than March as shown in Table 7-19. The maximum air and operative temperatures predicted are 34.3°C and 33.4°C in August while in March they are 41.5°C and 40.5°C respectively. The minimum air and operative temperatures predicted are 33.2°C and 32.5°C in August while in March they are 37.4°C and 38.0°C respectively.

Comment [A16]: addition

Hrs	MRT (°C) in August	MAT (°C) in August	MOT (°C) in August	Variance	MRT (°C) in March	MATe (°C) in March	MOT (°C) in March	Variance
1	32.2	33.6	32.9	0.0	39.6	40.5	40.1	0.0
2	32.1	33.5	32.8	0.0	39.5	40.1	39.8	0.0
3	32.1	33.5	32.8	0.0	39.3	39.8	39.5	0.0
4	32.0	33.3	32.6	0.0	39.1	39.5	39.3	0.0
5	31.9	33.2	32.6	0.0	39.0	39.4	39.2	0.0
6	31.8	33.2	32.5	0.0	38.9	39.2	39.1	0.0
7	31.7	33.2	32.5	0.0	38.8	39.1	38.9	0.0
8	31.8	33.3	32.5	0.0	38.7	39.2	39.0	0.0
9	31.8	33.4	32.6	-0.1	38.8	39.6	39.2	0.0
10	31.9	33.6	32.8	-0.1	38.9	40.1	39.5	0.0
11	32.0	33.9	32.9	-0.1	39.0	40.6	39.8	0.0
12	32.1	34.0	33.1	-0.1	39.1	41.0	40.0	0.0
13	32.3	34.2	33.2	-0.1	39.3	41.3	40.3	-0.1
14	32.3	34.3	33.3	-0.1	39.4	41.5	40.5	-0.1
15	32.3	34.3	33.3	-0.1	39.4	40.9	40.2	0.0
16	32.4	34.3	33.3	-0.1	39.5	39.8	39.6	0.0
17	32.4	34.3	33.4	-0.1	39.6	40.7	40.2	0.0
18	32.4	34.2	33.3	-0.1	39.7	41.3	40.5	0.0
19	32.3	34.1	33.2	-0.1	39.5	40.1	39.8	0.0
10	32.3	34.0	33.1	-0.1	39.2	36.7	37.9	0.1
21	32.2	33.9	33.1	-0.1	39.0	36.7	37.8	0.1
22	32.2	33.8	33.0	0.0	38.9	38.0	38.4	0.0
23	32.1	33.6	32.9	0.0	38.8	37.6	38.2	0.0
24	32.0	33.5	32.8	0.0	38.6	37.4	38.0	0.0

Table 7-19 Day-time natural ventilation and night purge: Design day analysis for coldest and hottest days using operative air temperature (MRT-Mean Radiant Temperature, MAT- Mean Air Temperature and MOT- Mean Operative Temperature)

The operative temperatures are higher than air temperatures showing the need to consider surface temperatures when evaluating comfort. Generally the temperatures experienced with the introduction of night purge are higher indicating that night time temperatures are not sufficiently low to solidify the PCMs in the building fabric. The operative temperatures predicted for both months fall outside the comfort bands calculated from Neutrality temperature (24°C -28°C) and standardised by EN15251 (22°C -27°C) throughout the day.

7.7.3 Mechanical day-time cooling and night-purge

The strategy examined is the mechanical cooling provided during work hours and natural ventilation after work-hours. The variables making up the base-case are shown in Table 7-1 and Table 7-14. The mechanically cooled base-case of PCM with transition temperature of 36°C, conductivity of 1.5W/m K and thickness of 10mm is adopted.

Results of the simulation shown in Table 7-20 and Figure 7-13 indicate that night-purging with PCM increases electricity consumption from 193,000kWh to 245,509kWh when mechanical cooling is provided during the work-day. This accounts for a significant 29% increase in electricity consumption from the base-case. This is due to night-time temperatures that are insufficient to cool the building and solidify the PCM material. This phenomenon is further studied in section 7.7.3.1 using design-day analysis.

	Mechanical cooling no night-purge	Mechanical cooling with NV night-purge (PCM)	Mechanical cooling with NV night-purge (no PCM)
Annual hours of discomfort (2340)	12	410	401
Discomfort per annum%	0.5	17.5	17.1
Annual electricity consumption per annum kWh	193,000	245,509	242,616
Difference in consumption from base-case	0	-55,509	-52,616
Difference in consumption from base-case %	0%	29%	28%

Table 7-20 Mechanical cooling and night-purge strategy

The discomfort hours for the strategy with PCM are 410; whereas the discomfort hours for that without PCM show an improvement at 401. The base-case without PCM shows a slight improvement of a total of 9 hours per annum of comfortable hours and saves 2,893kWh of electricity consumption from 245,509 kWh to 242,616 kWh.

However, the results show that ultimately, not operating night-purge while using mechanical cooling during working hours thermally performs best at 24 hours of discomfort annually and 181,277 kWh of electrical consumption. This may be due to night-time temperatures that are not low enough to cool the building fabric overnight.

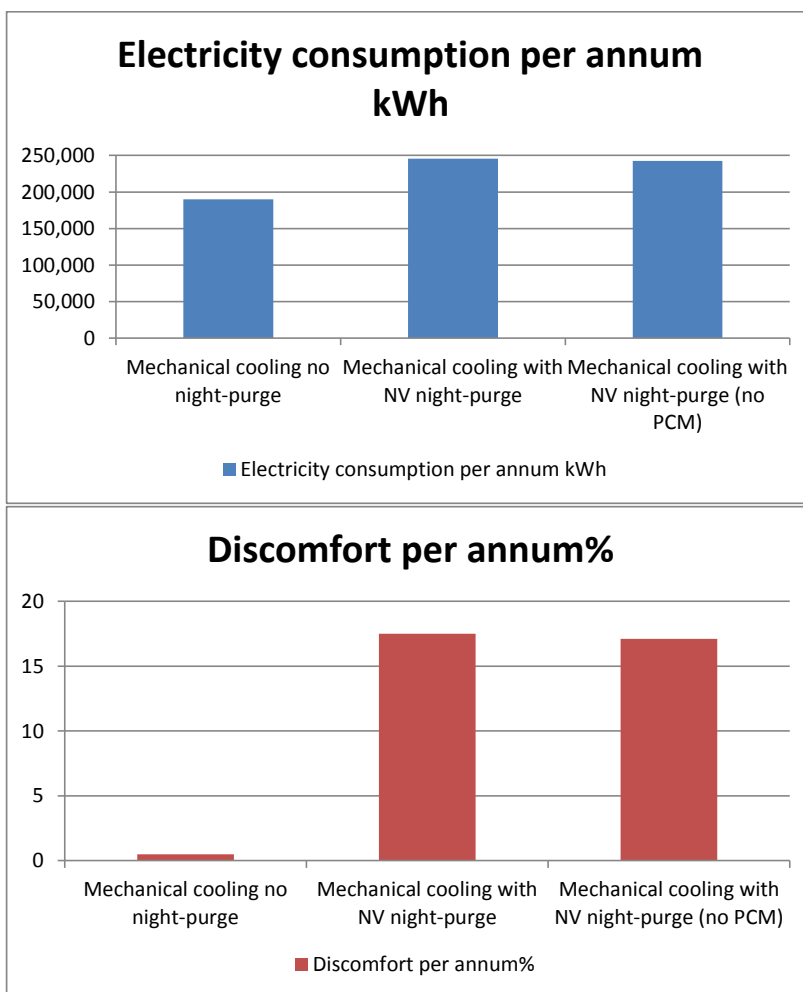


Figure 7-13 Night-purge strategy

The results in Table 7-21 show that when using air temperature as the indicator for thermal comfort, the yearly summation of discomfort hours is 12 for a mechanically cooled base case. However when considering surface temperature to calculate the operative air temperature, the discomfort increases to 49 hours. This is an increase from 0.5% to 2% of discomfort out of 2340 work-hours.

Comment [A17]: addition

	MC: Air temperature (°C)	MC: Operative temperature (°C)
January	2	9
February	3	13
March	4	18
April	1	6
May	2	3
June	0	0
July	0	0
August	0	0
September	0	0
October	0	0
November	0	0
December	0	0
Yearly Summation	12	49

Table 7-21 Mechanical cooling: Air versus operative temperature as indicators of annual comfort work-hours

7.7.3.1 Design-day analysis for day-time *mechanical* cooling and night purge using Operative temperature

Comment [A18]: addition

As mentioned in section 7.7.3 where results showed night-time temperatures are insufficient to cool the building and solidify the PCM material overnight, a further analysis is presented here using design-day analysis.

The results of the analysis on the hottest and coldest day when the building is mechanically cooled during the day shows a small difference between air and surface temperatures of -8.5% and 4.5% for August and March respectively. The positive values indicate that surface temperatures are higher than air temperature for both design days as shown in Table 7-22.

The ambient temperature is low enough not to switch on mechanical cooling in August and this accounts for the 4% difference in the variance between surface and air temperatures. This indicates the performance of the PCM in natural ventilation mode; the PCM is absorbing the heat without the enforced cooling effect of the mechanical system.

	MRT (°C) in August	MAT (°C) in August	MOT (°C) in August	Variance	MRT (°C) in March	MAT (°C) in March	MOT (°C) in March	Variance
Hr								
1	24.8	24.7	24.8	0.0	29.4	29.3	29.4	0.0
2	24.8	24.5	24.7	0.0	29.3	29.2	29.2	0.0
3	24.7	24.5	24.6	0.0	29.2	29.0	29.1	0.0
4	24.6	24.4	24.5	0.0	29.1	28.8	28.9	0.0
5	24.5	24.3	24.4	0.0	29.0	28.7	28.8	0.0
6	24.4	24.2	24.3	0.0	28.9	28.6	28.7	0.0
7	24.3	24.1	24.2	0.0	28.8	28.5	28.6	0.0
8	24.4	24.2	24.3	0.0	28.7	28.5	28.6	0.0
9	24.4	22.0	23.2	0.1	28.3	22.0	25.2	0.2
10	24.4	22.0	23.2	0.1	28.1	22.0	25.1	0.2
11	24.5	22.0	23.3	0.1	28.0	22.0	25.0	0.2
12	24.6	22.0	23.3	0.1	28.0	22.0	25.0	0.2
13	24.7	22.0	23.3	0.1	28.0	22.0	25.0	0.2
14	24.7	22.0	23.3	0.1	28.0	22.0	25.0	0.2
15	24.6	22.0	23.3	0.1	28.0	22.0	25.0	0.2
16	24.6	22.0	23.3	0.1	28.1	22.0	25.0	0.2
17	24.7	22.0	23.3	0.1	28.2	22.0	25.1	0.2
18	24.6	23.9	24.2	0.0	28.4	27.3	27.9	0.0
19	24.6	24.4	24.5	0.0	28.6	28.7	28.6	0.0
20	24.6	24.4	24.5	0.0	28.6	28.7	28.7	0.0
21	24.5	24.4	24.5	0.0	28.7	28.8	28.7	0.0
22	24.5	24.3	24.4	0.0	28.7	28.7	28.7	0.0
23	24.4	24.2	24.3	0.0	28.7	28.7	28.7	0.0
24	24.3	24.1	24.2	0.0	28.6	28.7	28.6	0.0

Table 7-22 Day-time mechanical cooling: Design day analysis for coldest and hottest days using operative air temperature (MRT-Mean Radiant Temperature, MAT- Mean Air Temperature and MOT- Mean Operative Temperature). Bold font denotes uncomfortable hours

Hr	Mean Radiant Temperature (°C) in August	Mean Air Temperature (°C) in August	Mean Operative Temperature (°C) in August	Variance	Mean Radiant Temperature (°C) in March	Mean Air Temperature (°C) in March	Mean Operative Temperature (°C) in March	Variance
1	26.8	29.2	28.0	-0.1	32.2	34.2	33.2	-0.1
2	26.8	29.2	28.0	-0.1	32.2	34.1	33.1	-0.1
3	26.8	29.3	28.0	-0.1	32.1	34.0	33.0	-0.1
4	26.8	29.2	28.0	-0.1	32.1	33.9	33.0	-0.1
5	26.8	29.2	28.0	-0.1	32.1	33.9	33.0	-0.1
6	26.8	29.3	28.1	-0.1	32.0	33.8	32.9	-0.1
7	26.9	29.3	28.1	-0.1	31.9	33.7	32.8	-0.1
8	26.8	27.3	27.0	0.0	31.8	32.1	31.9	0.0
9	26.7	26.6	26.7	0.0	31.7	31.6	31.6	0.0
10	26.4	21.9	24.2	0.2	30.9	22.0	26.5	0.3
11	26.1	22.0	24.1	0.2	30.3	22.0	26.2	0.3
12	26.0	22.0	24.0	0.2	30.0	22.0	26.0	0.3
13	26.0	22.0	24.0	0.2	29.8	22.0	25.9	0.3
14	25.8	22.0	23.9	0.1	29.6	22.0	25.8	0.3
15	25.6	22.0	23.8	0.1	29.4	22.0	25.7	0.3
16	25.5	22.0	23.8	0.1	29.3	22.0	25.7	0.3
17	25.4	22.0	23.7	0.1	29.3	22.0	25.6	0.2
18	25.6	27.5	26.6	-0.1	29.8	31.0	30.4	0.0
19	25.9	28.7	27.3	-0.1	30.3	33.1	31.7	-0.1
20	26.1	28.8	27.4	-0.1	30.4	32.5	31.4	-0.1
21	26.2	28.8	27.5	-0.1	30.5	32.3	31.4	-0.1
22	26.2	28.9	27.5	-0.1	30.6	32.6	31.6	-0.1
23	26.3	28.9	27.6	-0.1	30.7	32.3	31.5	-0.1
24	26.3	28.9	27.6	-0.1	30.7	32.2	31.4	0.0

Table 7-23 Day-time mechanical cooling and night purge: Design day analysis for coldest and hottest days using operative air temperature. Bold font denotes uncomfortable hours

The maximum air and operative temperatures predicted are 24.7°C and 24.8°C in August while in March they are 29.3°C and 29.4°C respectively. The minimum air and operative temperatures predicted are 23.2°C and 22°C in August while in March they are 25°C and 22°C respectively.

The results show that 58% of the time, operative temperatures predicted for the hottest day, in March fall outside the comfort bands calculated from Neutrality temperature (24°C -28°C). However as discussed in Section 7.7.3, the discomfort hours amount to only 0.5% per annum. For the base-case that is mechanically cooled during the day and also cooled through night purge at night, the results similar to the case for natural ventilation during the day, show night purge causes an increase in air temperatures above surface temperatures as shown in Table 7-23.

There is a difference between air and surface temperatures of -0.6% and 5.3% in August and March respectively. The negative value in the cooler month of August indicate that surface temperatures are higher than air temperature due to the absence of mechanical cooling similar to the case of mechanical cooling only. The ambient temperature is low enough not to switch on mechanical cooling in August as earlier discussed.

The maximum air and operative temperatures predicted are 29.3°C and 28.1°C in August while in March they are 34.2°C and 23.7°C respectively. The minimum air and operative temperatures predicted are 21.9°C and 23.7°C in August while in March they are 22°C and 25.6°C respectively. The results show that 66.7% of the time, operative temperatures predicted for the hottest day, in March fall outside the comfort bands calculated from Neutrality temperature (24°C -28°C). This is an increase of 8.7% discomfort compared with the mechanically cooled base case without night purge.

7.7.4 Setback cooling

As has been reported in Chapters 1, 2 and 5, Nigeria experiences a substantial amount of power outages over varying periods. The weeks experiencing maximum and minimum temperatures shown in Table 7-24 are used to test the effect of PCM on maintaining thermal comfort in the event of a power outage during working hours.

Design-days	Transition temperature	Justification
March 21- Hot design-day	36°C	Average maximum temperature in a naturally ventilated base-case
August 4- Cool design-day	24°C 22°C	Neutrality temperature Lower temperature limit of the comfort band

Table 7-24 Transition temperatures for power outage simulations

The transition temperatures 36°C, 24°C and 22°C are used to conduct the analysis. The temperatures are used because they are the maximum temperature in a naturally ventilated base-case, Neutrality temperature and lower limit in the comfort band for office buildings respectively.

The conductivity of 1.5W/m K and thickness of 10mm are held constant. The case without PCM is adopted as the base-case. These values in addition to those in Table 7-1 constitute the base-case.

Adequate mechanical cooling is supplied from the start of the working day at 8:00am till 12:00pm when it is switched off to simulate a power outage. 12:00 pm is chosen because the sun is at its peak around mid-day in Abuja.

Figure 7-14 shows the operational air profile of the design days March 21st and August 4th, corresponding to the hottest and coolest days of the year. The results show that August 4th achieves comfort with natural ventilation. This result is consistent for the case with no PCM, and those with PCM of transition temperatures 36°C, 24°C and 22°C. Therefore, subsequent results presented in this section will focus on March 21, the hottest day. The results cover:

- Analysing indoor temperature difference after power outage
- Analysing duration of thermal comfort after a power outage

7.7.4.1 *Analysing indoor temperature difference after power outage*

Table 7-25 shows the difference predicted in indoor air temperature during work-hours (8am-5pm) between naturally ventilated and mechanically cooled cases with different transition temperatures. On average, the difference between the naturally ventilated case with no PCM and the mechanically cooled case with no PCM is 1°C. The difference between the naturally ventilated case with PCM of transition temperature 36°C and the mechanically cooled case with PCM of transition temperature 36°C is 4.1°C. This is a desirable four-fold increase in temperature reduction from the case with no PCM which is also maintained for the cases with PCM of transition temperature 24°C and 22°C.

The maximum difference between the naturally ventilated case with no PCM and the mechanically cooled case with no PCM is 4.5°C. The maximum difference between the naturally ventilated case with PCM of transition temperature 36°C and the mechanically cooled case with PCM of transition temperature 36°C is 7.3°C. This is a desirable 2.8°C decrease in temperature from the case with no PCM which is maintained for the cases with PCM of transition temperature 24°C and 22°C.

Daily work-hours	Difference NV and MC, no PCM (°C)	Difference NV PCM 36(°C) and MC PCM 36(°C)	Difference NV PCM 24(°C) and MC PCM 36(°C)	Difference NV PCM 22(°C) and MC PCM 36(°C)
9	4.2	7.0	7.0	6.9
10	4.3	7.0	7.0	7.0
11	4.4	7.2	7.2	7.2
12	4.5	7.3	7.3	7.3
1	0.1	3.0	3.0	3.0
2	-1.7	1.4	1.4	1.4
3	-1.9	1.3	1.3	1.3
4	-2.2	1.3	1.3	1.2
5	-2.5	1.2	1.3	1.2
Minimum	-2.5	1.2	1.3	1.2
Maximum	4.5	7.3	7.3	7.3
Average	1.0	4.1	4.1	4.1

Table 7-25 Temperature difference between natural ventilation (NV) and mechanical cooling (MC)

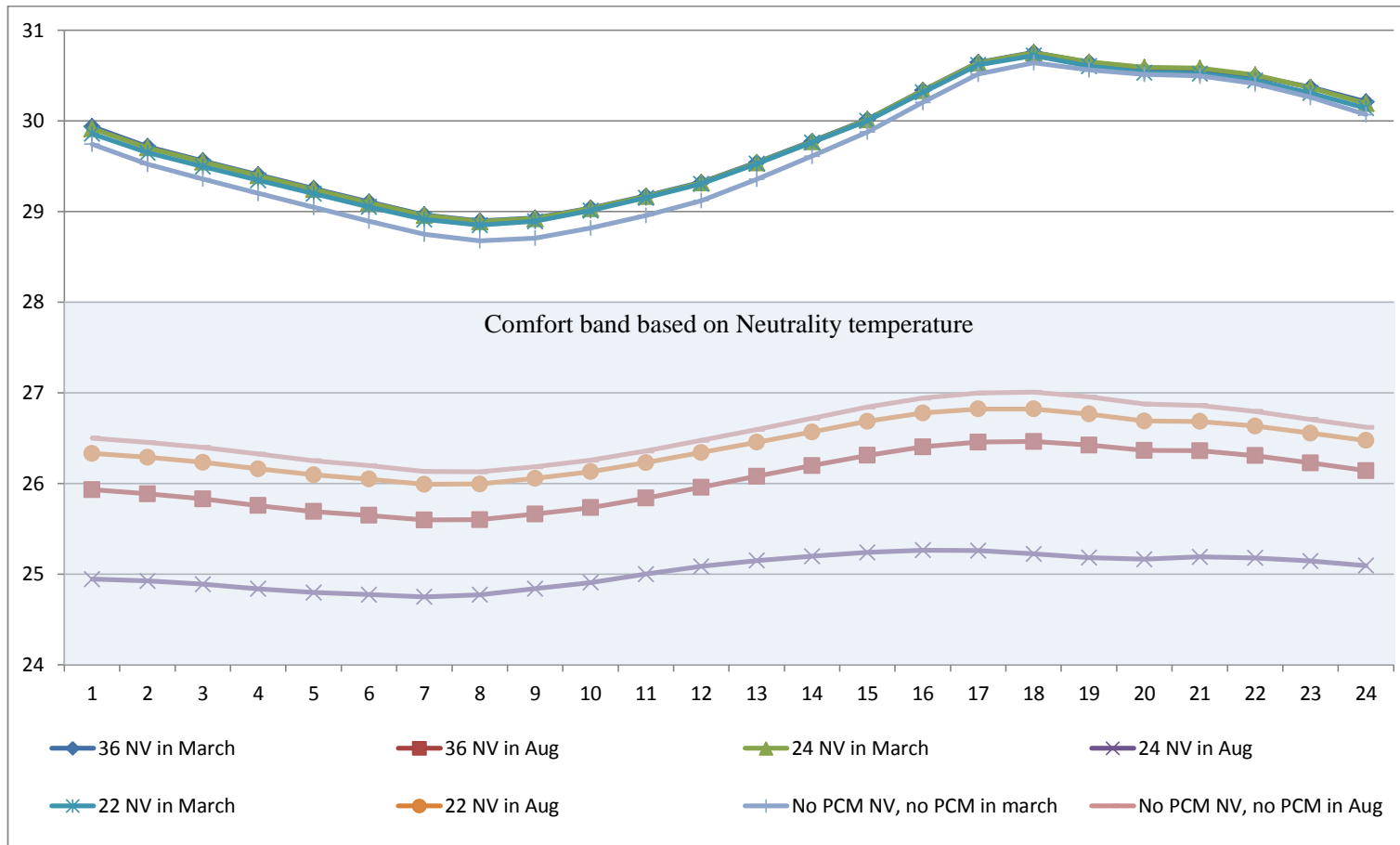


Figure 7-14 Design-day indoor temperatures with natural ventilation

The temperature reduction over a work-day between the naturally ventilated case with no PCM and the mechanically cooled case with no PCM is 12.2°C. The reduction between the naturally ventilated case with PCM of transition temperature 36°C and the mechanically cooled case with PCM of transition temperature 36°C is 36.6°C. This is a desirable three-fold increase in temperature reduction from the case with no PCM. The differences for the cases with PCM of transition temperature 24°C and 22°C are 36.7°C and 36.5°C respectively. PCM of transition temperature 24°C is therefore predicted to be in the lead of reducing the most temperature, albeit with a 0.2°C margin as shown in Figure 7-14.

7.7.4.2 *Analysing duration of thermal comfort after a power outage*

The aim is to examine the effect of duration of mechanical cooling on thermal comfort maintained after a power outage on March 21st. Simulations are conducted for cooling of 1 to 8 work-hours in hourly increments over the work-day. Figure 7-15 to Figure 7-17 show power outage simulations in cases with transition temperature 36°C, 24°C and 22°C. Table 7-26 and Figure 7-18 show the relationship between the duration of cooling hours and the duration of comfort predicted for cases of PCM with transition temperature 36°C, 24°C and 22°C in March.

The results show that for PCM with transition temperature 36°C, when cooled for an hour, only an hour of comfort can be maintained should there be a power outage. When cooled for 2 hours, comfort is maintained for 3 hours. When cooled for 3 hours, comfort is maintained for 4 hours. When cooled for 4 hours, comfort is maintained for 5 hours. When cooled for 5 hours, comfort is maintained for 7 hours. When cooled for 6 hours, comfort is maintained for 8 hours. When cooled for 7 hours, comfort is maintained for 9 hours. When cooled for 8 hours, comfort is maintained for 10 hours. The trend is maintained for PCM with transition temperature 22°C.

PCM with transition temperature 24°C shows a difference in performance when cooled for 5 hours; comfort is maintained for 9 hours instead of 7. For the rest of the hours cooled, the same 10 hours of comfort is maintained, higher than for PCM of transition temperatures 36°C and 22°C.

The combination of the slight margin of 0.2°C temperature reduction potential and longer duration of comfort maintained during a power outage makes PCM with transition temperature 24°C a better PCM compared with PCM with transition temperature 36°C or 22°C.

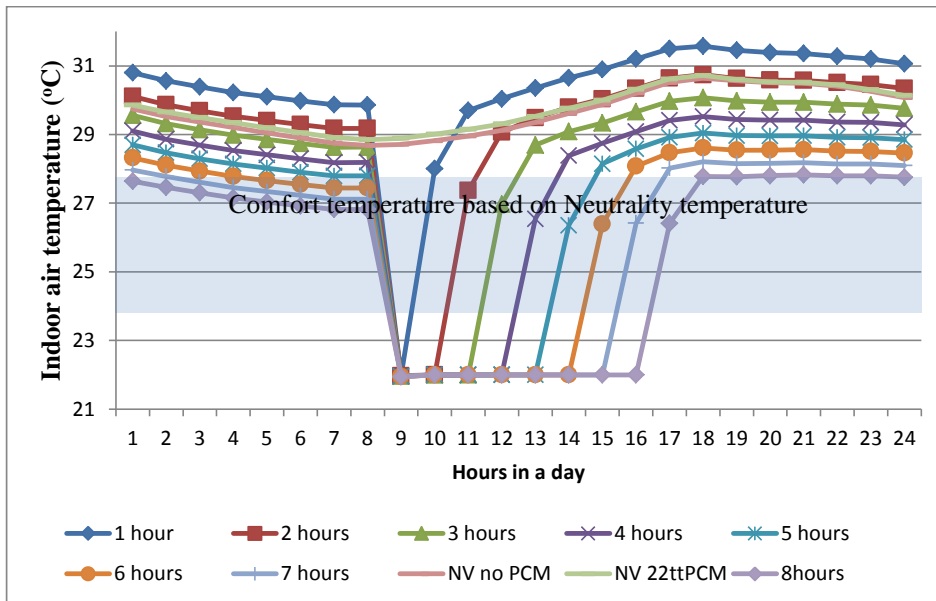


Figure 7-15 Power outage simulations for PCM of transition temperature 21°C on March 21

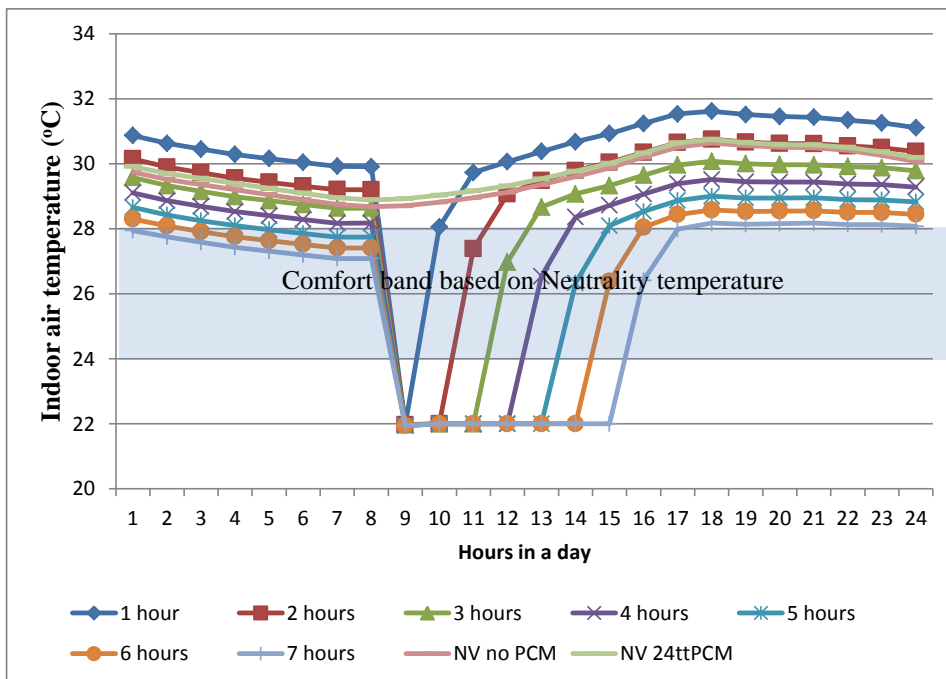


Figure 7-16 Power outage simulations for PCM of transition temperature 24°C March 21

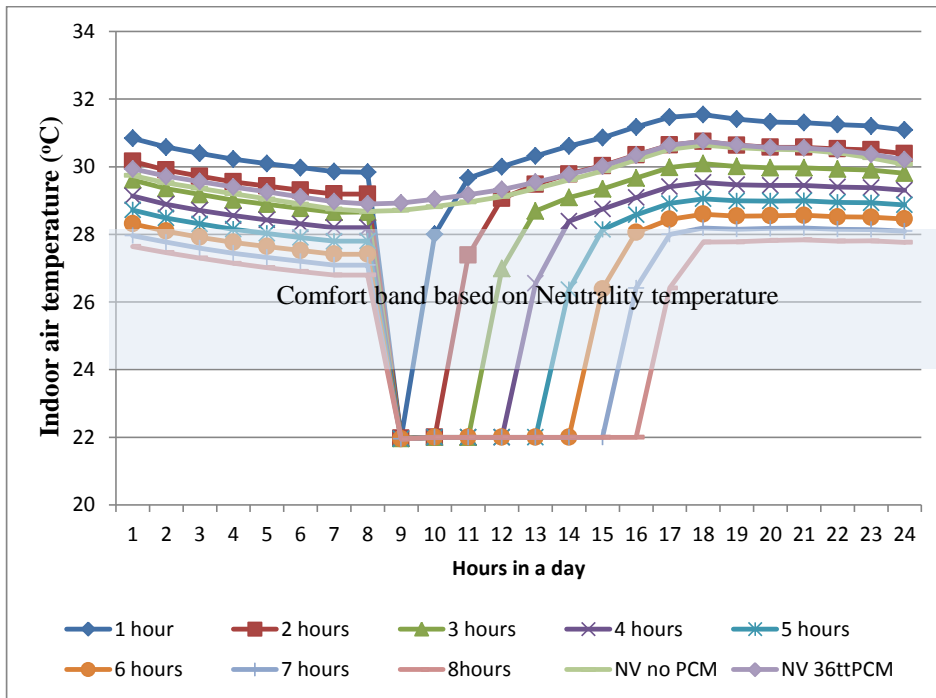


Figure 7-17 Power outage simulations for PCM of transition temperature 36°C March 21

PCM description	1 hour MC	2 hours MC	3 hours MC	4 hours MC	5 hours MC	6 hours MC	7 hours MC	8 Hour MCs
TT 36°C, Mar	1	3	4	5	7	8	9	10
TT 24°C, Mar	1	3	4	5	9	10	10	10
TT 22°C, Mar	1	3	4	5	7	8	9	10

Table 7-26 Duration of comfort maintained during power outage after mechanical cooling MC (TT is transition temperature)

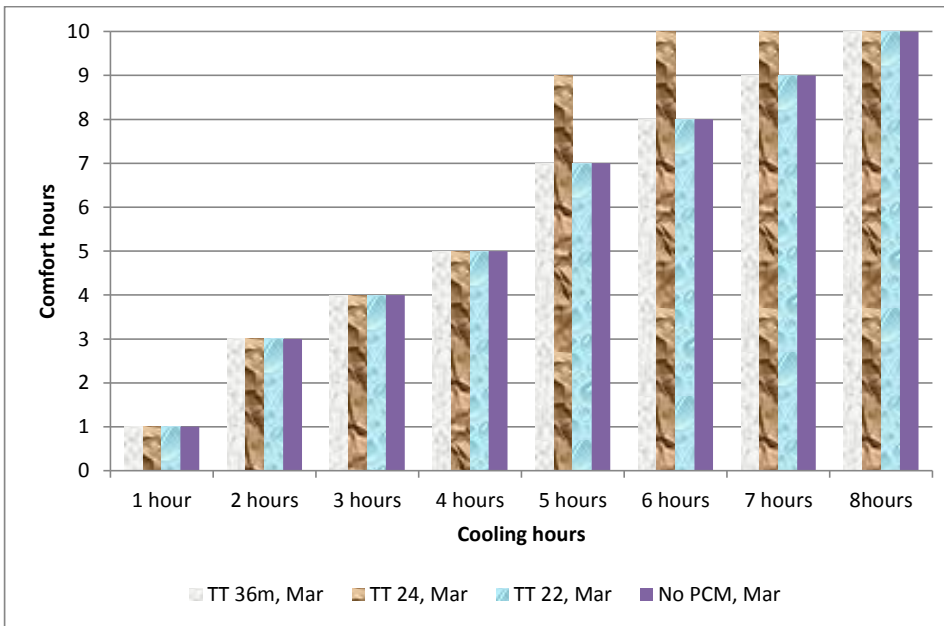


Figure 7-18 Relationship between mechanical cooling duration and comfort maintained during power outage

Furthermore, when work-hours are considered cooling the building for a maximum of 4 hours is optimum to achieve comfort for the rest of the working day. This indicates that the transition temperature should be at neutrality temperature in order to maintain comfort in the event of a power outage. This is to ensure that the PCM's transition temperature is high enough to be melted but low enough to reduce the highest peak of air temperature.

Comparing the evaluation of thermal comfort when using air against operative temperature shows a slight difference on the duration of comfort in a work-day as shown in Figure 7-19.

Whereas the optimum duration of cooling for air temperature as thermal comfort index is till 1pm, the optimum for operative temperature is cooling till 2pm.

Comment [A19]: addition

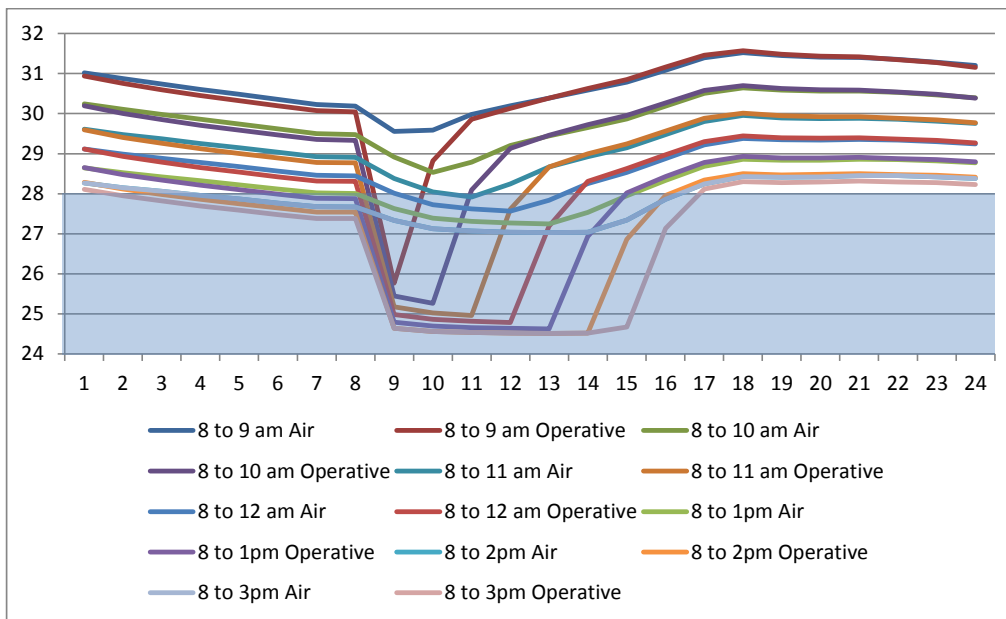


Figure 7-19 Power outage simulations for PCM: Air versus Operative temperature as index of thermal comfort

7.7.5 Cyclic cooling

Based on the results predicted in section 7.7.4, the operational strategy of cyclic cooling is examined. Cyclic cooling is the cooling of the interiors long enough to maintain comfort for a maximum duration within the working hours. The base-case of PCM with transition temperature 24°C and mechanical cooling of 5 hours is adopted. The thickness and conductivity of 10mm and 1.5W/m K and other variables in Table 7-14 are adopted. In section 7.7.4 it was established that the design-day August 4th could achieve comfort with natural ventilation. To examine rest of the time comfort is achieved with natural ventilation, an annual simulation of a naturally ventilated case is conducted.

Months	Average indoor air temperature (°C)	Mechanical cooling MC/ Natural ventilation NV
1	30.0	1
2	31.2	1
3	32.4	1
4	31.3	1
5	29.6	1
6	28.7	1
7	27.8	0
8	27.2	0
9	27.1	0
10	28.7	1
11	29.1	1
12	29.1	1

Table 7-27 Monthly comfort in naturally ventilated base-case (MC=1, NV=0)

Table 7-27 shows the result of monthly indoor air temperature over a year and only three months can maintain comfort. They are July, August and September; corresponding to the three coolest months in the year in Abuja.

Based on these results, the cyclic operational strategy ideally will have mechanical cooling switched on for all months except July, August and September.

The option of cooling in EnergyPlus chosen is ‘Ideal load air system’ which is set to turn on when the temperature goes above 24°C. The same option is maintained for the cyclic operational strategy. However, the cooling will only be turned on for four hours starting at 8am till 12 pm when it will be switched off. Thermal comfort is maintained for the rest of the day as predicted in Section 7.7.4.

Operational strategy	Mechanical cooling	Cyclic cooling with PCM	Cyclic cooling without PCM
Annual hours of discomfort (2340)	24	384	48
Hours of discomfort out of 2340 work-hours (%)	1	16	2
Annual electricity consumption (kWh)	193,000	179,096	162,009
Difference in electricity consumption (kWh)	0	13,904	30,991
Difference in electricity consumption (%)	0	7%	16%

Table 7-28 Cyclic cooling

Results show that the electricity consumption for the PCM with transition temperature 24°C is 179,096kWh, a reduction of 7% from full mechanical cooling during work-hours. The hours of discomfort predicted with this operational strategy are a manageable 16% as shown in Table 7-28.

The electricity consumption for the base-case without PCM is 162,009kWh, a reduction of 16% from full mechanical cooling during work-hours. This shows an improvement of 9% compared with the case with PCM; an indication that the heat stored in PCMs during the day is being released into the interior causing more discomfort. There is only a 2% of time experiencing discomfort with cyclic cooling without PCM, a 14% improvement from the case with PCM. Ultimately, comparing cyclic cooling with PCM and without PCM shows the case without PCM performs better.

The total reduction in electricity reduction per annum is 16%. This is a significant improvement compared to energy savings of 12.8% claimed by Diaconu and Cruceru (2010) who studied the influence of different parameters and system variables of a PCM impregnated wallboards in Algeria, a continental temperate climate.

7.7.5.1 *Design day analysis for Cyclic cooling using Operative temperature*

The results of the analysis on the hottest and coldest day when the building is cyclically cooled during the work day shows a small difference between air and surface temperatures of 2.6% and 4.5% for August and March respectively. The positive values indicate that surface temperatures are higher than air temperature for both design days as shown in Table 7-29. The maximum air and operative temperatures predicted are 24.9°C and 24.9°C in August while in March they are 30.9°C and 31°C respectively.

Comment [A20]: addition

Hr	MRT (°C) in August	MAT (°C) in August	MOT (°C) in August	Varia nce	MRT (°C) in March	MAT (°C) in March	MOT (°C) in March	Varia nce
1	25.0	24.8	24.9	0.0	31.1	30.9	31.0	0.0
2	25.0	24.8	24.9	0.0	31.0	30.7	30.9	0.0
3	25.0	24.7	24.8	0.0	30.9	30.6	30.7	0.0
4	24.9	24.7	24.8	0.0	30.7	30.4	30.6	0.0
5	24.9	24.7	24.8	0.0	30.6	30.3	30.4	0.0
6	24.9	24.6	24.7	0.0	30.5	30.1	30.3	0.0
7	24.8	24.6	24.7	0.0	30.3	30.0	30.2	0.0
8	24.9	24.7	24.8	0.0	30.3	30.0	30.1	0.0
9	24.8	21.9	23.4	0.1	29.6	22.0	25.8	0.3
10	24.8	22.0	23.4	0.1	29.2	22.0	25.6	0.2
11	24.8	22.0	23.4	0.1	29.0	22.0	25.5	0.2
12	24.8	22.0	23.4	0.1	28.8	22.0	25.4	0.2
13	24.9	24.2	24.5	0.0	29.1	27.7	28.4	0.0
14	25.0	24.9	24.9	0.0	29.6	29.6	29.6	0.0
15	24.9	24.8	24.9	0.0	29.8	30.0	29.9	0.0
16	24.9	24.8	24.9	0.0	30.2	30.3	30.3	0.0
17	24.9	24.9	24.9	0.0	30.5	30.6	30.6	0.0
18	24.9	24.8	24.8	0.0	30.6	30.7	30.7	0.0
19	24.8	24.7	24.8	0.0	30.6	30.7	30.6	0.0
20	24.8	24.7	24.7	0.0	30.6	30.6	30.6	0.0
21	24.8	24.6	24.7	0.0	30.6	30.6	30.6	0.0
22	24.8	24.6	24.7	0.0	30.5	30.6	30.5	0.0
23	24.7	24.5	24.6	0.0	30.5	30.5	30.5	0.0
24	24.7	24.5	24.6	0.0	30.4	30.4	30.4	0.0

Table 7-29 Cyclic cooling: Design day analysis for coldest and hottest days using operative air temperature (MRT-Mean Radiant Temperature, MAT- Mean Air Temperature and MOT- Mean Operative Temperature). Bold font denotes uncomfortable temperatures

The minimum air and operative temperatures predicted are 21.9°C and 23.4°C in August while in March they are 22°C and 25.4°C respectively. The results show that 88% of the time, operative temperatures predicted for the hottest day, in March fall outside the comfort bands

calculated from Neutrality temperature (24°C -28°C). However as discussed in Section 7.7.3, the discomfort hours amount to 16% per annum.

7.8 Retrofit flexibility of PCMs in office buildings in Abuja

Building use changes over time. Due to the possibility of retrofit, the performance of PCM with lightweight partitions within the heavyweight type of external walls common in Nigeria is studied. Lightweight partition to total surface area ratio is 1:4 while wall to surface area is 2:5. The partitions are made of two gypsum board layers with an air layer in the middle as shown in Figure 7-20 and Table 7-30.

Comment [A21]: addition

Building material	Thickness {m}	Conductivity {W/m K}	Density {kg/m3}	Specific Heat {J/kg-K}
Gypsum board	0.025	0.25	900	1000
Air	0.01	0.3	1000	1000
PCM	0.01	0.5	800	2000

Table 7-30 Lightweight construction for partitions

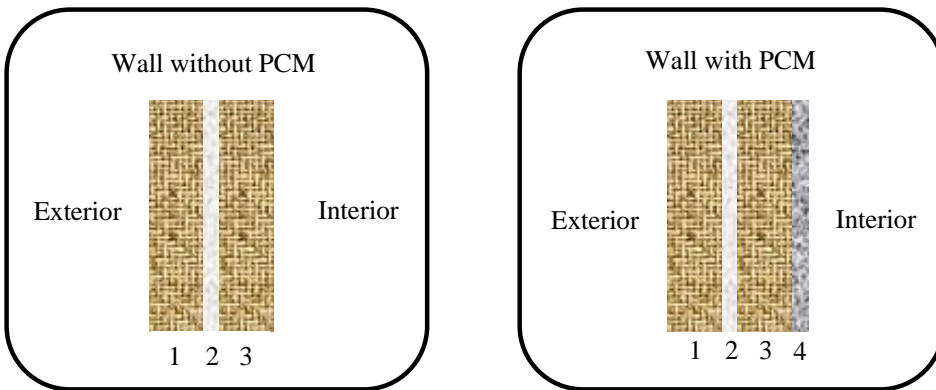


Figure 7-20 Lightweight construction for partitions

Nine results are predicted for simulations studying the following variables:

- Cooling strategy
- Construction of partitions
- Presence of PCMs

The results are compared with the results from the original heavyweight-type of construction described in Table 7-31. The U-value of the original wall without PCM is $1.4\text{W/m}^2\text{K}$ while that of the lightweight partition is $3.5\text{W/m}^2\text{K}$.

	Layer	Thickness
A	PCM Layer	10mm
B	Internal render	25mm
C	Sandcrete block layer	225mm
D	External render	25mm

Table 7-31 PCM wall system

The results are shown in Table 7-32 and Figure 7-21. They show that Simulation 1 predicts an electricity consumption of 193,000kWh and annual discomfort hours of 0. Simulation 2 predicts an electricity consumption of 118,523 kWh and annual discomfort hours of 197, 8% of 2340 annual working hours. Simulation 3 predicts an electricity consumption of 162, 009 kWh and annual discomfort hours of 48, 2% of annual working hours. Simulation 4 predicts an electricity consumption of 78,826kWh and annual discomfort hours of 600, 26% of annual working hours. Simulation 5 predicts an electricity consumption of 181,277kWh and annual discomfort hours of 12, 1% of annual working hours. Simulation 6 predicts an electricity consumption of 116,281kWh and annual discomfort hours of 219, 9% of annual working hours. Simulation 7 predicts an electricity consumption of 179,096 kWh and annual discomfort hours of 384, 16% of annual working hours. Simulation 8 predicts an electricity consumption of 86,612kWh and annual discomfort hours of 549, 23% of annual working hours. Simulation 9 predicts an electricity consumption of 83,396kWh and annual discomfort hours of 370, 16% of annual working hours.

The highest electricity consumption corresponds to Simulation 1, the full mechanical cooling of the heavyweight partitioned building with no PCM. The lowest electricity consumption on the other hand, corresponds with Simulation 4, the cyclic cooling of the lightweight partitioned building also with no PCM. However, Simulation 4 also achieved the highest thermal discomfort in all 9 simulations at 26% of working hours.

7-PCM performance in office buildings

	No PCM				PCM				
	Mechanical cooling		Cyclic cooling		Mechanical cooling		Cyclic cooling		Cyclic cooling Lightweight- PCM only on partitions
	Heavyweight	Lightweight	Heavyweight	Lightweight	Heavyweight	Lightweight	Heavyweight	Lightweight	
Yearly hours of discomfort (2340)	0	197	48	600	12	219	384	549	370
Discomfort per annum%	0%	8%	2%	26%	1%	9%	16%	23%	16%
Electricity consumption per annum (kWh)	193,000	118,523	162,009	78,826	181,277	116,281	179,096	86,612	83,396
Difference in consumption from base-case	0	74,477	30,991	114,174	11,723	76,719	13,904	106,388	109,604
Difference in consumption from base-case %	0%	39%	16%	59%	6%	40%	7%	55%	57%
Simulations	1	2	3	4	5	6	7	8	9

Table 7-32 PCM with lightweight construction

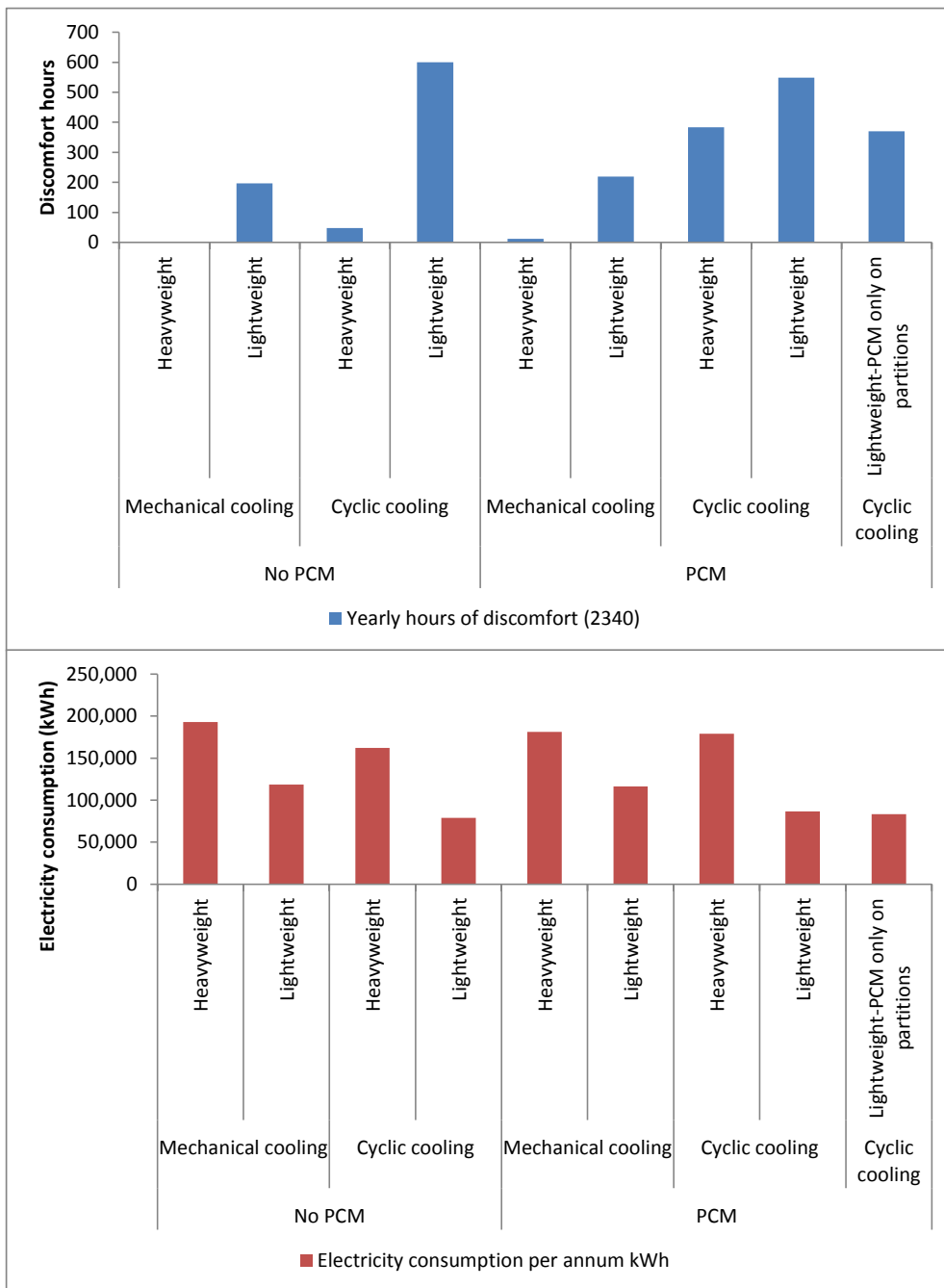


Figure 7-21 Comparing PCM performance between lightweight and heavyweight partitioning

As is expected cyclic cooling outperforms full mechanical cooling because the duration of cooling is reduced in cyclic cooling. Lightweight partitioning also outperforms heavyweight in the simulations, saving almost a 2-fold improvement in cyclic cooled building. This is due to the larger capacity of the heavyweight building to store heat during the day. Night time temperatures are too high to effectively cool down the building, causing an increase in the cooling required to keep the building occupants warm in the mornings.

However, the results also indicate that when the building is fully cooled mechanically, the presence of PCMs conserves electricity but when the building is cyclically cooled, the reverse is the case. This is because the PCMs absorb more heat when the building is cyclically cooled than when fully cooled. Therefore the cooling required in the mornings in cyclically cooled case is relatively higher than that required when the building is fully cooled. It is worthy to note that the amount of conservation might be higher in the full cooling strategy but in total, the electricity consumed in cyclic cooling is still less than that in full cooling strategy. Cyclic cooling also caused a reduction in thermal comfort when compared with full cooling.

Based on the comparisons, the simulation that performed best considering thermal comfort and electricity conservation is Simulation 9. This is the cyclic cooling of lightweight partitioned building with PCM only on the partitions and not on the heavyweight external walls. Even though the electricity consumption of the building with no PCM on lightweight partitions use less electricity, the thermal comfort achieved is improved by 10%.

This is an indication that lightweight construction in this climate may be better suited with PCM technology. This is because the added thermal mass in heavyweight construction traps unwanted heat within the building which night temperatures are too high to dissipate.

7.8.1.1 *Design day analysis using Operative temperature*

Comment [A22]: addition

The results of the analysis on the hottest and coldest day when the base case that has PCM in all walls-both lightweight partitions and heavyweight shell- and is cyclically cooled during the day shows a small difference between air and surface temperatures of 2.5% and 4.4% for August and March respectively. The positive values indicate that surface temperatures are higher than air temperature for both design days as shown in Table 7-33.

The maximum air and operative temperatures predicted are 24.8°C and 24.9°C in August while in March they are 31°C and 31.1°C respectively. The minimum air and operative temperatures predicted are 21.9°C and 23.4°C in August while in March they are 22°C and 25.3°C respectively.

The results show that 88% of the time, operative temperatures predicted for the hottest day, in March fall outside the comfort bands calculated from Neutrality temperature (24°C -28°C). For the base-case that has PCM only in the lightweight partitions and is cyclically cooled during the day, there is a small difference between air and surface temperatures of 5.7% and 7.8% for August and March respectively as shown in Table 7-34.

H	MRT (°C) in August	MAT (°C) in August	MOT (°C) in August	Varianc e	MRT (°C) in March	MAT (°C) in March	MOT (°C) in March	Varianc e
1	25.0	24.8	24.9	0.0	31.3	31.0	31.1	0.0
2	24.9	24.7	24.8	0.0	31.1	30.8	31.0	0.0
3	24.9	24.7	24.8	0.0	31.0	30.7	30.8	0.0
4	24.9	24.6	24.7	0.0	30.8	30.5	30.6	0.0
5	24.8	24.6	24.7	0.0	30.7	30.3	30.5	0.0
6	24.8	24.6	24.7	0.0	30.5	30.2	30.4	0.0
7	24.8	24.5	24.7	0.0	30.4	30.0	30.2	0.0
8	24.8	24.6	24.7	0.0	30.3	30.0	30.2	0.0
9	24.8	21.9	23.4	0.1	29.6	22.0	25.8	0.3
10	24.8	22.0	23.4	0.1	29.0	22.0	25.5	0.2
11	24.8	22.0	23.4	0.1	28.8	22.0	25.4	0.2
12	24.8	22.0	23.4	0.1	28.6	22.0	25.3	0.2
13	24.9	24.1	24.5	0.0	28.9	27.5	28.2	0.0
14	24.9	24.8	24.9	0.0	29.4	29.4	29.4	0.0
15	24.8	24.8	24.8	0.0	29.8	29.9	29.8	0.0
16	24.9	24.8	24.8	0.0	30.2	30.3	30.2	0.0
17	24.9	24.8	24.8	0.0	30.5	30.7	30.6	0.0
18	24.8	24.7	24.8	0.0	30.7	30.8	30.8	0.0
19	24.8	24.6	24.7	0.0	30.7	30.7	30.7	0.0
20	24.8	24.6	24.7	0.0	30.7	30.7	30.7	0.0
21	24.7	24.6	24.7	0.0	30.6	30.7	30.7	0.0
22	24.7	24.5	24.6	0.0	30.6	30.6	30.6	0.0
23	24.7	24.5	24.6	0.0	30.5	30.6	30.6	0.0
24	24.7	24.5	24.6	0.0	30.5	30.5	30.5	0.0

Table 7-33 Cyclic cooling with PCM in all walls: Design day analysis for coldest and hottest days using operative air temperature (MRT-Mean Radiant Temperature, MAT- Mean Air Temperature and MOT- Mean Operative Temperature). Bold font denotes uncomfortable temperatures

Hr	MRT (°C) in August	MAT (°C) in August	MOT (°C) in August	Variance	MRT (°C) in March	MAT (°C) in March	MOT (°C) in March	Variance
1	26.8	26.6	26.7	0.0	29.1	29.0	29.1	0.0
2	26.7	26.5	26.6	0.0	29.0	28.9	28.9	0.0
3	26.6	26.4	26.5	0.0	28.9	28.7	28.8	0.0
4	26.5	26.4	26.4	0.0	28.8	28.5	28.6	0.0
5	26.5	26.3	26.4	0.0	28.6	28.4	28.5	0.0
6	26.4	26.2	26.3	0.0	28.5	28.2	28.4	0.0
7	26.3	26.1	26.2	0.0	28.4	28.1	28.3	0.0
8	26.3	26.1	26.2	0.0	28.4	28.1	28.3	0.0
9	26.0	21.9	24.0	0.2	27.9	22.0	24.9	0.2
10	25.8	22.0	23.9	0.1	27.6	22.0	24.8	0.2
11	25.7	22.0	23.8	0.1	27.4	22.0	24.7	0.2
12	25.6	22.0	23.8	0.1	27.4	22.0	24.7	0.2
13	25.6	22.0	23.8	0.1	27.3	22.0	24.7	0.2
14	25.5	22.0	23.8	0.1	27.3	22.0	24.7	0.2
15	25.5	22.0	23.8	0.1	27.3	22.0	24.7	0.2
16	25.5	22.0	23.7	0.1	27.4	22.0	24.7	0.2
17	25.4	22.0	23.7	0.1	27.5	22.0	24.8	0.2
18	25.4	24.6	25.0	0.0	27.8	26.8	27.3	0.0
19	25.5	25.5	25.5	0.0	28.1	28.2	28.2	0.0
20	25.6	25.5	25.6	0.0	28.2	28.3	28.3	0.0
21	25.6	25.6	25.6	0.0	28.3	28.4	28.3	0.0
22	25.6	25.6	25.6	0.0	28.3	28.4	28.3	0.0
23	25.6	25.5	25.5	0.0	28.3	28.4	28.3	0.0
24	25.5	25.4	25.4	0.0	28.2	28.3	28.3	0.0

Table 7-34 Cyclic cooling with PCM only in lightweight partitions: Design day analysis for coldest and hottest days using operative air temperature (MRT-Mean Radiant Temperature, MAT- Mean Air Temperature and MOT- Mean Operative Temperature) . Bold font denotes uncomfortable temperatures

The maximum air and operative temperatures predicted are 26.6°C and 26.7°C in August while in March they are 29°C and 29.1°C respectively. The minimum air and operative temperatures predicted are 21.9°C and 23.7°C in August while in March they are 22°C and 24.7°C respectively.

The results show that 79% of the time, operative temperatures predicted for the hottest day, in March fall outside the comfort bands calculated from Neutrality temperature (24°C -28°C). This reduction in hours of discomfort hours from 85% to 79% in the hottest day leads to a significant annual reductuon of discomfort from 23% to 16%.

7.9 Thermal indices for evaluating PCM performance: Air and Operative temperature

Comment [A23]: addition

The analysis discussed in this section shows the importance of using a suitable thermal index when evaluating PCM performance in terms of thermal comfort.

The comparison between the results of comfort evaluations using air and operative temperature for PCM performance shows some interesting results. The results, in Table 7-35, Figure 7-22 and Figure 7-23 show that there is a difference between thermal comfort when evaluated using air and operative temperature. This is due to a difference in surface temperatures which affect radiant heat transfer, and is not considered if air temperature alone is the indicator of thermal comfort.

A variance between surface and air temperatures is calculated for each of the cooling strategies and the results are shown in Figure 7-24. The variance is given as the percentage difference between surface and air temperatures. A positive variance indicates that surface temperature is higher than air temperature and vice versa.

In majority of the cooling strategies the variance is positive except when Night purge is employed. There is a negative variance for the cases where Night purge in addition to day time natural ventilation as well as in addition to mechanical cooling is employed. However, in March, the variance becomes positive for the mechanically cooled base case. This is due to the cool air mechanically supplied by the cooling system as soon as air temperature is 24°C. The negative variance in Night purge is caused by the active heating and melting regime in the PCM in natural ventilation mode during the night. The negative difference is reduced by mechanical cooling due to the cool air supplied by the mechanical system. As the mechanical cooling only comes on when indoor temperature reaches 24°C, so in August there is a little negative difference caused by the higher indoor temperatures due to a lack of mechanical cooling. In March when the mechanical cooling is on most of the time, the variance is positive due to the cool air supplied by the cooling system.

7-PCM performance in office buildings

Cooling strategies	August					March						
	Max air temperature (°C)	Max operative temperature (°C)	Min air temperature (°C)	Min operative temperature (°C)	Variance (%)	Max Variance (°C)	Max air temperature (°C)	Max operative temperature (°C)	Min air temperature (°C)	Min operative temperature (°C)	Variance (%)	Max Variance (°C)
Daytime NV	26.46	26.46	25.6	25.68	0.4	0	30.76	30.71	28.9	29.05	0.5	-0.4
Daytime NV and NP	34.30	33.4	33.2	32.5	-5.1	-0.9	41.5	40.5	37.4	38	-1.1	4.2
Daytime MC	24.7	24.8	23.2	22.0	4.5	0.1	29.3	29.4	25.0	22.0	8.5	-4.4
Daytime MC and NP	07:12:00	28.1	21.9	23.7	-0.6	-1.2	34.2	33.2	22	25.6	5.3	-0.6
CC with PCM in existing walls	24.9	24.9	21.9	23.4	2.6	0	30.9	31	22	25.4	4.5	-2.6
CC with PCM in all walls	14:24:00	24.9	21.9	23.4	2.5	0.3	31	31.1	22	25.3	4.4	-2.2
CC with PCM in partitions only	14:24:00	26.7	21.9	23.7	5.7	0.1	29	29.1	22	24.7	7.8	-5.6

Table 7-35 Air temperature versus operative air temperature; NV=Natural Ventilation, NP=Night Purge, MC= Mechanical cooling, CC=Cyclic Cooling, HW=Heavyweight, LW=Lightweight

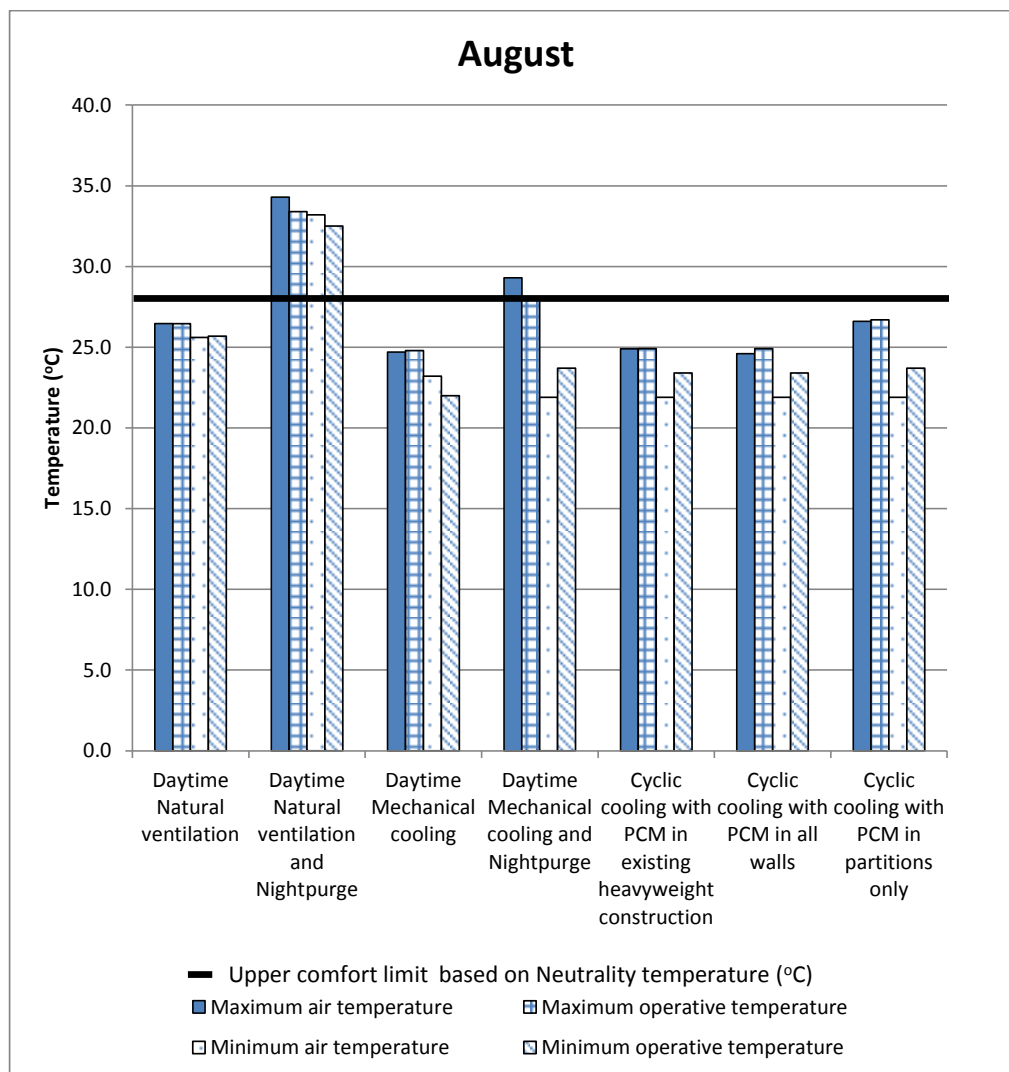


Figure 7-22 Air temperature versus operative air temperature: Maximum and minimum in August

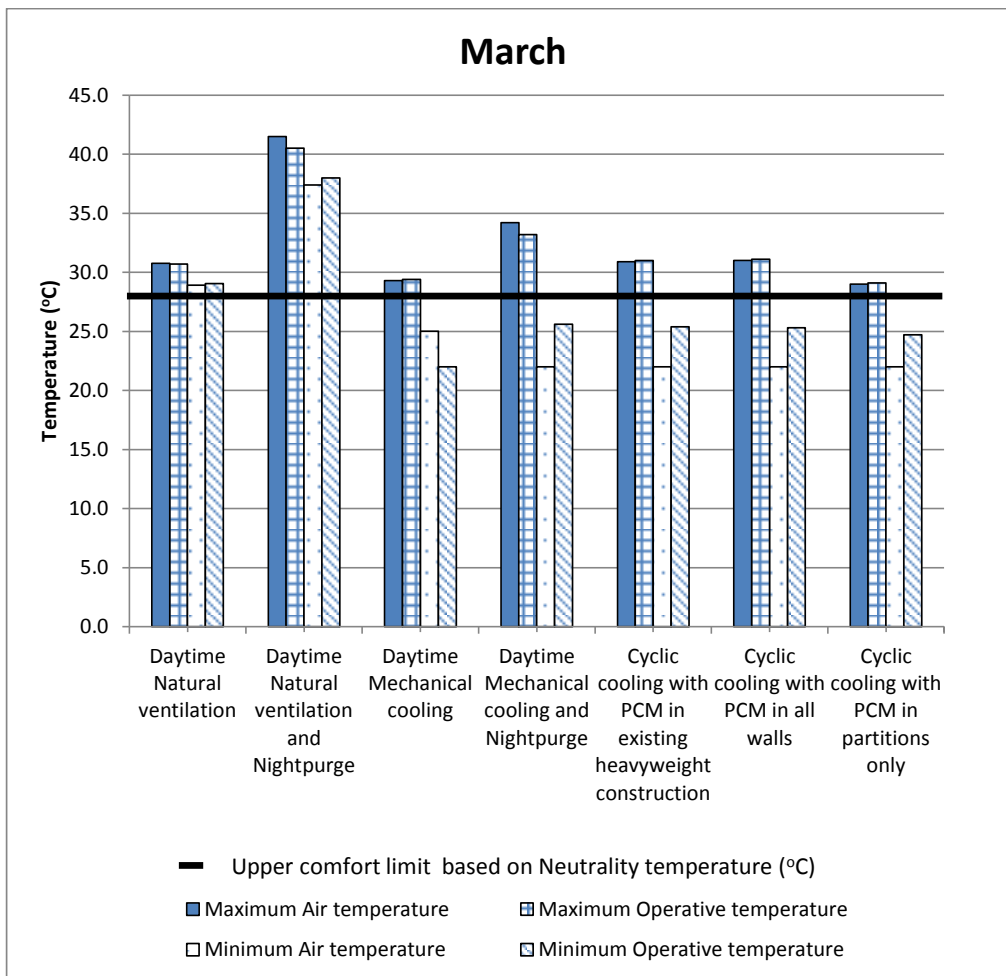


Figure 7-23 Air temperature versus operative air temperature: Maximum and minimum in March

In August, the highest variance is predicted for cyclic cooling and in March for mechanical cooling strategies. The lowest for both months are for the naturally ventilated basecase. This indicates the bigger need to consider surface temperatures for air-conditioned spaces. Generally the variance in March is more evident than in August. The maximum difference between air and operative temperature is 1.2°C.

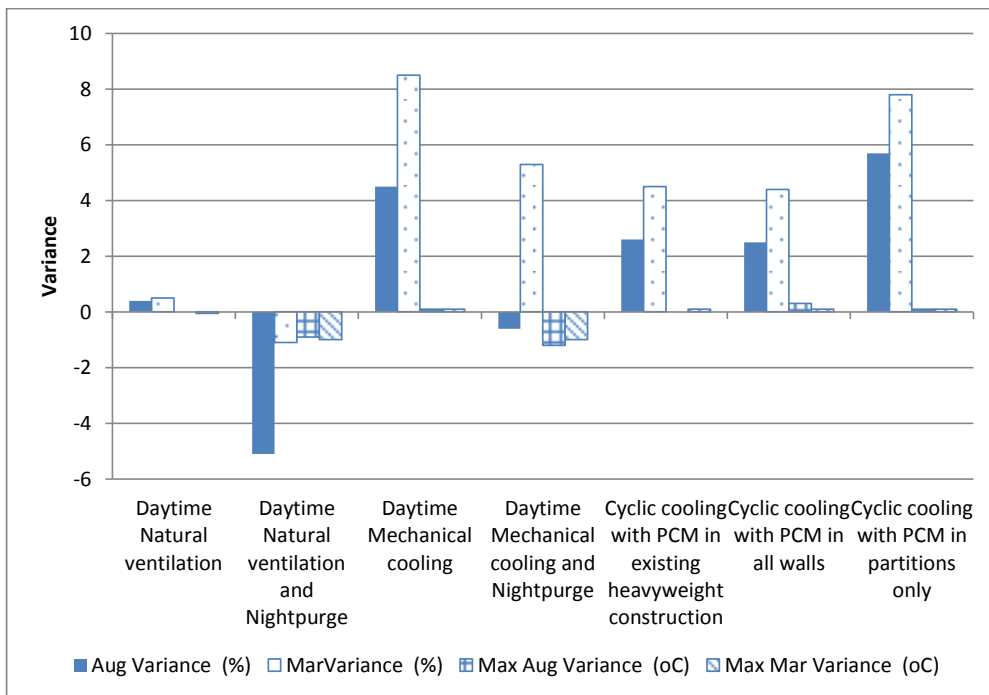


Figure 7-24 Air temperature versus operative air temperature: Variance

Cooling strategy	Discomfort hours		Variation
	Air temperature	Operative temperature	
Daytime natural ventilation	2,340 (100%)	2,340 (100%)	0
Natural ventilation + Nightpurge	2,340 (100%)	2,340 (100%)	0
Daytime mechanical cooling	12 (0.5%)	49 (2%)	1.6%
Daytime mechanical cooling + Nightpurge	410 (17.5%)	443 (18.9%)	1.4%
Cyclic cooling	563 (24%)	586 (25%)	1%

Table 7-36 Difference in annual discomfort hours between air and operative hours

The Table 7-36 shows the annual hours of discomfort predicted for comfort analyses using air and operative temperatures. For the base-case naturally ventilated in the daytime only, the temperatures are uncomfortable during all work-hours (100%). This is the same for the base-

case naturally ventilated during the day and night. When the base-case is mechanically cooled, thermal discomfort evaluated using air temperature as thermal index is 12hours (0.5% of work-hours). On the other hand, using operative temperature increases discomfort to 49 hours (2% of work-hours), a 1.6% increase in discomfort. A similar increase of 1.4% is predicted for the case of daytime mechanical cooling and nightpurge; from 410 to 443 hours of discomfort. The case of cyclic cooling shows a 1% increase from 563 to 586 hours of discomfort annually. This translates to an increase in discomfort from 24% to 25% of work-hours.

7.10 Conclusion

A novel cooling strategy is developed called cyclic cooling. Cyclic cooling is the cooling of the interiors long enough to maintain comfort for a maximum duration within the working hours.

Cyclic cooling is evaluated with PCM with transition temperature 36°C, 24°C and 22°C; and without PCM. Results show that PCM with transition temperature 24°C and mechanical cooling of 5 hours from 8am-2pm is adopted. This leads to a saving of 13,904kWh of overall electricity per annum.

However, results also show that the case without PCM saves more electricity with a reduction of 16% when compared with the case with PCM which saves 7% per annum, a savings of 30,991kWh.

The effect of type of construction of partitions on PCM performance is also studied and results indicate that lightweight construction in this climate may be better suited with PCM technology. Results show almost a 2-fold improvement in consumption in the lightweight partitioned building cooled cyclically, compared to the heavyweight partitioned building. This is because the added thermal mass in heavyweight construction traps unwanted heat within the building.

It should be noted that these results are applicable only for the test case presented in this research. The internal partitioning and spatial planning of the base case are determined by a combination of variables so future research is required to evaluate the generalizability of these results to similar buildings. Lightweight partition to total surface area ratio is 1:4 while wall to total surface area is 2:5.

The results also show the need to consider suitable thermal indices when evaluating comfort. A comparison of operative and air temperature as thermal comfort indicator shows that operative temperatures are generally higher than air temperatures and the difference is greater

Comment [A24]: addition

when the building is mechanically cooled. This indicates the need to consider surface temperatures when evaluating comfort.

A look into the transition temperature showed that the temperature that reduced the most electricity consumption and improved thermal comfort in a fully mechanically cooled base-case is 36°C within a range between 21°C and 36°C. The range falls within the lower and higher average room air temperatures experienced in the naturally ventilated base-case.

It should be noted that 36°C is proposed only for the fully mechanically cooled base case. An analysis of using air and operative air temperature as indicator of thermal comfort shows a slight annual difference of 1.5% between the two. This is because 36°C is out of the comfort range. For transition temperature within the comfort range, there is no difference in results between the 2 indicators.

The optimum thickness for the PCM system was shown to be 10mm when compared with 50mm and 100mm. Below 10mm, PCM layers lack enough heat capacity to store a significant amount energy. Above a certain amount, the PCM performance drops relative to its conductivity as the phase transition is slow. Hence parts of the PCM remain in an unwanted state.

The optimum conductivity is 1.5 W/m K. The trend showed the higher the conductivity the better the thermal performance, however the change is small and the phase change is adequate at 0.5 W/m K.

A PCM model is optimized for thermal comfort and energy conservation for use in warm climates therefore has transition temperature of 24°C, 0.5W/m K conductivity, and a thickness of 10mm. This model has the potential to reduce annual electricity consumption by 6.1% (193,000kWh to 181,277kWh). Figure 7-25 and Table 7-37 show the simulations and results.

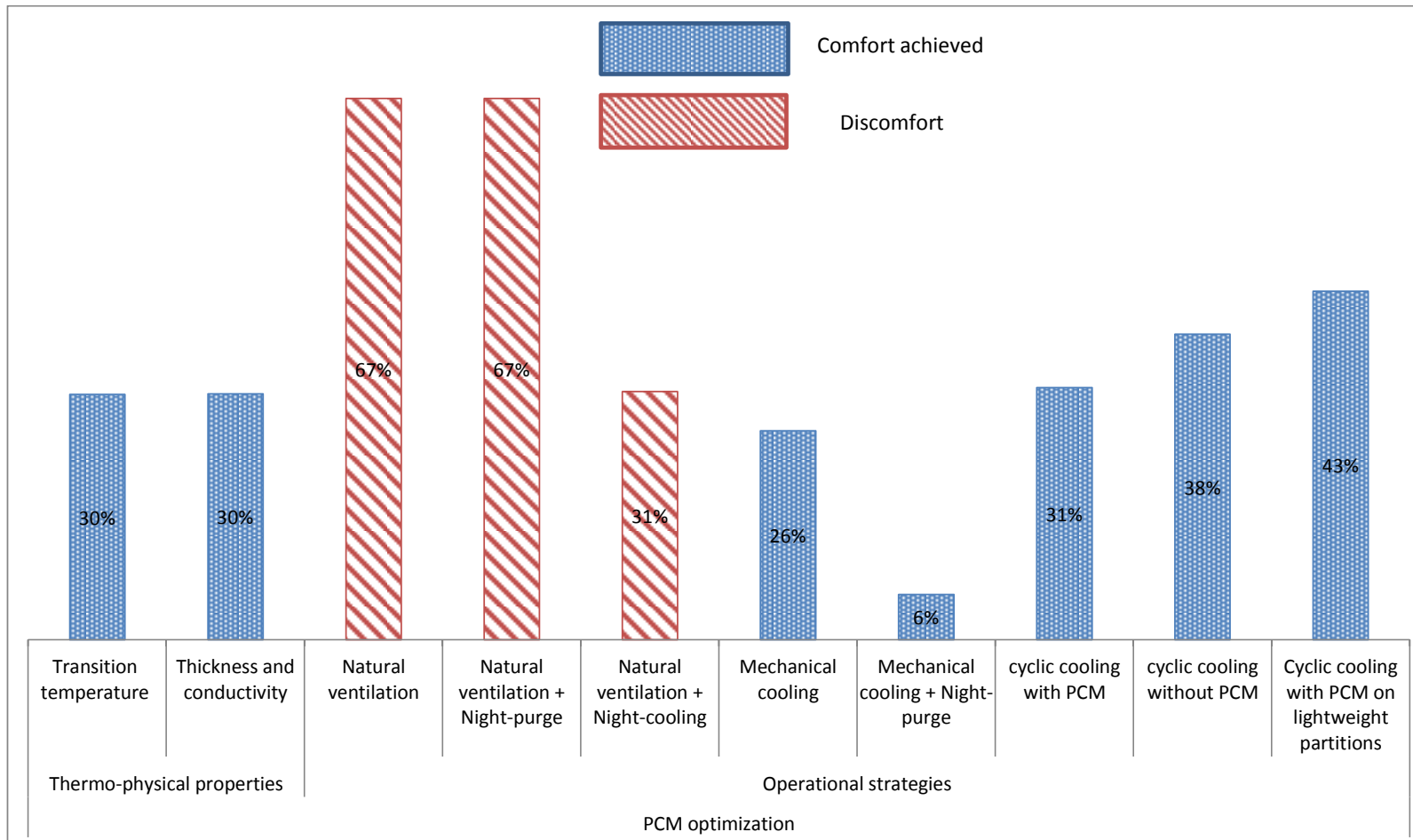


Figure 7-25 Electricity conservation

Operational strategies	Day-time natural ventilation	Day-time natural ventilation and night-purge	Day-time mechanical cooling and night-purge	Day-time mechanical cooling			Cyclic cooling			
				No PCM	Transition temperature (°C) for conductivity and thickness 1.5W/m K and 10mm	24°C, 1.5 W/m K and 10mm	No PCM	Optimized thermo-physical properties	PCM on lightweight partitions only	
Thermo-physical properties	Across all thermo-physical properties	Across all thermo-physical properties	Across all thermo-physical properties	No PCM	22	31	36	24°C, 1.5 W/m K and 10mm	24°C, 1.5W/m K and 10mm	PCM on lightweight partitions only
Electricity consumption (kWh)	86,390	86,390	245,509	193,000	191,577	184,454	181,277	179,096	162,009	83,396
Thermal discomfort during working hours (%)	100	100	17.5	0	0.9	1	0.5	16	2	16

Table 7-37 Simulation breakdown

The following analyses examine the monthly electricity consumption and thermal performance between the following operational strategies:

1. Natural ventilation
2. Natural ventilation and night purge
3. Day-time mechanical
4. Day-time mechanical cooling and night-purge
5. Set-back cooling
6. Cyclic cooling

The optimum strategy is the cyclic mechanical cooling of the interior, reducing up to 38% of electricity consumption while maintaining thermal comfort. Day-time mechanical cooling with PCM predicted adequate thermal comfort and reduced the amount of electricity consumed by 6.1%. Day-time mechanical cooling and night-purge brings in hot air, thereby increasing electricity consumption by 184% and causing discomfort 17.5% of working hours. Natural ventilation during the day and at night brings in hot air, causing discomfort 100% of work-hours. Natural ventilation and night-time cooling of PCM with mechanical means only failed due to the amount of uncomfortable hours experienced. Discomfort is experienced for up to 100% of working hours.

The effect of orientation on PCM performance was analysed. The rooms in the east direction thermally perform worst, followed by west, the south and finally north as initially reported. The discomfort trend agrees with that of orientation optimization conducted in Chapter 5; the best orientation should place the principal axis along the north-south axis.

The weeks experiencing maximum and minimum temperatures are used to test the effect of PCM on maintaining thermal comfort in the event of a power outage during working hours. Adequate mechanical cooling is supplied from the start of a working day in the hottest season, March from 8:00am till 12:00pm when it is switched off to simulate a power outage. 12:00 pm is chosen because the sun is at its peak around mid-day in Abuja. Results show that PCM with transition temperature 24°C performs better compared with PCM with transition temperature 36°C and 22°C.

8 CHAPTER 8

CONCLUSION

Contents

8.1 Overview

8.2 Contributions to knowledge

8.3 Recommendations and future work

Problem	Chapter one: Introduction- 'Nigerian buildings and Energy use'		
Theoretical framework	Chapter two: Literature review- 'Phase change materials as energy conservation mechanisms in buildings'		
Methodology	Chapter three: 'Methodology'	Chapter four : 'Validation study'	
Results	Chapter five: 'Disaggregating primary electricity consumption for office buildings in Nigeria'	Chapter six: 'Optimizing thermal and energy performance of buildings'	Chapter seven: 'PCM performance in office buildings'
Conclusion	Chapter eight: Conclusion		

8.1 Overview

The basis of this study originates from a personal experience of the electricity shortage facing the Nigerian public. In response, energy conservation and efficiency practices and technologies are required to ensure rationalized consumption of energy in the country (Sambo, 2008).

In the first chapter, Nigerian energy generation, distribution and consumption are discussed and the problems are highlighted. Energy consumption in office buildings is one of the highest compared to the consumption of other building types.

The aim of this investigation is to evaluate the potential of incorporating Phase Change Materials (PCM) in buildings in hot climates in order to conserve energy while maintaining thermal comfort. PCMs are examined as energy conservation mechanisms in the context of office buildings in Abuja. PCMs are materials that have the capacity to store and release heat in buildings. Energy storage allows storing of excess energy that would otherwise be wasted and it also allows bridging the gap between energy demand and supply.

The following objectives are achieved in the course of the study:

1. Establishing the gaps in PCM literature for the scope of office buildings in Nigeria
2. A method for collecting complex electricity consumption data in places suffering from power outages is presented
3. Electricity consumption in Nigerian office buildings is aggregated in order to examine the significance of saving electricity in the cooling load through the use of PCMs
4. The potential for energy savings within the cooling load is investigated
5. A computer simulation method of calculating the potential for energy savings with PCM is presented
6. A model for a passively optimized PCM for office buildings in warm climates is optimized
7. The potential effect of PCM enhanced building fabric on thermal comfort and energy consumption is examined
8. Using a suitable thermal index for evaluating thermal comfort

8.1.1 Phase Change Materials (PCM) gap in knowledge

The knowledge gaps within literature for PCM used for energy conservation and thermal comfort are explored in Chapter 2. A literature search shows gaps exist in the properties and

applications of the PCM suitable for office buildings in composite hot and humid and hot and dry climates.

PCMs are able to store and release a combination of sensible and latent heat energy. Sensible heat storage occurs with change in temperature, while latent heat storage is based on the heat absorbed or released when a storage material undergoes a phase change. The phase change that accompanies latent heat storage can be in the following forms: solid–solid, solid–liquid, solid–gas, and liquid–gas and vice versa. Solid–liquid transitions have proved to be the most economically attractive for use in thermal energy storage systems (Sharma *et al.*, 2009).

Solid-liquid PCM are classified as organic, inorganic and a combination of compounds known as eutectic compounds (Farid *et al.*, 2004). Research by Ahmet, (2005) and Diaconu and Cruceru, (2010) show combinations are possible to achieve a PCM of certain thermo-physical and chemical properties. On this basis and due to the hypothetical nature of this study, the chemical content of PCM suitable for the context is ignored in this research. Of import are the thermo-physical properties and cooling strategies suitable for maintaining thermal comfort in building applications.

Historically, PCM have been incorporated into buildings by immersing porous materials such as wallboards into liquid PCM. This method suffered from leakage and fire hazards. Other methods include direct incorporation; macro and micro- encapsulation; and most recently as shape stabilized PCM components (SSPCM). However similar to the chemical classifications of PCM, the hypothetical nature of this research allows for the type of incorporation to also be ignored. Once optimized, the thermo-physical properties of PCM are input in computer models rendering the containment method of little significance.

The PCM variables of significance on the other hand are a large surface area, high thermal conductivity, and most importantly a transition temperature lying in the practical range of operation (Farid *et al.* (2004).

It has been shown that a narrow transition temperature of 1 °C is best to reduce the indoor temperature swing and improve the thermal comfort (Zhou *et al.*, 2007; Pasupathy *et al.*, 2008b). A wider phase transition zone provides poorer thermal performance due to the less energy storage. On this basis, rather than a range of transition temperatures for the proposed PCM, a single transition temperature is adopted.

If the transition temperature is too high, the quantity of heat stored by the PCM is reduced and if it is too low, it's difficult to maintain the indoor air temperature under a comfortable level (Zhang *et al.*, 2006). The literature reviewed shows a gap exists in the suitable PCM

transition temperature for the composite climate of Abuja compelling the examination of this thermo-physical property.

Studies (Xu *et al.*, 2005; Zhou *et al.*, 2008) found the conductivity of SSPCM to be adequate at 0.5 W/m K, above which the conductivity of the PCM does not affect the PCM system's thermal performance. This claim and the effect of thickness of the PCM is examined during the course of the study. A large surface area is reported to increase the melt/solidification rate of PCM panels (Zhou *et al.*, 2008; Xiao *et al.*, 2009; Isa *et al.*, 2010).

In warm climates where night time temperatures are not low enough to charge the PCM, an active night time cooling process is required to prevent hysteresis (Voelker *et al.*, 2008; Isa *et al.*, 2010; Susman *et al.*, 2010).

All the above variables affect the performance of PCM in buildings. Diaconu and Cruceru (2010) predict a total energy conservation of reduction of 12.8% and reduction of the total cooling load of 1% by simulating the performance of a PCM wallboard in Algeria- a continental temperate climate. In Castell *et al.*, (2010b), total energy consumption was reduced by 15% in an experimental cubicle made of micro-encapsulated PCM enhanced brick in the Mediterranean. Also in the Mediterranean, maximum and minimum temperatures were reduced by 1°C and 2°C respectively by the passive use of PCM in concrete (Cabeza *et al.*, 2007). A reduction of about 3°C has been recorded with the use of PCM in an active system by Voelker *et al.* (2008).

In conclusion, the transition temperature, conductivity and thickness are optimised for saving energy while maintaining thermal comfort in Nigerian office buildings.

8.1.2 A method for collecting complex electricity consumption data in places suffering power shortages

A quantitative research strategy using energy audit style of cross-sectional data collection is used. Selective sampling was adopted due to availability of data, access into the building, building type, time and financial constraints. Abuja the capital city of Nigeria is chosen as the location and climate for generating a base-case. Abuja is a composite climate of hot and dry, and hot and humid climates.

The energy audit utilised the following data collection instruments:

- Self-administered questionnaires
- Unstructured non-participant observation and

- Literature review of national statistics, building regulations, and climatic data

A novel contribution is made for collecting electricity data for the contextual case existing in Nigeria; where there is an erratic power supply and back-up power generators are employed for a significant duration. During the energy audit process, the hours of electricity supplied by the utility and by other alternative sources is required and a method of estimation is developed. The technique involves calculating the difference in total working hours from hours of back-up power recorded. This is duration of electricity supplied by the utility, Q_u . The method of estimation that accounts for consumption covered for both utility and back-up power supply is Equation 8-1 is:

$$Q_g = (Q_u \times G)/U \quad \text{Equation 8-1}$$

Where U and G are percentage of time that utility and back-up generators are in use respectively. All Q are in (kWh).

8.1.3 Aggregated electricity consumption in Nigerian office buildings

A literature search for information on electricity consumption in Nigerian office buildings showed a paucity of data leading to a field data collection exercise. From the data collected, total electricity consumption is disaggregated into cooling, lighting and appliance end-uses consuming 40%, 12% and 48% respectively.

8.1.4 Opportunity for energy conservation

The analyses provide two indicators of an opportunity for energy conservation in the buildings audited. They are:

1. A large cooling load aggregate
2. Poor alignment between electricity consumption and climate

8.1.4.1 A large cooling load aggregate

Total electricity consumption is disaggregated into cooling, lighting and appliance end-uses consuming 40%, 12% and 48% respectively. The substantial contribution by cooling is an indication that targeting this end-use will provide significant energy savings.

8.1.4.2 *Poor alignment between electricity consumption and climate*

Degree day calculations are beneficial for early stage building energy calculations (CIBSE, 2004). They are used to examine opportunities for energy conservation in the audited office buildings.

The recorded monthly electricity consumption data from five buildings in three cities in Nigeria are tested for their alignment to the weather profile using degree-days. A correlation between energy consumption and degree-days highlight opportunities for energy savings. Results show major discrepancies. R^2 for buildings 1-5 are 0.06, 0.026, 0.022, 0.129, and 0.136 respectively. This means that climate accounts for only a maximum of 13.6% of electricity consumption in building 5. Other factors affecting consumption include building fabric, poor user controls, poor system or building design and inadequate data.

However, this result also indicates an opportunity for energy savings in cooling consumption; in terms of modifying the building construction, the cooling system, and occupants behaviour.

Neutrality temperature is adopted as base temperature required to calculate degree-days. The highest correlation depicted by R^2 between different values for base temperature is 0.36 which corresponds with neutrality temperatures of 26°C, 26.3°C, and 26.4°C for Kaduna, Abuja and Lagos respectively. This is an indication of the suitability of using neutrality temperature as the base temperature for cooling degree day calculations.

8.1.5 *Computer simulation for energy conservation with PCMs*

Parametric analyses using computer simulations are used first to bio-climatically optimize a base-case model on which to study the performance of the proposed PCM. Secondly, they are used to examine the thermal performance and energy savings due to the incorporation of PCMs.

Quasi-experiments using computer simulations by building energy simulation software Energyplus which requires a modelling plug-in DesignBuilder are analysed by statistic and methods on the 5 buildings that had adequately filled the questionnaires from the fieldwork. Computer simulations are suited to the non-linear nature of PCM problems and the thermo-physical properties of the liquid-solid phases. Simulations also allow for cost effective and timely examination of multiple variables when compared with experiments.

Comparative type of validation for the simulations are conducted for which experimental data are essential (Ibáñez *et al.*, 2005; Kuznik and Virgone, 2009b; Agyenim *et al.*, 2011). A

validation exercise testing both the ability of the user and the capability of the software to predict the performance of PCM is conducted for EnergyPlus. The experimental data from published literature and simulated results are compared to those predicted using EnergyPlus modelled by the researcher. The work of Kuznik *et al.* (2009b) presents details of an investigation into the performance of PCM wallboards in a scaled model using a climatic chamber. The results and specifications presented are used to create a model and simulations are run using EnergyPlus. Results show an agreement of values is achieved within an accepted root mean square error of 10.4%, indicating the suitability of using EnergyPlus to simulate PCM and the user's ability to model PCMs incorporated in the building fabric.

8.1.6 Bio-climatically optimizing thermal and energy performance of buildings

A total of 67% of total electricity consumption may be conserved passively right from the design through to operational stages in office buildings in warm climates such as Abuja. Whereas 26% can be reduced simply by considering the climate in the design stage, the remaining 41% may be conserved by switching from mechanical cooling to natural ventilation providing the building occupants are in thermal comfort.

Electricity conservation and thermal comfort are affected by many factors which start right from the design stage, through the operational stage, up to the demolition stage. Bioclimatic design principles are beneficial right from the design stage because buildings are designed based on natural ventilation, local climate and materials, and using renewable and clean technologies (Khalifa and Abbas, 2009). Bio-climatic design principles therefore allow buildings to maintain comfort with minimal mechanical support. There are two approaches to evaluating thermal comfort for building users; the rational or adaptive approach. Both methods are used to measure comfort in office buildings in this research.

The rational method used is the PMV-PPD as used by the European standard EN15251 (Olesen, 2010). Based on the PMV-PPD, the comfort zone lies between 22°C and 27°C for mechanically cooled office buildings.

The adaptive method used is Neutrality temperature developed by Nicol and Humphreys (2001). This is the temperature at which the body is comfortable, requiring neither cooling nor heating. For Abuja, the neutrality temperature calculated by Equation 8-2 is 26.3°C. The comfort zone is $\pm 2^\circ\text{C}$ from neutrality temperature (Nicol *et al.*, 2012). Therefore the comfort band is between 24.3°C to 28.3°C. Adaptive comfort is used only for natural ventilation cooling strategies.

$$T_n = 17.8 + 0.38(T_{ave}) \quad \text{Equation 8-2}$$

Where T_n is Neutrality temperature, and T_{ave} is mean monthly temperature.

A bio-climatically optimized base case model is created. The modelling and simulation is done by the software DesignBuilder and EnergyPlus respectively (DesignBuilder, 2011; EnergyPlus, 2011). The sources of variables making the base-case are:

1. Data collected from field during the energy audit
2. Nigerian building code
3. Bio-climatic design variables for hot climates in literature They are geometry, orientation, glazing, shading, airtightness and insulation

Results show that for mechanically cooled buildings in Abuja, more energy is conserved with a compact geometry, the principal axis lying along north-south, improving air-tightness, window hood shading and bronze tinting of glazed areas, and roof insulation. Some conservation techniques tested that have no significant effects on thermal performance are wall insulation, double glazing and lowE glazing. These results highlight the benefit of running dynamic simulations at any stage to compare thermal and energy performance of buildings.

By switching from mechanical cooling to natural ventilation a reduction of 67%, from 260MWh to 86MWh per annum is possible. On the other hand, conducting preliminary simulations at the initial design stage is beneficial for a mechanically cooled building as shown by a 22% reduction in total consumption from 260MWh to 204MWh. The base-case performs better than the benchmark for good practice by CIBSE (2004). It is worthy of note that occupant behaviour has not been factored into the calculations, which accounts for a large amount of inefficiency in building energy consumption.

Shading the building's glazed areas and making the building air-tight provide the greatest energy savings at 13% while insulating the roof provides the least at 3%. Optimizing geometry has the potential of up to 5% energy savings while orientation and glazing have more potential at 8%.

Further savings may be achieved by changing HVAC systems to more efficient ones, improving building occupant behaviour, and introducing smart building materials within the building fabric, which is outside the scope of this presentation.

Building energy calculation is especially beneficial at the early stage of design to enable designers to make informed decisions on the electricity use in the operational stage of the buildings. This will not only prevent poor building performance due to electricity failure, but also adapt buildings to the endemic electricity crisis in Nigeria.

8.1.7 PCM performance in office buildings

The effect and optimization of PCMs for regulating interior temperature thereby reducing the need for mechanical cooling is evaluated. The optimization process is conducted for the PCM's thermo-physical properties and cooling strategies that improve its performance. A case for the retrofit of buildings with PCM is made by studying PCM in lightweight partitioned buildings in Abuja and results indicate that lightweight construction may be better suited with PCM technology. Results show almost a 2-fold improvement in consumption in the lightweight partitioned building cooled cyclically, compared to the heavyweight partitioned building. This is because the added thermal mass in heavyweight construction traps unwanted heat within the building.

The PCM evaluated is a hypothetical one based on what is suitable for the climate and building type according to literature reviewed in Chapter 2. It has been established that the thermo-physical properties of PCM products can be manoeuvred to achieve suitable outcomes (Ahmet, 2005).

A parametric analysis is conducted to optimize the performance of PCM in office buildings. A novel mechanical cooling operational strategy is developed called cyclic cooling. Cyclic cooling is the cooling of the interiors for a prescribed number of hours in an effort to maintain comfort for an optimum duration within the working hours. Cyclic cooling is evaluated with PCM and without. Results show that the case without PCM saves marginally more electricity with a reduction of 7% for the base-case with PCM and 16% for the case without PCM compared to full mechanical cooling.

The simulations are initiated using the bio-climatic model presented in Chapter 6 and firstly, analyses the effect of varying and optimizing thermo-physical properties of the PCM system on energy and thermal performance. The transition temperature is the principal thermo-property affecting the thermal performance of a system. Further to transition temperature, the thickness and conductivity of the PCM are examined. The analysis is done using degree day and descriptive statistics to evaluate the thermo-physical properties suitable for hot climates.

Secondly, the cooling strategies that encourage the operation of the PCM are examined. The strategies include natural ventilation, night-time mechanical cooling, adequate day-time mechanical cooling, and night-purge. The result is a PCM system model for use in warm climates.

8.1.7.1 Transition temperature

A look into the transition temperature showed 24°C performed best in terms of both electricity consumption and thermal comfort within a range of 21°C and 36°C. The range falls within the lower and higher room air temperatures respectively. For the purpose of maintaining comfortable temperature, the transition temperature should be as low as the lowest average ambient air temperature. This is to ensure that the PCM's transition temperature is high enough to be melted but low enough to reduce the peak air temperature. For the purpose of maintaining comfortable temperature in mechanically cooled buildings during power outages, incorporating PCM in the building fabric can help maintain thermal comfort especially in the hotter months. This is shown in setback cooling analyses in Chapter 6.

8.1.7.2 Thickness and conductivity

The optimum thickness for the PCM system was shown to be 10mm when compared with 50mm and 100mm. Below 10mm, PCM layers lack enough heat capacity to store a significant amount energy. Above a certain amount, the PCM performance drops relative to its conductivity as the phase transition is slow. Hence parts of the PCM remain in an unwanted state.

Looking at a combination of conductivities and thicknesses showed the optimum conductivity to be 1.5 W/m K. The trend showed the higher the conductivity the better the thermal performance, however the change is small and the phase change is adequate at 0.5 W/m K.

Based on the optimization of transition temperature, thickness and conductivity, the values producing best thermal and energy performance are 36°C, 10mm and 1.5W/m K respectively. Some of the analyses examine the energy and thermal performance between:

1. Natural ventilation
2. Mechanical cooling
3. Set-back cooling
4. Cyclic cooling

8.1.7.3 *Natural ventilation*

Natural ventilation during the day and at night brings in hot air, thereby increasing the amount of electricity required to cool down the building. The strategies of passive use of PCM with natural ventilation and night-time cooling of PCM with mechanical means only failed due to the amount of uncomfortable hours experienced. Discomfort is experienced for up to 100% of working hours.

The effect of orientation on PCM performance was analysed. The rooms in the east direction thermally perform worst, followed by west, the south and finally north as initially reported. The discomfort trend agrees with that of orientation optimization conducted in chapter 5; the best orientation should place the principal axis along the north-south axis.

8.1.7.4 *Mechanical cooling*

Day-time cooling of PCM with mechanical means presented adequate comfort but increased the amount of electricity consumed compared to natural ventilation by 52%. There is a marginal improvement of 0.1% between the cooling required for the case with PCM compared to that without. Further analyses is conducted to examine more effective strategies.

8.1.7.5 *Setback cooling*

Setback cooling is the provision of adequate mechanical cooling from the start of a working day at 8:00am till 12:00pm when it is switched off to simulate a power outage. 12:00 pm is chosen because the sun is at its peak around mid-day in Abuja. The weeks experiencing maximum and minimum temperatures are used to test the effect of PCM on maintaining thermal comfort in the event of a power outage during working hours. The results look at:

- Analysing indoor temperature difference after power outage
- Analysing duration of thermal comfort after a power outage

Results show that PCM with transition temperature 24°C performs better compared with PCM with transition temperature 36°C and 22°C.

PCM with transition temperature 24°C shows a difference in performance when cooled for 5 hours; comfort is maintained for 9 hours instead of 7. For the rest of the hours cooled, the same 10 hours of comfort is maintained, higher than for PCM of transition temperatures 36°C and 22°C.

PCM with transition temperature 24°C also shows a slight margin of 0.2°C temperature reduction potential and longer duration of comfort maintained during a power outage compared with PCM with transition temperature 36°C or 22°C.

Furthermore, when work-hours are considered cooling the building for a maximum of 5 hours is optimum to achieve comfort for the rest of the working day.

8.1.7.6 *Cyclic cooling*

Cyclic cooling is the cooling of the interiors for a prescribed number of hours in an effort to maintain comfort for an optimum duration within the working hours. Cyclic cooling is evaluated using PCM with transition temperature 24°C and without PCM.

Results show that the case without PCM saves marginally more electricity with a reduction of 7% for the base-case with PCM and 16% for the case without PCM compared to full mechanical cooling.

8.1.7.7 *PCMs in lightweight constructions in Abuja, Nigeria*

Results show almost a 2-fold improvement in consumption in the lightweight partitioned building cooled cyclically, compared to the heavyweight partitioned building. This is because the added thermal mass in heavyweight construction traps unwanted heat within the building.

8.1.7.8 *Thermal indices for PCM performance*

The results from a comparison of comfort temperatures between using air against operative temperatures as indicators of thermal comfort show the need to consider surface temperature in addition to air temperature especially in mechanically cooled buildings. It also shows that the variation between air and surface temperature is bigger in mechanically cooled buildings than naturally ventilated ones; in the hotter months than in cooler.

Surface temperatures are generally higher than air temperatures except in buildings where Night purge is employed as a cooling mechanism.

8.2 **Contributions to knowledge**

The contributions of this study to knowledge include:

- Novel data collection method for places suffering power outages
- The aggregates making up total electricity consumption in Nigerian office buildings
- Bio-climatic office model for Abuja climate
- Optimized PCM thermo-physical properties suitable for office buildings in Abuja climate
- Cyclic cooling
- PCMs on lightweight partitions

8.2.1 Data collection for power outage

A novel contribution is made for collecting electricity data for the contextual case existing in Nigeria; where there is an erratic power supply and back-up power generators are utilized for a significant duration. The technique involves calculating the difference in total working hours from hours of back-up power recorded as the utility supply hours.

8.2.2 Aggregate electricity consumption for Nigerian office buildings

Data collected is aggregated to end-uses; cooling, lighting and appliances usable for parametric analysis using perturbation techniques. Cooling, lighting and appliance loads account for 40%, 12% and 48% respectively.

8.2.3 Bio-climatic office model for Abuja

For mechanically cooled buildings in Abuja, more energy is conserved with a compact geometry, the principal axis lying along north-south, improving air-tightness, window hood shading and bronze tinting of glazed areas, and roof insulation. Some conservation techniques tested that have no significant effects on thermal performance are wall insulation, double glazing and lowE glazing. Conducting preliminary simulations at the initial stage is beneficial for a mechanically cooled building as shown by a 26% reduction in total consumption.

8.2.4 PCM thermo-physical properties suitable for Abuja

Based on the optimization of transition temperature, thickness and conductivity, the values producing optimum thermal comfort and energy conservation are 36°C, 10mm and 1.5W/m K respectively. These values are dependent on climate and operations. The values optimised in this research are limited to office buildings in warm climates.

8.2.5 Cyclic mechanical cooling strategy

A novel mechanical cooling operational strategy is developed called cyclic cooling. Cyclic cooling is the cooling of the interiors long enough to maintain comfort for a maximum duration within the working hours. Cyclic cooling with PCM of transition temperature 24°C. and without PCM, and mechanical cooling of 5 hours is adopted and without. Results show that the case without PCM saves marginally more electricity with a reduction of 73% and 74% respectively.

8.2.6 PCMs on lightweight partitions

This research indicates that the added thermal mass in heavyweight construction traps unwanted heat within the building compared with lightweight construction. This means the cooling system has to produce more cooling to achieve thermal comfort in the building. The results indicate that lightweight construction in this climate may be better suited with PCM technology, showing almost a 2-fold improvement in electricity consumption. This is because the lightweight partitions lose and gain heat faster. In mechanically cooled office buildings especially, this can be desirable.

8.3 Recommendations and future work

Recommendations for energy conservation with PCMs in office buildings in Abuja include the further study of:

- Micro-encapsulated PCM in sandcrete block
- PCMs in light-weight buildings in Abuja
- PCM in hot and dry climate
- Field validation of results
- PCMs in active systems
- Cost effectiveness of using PCM for energy conservation

8.3.1 Micro-encapsulated PCM in sandcrete blocks

Cabeza et al., (2007) set up an experiment consisting of two identically shaped cubicles of concrete, one with conventional concrete, and the other one with the modified concrete, called the Mopcon concrete in the locality of Puigverd of Lleida, Spain. Results obtained during summer show that while the maximum ambient temperature was 31°C, the west wall of the cubicle without PCM reached 39°C. That of PCM reached only 36°C, showing a difference of 3°C. The maximum temperature in the wall with PCM also shows a time-lag of 2 hours later when compared with the wall without PCM. This shows the thermal inertia of the PCM wall is higher. The minimum temperatures show a 2°C difference also, from 22°C to 20°C.

These results varied from the ones predicted in this result primarily due to the retrofit nature of the PCM and the weather profile. A study of PCM concrete should be conducted to test its performance in Abuja.

8.3.2 PCM in hot and dry climates

PCM performance should also be evaluated in the more arid parts of Nigeria, where large diurnal temperature swings are experienced. In this study, results show that night-time temperatures are too high to solidify the PCMs and so natural ventilation failed as a cooling strategy. In hot and dry areas in Nigeria there may be sufficient variation between the diurnal temperatures to allow for natural ventilation thereby reducing electricity consumption further.

8.3.3 Field validation of results

Field study of PCMs in Nigerian buildings should be explored to evaluate how PCMs perform in real-life settings. Although the software used in this research have been validated, the results may vary due to building occupant behaviour or errors in modelling and weather data. Bio-climatic design principles should also be evaluated in the field to further explore their potentials.

8.3.4 PCM in active systems

Passive use of PCM in the building fabric in Abuja climate has proven to be ineffective in achieving thermal comfort. Future work should be conducted in active systems that incorporate effective cooling mechanisms of the PCM when required. Tyagi *et al.* (2012) investigate an active system for cool energy storage experimentally. Different heat loads are used to study the system's performance and results show that there is a significant variation in the time duration to maintain thermal comfort temperature with different heat loads. Comfort is maintained for 9h, 3:30h and 2:30h for the systems with 1kW, 2kW and 3kW heat load respectively. The results indicate the viability of incorporating PCM in an active cooling system rather than as 2 separate passive and active systems.

9 APPENDICES

9.1 Appendix A- Energy audit questionnaire

Survey Information

This questionnaire is the first part of an energy auditing survey to calculate the average electricity consumed in office buildings in Nigeria. Information will cover building information, occupancy and operational schedules, lighting, ventilation and air-conditioning etc. A further walk-through investigation will be conducted on-site for calculations to complete the survey.

Questionnaire Consent Form

I, (participant's name), on behalf of(organization's name) understand that I am being asked to participate in a questionnaire activity that forms part of data collection required for the completion of PhD thesis for Amina Batagarawa.

I understand that the questionnaire will be conducted in person/email. I also understand that my participation in this project is completely voluntary and that I am free to decline to participate, without consequence, at any time prior to or at any point during the activity. .

I understand that the results of this activity will be used for the purpose of a PhD thesis and the information I provide may be published, anonymously (*circle if organization wishes to remain anonymous*), in journals or conference proceedings. All survey/questionnaire responses, notes, and records will be kept in a secured environment

I also understand that there are no risks involved in participating in this activity, beyond those risks experienced in everyday life.

I have read the information above. By signing below and returning this form, I am consenting to participate in this questionnaire project.

Signature: _____

Date: _____

Please keep a copy of this consent form for your records. If you have other questions concerning your participation in this project, please contact me at:

Telephone number: +4479784070

Email address: amina.batagarawa@ncl.ac.uk

BUILDING CHARACTERISTICS				
Gross Floor Area: _____ Gross Sq.M x Ceiling Height _____ M = volume _____M ³				
Conditioned Floor Area: _____ (if different than gross floor area)				
Total door Area: _____ (all in Sq.M)		No of rooms		No of floors
Glass doors _____	Wood doors _____	Metal doors _____	Garage doors _____	
Total Exterior Glass Area: _____sq.M. Single Panes _____sq.M. Double panes _____sq.M.				
	North	South	East	West
Total Area				
Single Pane				
Double Pane				
Total Exterior Wall Area: _____ sqM Material: []Masonry []Wood []Concrete []Stucco []Other				
Total Roof Area: _____sqM Condition: []Good []Fair []Poor				
Insulation Type: _____Roof _____Wall _____Floor				
Insulation Thickness: _____Roof _____Wall _____Floor				
Any shading device on windows? Yes/no Describe:				
Metering: Is this building individually metered for electricity? []Yes []No				
Describe general building condition:				
Building category:				

9-Appendices

Notes

Building Occupancy Profile

Does any worker use energy during nights and weekends? Yes / No. Comment & give details of areas:
--

Daily Profile

	6 a m	7a m	8a m	9a m	10a m	11a m	12p m	1p m	2p m	3p m	4p m	5p m	6p m
No of employees present													

Weekly Profile

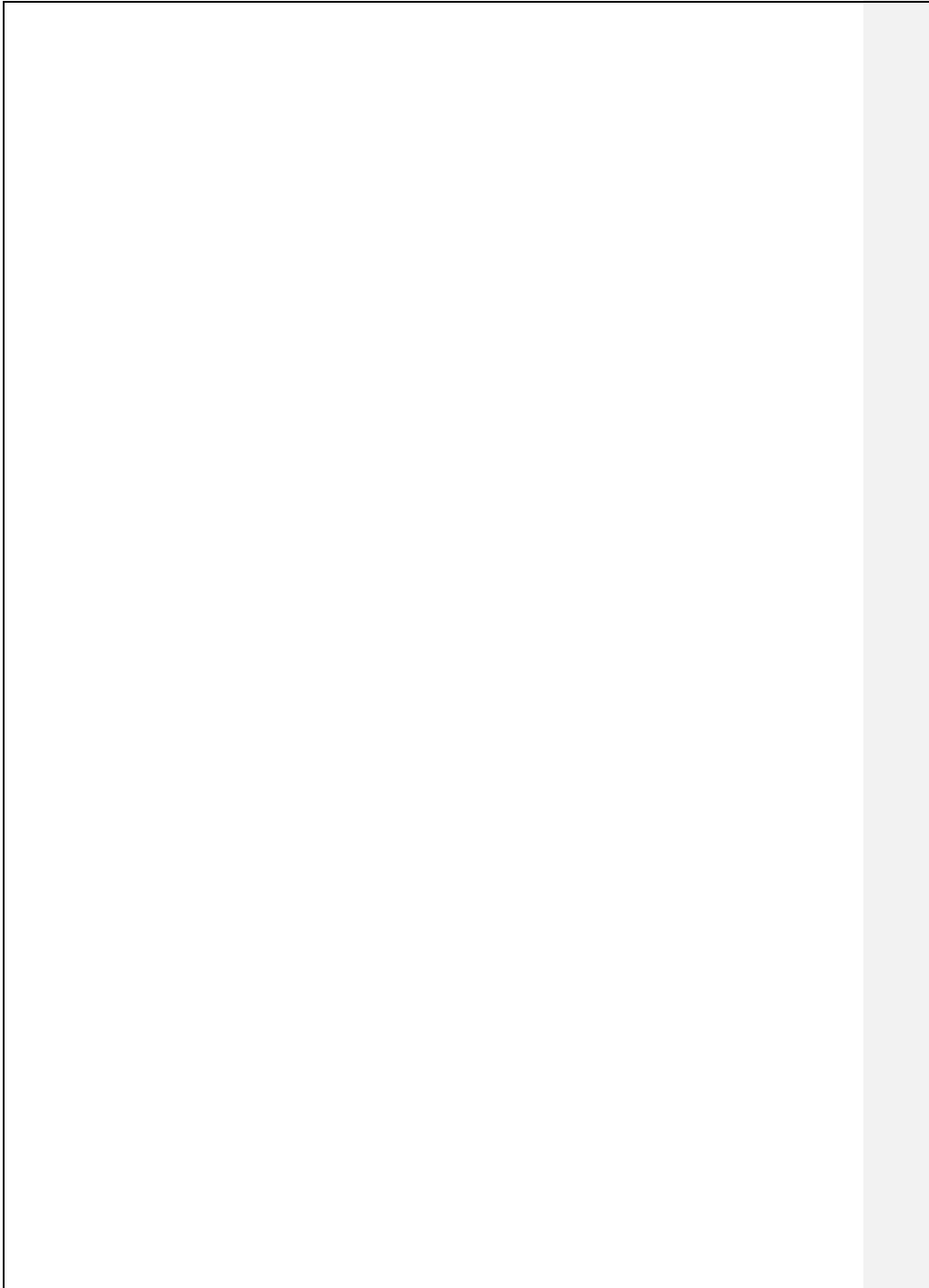
	Mon day	Tuesday	Wednes day	Thursda y	Friday	Saturday	Sunday
No of employees present							

Annual Profile

Jan	Feb	Marc h	Apri l	May	June	July	Aug	Sept	Oct	Nov	Dec
No of employees present											

Building occupancy schedule

SITE SKETCH



Indicate compass direction with a north arrow. Get maps and pictures of site and surrounds

ANNUAL ELECTRICITY USE AND COST									
Total installed electrical power [kW] :									
Account Number			Meter Number				Year of Record		
							From / To		
Maximum kW Demand W/O charge			Phase: single/3-phase				Building size (M ²)		
Minimum Power Factor W/O charge									
Meter Read Date	KWh*	KWh/gross	Annual	Energy	KW-	Fixed	P.F. *	and Demand	Total Cost
From	Used	sq.ft. **	(EUI)	Cost	KVA	Service	Cost***		
To			BTU/sqft		Demand	Cost			
			(000)						
Total									

Conversion: 3413 BTU/kWh

*KW – Kilowatts, KVA – Kilo-Volt-ampere, KWH – Kilowatt hour, P.F. – Power Factor

Total annual kWh divided by the building’s gross sq. ft. *If demand and/or power factor are metered and billed, energy cost here.

9-Appendices

ANNUAL ALTERNATIVE POWER USE AND COST							
Building Size (M ²)				Fuel Type			
Billing Period	Fuel consumption	Conversion Factor	MMBTU	Annual (EUI) kWh/M2.	Cost \$	Alternative generator capacity	Alternative generator condition
From	To						
Total							

HEATING PLANT			
Is building mechanically heated? []Yes []No			
	PRIMARY	SECONDARY1	SECONDARY2
System Type Code			
How many each type			
Rated Input Consumption			
Rated Output Capacity			
Energy Source Code			
Maintenance Code			
Control Code			

A. System Type Code B. Energy Source C. Maintenance Code D. Control Code

9-Appendices

- 1. Fire tube-Steam
- 2. Water tube-steam
- 3. Fire tube-hot water
- 4. Water tube-hot water
- 5. Electric Resistance
- 6. Heat pump with aux. Elec.heat
- 7. Purchased steam
- 8. Other (explain)

- 1. Natural Gas
- 2. LP Gas
- 3. #2 Fuel Oil
- 4. #4 Fuel Oil
- 5. #6 Fuel Oil
- 6. Electricity
- 7. Coal
- 8. Wood
- 9. Solar
- 10. Purchased Steam

- 1. Good
- 2. Average
- 3. Fair
- 4. Poor

- 1. Manual
- 2. Somewhat automated
- 3. Highly automated

Operation Profile:

_____hrs/weekday _____hrs/Sat. _____hrs/Sun. _____wks/yr

Estimated annual hours of operation _____

From (month) _____ through (month) _____

Thermostat set points:

Day: _____ Night/weekends: _____ Heating Degree Days: _____

9-Appendices

COOLING PLANT										
Is building mechanically cooled? []Yes []No										
Space/room	System Type Code	Energy Source Code	Maintenance log				Control Code	Voltage Code	Special features	

(A) System type code (B) Energy source code (C) Maintenance Code (D) Control Code (E) Voltage Code (F) Special features

- 1. Reciprocating chiller
- 2. Centrifugal chiller
- 3. Absorption chiller
- 4. Solar assisted-absorption chiller
- 5. Evaporative chiller
- 6. Heat pulmp
- 7. DX system
- 8. Screw compressor
- 9. Window or thru-wall unit
- 10. Other (define)

- 1. Electric Motor
- 2. Combustion engine
- 3. Steam turbine
- 4. Steam boiler
- 5. Purchased steam

- 1.Date and frequency of maintenance from logs or HR

- 1. Manual
- 2. Somewhat Automated
- 3. Highly Automated

- 1. 120/single phase
- 2. 208-220/single phase
- 3. 208-220/3-phase
- 4. 440-480/3-phase

- 1.Bacteria/germ/odour elimination
- 2.Adjustable thermostat
- 3.Variable Fan speed
- 4.Slide out filter: for easy maintenance and cleaning
- 5.Digital temperature control
- 6.Sleep settings

Operation Profile:
 _____ hrs/weekday _____ hrs/Sat _____ hrs/Sun _____ wks/yr
 Estimated Annual hours of Operation _____
 From (month) _____ through (month) _____
 Cooling Degree days _____

HVAC DISTRIBUTION SYSTEM			
	PRIMARY	SECONDARY1	SECONDARY2
System Type Code			
Maintenance Code			
Control Code			

(A) System Type Code

1. Single Zone
2. Multi Zone
3. Dual duct
4. Variable air volume
5. Single duct reheat
6. 2-pipe water
7. 4-pipe water
8. Window unit
9. Unit ventilator
10. Fan Coil
11. Unit heater
12. Other (define)

(B) Maintenance Code

1. Good
2. Average
3. Fair
4. Poor

(C) Control Code

1. Space thermostat
2. Outside temperature sensors
3. Time clocks
4. Energy management system
5. Auto supply temp reset
6. Economy cycle
7. Heat recovery
8. Other (define)

LIGHTING						
Buildin g Area*	Type Code of fixtur e	Approximat e number of fixtures	Averag e watts per fixture	Operatin g hours/da y	Average footcandles* *	Control Switching/dimmi ng

Operation Profile:

_____ hrs/weekday _____ hrs/Sat _____ hrs/Sun
 _____ wks/yr

Estimated Annual hours of Operation _____

From (month) _____ through (month) _____

Cooling Degree days _____

- A. Incandescent
- B. Flourescent
- C. Mercury Vapor
- D. High Pressure Sodium
- E. Low Pressure Sodium
- F. Metal Halide

*Include indoor and outdoor areas.

** Optional

Comments : (e.g., specially installed energy saving fixtures, bulbs, controls such as wall switchers, timeclocks, dimmers, etc.)

APPLIANCES							
Room description	Appliance	Quantity	Load factor Energy meter reading	energy efficiency ratio, EER= Btu/Power (in watts)	Condition	No of hours used per annum	Electricity consumption per annum

APPLIANCES USAGE PATTERN													
Appliance (on/off/stand by)	6a m	7a m	8a m	9a m	10a m	11a m	12p m	1p m	2p m	3p m	4p m	5p m	6p m

TEMPERATURE PROFILE (OPTIONAL)/ROOM DESCRIPTIONS			
Room	Interior temperature		Outside temperature
			Time of day

9.2 Appendix B to D-

- A. Sample EnergyPlus
- B. Abuja weather file
- C. Sample data from fieldwork

This CD contains 3 files. The first file shows a building model with PCM of transition temperature 24°C, thickness 10mm, conductivity 1.5 and mechanical cooling from 8am till 12pm. The second file is the Abuja weather file used to simulate the climatic context of base-case. And the last shows the record of data collected in three buildings during the energy audit in the field.



basecase24mtpcm five hour of pcm cooling till 12pm 10mm 1.5k optimized annual.idf

10 REFERENCES

1 REFERENCES

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