‘Passive System Integration for Office Buildings in Hot Climates’

By

John Paul Brittle

B.Sc (hons) M.Sc CEng MCIBSE

Doctoral Thesis

Submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy at
Loughborough University,
Loughborough, Leicestershire

CERTIFICATE OF ORIGINALITY

This is the certify that I am responsible for the work submitted in this Thesis, that the original work is my own exempt as specified in acknowledgements, footnotes or in references, and that neither the dissertation nor the original work contained herein has been submitted to this or any other institution for the award of a degree or for any other purpose.

Signed: ....

Print Name: ......John Paul Brittle.................................

Date: ....25/01/2017..

List of Publications

Brittle, J. P, Eftekhari, M.M & Firth, S.F (2013) *'Mechanical cooling energy reduction for commercial buildings in hot climates: Effective use of external solar shading incorporating effects on daylight contribution.'* 13th Conference of International Building Performance Simulation Association, France.

Brittle, J. P, Eftekhari, M.M & Firth, S.F (2014) *'Mechanical cooling energy reduction for commercial buildings in hot climates: effectiveness of combined passive systems.'* Building Simulation and Optimization BSO14, University College London, London

Brittle, J. P, Eftekhari, M.M & Firth, S.F (2014) *'Combined passive system selection strategy for low carbon commercial buildings.'* Zero Carbon Buildings Today and in the Future, Birmingham City University, Birmingham, England, UK.

Brittle, J. P, Eftekhari, M.M & Firth, S.F (2016) *'Mechanical ventilation & cooling energy versus thermal comfort: a study of mixed mode office building performance in Abu Dhabi.'* 9th Windsor Conference: Making Comfort Relevant, Cumberland Lodge, Windsor, England, UK

Brittle, J. P, Eftekhari, M.M & Firth, S.F (2016) *'Mixed mode ventilation & cooling in commercial buildings: concepts for passive system integration.'* Zero Carbon Buildings Today and in the Future, Birmingham City University, England, UK

Brittle, J. P, Eftekhari, M.M & Firth, S.F (2016) *'PDEC tower cooling energy performance assessment using specific enthalpy calculation methodology.'* IBPSA Building Simulation & Optimisation, Newcastle University; Newcastle, England, UK

Brittle, J. P, Eftekhari, M.M & Firth, S.F (2016) *'Impacts of external solar shading devices for typical office building in a hot climate: Simplified Design Methodology for Engineers.'* Solar Energy, Elsevier *(Under Review)*

Abstract

Passive ventilation and cooling systems can offer energy savings when combined into a mechanical ventilation and cooling strategy for office buildings. At early design stages, it is difficult to predict actual energy savings as current design and calculation tools are limited and do not allow assessment for energy reductions when attempting to use typical passive options such as solar chimneys, rain screen facades, ventilated double facades, passive downdraught evaporative cooling and earth ducts. The only passive systems that are directly incumbent to dynamic thermal modelling software are natural ventilation and external solar shading. Currently, impacts of passive systems on annual building energy performance is unclear and lacks clarity. In hot climates, this is even more problematic as buildings need to endure higher external temperatures and solar irradiation. Understanding minimal energy performance reductions for each passive system can aid with design decisions regarding building ventilation and cooling strategies.

The aim of this study is to investigate how existing passive ventilation and cooling system design and operational strategies can be improved to reduce mechanical ventilation and cooling energy consumption for commercial buildings in hot climates. Theoretical commercial building models are created using dynamic thermal simulation software to determine minimum mechanical ventilation and cooling energy values, which are verified against published bench marks, known as base case models. These base case models are simulated using weather data from four different hot climates (Egypt, Portugal, Kenya and Abu Dhabi). Impacts of passive system energy performance are afforded by using either dynamic thermal simulation or fundamental steady state analysis identifying approximate passive ventilation and cooling potentials for reducing mechanical energy. These percentage reductions are created based upon passive system parameters and weather data, using appropriate methodology. From these findings new simplified design guidelines, integration strategies and performance design tools are created including a new passive system energy assessment tool (PSEAT) using Microsoft Excel platform to ensure that a wider audience can be achieved in industry. The design guidance and integration strategies are developed and simplified to enable architects, building services engineers and alike, to apply with speed and accuracy influencing the design process and improve confidence in desired passive solution.

Key Words: Passive Systems, Passive Cooling, Annual Energy Consumption, Design Guidance, Integration Strategies, Tools, Verification.

Acknowledgements

Well…here I am! A long hard five years of my life, which has been eventful to say the least. I often think back to when I was finishing my master's degree in August 2011 and I asked my partner, Daniela, what she thought about me starting a PhD. Her answer was blunt to say the least, *'you are joking…?'* I will always remember that moment as I made the decision to apply and never looked back. During this experience I have had many friends and colleagues ask me if I was mental, stupid and crazy for attempting such a feat. I always responded with a crazed comical look and said, *'the doctor is in…'* in which they replied, *'you're not a doctor yet!'* Working while doing this research is very difficult and requires a certain level of ambition and determination. The first two years were the worst, trying to learn how to do research on a daily commute to London Euston (train) and complete a full time job. Also, which is most important, helping to bring up our two beautiful children, Imogen May and Harry Jay. They have been incredible from the day they were born and I am extremely grateful for their good behavior; 90 percent of the time. To add to the madness, we were married on 12th December 2014 and bought a house in August 2015. After completion, we discovered the building had severe rain damage to the rear roof and throughout the back walls, not picked up by surveyors. Having no choice, I ended up rebuilding it on my own for 5 months completing back breaking work (long weekends), as well as working away from home during the week on secondment for Atkins Global. This was the most difficult part of my life, being away from my family and trying to build a home, which I am happy to say now we are extremely proud of. In January 2016, I was promoted to Associate Grade at Atkins Global which I am very proud of and took a lot of effort to achieve such a senior level.

However, all of this could not been achieved without support from my loving wife, Daniela. Although she wants me to achieve the PhD, she has kept me grounded with constant nagging about important things such as spending time with our children and completing our home. There were also constant complaints regarding me working all the time and a claim that I love my laptop computer more than her…that does make me smile.

Now, there have been a number of people who have helped me on this journey and to whom I am extremely grateful. One in particular is my lead supervisor Dr Mahroo Eftekhari. A couple of words to describe Mahroo would be intelligent, enthusiastic and kind. She is real inspiration and I am honored to have been under her wing. Another person I would like to say a big thank you is Professor Malcolm Cook, who gave me the confidence to continue with this process. Thanks also to Dr Steven Firth who has offered sound academic advice helping to improve quality of this work and assisting with comments of my conference papers. For my work colleagues at Atkins Global, a few people I would like to thank are Richard King, David Roberts, Ashley Evans and Matthew Zalewski. These individuals helped me think about industry application. For my friends, thanks goes to Joanne Alexander-Weller, Stuart and Heather Warden.

One lesson I have learned in life, never let go of your dreams and aim as high as possible. To echo one of my heroes, Michael Faraday; *‘But still try, for who knows what is possible?’*

Table of Contents

3. Research Methodology 65

List of Tables

List of Figures

Acronyms

ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
ACD	Air Control Damper
BEMS	Building Energy Management Systems
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
BER	Building Emission Rate
BRUKL	Building Regulations United Kingdom Part L
BSRIA	Building Services Research and Information Association
CIBSE	Charted Institution of Building Services Engineers
COP	Co-efficient of Performance
CFD	Computational Fluid Dynamics
CHAM	Concentration Heat and Momentum
CAV	Constant Air Volume
DTS	Dynamic Thermal Simulations
DEC	Display Energy Certificate
ED	Earth Ducts
EPC	Energy Performance Certificates
EWY	Example Weather Year
HVAC	Heating, Ventilation & Air Conditioning
IPCC	Inter-governmental Panel on Climate Change
IES VE	Integrated Environmental Solution Virtual Environment
LEED	Leadership in Energy & Environmental Design
NV	Natural Ventilation
NCM	National Calculation Method
PDEC	Passive Downdraught Evaporative Cooling
PSEAT	Passive System Energy Assessment Tool
PHEONICS	Parabolic Hyperbolic or Elliptic Numerical Integrated code series

PVC	Polyvinyl Chloride
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
RIBA	Royal Institute of British Architects
RSF	Rain Screen Facades
SS	External Solar Shading
SC	Solar Chimney
SBEM	Simplified Building Energy Model
TER	Target Emission Rate
TRY	Test Reference Year
TMY	Test Meteorological Year
VAV	Variable Air Volume
VRF	Variable Refrigerant Flow
VDF	Ventilated Double Facades

Nomenclature

A	Area of facade/Wall (VDF/RSF) (m^2)
A_{fw}	Area of facade wall for ventilated double facade (m^2)
A_g	Area of Glazing (m^2)
A_L	Area of louver (m^2)
ρ	Air density (kg/m^3)
A_{rsf}	Area of rain screen facade weatherboard (m^2)
Q_{Infil}	Air Infiltration Heat loss (W)
T_{CA1}	Air temperature of cavity (VDF) (^{o}C)
T_{CA2}	Air temperature of cavity (RSF) (^{o}C)
ω_T	Air moisture content limit (total) (g/g)
ω_a	Air moisture content (g/g)
CO_2	Carbon Dioxide
Qe	Calculated energy reduction for mixed mode operations (kWh)
Q_{PDEC}	Cooling Capacity of Passive Down draught Evaporative Cooling System (W)
q_v	Design Air Flow Rate Through the Fan (m^3/s)
ΔT	Difference in Temperature
$^{\theta}T$	Difference in external to internal air temperature (^{o}C)
ΔT	Difference in external to internal air temperature (^{o}C)
d	Distance (m)
db	Dry Bulb Air Temperature (^{o}C)
^{o}C	Degrees Celsius
K	Degrees Kelvin
DF	Daylight Factor
h	Enthalpy (kJ/kg)
A_{eff}	Effective opening area (m^2)
eff_{gRSF}	Effective g value of RSF weatherboard
eff_{gg}	Effective g value of VDF Outer glazing
Ei	Illuminance due to daylight at a point on the indoors working plane units (Lux)

Q_{ED}	Earth Duct Heat Loss to ground (W)
$ø_s$	External Solar Radiation (W/m^2)
gEff	Effective g-value of the window and blind
A_1	Free area of lower ventilation grill (m^2)
A_2	Free area of higher ventilation grill (m^2)
Q	Flow rate of air (l/s)
Q_f	Fabric Thermal Heat Loss (W)
Q_{fab}	Fabric Heat loss (W)
x	Humidity Ratio
h_c	Heat transfer co-efficient of air (natural) ($W/(m^2K)$
Di	Inner Diameter of Earth Duct (mm)
Q_v	Infiltration Thermal Heat Loss (W)
T_i	Internal Air Temperature (ºC)
kW_c	Kilowatt of cooling (kW)
kWh_c	Kilo Watt hours of cooling (kW)
$kgCO_2$	Kilograms of Carbon Dioxide Gas
Q_l	Latent heat gain (W)
L	Length (m)
$MV_{(t)}$	Mechanical Ventilation Operation (hours)
M_a	Mass flow rate of air (kg/s)
ω	Moisture content (g/g)
CH_4	Methane
$MV_{(t)}$	Mechanical Ventilation Operation (hours)
N_2O	Nitrious Oxide
$NV_{(t)}$	Natural Ventilation Activation (hours)
N	Number of Infiltration air changes/hour
Do	Outer Diameter of Earth Duct (mm)
T_o	Outside Air Temperature (ºC)
P	Pressure drop (Pa)
A_p	Perimeter floor Zone (m)
%RH	Relative humidity
ε	Ratio of opening area

Q_g	Rate of heat gain through standard glazing (W)
Q_f	Rate of heat gain through standard wall (W)
Q_{FG}	Rate of heat gain through VDF glazing (W)
Q_{RSF}	Rain Screen Façade Solar Heat Gain (W)
QV_T	Revised time for mixed mode operation (hours)
Q_{VDF}	Rate of heat gain into VDF cavity (kW)
Q_{RSF1}	Rate of heat gain into RSF cavity (kW)
Q_{RSF2}	Rate of heat gain into space using RSF (kW)
Q_{Sim}	Simulated Cooling Load (kWc)
C_{pa}	Specific heat capacity of air (kJ/kg)
Q_{st}	Sub-terrain heat loss (W)
Q_{SC}	Solar Chimney Heat Gain (W)
Q_{SG}	Solar Heat Gain (W)
h_x	Specific heat capacity of supply air (kJ/kg)
C_P	Specific Heat Capacity of Water (kJ/kg)
Q_s	Sensible heat gain (W)
ϕ_{SL}	Solar Load Per Unit Floor Area (m^2)
C_{pa}	Specific heat capacity of air
I	Solar Radiation (W/m^2)
Eo	Simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky (Lux)
Qed	Total surface heat loss from earth duct (W)
U	Thermal Conductivity (W/m^2 K)
R	Thermal Transmissivity (W/m K)
Q_{TR1}	Total heat reduction (VDF) (W)
Q_{TR2}	Total heat reduction (RSF) (W)
U_{RSF}	Thermal conductivity of external weather board (W/m^2 K)
Ti_{PDEC}	Temperature of air entering sub-terrain level (^oC)
R	Thermal Conductivity of Material (W/m K)
U_g	Thermal conductivity of glazing (W/m^2 K)
Δp	Total Pressure across Fan (Pa)

V Volume (m^3)

Q_{VDF} Ventilated Double Facade Heat Loss (W)

$\Delta\omega_m$ Water Flow Rate of change from water microniser (kg/s)

W/m^2 Watts Per Meter Squared

l Wall Thickness (metres)

Chapter 1

Introduction

To overcome issues of excessive building energy consumption and carbon dioxide production, worldwide governments are now encouraging the use of passive ventilation/cooling systems and renewable technologies such as ground source heat pumps in order to offset energy produced by fossil fuelled sources e.g. natural gas, oil and coal (United Nations, 2014). Furthermore, passive ventilation and cooling systems have the added benefit of using minimal energy for operation (actuation) therefore an ideal solution for utilisation, where possible. Every decade, revised/new legislation is introduced by countries i.e. Paris COP21 conference outcomes (United Nations, 2016) which provides more rigorous design criteria for building performance. The apparent goal is to reduce building carbon emissions as far as reasonably practicable. New buildings should be designed with a sustainable ethos incorporating appropriate energy efficient strategies and techniques to achieve low carbon operation. Currently, these are difficult to achieve as passive buildings prove very complex in terms of geometry and requires materials with higher embodied energy for construction, material processes (concrete) and transportation.

1.1 Hot Climates

In warmer or hot climates, various definitions are provided where local climate is either hot humid or hot arid. However, in warmer climates such as are Lisbon, Portugal, these are described as a sub-tropical Mediterranean climate where maximum average dry bulb air temperatures range from 15 to 28 degrees Celsius. However, temperatures can reach as high as 41.8 degrees Celsius (IPMA, 2016). In Nairobi, Kenya, warm and temperate climates are encountered where maximum average dry bulb air temperatures range from 22.3 to 27.7 degrees Celsius (Climate Data, 2016) indicating sustained high average temperature. It is difficult to provide an exact definition on what is a hot climates as literature, including associate sources, provides varying descriptions. This is even more problematic as a hot summer in England can be defined as a hot climate provided it maintains yearly weather cycles. The factors that define a hot climate are amount of solar radiation per annum, maximum average dry bulb temperature, relative humidity and wind velocity. These variables can fluctuate significantly and it is difficult to design for all climate scenarios. Defining the term hot climate is difficult therefore this research focuses on cities with higher temperature and solar irradiation levels.

In addition to the above, extreme areas such as the Sahara desert in North Africa provide an inhospitable environment for human survival. Countries such as Australia, Spain, Libya, Sudan, Saudi Arabia, United Arab Emirates and India have similar climates where buildings have to cope with high solar gains, high external air temperatures, variable wind speeds and large daily external air temperature changes. When constructing buildings in these types of environments, it is important for the building design to accommodate for higher solar irradiance and prolonged high external air temperatures with average monthly temperatures ranging from 30 to 50^{o}C.

1.2 Mechanical Ventilation/Cooling and Thermal Comfort

As engineers prefer fixed design conditions for mechanical ventilation and cooling operation, designs of BEMS activates HVAC systems when external average dry bulb air temperatures exceed 24^{o}C for office buildings. Modern office buildings utilise passive systems such as natural ventilation and ventilated double facades to minimise mechanical ventilation and cooling plant energy consumption without the need for continuous operation.

Low carbon office buildings are now designed to encompass mixed mode (hybrid) operation where mechanical ventilation, natural ventilation and passive systems are combined together. In these climates, large quantities of electrical energy is often used to mechanically cool indoor environments and maintain internal comfort temperatures. Room overheating is a particularly important problem for office buildings as high internal temperatures have an impact on a person/s productivity and wellbeing. To overcome this issue, mechanical cooling is provided to effectively remove these heat gains from the internal occupied spaces (fluid based heat transportation). The size of these cooling systems depends on factors such as infiltrated heat gain, external air temperatures, ventilation supply air temperature and heat gains from occupant's (sensible and latent), equipment and building envelope by direct solar radiation and thermal convection/conduction heat transfer mechanisms.

For building environmental designers, the main goal is to maintain thermal comfort for internal environments which has a design range of 5-10% with minimum amounts of mechanical cooling. As stated in BS EN ISO 7730 (2005), humans have a tolerant level of discomfort +/-5% dissatisfied and therefore it is important to maintain internal temperatures, as these can vary throughout the day. In order to avoid human discomfort or overheating (possible heat stroke), internal air temperatures should be monitored and controlled accordingly. Furthermore, adaptive approach studies have identified that human beings are more tolerant towards naturally ventilated buildings than their mechanical counterpart (De Dear et al, 1998) hence cooling set points can be set ranging from >24^{o}C to <28^{o}C. Although temporary discomfort is not permanent tolerance, careful consideration must be given to set point system conditions.

In modern building services, fresh air delivery uses efficient types of mechanical ventilation systems such as Variable Air Volume (VAV) or fan coil systems. For internal space cooling, efficient refrigerant based cooling systems are adopted such as Direct Expansion (DX) split and Variable Refrigerant Flow (VRF) which operate when internal air temperature start to exceed room temperature set points. These refrigerant based systems are very efficient and operate with high coefficients of performance (COP) using Diakin (2016) or Mitsubishi Electric (2016) systems. Although effective, these can have limited application due to the physical unit size, unit weight and energy requirement with some large scale office buildings hence requiring large quantities of cooling. This increases equipment capital cost and operational electricity energy consumption. Furthermore, this results in negative secondary effects such as the production of anthropogenic carbon dioxide and high yearly energy costs.

As an example of using more traditional methods of building energy reduction, a parametric study was completed by Iqbal & Al.Homoud (2007) for an office building in Dhahran, Saudi Arabia, which determined building energy reduction capability using new mechanical ventilation and building envelope enhancements. It recognised that consequential improvement to glazing and use of variable air volume (VAV) provided an annual energy reduction of 7% and 17% respectively.

1.3 Passive Ventilation and Cooling Systems

Natural ventilation and passive cooling have limitations with regards to building integration. Natural ventilation is a process of allowing air to flow through buildings without the need of mechanical equipment during occupied hours. General building configurations involving natural ventilation include a central atrium and cellular spaces connected via low and high level dampers and windows connecting to the atrium space. Thermal chimneys area ideally situated around, or near to, the building perimeter to encourage air buoyancy by increased internal stack temperatures and upward directional air flow causing stack effects. Stack effect is the movement of air into and out of buildings resulting from air buoyancy. Ideal conditions for effective natural ventilation are non-exposed external facades with the provision of wind breaks, adjacent buildings to absorb solar heat gains; external solar shading to south facing windows; suitable internal geometry for low resistance air flow; use of low-e glazing with low thermal conductivity (U value); increased thermal mass (a heavy weight building); effective building energy management system (BEMS); and air tight buildings complete with sealed dampers. A basic concept cross natural ventilation strategy is detailed below in Figure 1.1 (Actual, 2015):

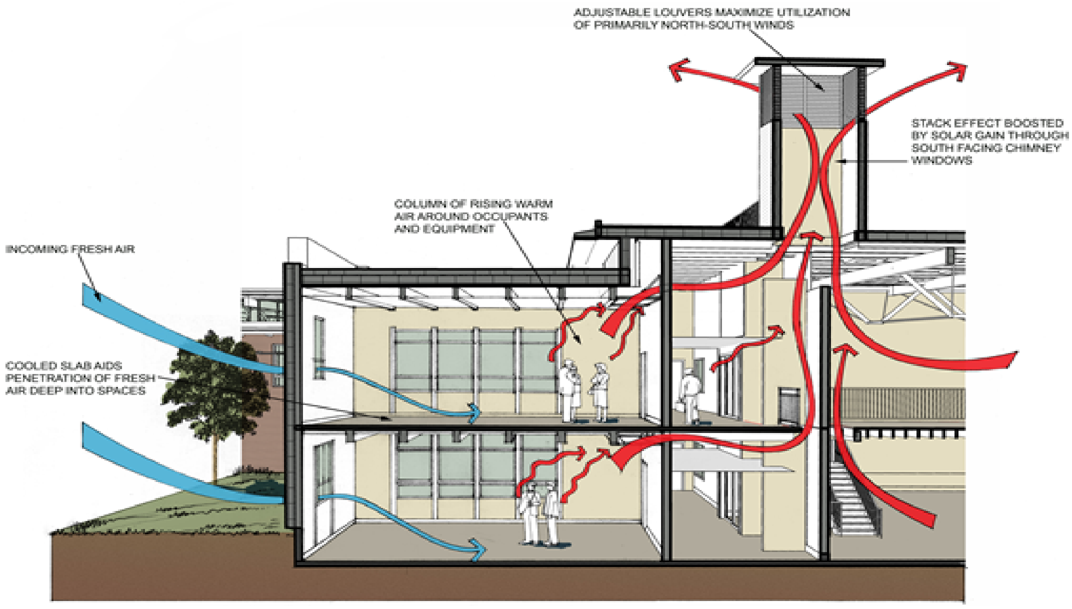


Figure 1.1- Basic Natural Ventilation Concept for Office Type Buildings (Actual, 2015)

A major factor for this area of research is the external climate and in particular, how hot external environments influence passive buildings (Sanusi, et al., 2012). Typically countries that are closer to the equator, at lower altitudes, away from coastlines suffer much hotter environments with varying relative humidity levels. Associated building DTS is an extremely important part of the passive design process and needs to be rigorous.

When attempting to control natural ventilation and passive cooling systems in these type of environments (Krausse et al., 2007) (CIBSE, 2009), more advanced building control strategies are required using sophisticated logic control making small changes based upon internal dynamic temperatures and humilities. For natural ventilation to operate effectively, design intent means that larger apertures and lower internal resistance to air flow should be provided. Furthermore control has an increased element of complexity and is limited control over driving forces (wind velocity and direction).

Previous studies completed for buildings show extensive thought with regards to the implementation of effective design strategies for successful operation and lower HVAC energy consumption (Appendix A). The goal of mitigating high levels of carbon in all building processes (embodied, material transportation and operation) is also a complex and difficult challenge for designers to overcome. The aim to achieve low carbon operation has been demonstrated by Passivhaus (2012) for cold climate, mainly European type buildings. This uses strategies such as super-insulation, low U-values for glazing and whole house mechanical ventilation with heat recovery. This method has be adapted for offices named passivoffice as defined by Building (2016) for Stag Teaching facility, Powys, Wales.

In terms of building cooling, common design strategies employed limit external supply air temperature to no greater than 24^{o}C. For average external air temperatures greater than 24^{o}C, further solar passive techniques are required such as solar shading, low-e glazing and cooling techniques i.e. supply air cooling coils in air handling units. Other strategies identified by research (Iqbal and Al.Homoud, 2007) are alternate mechanical ventilation methods such as constant air volume and variable air volume (CAV & VAV), set point temperature change i.e. increase from 24^{o}C to 25^{o}C, night time cooling and scheduling office lighting and cooling (in line with actual occupied building patterns) are identified energy saving methods.

When reviewing measures to improve and optimise building cooling energy performance, Groenhout et al. (2010) highlights building envelope improvements such as use of lightweight structures with insulation and radiant barrier and extensive use of louvers and breezeways. Mixed mode buildings (CIBSE, 2000) significant mechanical energy saving advantages, where natural ventilation can be maximised until external air temperature exceeds a thermal comfort set point temperature. For passive systems design of rain screen façades, manufactures guidance is used (Just Façades, 2014) along with research papers (Marinoscia et al., 2011). This demonstrates that incorporating passive systems into mixed mode buildings will significantly reduce annual energy demand for mechanical ventilation and cooling operation.

1.4 Passive System Integration

Where energy is limited or suffering from fuel poverty (developing countries), more innovative methods/technologies are required to cool internal spaces include, but not limited to, natural ventilation (NV), solar shading (SS), ventilated double facades (VDF), passive downdraught evaporative cooling (PDEC), earth ducts (ED), rain screen facades (RSF) and solar chimneys (SC). These systems are used in order to reduce electrical power loads and annual electrical demand for HVAC systems.

To demonstrate how useful an individual passive system is in assisting with mechanical cooling energy reduction, a study completed for a stock exchange building in Malta (Ford, 2002) indicates that passive building strategies can achieve a 48% reduction of energy when incorporating passive downdraught evaporative cooling (PDEC) system. This study show that buildings combining a passive system with HVAC aids significantly with removal of significant peak daily solar heat gains and maintain internal temperatures.

Incorporation of passive systems can be problematic in hotter climates as high external temperatures make natural ventilation an undesirable option to implement as hot air will be introduced into the space hence mechanical cooling will still be required; to reduce incoming air temperatures.

In order for passive designs schemes to be incorporated in buildings effectively, there is a high level of human skill and experience required. Low carbon buildings should be extensively modelled (CIBSE, 1998), employ techniques such as Dynamic Thermal Simulations (DTS) for building thermal energy performance and Computational Fluid Dynamics (CFD) to accurately predict internal air/temperature flows. Other important factors are building services controls i.e. building energy management system (BEMS) and control methodology. This requires careful design and should be tailored to individual building requirements and internal conditions.

1.5 Passive System Design Guidelines and Tools

Currently there a significant amount of simplified design guidance available for individual passive systems such as natural ventilation application and control strategies using CIBSE (2005c), CIBSE (2009) and British Standard (1991) however, for hot climates, passive system design guidelines and integration strategies related to mechanical ventilation and cooling energy performance limited and only provides focus for analysis of specific parameters i.e. reducing over heating hours using active thermal mass strategies (Warwick, 2010). Furthermore, natural ventilation design strategies and concepts are available by Axley (2001). Currently, existing publications does not identify potential energy saving associated with passive systems when combined with mechanical ventilation and cooling electrical energy performance. For passive system integration with mechanical (HVAC) systems for hot climates, further important questions are raised:

- What does existing literature provide in terms of design guidance, benchmarks and calculation methods for analysing annual energy performance of passive systems?
- How effective are passive systems in reducing external air temperature before it enters the building?
- What are the key design parameters and limitations for each passive system in terms of practical application?
- What are the maximum ventilation and cooling potentials available for each passive system?
- What is the total amount of HVAC energy saved when using passive systems?
  Do passive ventilation and cooling system have the same energy reductions for different hot climates?

There is research scope to complete comprehensive analysis to understand fundamental impacts on electrical energy consumption when combining passive systems with HVAC operation for office buildings located in hot climates. The benefits of understanding these energy reductions, in kWh, can be applied across the industry and provides a fully substantiated methodology which can apply to all office buildings. The passive system design guidelines and integration strategies which are developed in this research and provides another type of approach to energy performance assessments when combining passive systems with mechanical ventilation and cooling systems. As a by-product, this research provides a passive system energy assessment tool (PSEAT) in order to determine how much electrical energy can be saved, as a percentage, when multiplied against total building mechanical ventilation and cooling energy demand, when full time HVAC operation is required.

1.6 Research Aims and Objectives

The aim of this research is to investigate how existing passive ventilation and cooling systems design and operation strategies can be improved to reduce mechanical ventilation and cooling energy consumption for office buildings in hot climates.

This aim will be achieved through five objectives as detailed below:

Objective 1- Literature Review

Comprehensive literature review on existing passive ventilation and cooling techniques used in hot climates. This objective is to determine how these are currently implemented and how these affect HVAC energy performance. Case studies are also analysed for buildings located in various climates, where available.

Objective 2- Mechanical Cooling Load and Energy Performance for Theoretical Base Case Building Models

Create and develop theoretical base case office building models located in a hot climate using DTS software. Theoretical office building models with full mechanical cooling and ventilation are created and developed accordingly. These are also designed to enable future integration of passive ventilation and cooling systems, both individually and combined, to ascertain effectiveness of cooling energy reduction, specifically at peak summer times.

Objective 3- Effectiveness of Passive Systems

Each passive system is assessed in terms of effectively reducing mechanical ventilation and cooling energy per year using theoretical base case office building models using different hot climates. Key performance parameters are identified to highlight how optimum operation can be achieved when combined with HVAC systems and highlight differences in terms of performance between climates.

Objective 4- Comprehensive Passive System Design Guidance and Integration Strategies

Create and develop passive system design guidance and strategies for individual and combined passive systems application for office type buildings in hot climates. Furthermore, the range of operation is defined for each passive system. For an individual passive system, physical parameters are identified to improve performance during the design stage.

Objective 5- Passive ventilation and cooling performance assessment tool

Create and develop performance assessment tools to enable future assessment of passive system performance and their combined operation.

1.7 Hypothesis

The hypotheses to be tested in this research are stated below:

Hypothesis 1: *Percentage electrical energy reductions can be calculated for each passive system when combining with mechanical ventilation and cooling operation.*

Hypothesis 2: *New simplified passive system design guidance and integration strategies can be created based upon performance assessment calculations.*

1.8 Basic Methodology

The methodology was approached by applying theoretical base case models using dynamic thermal simulations (DTS) located in four hot climates and fundamental analytical methods in order to quantify energy savings when applying passive systems. To achieve these objectives, two new DTS building models are created to provide annual base case performance values for mechanical ventilation and cooling energy. Each passive system is analysed according to software capability and available analytical methods to determine percentage energy reduction for a given climate; which is then deducted from the base case models. The investigation will include analysis and comparisons of internal air temperatures (T_i), sensible and latent heat gains (kW), energy consumptions (kWh), passive system effective energy reduction for cooling (kW_r) and passive system reduction effectiveness (%).

Passive ventilation and cooling systems selected for this research are natural ventilation, solar chimney (thermal), external solar shading, ventilated double facades, rain screen façade, passive downdraught evaporative cooling and earth ducts (ground to air heat exchangers). Combining these with the building ventilation system or geometry can allow the building to benefit from annual mechanical ventilation and cooling energy reductions. These are selected as they are directly affected by external air temperature, direct solar radiation and humidity. Furthermore, combining these systems with each other can be complex as architectural restrictions take precedence, so energy reducing benefits, capital cost and aesthetic considerations are major driving factors. To identify a logical combination, Figure 1.2 shows a typical strategy for combining systems in the most effective method possible.

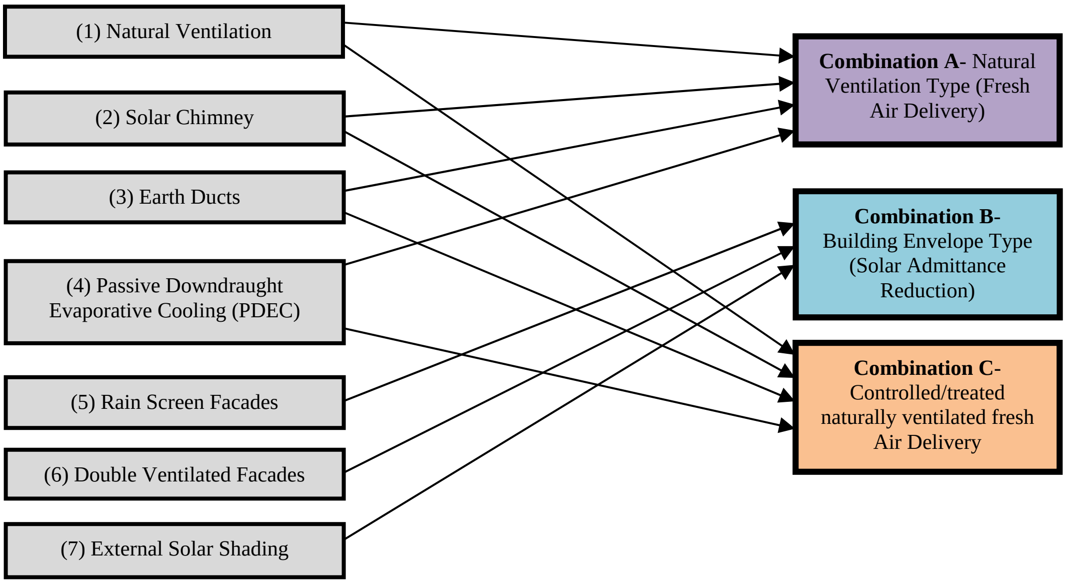


Figure 1.2- Effective Combination of Passive Ventilation and Cooling Systems (Brittle et al., 2014b)

Figure 1.2 highlights different combinations as A is for fresh air delivery systems, B is envelope protection against solar heat gains, C is controlled air flow for specific humidity and supply air control. More details of the research methodology and approaches refer to chapter 3.

1.9 Original Contribution to Knowledge

This research has contributed to the development of new simplified approach to passive ventilation and cooling design guidance and integration strategies for building implementation and approximating passive ventilation and cooling system energy performance for office buildings in hot climates, as defined on page 1. In addition to this, a new passive system energy assessment tool (PSEAT) has been created for assessment of passive system/s combined with mechanical systems, which is a by-product of this research. This research differs to other published works, as it provides an in depth analysis to how passive system energy is assessed and identifies simplified approaches for integration within mixed mode ventilation building in terms of design. Existing literature is limited to specific passive system parameters such as temperature analysis across thermal boundaries and understanding optimal performance. By using this research, in industry practicing architects and building services engineers can apply this method directly to new or existing building designs as an effective *'ready to use'* design method. This work has been published in academic conferences in form of papers and journal paper as detailed in the list of publications. These highlighting the benefits to the academic community.

1.10 Structure of Thesis

The structure of the thesis chapters is as follows:

- Critically review existing literature (Chapter 2) on passive ventilation and cooling techniques used in hot climates. This also includes descriptions of each passive system showing basic design principles of individual passive systems and practical applications. Case studies are included detailing how these can be incorporated within buildings. Performance of these systems is reviewed and critically analysed to determine how much HVAC energy can actually be saved.
- Research methodology (Chapter 3) detailing how performance analysis is completed for passive systems (individual and combined), theoretical office building models (base case) including verification and simulation tools. Furthermore, sub-methodologies are provided to identify how ventilation and cooling energy reductions are determined and subtracted from base case models. Analytical approaches are comprehensively detailed as these provide a foundation for the performance assessment calculations.
- Dynamic mechanical cooling energy performance assessment (Chapter 4) for solar shading techniques are completed using DTS in order to determine average mechanical cooling reductions available over a yearly period also assessing impacts on day lighting contribution. Results are shown in the form of line graphs, bar charts and tables. All results obtained are verified against existing published values, where possible. Final outcomes are discussed in depth and available percentage reductions for mechanical cooling energy per year when compared to a

theoretical building model base case. Impacts on day lighting are inter-compared against the base case model using a different application within the DTS software.

- Analytical energy performance assessment (Chapter 5) for passive ventilation and cooling systems is presented using DTS and analytical approaches in order to determine average mechanical ventilation reductions and cooling available over an yearly period. The systems used in this study are natural ventilation, solar chimney, ventilated double facades, rain screen facades, passive downdraught evaporative cooling (PDEC) and earth ducts. Results are shown in the form of line graphs, bar charts and tables. All results obtained are verified accordingly against previous research, where applicable. External solar shading is also run for this building model. Final outcomes are discussed in depth and available percentage reductions for each system are identified, when compared to a theoretical building model base case.
- Further results analysis is completed in chapter 6 passive system performance review, sensitivity analysis & error (1 & 2), verification (cross referencing), energy performance analysis, uncertainty in values and development of basic visual passive system design tools. Furthermore, this chapter details development of the research by-product Passive System Energy Assessment Tool (PSEAT). This includes details on how a practicing architects and building services engineer can use outputs from DTS software within this performance assessment tool. PSEAT platform uses Microsoft Excel and calculated percentages (generated in chapters 4 and 5) for each passive ventilation and cooling system. The values obtained provide an approximate level of mechanical energy reduction.
- Passive system design guidance and application strategies (chapter 7) identify simplified design methods for incorporating passive systems within mixed mode office type buildings. This chapter also includes passive system operational ranges and limits, passive system relationships and interactions, global locations and

climates, physical application, geometric design strategy and passive system integration and control strategy.

- Conclusion of this work highlighting main contributions and findings are presented (chapter 8).

A thesis navigation flow diagram is detailed below in Figure 1.2 (below) providing a high level overview of this thesis structure. Section A details current work available and context for this study; Section B details novel research completed for passive systems estimated performance assessment, combined passive system performances and overall effectiveness. Section C details contribution to new knowledge detailing passive ventilation and design guidance/strategies and performance assessment tools.

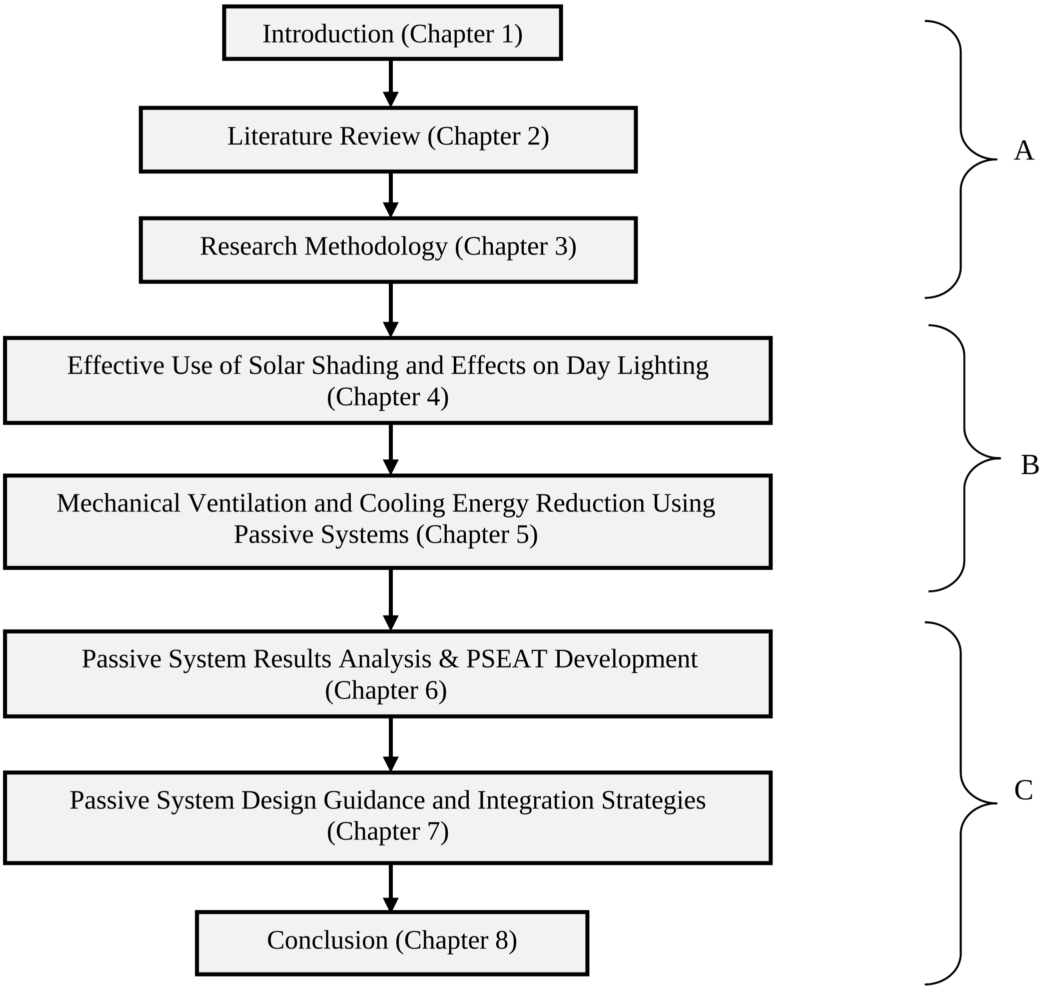


Figure 1.2- Thesis Navigation Flow Diagram

Chapter 2

Literature Review

2.1 Introduction

This chapter critically reviews existing literature on passive ventilation and cooling techniques used in buildings located in hot climates. This includes existing methods and analysis on how these systems perform in terms of annual energy saving and air temperature reduction. This literature review includes building design for hot climates (2.2), low carbon design methods (2.3), mechanical cooling energy reduction techniques (2.4) and passivhaus (2.5). For individual passive ventilation and cooling systems, detailed reviews are carried out on natural ventilation (2.6), solar chimneys (2.7), solar shading (2.8), ventilated double facades (2.9), rain screen facades (2.10), passive downdraught evaporative cooling (2.11) and earth ducts (2.12). Each section is structured as description, design and critical reviewed to determine how much HVAC energy can actually be saved.

2.2 Building Designs for Hot Climates

2.2.1 Hot Climates

There are various description what a hot climate as there are three generic categories these are defined:

- Hot and Dry (Arid)- Deserts
- Hot Humid- Tropical
- Hot and mild- Sub-Tropical

Conditions are based on higher dry bulb temperatures, relative humidity and greater amounts of solar radiation when compared to cooler climates such as Scotland, Iceland and Canada.

For global hot climates regions, these are identified in Figure 2.1 below (Climate and Weather, 2016). To clarify the figure below, RED indicates tropical climate (Hot and Humid), Orange Indicates dry climate (Desert), light yellow is mild climate (warm and humid), green is continental climate (cold and humid), polar climate (very cold and dry) and white is mountain areas (altitude affected climates).

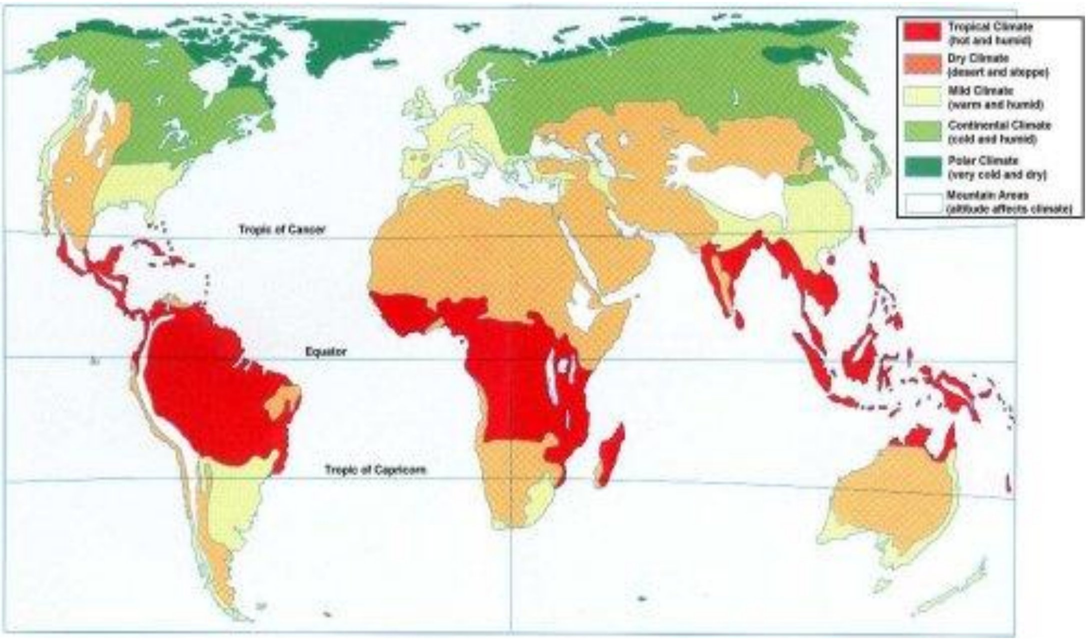


Figure 2.1- Climate Regions (Climate and Weather, 2016)

2.2.2 Environmental Conditions for Hot Climates and Thermal Comfort

Environmental conditions for hot climates are difficult to define as each human has different tolerances to heat in terms of thermal comfort (CIBSE, 2013a). However, where temperatures exceed 24 degrees Celsius, greater level of discomfort are realised. According to British Standard (2005), human thermal comfort is attributed to the following:

- Dry bulb temperature
- Wet Bulb temperature
- Mean Radiant temperature
- Air speed
- Level of Clothing
- Metabolic Rate

Using this thermal comfort assessment approach (British Standard, 2005), PMV and PPD can be calculated in order to appromate number of people dissatisfied with their environment. When comparing this to the adaptive approached defined by De Dear & Brager (1998), human interaction with their environment means that humans are more tolerant to areas where individuals can independently control their thermal comfort i.e. have access to openable windows, have a drink when necessary and reduce their level of clothing. The primary factors that De Dear and Brager (1998) identified are behavioral, physiological, and psychological.

For this research, the adaptive thermal model is ideally suited as it allows for greater internal office dry bulb set point temperatures to enable greater mechanical cooling reductions using natural ventilation methods.

2.2.3 Climate Change

Climate change and anticipated climate change scenarios are detailed as a basis for this research. The Intergovernmental Panel on Climate Change's (IPCC) climate change scenarios indicate monthly averages available from the 2020s, 2050s and 2080. There is evidence that global surface mean radiant temperature is increasing: *'In actual terms, global mean surface temperatures have risen by 0.74^{o}C, with an uncertainty boundary of 0.18^{o}C* (IPCC, 2007a).' In certain countries (European), local climatic regions will experience warmer weather conditions in the next 50 years, with northern hemisphere countries possibly becoming similar to Mediterranean climates (European Environment Agency, 2016). In other regions of the world, the IPCC provides scenarios and data based on other theorem. As determined by the greenhouse effect, further pollution of the earth's atmosphere, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), will affect levels of radiative forcing in relation to whether the planet is warmed or cooled.

2.2.4 Impact of Increasing Temperatures

The level of analysis for weather variables includes minimum/maximum average dry bulb temperature, relative humidity and wind speed (World Metrological Organisation, 2012).

Climate predictions coupled with increasing effects on global temperature increases prove very difficult to predict and there appears to be some disagreement between scientists regarding the level of impact on North and South Pole ice caps and the rate of evaporation/melting. Further factors identified on the [1]Zeitgeist list for 'climate' comprises temperature (+), sea level (+), snow cover (-), drier summers, summer overheating, precipitation in winter and increased intensity of weather events.

Negative impacts of increasing global temperatures include rising sea levels (glacial melting), habitat destruction, disease and negative economic impacts (agriculture). The Department of Trade and Industry (2004) states: *'Without considerable effort from international communities to reduce emissions, earth's temperature is likely to rise at a faster rate than any time in the last 10,000 years or more'.* As the IPCC (2007b) states, there are two main contributors to negative global warming effects: building energy consumption and industry. Key mitigation methods include:

1. Use of energy efficient lighting and maximising daylighting.
2. More efficient heating and cooling devices.
3. Improved insulation.
4. Passive and active solar designs for heating and cooling.
5. Alternative refrigerant fluids with zero Global Warning Potential (GWP).

2.2.5 Building Adaptation for Hot Climates (Case Study)

Yilmaz (2006) completed thermal comfort analysis on two residential buildings in Mardin, Turkey. This study analysed a traditional 17th-century type house called a Mungan house and modern premises called a Demir house built after 1990. The construction for the Mungan house had stone walls (1.2 metres thick) while the Demir house had brick walls (0.19 metres

---

[1] Zeitgeist translates to spirit of the times (German). This highlights current affairs associated with political and social factors associated with climate change.

thick). Following Yilmaz's measurement and questionnaire analysis, the research showed that the Mungan property provided a cooler internal environment.

The analysis for these buildings showed that the walls for the traditional type buildings were thicker and had a greater thermal mass. Yilmaz (2006) explained: *'The inner surface and indoor air temperature are almost 10^{o}C lower for the masonry wall in July, however its U-value is almost three times higher than other walls constructed to the standard. That means that thermal mass is more important than the U-values in hot-dry climate and energy conservation standards should certainly consider this property envelope in this climatic zone where cooling energy conservation is more important than the heat energy conservation.'* Yilmaz (2006) also stated that the heat storage capacity of the building envelope should be considered by the Energy Conservation Standard (TS 825) and that the best-performing building had a lower U-value, hence achieving better internal thermal comfort.

2.2.6 Passive Ventilation and Cooling in Hot Climates

Passive cooling is a major challenge for buildings situated in hot climates. As identified by Ahuja and Rao (2005), the two major factors affecting natural cooling in hot climates are economic conditions and influencing factors. The influencing factors include:

- Orientation
- Vegetation pattern
- Water bodies
- Street width
- Landform
- Open spaces and build form
- Building configuration
- Controlling parameters (wind catchers)

Passive techniques and systems can be employed to minimise peak diurnal heat levels in order to reduce levels of mechanical cooling via variable refrigerant volume systems or similar. The basic requirement is to ensure that internal temperatures do not exceed 24^{o}C as the level of dissatisfied occupants (PPD and PMV) will increase as stated in BS EN ISO 7730:2005. Guidelines vary between documents although good practice states that rooms shall not overheat above 28^{o}C for more than 1 per cent of annual occupied hours (CIBSE Guide A, 2015).

Overheating for indoor comfort temperatures (non-air-conditioned) recommend a benchmark of 25^{o}C (offices, school, retail) and 23^{o}C for bedrooms should not be exceeded. Main parameters for consideration with a building model, in line with TM52 (CIBSE, 2013a) are*;* *'... four important physical parameters: air temperature; radiant temperature; humidity and air movement; and also information about clothing and activity.'* Furthermore, additional criterion is used for benchmark of school buildings, where rooms are not allowed to exceed 28^{o}C for more than a set number of hours (120 hours respectively) per annum and must not exceed 32^{o}C at any time (BB101, 2006). CIBSE (2002) TM29 identifies that control of cold radiation via glass or similar materials has a considerable impact on building heating load during the winter periods. CIBSE (2016) Guide A states that radiant symmetry should be limited to 10 degrees Kelvin. This also has the reverse effect in summer periods, especially in buildings located in hot climates where window heat gains can exceed 250W/m^2 (BSRIA, 2009), in essence acting as an internal space radiator. For multi-storey office type buildings with high areas of glazing, radiant heat exchange from glazing to occupied space acts as an additional heat source. The viable option to maintain internal temperatures is to install mechanical high COP air conditioning systems.

Generally, mechanical systems are the most common method of cooling in such climates where the cooling coils in air handling units have to treat high volumes of external hot dry air with variable moisture content, which means there maybe be a requirement for dehumidification (Engineering Toolbox, 2016a). This problem is compounded thermodynamically as more energy is required to provide close control of air/water moisture content (kg/kg) via a humidification process, for example using steam injection or spray humidification. The energy required for this process can be viewed as counterproductive when using air handling units, as a considerable of amount of energy is used to cool and then possibly reheat (terminal). This is to ensure moisture levels are maintained at relative humidity between 40 and 50 per cent. This level of environmental control will employ comfort cooling/humidity across broader ranges. To aid with passive cooling strategies, passive performing materials and systems are used to reduce mechanical plant load/capacity while maintaining internal thermal performance.

In hot-humid climates such as Abu Dhabi, it is common to use humidity control with desiccant cooling methods and solar open air conditioners that control air moisture content to suitable levels. Furthermore, wind towers used to dehumidify hot-humid air as it enters the tower can be used; however, they have limited application (Francis, 2011). For another type of low-carbon desiccant cooling for hot-dry climates, Francis (2011) discussed the use of evaporative cooling from the roof structures: *'In such a cycle, latent energy is released by the evaporation cycle may be transmitted to the surrounding air through an exchanger, where vapour is condensed and used again. A desiccant system can be used to dehumidify the air in the closed system thus lowering the dew point which may render the system more efficient.'* This statement refers to the fact that if the roof was sealed as part of a desiccant system, the roof would act as an evaporative heat shunt transferring latent heat between two surfaces. It also identifies that this may not be suitable in these climates due to scarcity of water.

2.3 Low Carbon Building Design Methods

In order to design effective passive buildings, parameters such as the building envelope, internal heat gains and ventilation strategies require careful consideration for how these can be implemented. These parameters are detailed below:

1. Building Envelope: Good insulation and air tightness are important parameters for minimising heat demand and control of building thermal storage (Barnard et al., 2001 and Sadineni et al., 2011).
2. Internal Heat Gains: For example, this refers to lighting, computer equipment, cooking equipment and human occupancy. Barnard et al. (2001) state that *'...maximisations of internal heat gains is also a prerequisite for the success of night cooling and other techniques.'* They state that reducing lighting loads, enhancing lighting control, optimising daylighting and implementing localised mechanical ventilation extract identify and conceptualise methods to implement such strategies without affecting construction complexity, programme and economics are measures that should be employed. These require more consideration when applying benchmark values as detailed in CIBSE (2016) and BSRIA (2011) as these values do not consider stated approaches hence further energy performance analysis is required.
3. Operating Period: 24-hour operation is more desirable as night-time cooling is not required due to increased thermal mass hence internal air temperature can be maintained for longer evening periods (Shaviv et al., 2001).
4. Mechanical Ventilation Design: *'An important consideration for mechanical ventilation systems is to minimise fan pressure drops, this can dramatically affect the energy expended in introducing cooling and hence the effective coefficient of performance (COP) of the system* (Barnard et al., 2001).' This is also recommendations of CIBSE (2005a).
5. Thermal Mass of Furniture: *'The impact of furniture as a source of thermal mass is not taken into account because this then represents worst case. If required, a "mass factor" can be introduced* (Barnard et al., 2001).' Further studies are also taking into account effects of furniture (Zhou et al., 2007) where they state that; 'The internal thermal mass affects the decrement factor and the time lag of indoor air temperature.'

When considering these factors at the design stages, as far as it is reasonably practicable, the building must achieve low solar admittance (summer) (CIBSE, 2015), low heat loss (winter) (CIBSE, 2016), suitable air quality (CIBSE, 2005a) and maximum day lighting provision (CIBSE,1999a).

Although passive techniques are starting to become more common, efficient mechanical systems such as air/ground source heat pumps still require significant amounts of electrical energy to maintain air ventilation/heating and heat recovery systems for winter conditions. Where lower external temperatures occur, buildings can only satisfy heat demand provided that the external air temperature does not fall below a specific design temperature, i.e. -4^{o}C (CIBSE, 2015), and it would therefore be anticipated that the building would fail to satisfy the internal air temperature for ‘x’ hours annually. For summer conditions it is the reverse effect: a maximum internal temperature of 28^{o}C (CIBSE, 2013a) may not be exceeded for the estimated time of the year, which is dependent on location, altitude and orientation. Further questions would be how this type of building performs over a 25-year period, for example, structural movement and material degradation influences air infiltration/exfiltration. CIBSE (2016) discusses air leakage index, air permeability and acceptable air infiltration.

Passive system design and application is a complex process and requires a great deal of expertise, skill and assessment. Common ventilation and cooling strategies for passive system incorporation apply to hybrid type commercial buildings that have mixed-mode operation (CIBSE, 2000). This ability to switch from natural ventilation to mechanical cooling is highly desired where a higher temperature band for natural ventilation should be designed in accordance with British Standard (1991), CIBSE (2013a) and CIBSE (2016), i.e. internal BEMS set point temperature as close to 28^{o}C as possible before comfort design parameters fail and operation of mechanical systems is required. Each passive system has a maximum cooling capacity where external air temperature is the major driving factor for performance, i.e. higher air temperature means lower effectiveness. All natural systems have greater complex boundaries when compared with their mechanical counterparts (unable to guarantee/control constants) and building designers must take greater consideration regarding the effects on building envelope and internal space geometry in accordance with CIBSE (2016) and British Standard (1991). The selection of each system for hot climates becomes even more problematic as natural ventilation should be minimised during peak diurnal periods in spring/summer seasons where external air temperature exceeds 26ºC. Mechanical systems are currently required to maintain indoor comfort temperature when external air temperature exceeds design parameters; combining passive systems together can greatly reduce associated annual ventilation and/or cooling energy as decribed by Greeno (1997) and Chadderton (2004).

Individually, these systems can provide effective reduction of solar heat gains and this chapter reviews in more detail the application of each passive system in terms of design, configurations used (ideal) and practical application. Additionally, this chapter details how these passive systems work analytically and how these can be incorporated within building designs highlighting limitations in terms of physical application and performance. The passive systems analysed in this research are natural ventilation, solar chimney, solar shading, ventilated double facades, rain screen facades, passive downdraught evaporative cooling and earth duct. These systems have been adopted all over the world in the past couple of decades and some even over centuries (natural ventilation), as the benefits are becoming more recognisable and energy saving more apparent, especially with the global cost of producing electrical energy for these systems increasing annually. For case studies and references refer to Appendix A.

2.4 Mechanical Cooling Energy Reduction Techniques

2.4.1 Modern Mechanical Cooling Systems

Modern building services systems include a method of maintaining internal ambient air temperature providing close control of thermal comfort for occupants. As detailed by Oughton and Hodkinson (2008) and CIBSE (2005a), the main systems that are available (though not an exhaustive list) are as follows:

- Air Handling Units with Coiling Coils (Centralised): Used for large-scale buildings, supply air is cooled via chilled water or refrigerant coils (cooling battery). These systems can either be VAV or CAV.
- Air Handling Units with Recirculated Air (Centralised): To reduce cooling loads, recirculation is added as return air from spaces will still be lower than external air temperature with twenty per cent of fresh air added to dilute pollutants (80 per cent recirculation). These systems can either be VAV or CAV.
- Direct Expanding (DX) Split Cooling System: This uses refrigerant gases to transport sensible and latent heat from internal coils (cassette unit) to external coils (condenser). These are local to the rooms and design restrictions apply, for example, pipework length must not exceed 45 metres. This applies to all refrigerant-based systems.
- Variable Refrigerant Volume (VRV): These are refrigerant-based heat transportation systems where multiple rooms are heated or cooled simultaneously.
- Variable Refrigerant Flow: Similar to the VRV but allows flow to be diverted so individual rooms can be either heated or cooled. This has energy-saving benefits as heat from one space can be transferred to adjacent spaces.
- Absorption Cooling: Using thermodynamic heat exchange (lithium bromide solution), low-energy cooling and heat generation can be provided. This uses a complex system of evaporators, absorbers, generators and condensers (Chadderton, 2004). Although efficient, there must be heat dissipation such as a process heating requirement.
- Desiccant Cooling Systems: These use hydroscopic materials to control the amount of latent heat cooling required for a space. These are normally thermal wheels installed in air handling plants, as mentioned above, and used in facilities such as swimming pools.

Manufacturers such as Diakin (Diakin, 2016), Mitsubishi (Mitsubishi Electric, 2016) and Flaktwood (Flaktwood, 2016) provide new cooling equipment products on an annual basis to improve system performance. The variables that differ are COP, coil contact factors and external air temperature operating ranges.

Mixed mode ventilation (Hybrid) buildings operate between two different modes, most often using natural ventilation and centralised mechanical ventilation (CIBSE, 2000). Operation is based on thermal building load and indoor air quality. As this increases/diminishes, mechanical systems will switch to provide full operation. This is normally based on room temperature (dry bulb) and carbon dioxide detection via sophisticated BEMS. Integration of passive systems described above will aid in extending the upper temperature range where mechanical operation will only be necessary for higher temperatures (>28^{o}C). This would be effective provided BEMS is correctly set up and bias is omitted from the system (CIBSE, 2009).

2.4.2 Concepts for Improving Passive Building Performance

Passive building optimisation provides a unique challenge as the chaotic nature of weather patterns makes it very difficult to standardise ideal characteristics for passive building design such as geometry and control philosophy. When defining building optimisation, Hyvfirinen and Karki (1996) state that: *'The building optimization can be performed with respect to both design and control variables.'* In the first instance, optimisation of passive measures should be designed to reduce air temperature where thermal comfort is highlighted as the primary objective function. The main methods of reducing building solar gains, as considered by Groenhout et al. (2010), are detailed in Table 2.1 below.

Table 2.1- Options Table for Optimisation Methods (Groenhout et al., 2010)

Concept	Purpose
Use of Extended Eaves	Creates overshadowing and prevents penetration of direct solar gain into building spaces and onto the building fabric
High Ceilings	To prevent build-up of heat in the occupied zone
Use of Mechanical Fans	To increase physiological cooling through evaporation of perspiration due to increased air movement
Use of Lightweight Structures with Insulation and Radiant Barrier	Increase the thermal lag of the building fabric without increasing the heat storage capacity of the structure. Radiant barriers prevent the transfer of radiant heat from warm or hot surfaces into the space
Extensive use of Louvres and Breezeways	Allow cross-flow ventilation, purging and aid in moisture removal

Groenhout et al. (2010) continue to state that following completion of CFD analysis the removal of false ceilings and split eaves on one side of a wall dramatically reduces the amount of re-circulating air above seated occupants. They also explain that well-ventilated buildings will moderate levels of lightweight thermal mass and insulated façades provide a suitable basis for naturally ventilated spaces in tropical climates. *'The selection of the optimum combination of materials can result in the reduction in peak effective temperature of between 2^{o}C to 5^{o}C* (Groenhout et al, 2010)*.'* When comparing this statement with the case studies in Appendix A, buildings that have significantly higher amounts of external air flow can help maintain temperatures. However, series connections via apertures within the building and larger openings at a low level. This potentially introduces a problem for tropical climates as humidity control is a problem.

2.4.3 Existing Simplified Building Design Tools

There are a number of simplified design tools that existing to aid with the design of low carbon and passive building design in which some can be used within industry. These are detailed below:

- Reduction of overheating hours using active thermal mass strategies (Warwick, 2010).
- Natural ventilation design strategies and concepts are available by Axley (2001).

- Zhou et al., (2007) developed a simple tool for estimation of indoor air temperature for certain external and internal thermal mass and to determine the internal thermal mass needed to maintain required indoor air temperature for certain external wall for naturally ventilated building based upon specific conditions.
- Shaviv et al., (2001) created a simplified design tool for to predict from the temperature swing of the location the maximum indoor temperature decrease due to the thermal mass and night ventilation.
- For analysis of window shading effects of external solar shading, Sustainable by Design (2016) show a usable online tool for basic shading analysis.
- For natural ventilation temperature assessment and energy reduction, Coolvent (2016) provides a design tool to complete early design stage assessments.
- WBDG (2016) provide simplified design guidance for natural ventilation design and offers basic overview of parameters that require considering for this passive approach.
- Earth to air heat exchangers (earth ducts) simplified tool for performance analysis is developed by Muehleisen (2014) and enable calculation of length of duct required for a desired level of heat transfer effectiveness.

The passive system design guidelines and integration strategies developed in this research are building design focused within industry and provides an alternative approach to applying these systems. This research enables accelerated annual energy performance assessment and enables design techniques to be applied at early design stages (RIBA, 2014), which are accessible to a wider audience such as architects and building services engineers. This omits the necessity for specialist knowledge or expertise. Furthermore, PSEAT tool created is a niche design tool specific for cooling energy performance assessment when combined with mechanical cooling systems within industry and early design stages for accelerated performance assessment based on base case cooling loads which are either approximated by benchmarks against floor area or DTS base case values. For further details refer to chapter 6.

2.4.4 Software for Passive Building Analysis

In order to successfully simulate individual and combined passive ventilation and cooling systems, a review of existing software is necessary to determine accurate low-carbon building performance prediction and whether it is capable of calculating multi-variables simultaneously. For dynamic thermal simulation (DTS), annual energy and carbon dioxide emission analysis is a common method in industry and research. For CFD, anticipated temperature stratification and airflow direction can be approximated. This uses finite volume methods of predicting temperature or air movement/velocities for a selected volume. As indicated in Table 2.2, software capabilities as shown to identify what software can simulate which passive ventilation and cooling system.

Table 2.2- Available Software and Capability

Software Capable of Simulation (Dedicated Passive System Design Tools)	Manufacturers' Available Software				
	IES VE (IES VE, 2016)	DESIGN BUILDER (ENERGY PLUS) (Designbuilder, 2014)	EDSL TAS (EDSL, 2016)	CHAM (PHOENICS-FLAIR) (CHAM, 2016)	ANSYS (FLUENT)
Natural Ventilation	Yes	Yes	Yes	Yes	Yes
Solar chimneys	No	No	No	Yes	Yes
Solar shading	Yes	Yes	Yes	Yes	Yes
Ventilated Double Façades	No	No	No	Yes	Yes
Rain screen ventilated facades	No	No	No	Yes	Yes
PDEC	No	No	No	Yes	Yes
Earth ducts	No	No	No	Yes	Yes

The software options lack sufficient capability to accurately simulate all passive systems simultaneously making it difficult in terms of software selection. Elements of passive systems can be modelled but will need further analytical calculations and verification by the end user.

For dynamic thermal assessment of existing passive systems using computational analysis, this work uses existing software available in the market place has been selected for use within this work. For theoretical commercial building models A.1, this has been created and simulated using IES VE 6.4.0.10 incorporating finite differencing calculation methods. In particular, dynamic diurnal solar gains and annual energy consumption are calculated using Suncast and Apache. Where daylighting analysis was completed to identify negative impacts on secondary parameters, daylighting calculations have been completed for each type of solar shading using CIE clear skies weather data using IES VE FlucDL is used for 29th July at 1200 hours. For artificial lighting calculations, Dialux software version 4.10 was used to determine light levels and energy consumption (section 4.9, Chapter 4). For theoretical commercial building model B.1 and B.2, software used is Designbuilder (2014) was used. Designbuilder software version 3.0.0.105 using DB Sim v1.0.2.1 was used with a solution algorithm of finite differencing. Adaptive convection algorithms are used for inside convection and McAdams algorithm used for outside convection. The reason for why different software selected was during the research period for building models A.1 and B.1, it was discovered that Designbuilder software has more user friendly inputs and simulation interface without any need to continuously repeating navigation processes to achieve DTS results. For example, IES VE requires users to navigate and select multiple program dialogue boxes where Designbuilder has more simplified and provides more clarity with parameter selections. The advantage Design builder has over IES VE is the software platform modelling sections are much easier to use and a model can be created and simulated much faster. The clarity of graphics is much better in terms of visual representation and help sections are readily available at each section with all terms/parameters fully explained. Designbuilder also allows for more complex shapes to be generated faster when compared to IES VE. It is important to identify that Designbuilder is a software interface for Energy plus and this a free validated tool (Energy Plus, 2016).

The DTS and analytical performance assessments completed in this research are used to derive PSEAT providing a comprehensive and transparent methodology for use in industry.

2.4.5 Evaluation of Building Energy Performance

As denoted in CIBSE (2013b), this document provides guidelines for evaluating building simulations against benchmarks. The document states that building services energy consumption appears to be 50-150% more than models predict at detailed design stage.

Building simulated results should be compared against benchmark values stated in Blue Book (BSRIA 2009) and BSRIA Rules of Thumb Guide (BG 14 2003) in the first instance. For building design parameters, these are provided by the Blue Book *(BSRIA 2009)* and BSRIA Rules of Thumb Guide *(BG 14 2003).* Values stated are an average for typical buildings, detailed below (typical):

a. ***'Total cooling load:*** General office 125 W/m^2***;*** interior zones 75 W/m^2 (more than 7 m from windows); *perimeter zones* 65 per cent glazing 180 W/m^2; 60 per cent glazing 120 W/m^2'; *retail buildings: 140W/m^2; computer suites approx. 400W/m^2.'*

b. ***'Solar Gains:*** *Windows with internal blinds 250W/m^2 of glass.'*

c. ***'Air Handling Unit:*** *Air* velocities *2.5 to 4 m/s.'*

d. ***'Energy Consumption:*** *Residential care home electricity 59KWh/m^2 and fossil fuels 75KWh/m^2.'*

e. ***'Carbon Dioxide Emissions:*** Natural gas 0.19 KgCO_2/KWh; electricity 0.46 KgCO_2/KWh; coal 0.30 KgCO_2/KWh.'

f. ***'Electrical Consumption:*** *Lighting 10-12W/m^2; air-conditioning 60W/m^2; small computer rooms 200-400W/m^2.'*

To achieve this, U-values and air permeability guidelines (HM Government, 2010a), are set out to provide guidance for building design and performance analysis, as shown in Table 2.3 below. There is no changes to parameters between two revisions of this standard.

Table 2.3- Part L2A Limiting Fabric Parameters (HM Government, 2010a and HM Government, 2016)

Parameter	Limiting Value (HM Government, 2010a)	Limiting Value (HM Government, 2016)
Roof U-value	*0.25W/m^2K*	*0.25W/m2K*
Wall U-value	*0.35W/m^2K*	*0.35W/m2K*
Floor U-value	*0.25W/m^2K*	*0.25W/m2K*
Windows, Roof Windows, Roof Lights, Curtains, Walling and Pedestrian Doors	*2.20W/m^2K*	*2.20W/m2K*
Vehicle Access and Similar Large Door U-Values	*1.50W/m^2K*	*1.50W/m2K*
High Usage Entrance Door U-value	*3.50W/m^2K*	*3.50W/m2K*
Room Ventilators (Inc. Smoke Vents) U-value	*3.50W/m^2K*	*3.50W/m2K*
Air Permeability	*10m^3/(h.m^2) @ 50Pa*	*10m^3/(h.m^2) @ 50Pa*

Ventilation rates for office buildings range from 20 l/s (printers and photocopiers) to 60 l/s (kitchens). The whole building ventilation rate shall be designed to ensure a minimum ventilation rate of 10 l/s/person is achieved (HM Government, 2010b).

For this research, HM Government (2010a) standards are used as these are more comprehensive and clear providing a solid foundation when compared to other countries regulatory requirements or building codes which have higher U values as detailed below in Table 2.4 for Portugal.

Table 2.4- U Values for Portugal

Parameter	Portugal (low/high)	Source
Roof U-value	*0.5/0.7W/m^{2}K*	(Eurima, 2016)
Wall U-value	*0.4-0.5W/m^{2}K*	(Eurima, 2016)
Floor U-value	*Non Specified*	(Eurima, 2016)
Windows, Roof Windows, Roof Lights, Curtains, Walling and Pedestrian Doors	*2.8W/m^{2}K*	(Zebra 2020, 2016)

There does not appear to be any air permeability values available.

2.4.6 Mixed Mode Ventilation & Cooling Systems in Commercial Buildings

Mixed mode or hybrid ventilation and cooling for buildings requires a specific set of strategies to ensure complementary operation (CIBSE, 2000). The aim to maximise natural ventilation until external air temperature exceeds a pre-set design value and control (Martin, 1996), after which the HVAC systems will activate and take over ventilation and cooling. As daytime temperatures start off lower in the morning, natural ventilation will suffice. As external air temperature increase above pre-set limits at time e.g. 1100hrs, BEMS will activate air handling plant including cooling batteries to reduce supply air delivered into the spaces. The load of

HVAC system will increase further due to heat gain decrement factor (time lag) via structure. After approximately 1600 hours, cooling load will reduce, as daily air temperature follows a sinusoidal pattern. The building would then switch operation back to natural ventilation mode and operate night cooling to discharge heat stored in the thermal mass (thermal inertia). For daytime operation, The rate at which thermal time lag (NewLearn, 2016), in terms of rate of solar gain admittance through building at a point in time, is determined by the thermal mass or weight of the building (light, medium or heavy) (Groenhout et al., 2010) and levels of air infiltration (HM Government 2010a). Changeover operation can consist of either seasonal changeover (CIBSE, 2000) i.e. windows open able in milder weather; night cooling; top up cooling and local changeover (window detectors to switch off local HVAC).

In the case of natural ventilation mode, external air temperature and wind pressure are the primary drivers for this operation. Should wind pressure be insufficient, HVAC plant will be used to maintain room temperature and carbon dioxide levels. The most widely used strategy is concurrent operation when HVAC plant works in parallel with natural ventilation. As stated by CIBSE (2000); *'...buildings can be 'trickle charged', where a low rate of background ventilation (typically 1-3 Air changes per hour and full fresh air) is provided, to which cooling and dehumidification can be added to boost performance if required.'*

The diagram in Figure 2.2 below show the concurrent operation of a simple space (University of California Berkeley, 2013). This shows basic air flows from openable windows promoting cross flow and air flows to ceiling void via recirculation air handling unit.

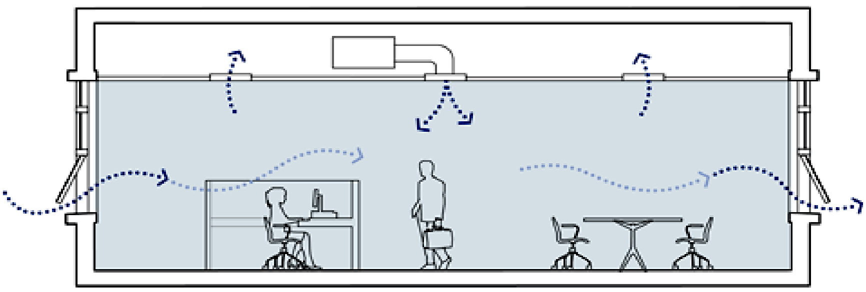


Figure 2.2- Concurrent Mixed-mode Operation (University of California Berkeley, 2013)

The main aim is to exploit the building fabric by minimising internal heat gains via the following (CIBSE, 2000):

- Windows Using Solar Shading Devices
- Thermal Inertia through building fabric (thermal storage)
- Air Tightness and trickle ventilation

The design must consider tradeoffs to encompass the wider view and impacts on day lighting; artificial lighting, glare and noise should be analyses to avoid any detrimental effects to the building design (CIBSE, 2000).

It has been identified by Krausse et al (2007) & Short et al (2009) important concepts created at RIBA stage 2 are not always carried through to practical completion and implemented in building operation. One important point was low carbon building operate most effectively when managed by enthusiastic facilities management, vital to successful performance (Short et al, 2009).

From RIBA plan of work (RIBA, 2014) stages 2 to 5, it is important to complete accurately, as far as reasonably practicable, computational building simulations based on decisions made at concept design stages, to ensure that anticipated results are not vastly different at each stage of the design. At the latter design stages (RIBA Stages 4/5), simulation tools can be used to *'iron out'* any potential problems, via the use of notional buildings and SBEM methodologies (country specific criterion). As an example of application using standards created in the United Kingdom (British), there are upper limits on overheating, criteria includes: BER<TER, U values achieved *HM Government (2010a)*; air permeability does not exceed limiting value, for example, $10M^3/(h.M^2)$ @ 50Pa *(HM Government, 2010a*) and limiting of solar gains. Case studies complied within CIBSE (2005b) show that climate adaptation options include switching off unnecessary heat gains and to '*absorb'* by increasing thermal mass.

Computational analysis is the most effective tool at these initial design stages, *'..., the remaining viable options are explored in more detail, requiring more rigorous analysis of the key design elements. Some very detailed modelling might be required to prove particular strategic concepts in order to avoid time and money being wasted later if the design has to be revised fundamentally (CIBSE, 1998).'* Dynamic thermal simulations are particularly effective where current market software such as IES VE, EDSL, Design Builder. Dynamic thermal simulation engines produce documents that include SBEM output, EPC and BRUKL compliance. For CFD analysis, PHOENICS software (CHAM, 2016) provides more detailed air flow analysis for air change rates air, air flows and direction in steady state analysis. In many cases budget is the primary driver to decide if passive strategies are included within construction schemes, as complex geometries and thermal mass is unfortunate side effect. Although budget can be contributing factor to decision made, design team members are required to provide significantly more time for passive strategies, in order to design acceptable solutions with assistance from computational models. The primary aim of any system design is to maintain internal environmental room conditions in accordance with legislation and guidelines.

2.4.7 Construction Design Processes & Guidance

At initial design stages, set out by the Royal Institute of British Architects (RIBA, 2014) plan of work stages 1, 2 & 3, passive design should be readily discussed between design team members, such as architects, building services engineers, low carbon energy engineers, structural engineer and client team, to discuss feasibility and eventual concept of incorporating natural ventilation and passive cooling strategies. As legislation is currently becoming more stringent (design criteria), buildings should be designed with a sustainable ethos incorporating all available low carbon strategies and techniques to achieve either zero energy or zero carbon. Currently, this proves very difficult to achieve as embodied processes have a major impact such as using concrete and wood sourced from different countries (carbon associated with transportation). It seems the only solution is to build a wooden hut adjacent a sustainable forest with no windows, electricity, heating and cooling. Could this be a sustainable habitat for human being in a hot climate? The point is targets have to be set realistically in order to construct a very well performing passive buildings, hence there will be some level of negative impacts; for instance, increased embodied energy. To date, mixed mode complementary type buildings are the most acceptable using latest modern technologies. Mechanical system are required should passive performance diminish. Experienced design teams offer high performance passive buildings, where confidence is high as past buildings prove successful from concept to completion. The operation of the building and its related performance would then rest on energy performance certificates (EPC) (Gov.uk, 2016), display energy certificates (DEC) and facilities management. There appears very little thought for future building performance and most importantly *'future building energy performance'.* BSRIA Soft landings (BSRIA, 2016), BREEAM (BREEAM, 2011) and LEED (USGBC, 2016) assessments help provide further responsibility for buildings post construction and further input from design engineers to measure how passive buildings performing with credits obtained by seasonal commissioning (HVAC) for 12-24 month periods.

2.4.8 BREEAM Requirements

The aim of BRE Environmental Assessment method (BREEAM, 2011) is to mitigate impacts to the environment made by the building, provide recognition that the building has environmental benefits, environmental labelling and stimulate demand for sustainable buildings. There are a number of documents published by BRE which encompass a wide range of building types such as healthcare and education. For the purposes of this document, BREEAM (2011) technical manual will be used as a base document to highlight guidelines. It is noted that all documents are similar and tailored to specific legislation, e.g. Health and Technical Memorandum requirements. Grades are categorised from pass to outstanding depending on number of credits achieved.

The main benefit is funding via government grants or other professional funding bodies. The main credits that apply to building simulation are (BREEAM, 2011):

- Health and Wellbeing 2 (Hea2) - Potential for natural ventilation (1 Credits Available) - occupied spaces of the building are designed to be capable of providing fresh air via a natural ventilation strategy i.e. openable windows area in each occupied space is equivalent to 5% of gross internal floor area or design strategy demonstrates adequate cross flow of air to maintain thermal comfort conditions.
- Health and Wellbeing 3 (Hea3) - Thermal Comfort (2 Credits Available) - thermal modelling has to be carried out using software in accordance with CIBSE (1998). The computer simulation demonstrates that the building design and services are in accordance with CIBSE (2016) and overheating criteria compliance is achieved.
- Energy 1 (Ene1)- Reduction of CO_2 Emissions (15 Credits Available)- A number of credits is dependent of the energy performance ratio.
- Energy 4 (Ene5)- Low or Zero Carbon Technologies (5 Credits Available)- Provide stage 2 feasibility report on all plausible technologies such as photovoltaic’s, ground source heat pumps, solar thermal hot water, air source heat pumps, free cooling (1 Credit), renewable energy supply contract (1 Credit) and combined heat and power. These systems should be designed on the basis of report recommendations. Between 10 to 30 percent reductions in energy made, a three credits can be achieved from the total.
- Innovation 1 (In001)- 10 Credits are available for going above and beyond for energy and carbon dioxide reduction, for example; if an further carbon emission reductions are achieved for Energy 1, then additional credits can be proportioned in line with this improvement.

In many instances some of these credits cannot be achieved in their entirety due to client changes, budget constraints or physical restriction therefore the appointment and guidance of an approved BREEAM assessor is paramount.

2.5 Passivhaus

For domestic passive buildings, a design strategy called *Passivhaus*, created in Germany, is adopted to minimise heat losses and energy consumption in colder European climates. The main aim is to construct a building where, in winter seasons, annual space heating energy consumption shall be no greater than 15kWh/m^2/year. In order to achieve this, the following criteria must be adhered (Passivhaus, 2012):

- Superinsulation: Opaque U-values must be less than 0.15W/m^2 k.
- U-values for windows and doors need to be 0.8W/m^2 k or less (for both frame and glazing).
- Thermal bridging needs to be minimised and ideally eliminated.
- Air tightness: 1m^3/hr/m^2@50pa or less.
- Whole house mechanical ventilation with heat recovery (75 per cent efficiency or better, with a low specific fan power).

The *Passivhaus* standard concentrates on the winter time energy consumption, but this leaves the question of how can this be adopted for hot climates? The benefits of superinsulation and air tightness will reduce admittance of peak summer heat gains, but can only perform effectively where temperatures do not exceed 25ºC for 10 per cent of hours per annum (Passivhaus, 2012). For temperatures greater than 25ºC, further solar passive techniques are required such as solar shading, low-e glazing and cooling techniques such as supply air cooling coils.

In the education sector, passivoffice buildings are now being created achieving requirements as detailed for domestic buildings. Examples of this is Stag Teaching facility, Powys, Wales (Building, 2016). The article states that after difficult design issues, the target reduction was 120kWh/m^2/year where it was actually achieving approximately 80kWh/m^2/year.

2.6 Natural Ventilation

2.6.1 Description

The basic principle of natural ventilation design is to provide fresh air into all internal spaces by drawing in outside air and encourage buoyant airflow through a structure while using stack/wind effects (British Standard, 1991). Air is supplied to an occupied space across multiple levels via a series connected aperture arrangements; this normally includes a sub-terrain level or labyrinth to allow controlled amounts of supply air via low-level motorised air dampers. The benefits of this method of ventilation is to effectively switch off mechanical ventilation hence minimal electrical energy is used (damper actuation only).

2.6.2 Design

Natural ventilation towers/stacks are ideally situated around the building perimeter or nearby to encourage air buoyancy and upward directional airflow causing stack effects. Wind effects and direction are a major factor for differential pressures experienced in each chimney stack, which can have an impact on airflow rates (litres/second). Figure 2.3 below indicates the basic airflow arrangements that can be found in typical mixed mode (hybrid) type building; where ACD is air control damper. The arrows show air flow and direction. Blue arrow signifies cooler air flow (around 19^{o}C) into the building, yellow arrows are internal air flow at around 21-22^{o}C and red arrows signify warmer exhaust air at 23-25^{o}C. The air temperature increase is due to energy absorbed by air from internal building fabric and heat gains. As detailed in British Standard (1991), Bahadori, M (1984) and Martin, A.J, (1996), for common air delivery to all floors, a central or offset atrium plenum allows air to rise and pass into occupied spaces via internal air control dampers. In the occupied room, both inlet and outlet air dampers will actuate simultaneously to allow balanced air cross-flow to remove polluted air such as human odour, volatile organic compounds, carbon dioxide, human and equipment heat gains.

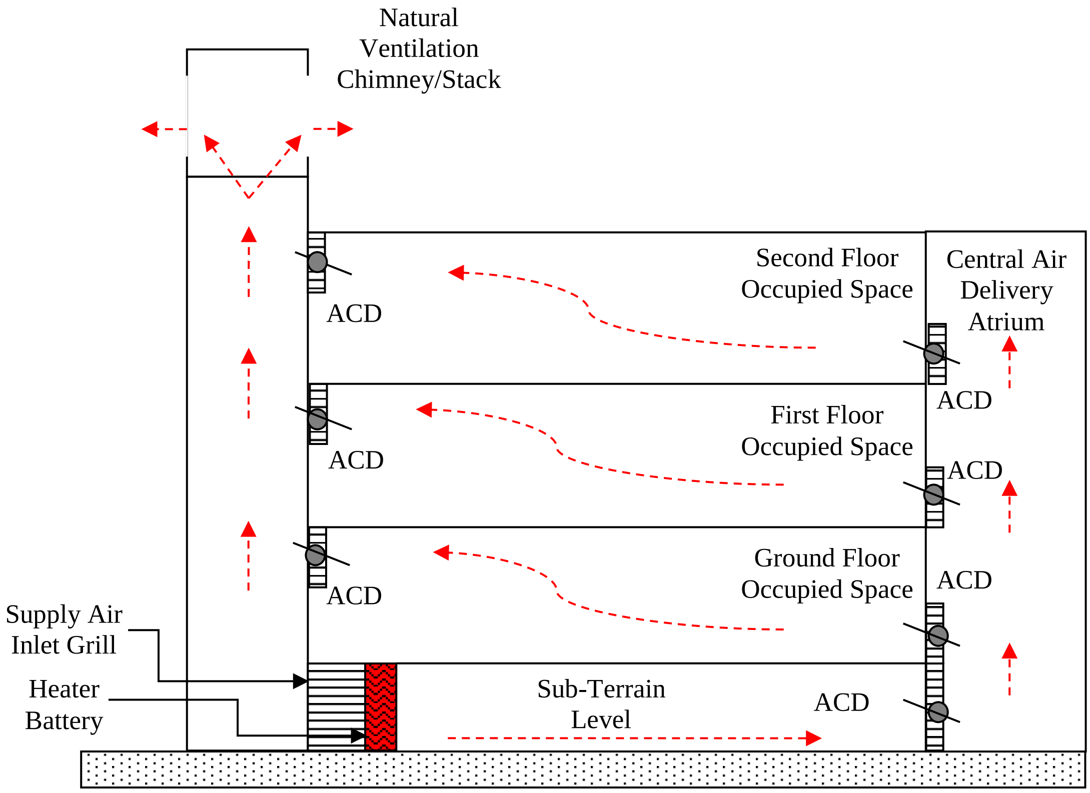


Figure 2.3- Typical Natural Ventilation Strategy

In colder climates, inlet supply air may require preheating using a heater battery arrangement which will increase air enthalpy. Wind effects at lower levels are particularly important as without external pressure in the right orientation, stack-induced effects will be solely relied upon. For larger more complex natural ventilated buildings, general configurations are based around a central atrium (full height) and cellular spaces connected via low/high-level dampers/windows to the atrium space.

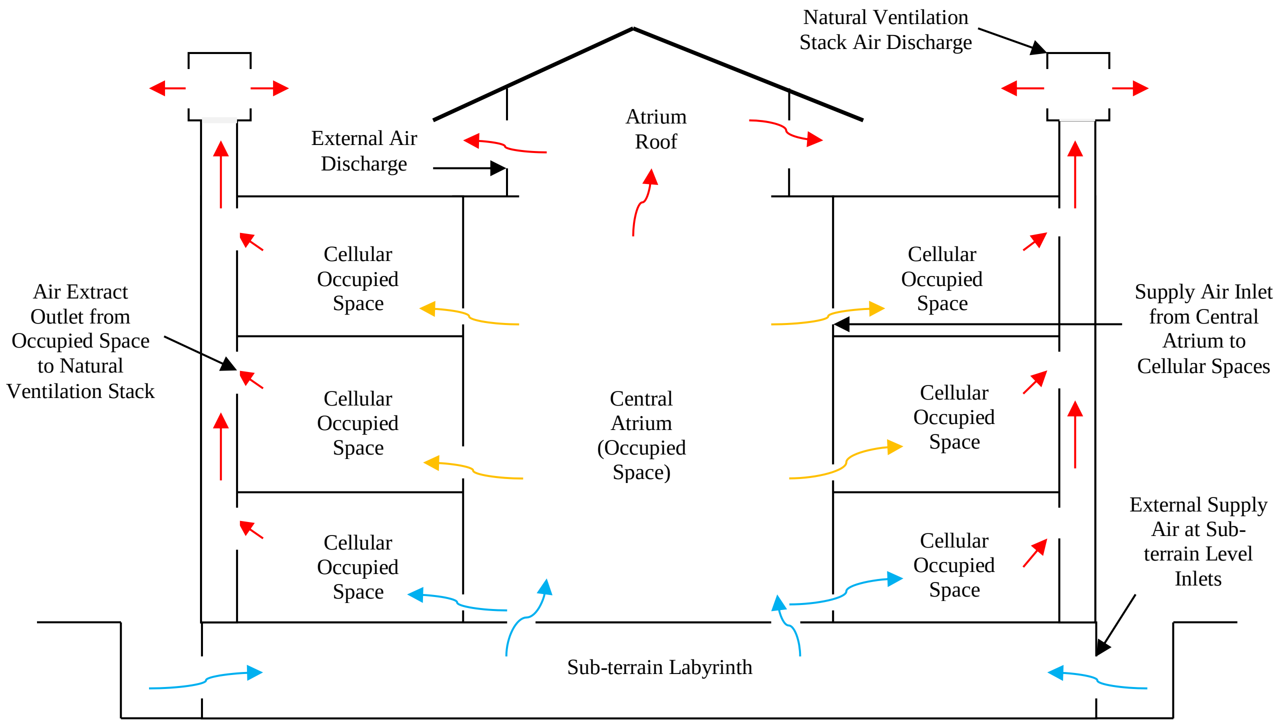


Figure 2.4- Basic Principles for Naturally Ventilated Building Geometry

For general natural ventilation using a central atrium for fresh air delivery (Figure 2.4), external air will flow via sub-terrain labyrinth a central atrium, where air will flow upward naturally through dampers into adjacent cellular spaces. Two types of control philosophy are used for each type of model depending on whether ventilation or cooling is required. Design of internal geometry as the internal structure must be carefully considered and designed (ideally) around a central core or atrium as analysed by Krausse et al. (2007), Short et al. (2009), ENoB (2011) and Svensson (2011). As general guidance, should the rooms exceed 24℃ or 1200ppm CO_2, the building energy management system (BEMS) should activate. Many existing buildings constructed in this manner have proven to be very successful such as Lancaster Library, Coventry University (England) (Krausse et al., 2007) and University College London School of Slavonic and East European Studies (Svensson, 2011).

2.6.3 Critical Review of Annual Performance

Case studies and papers have identified that during handing over periods a great deal of attention is required to ensure strategies and systems are performed as envisaged at the concept design stage. Many issues appear to be related to the BEMS and actuator device's integrity. It has been shown that a 12 to 24 month period is required to ensure system compliance is sought (Svensson, 2011). External air is transferred via motorised dampers, which are initiated by local control sensors in rooms via BEMS. Companies such as Trend and SSE controls design and supply such devices to suit building requirements based on desired airflows through low and high level apertures.

When reviewing domestic residences in hot climates using natural ventilation, a case study completed in Thailand, a tropical wet climate, Tantasavasdi et al., (2007) identified that increasing the area of a natural air ventilation opening to 20 per cent of functional floor area improves the average air velocity and percentage of comfortable hours when using cross-ventilation. The study also provided further recommendations: large trees can provide a reduced shading area; functional spaces should have at least two openings in walls; the separation distance between vents should be as far as possible to prevent short-circuiting.

For examples of naturally ventilated buildings (general case studies), refer to Appendix A.2 to A.6.

2.7 Solar Chimneys

2.7.1 Description

A way to enhance natural ventilation is to increase thermal gains to chimney stacks in order to increase air buoyancy as it flows out of the exit aperture. This is achieved using solar (Thermal) chimneys as these have one transparent (glass) or opaque (highly absorbent material) side, usually south-facing, to capture a maximum amount of solar heat in order to raise the internal wall temperatures of the stack. As air flows into the chimney from the occupied space, e.g. 24°C, air temperature can be increased further as it gains thermal energy from the solar chimney stack.

2.7.2 Design

The main aim of a solar chimney is to increase air buoyancy and air velocity by ensuring the maximum amount of heat gain can be achieved. The transparent surface or opaque black body should be designed to maximise solar heat absorption. The basic configuration is shown below in Figure 2.5 which shows the location of the opaque/transparent surface where it encourages heat gains into the chimney stack. This figure shows the type of surface, which is south-facing, will affect the solar chimney's wall surface temperatures. The higher the wall surface temperature, the greater the air buoyancy and air velocity. Control of the stack will be identical to natural ventilation where automatic control dampers are regulated by the BEMS. These control airflow based on room air temperature (>24°C) and carbon dioxide levels (>1500ppm).

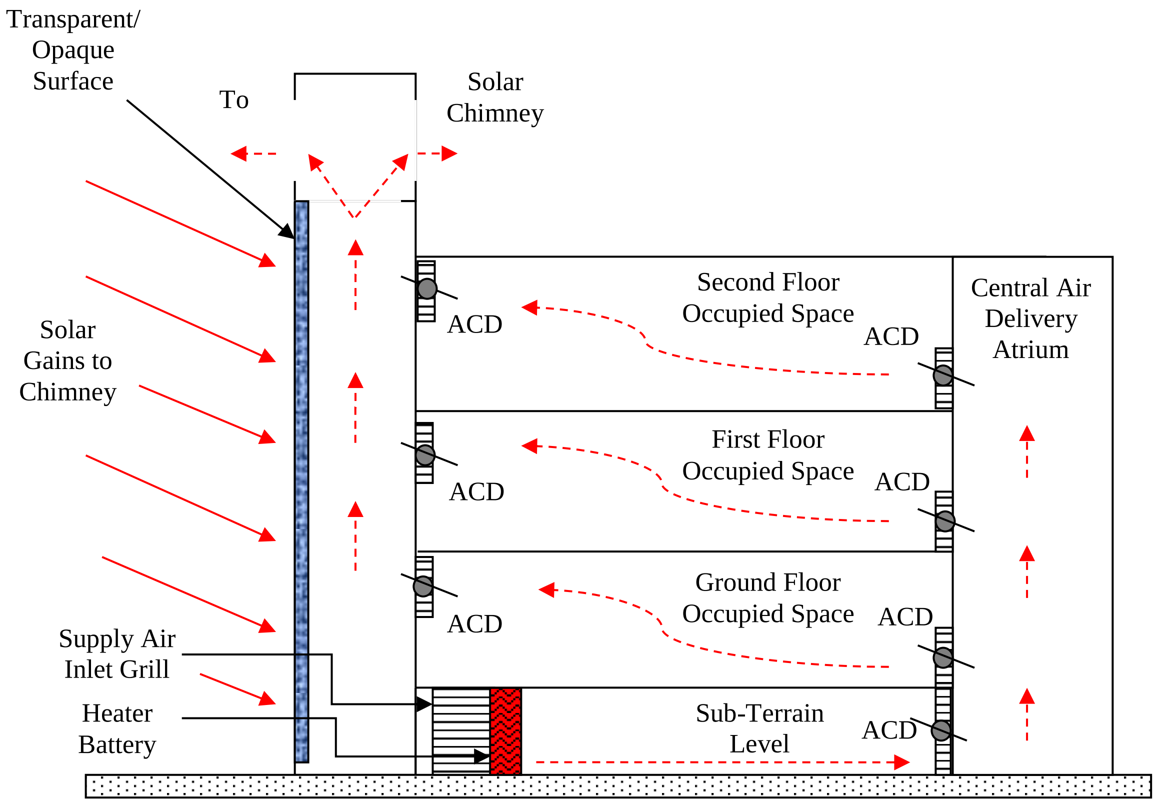


Figure 2.5- Solar Chimney and Natural Ventilation Strategy

2.7.3 Critical Review of Annual Performance

One factor affecting solar chimneys is the height of the building. As discovered by Chatzipoulka (2011) via the use of WinAir software for Computational Fluid Dynamics (CFD) analysis, for a greater number of floors, a rate of air backflow is created at the upper inlets of the chimney stack. Additionally unequal airflow distribution also occurs at the upper stack levels.

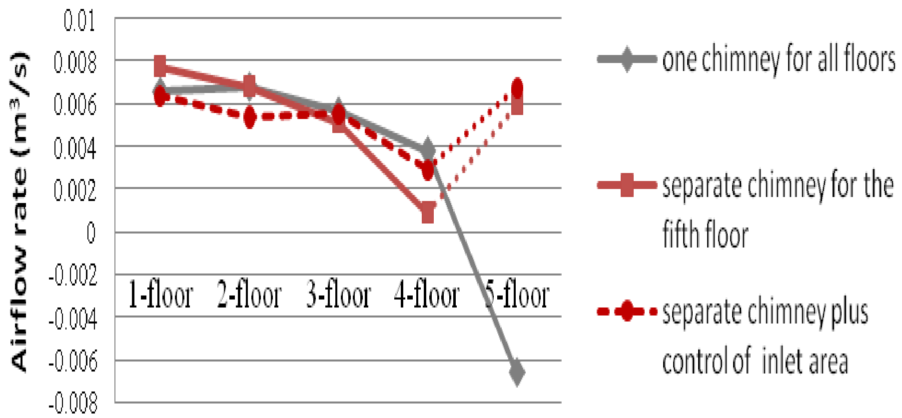


Figure 2.6- Airflow Rates at Each Floor of the Five-storey Model Applying One Chimney; Providing Separate Chimney for the Fifth Floor; and as Previous but with Inlet Area Control (Chatzipoulka, 2011)

From analysis of the results shown in Figure 2.6, one solar chimney was insufficient for beyond the fourth-floor level (approximately 12-16 meters) and additional separate chimneys had to be provided. This was to maintain upward airflow rates to the fourth and fifth floors. This also appears to have some level of optimisation with the provision of air inlet control, which raises the airflow by 0.002m^3/s.

For examples of solar chimney (general case studies), refer to Appendix A.7.

2.8 External Solar Shading

2.8.1 Description

Solar shading comes in many shapes and form, such as external fixed, external automated, internal blinds or automated blinds. These consist of long rectangular angled strips of a given depth and angled within a purpose-made support frame placed in front of windows which are consistently exposed to the sun. The purpose of such a device is to minimise solar heat gains without adversely affecting daylighting effects through the windows. When considering the design of external façade fixed solar shading, the aesthetic qualities at human eye level are a major factor and design can generally be influenced more by architects and how they envisage the building will look. The variety is practically unlimited and materials such as wood, aluminium and steel are used to create shapes that enhance the visual impact of southern-facing facades while minimising solar heat gains and optimising daylighting, and if implemented correctly, provide effective glare control.

2.8.2 Design

For a low-cost form of daylighting and glare control, internal room blinds are used and can be decorative or functional depending on the interior design. The negative impact of this system is that solar gains cannot be substantially reduced, as a percentage of radiant solar heat gain is transmitted through the window pane, depending on the U-value, is absorbed into the blind device and re-radiate into the interior space. Automated controls can be incorporated into either type of shading device via BEMS hence providing a level of autonomy and minimising human interaction.

To design effective external solar shading devices, selected devices should be opaque, have minimal thermal conductivity, and preferably be 0W/m^{2}k with a suitable overhang depth (O_D). Common forms of shading device types are shown below in Figure 2.7 based on Windows and Daylighting (2013), which appear to be basic common configurations. Furthermore, Figure 2.6 also shows the relationship between the overhang depth (OD) and window height (W_h), where the greater $O_{D,}$ the greater the reduction of solar gains and daylighting (directly proportional). The shading devices are angled at a maximum cut-off angle of 45 degrees (Lieb, 2001) with effective window height (Ewh) maximised (CIBSE, 2006).

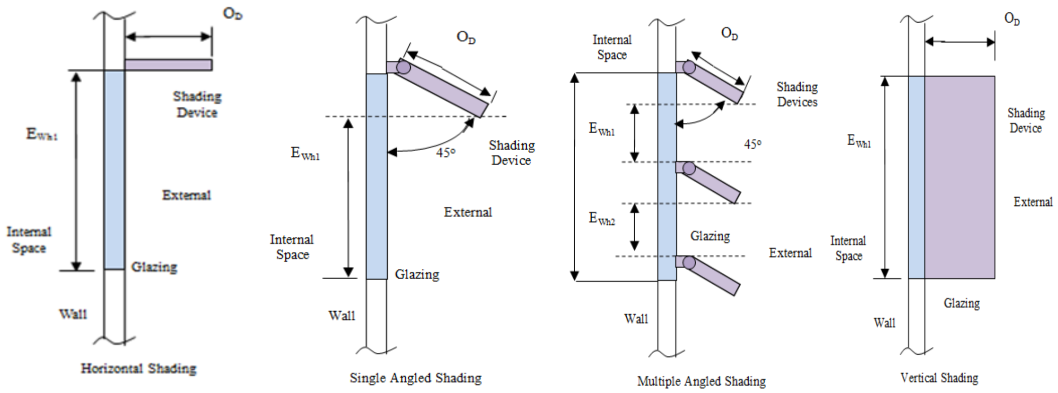


Figure 2.7- Common Forms of External Solar Shades (Brittle. et al, 2013)

The primary function of a solar shade is to reduce direct solar radiation through windows and glazing on eastern, southern and western elevations as much as possible via one of the methods shown in Figure 2.7. The general principle is that a greater reduction in effective window height means higher solar heat gain reduction. The negative impact is the reduction in daylighting contribution (daylight factor) increasing the need for artificial lighting and electrical energy consumption.

2.8.3 Critical Review of Annual Performance

Solar shading for solar heat gains and daylighting can be described as being indirectly proportional, i.e. the more shading that is required, the greater the day lighting contribution is reduced. Solar shading devices offer energy savings during summer periods by limiting short-wave radiation effects. The negative impact is that this will deflect wanted solar gains for cooler seasons (autumn/winter). As noted by Walliman and Resalati (2011) in their review of solar shading devices based in Shiraz, southern Iran, the maximum temperature is 37°C in July and 11°C in January (annual average temperature 24°C). Solar shading devices using 20cm horizontal louvres provided a 32 per cent saving in cooling load with 2 per cent less with vertical louvres. From this analysis, a 42 per cent saving could be realised but the authors were unclear about their proposed shading model (material, length and position) within their simulation (IES VE), which raises a question about the validity of the analysis completed (Walliman and Resalati, 2011).

With regards to incorporation and optimisation of solar shading within ventilated double facades, shading device locations are ideally one-third of the depth of the façade cavity with adequate ventilation to the space above and below. Additionally, it should not be located too close to the glazing’s outer panes as this would cause build-up of excessive heat in this layer. Determining the most effective position is very difficult at the planning stage (Lieb, 2001) as façades lack sufficient detail at this stage.

For examples of external solar shading (general case studies), refer to Appendix A.8.

2.9 Ventilated Double Facade

2.9.1 Description

Ventilated double facades provide a full-height ventilated space to allow solar gains to be captured with a percentage of solar heat energy received ventilated out of external louvres at a high level. This passive system is generally comprised of two glazed sections with a significant air gap to allow natural ventilated air to increase in temperature and circulate out of the upper outlets. These can also incorporate solar shades, which also reduces daylighting. Loncour et al. (2004) classify different types of double ventilated facades in terms of natural ventilation, mechanical ventilation and mixed mode (hybrid) ventilation.

2.9.2 Design

For the design of the ventilated double façade, Figure 2.8 shows outer pain which is normally glass and inner pain which is also glass to allow light penetration into a space. The low level and high level outlets are shown and red arrows indicate how air flows vertically from lower to upper inlets. For summer conditions the inlets/outlets are open and winter periods these are closed.

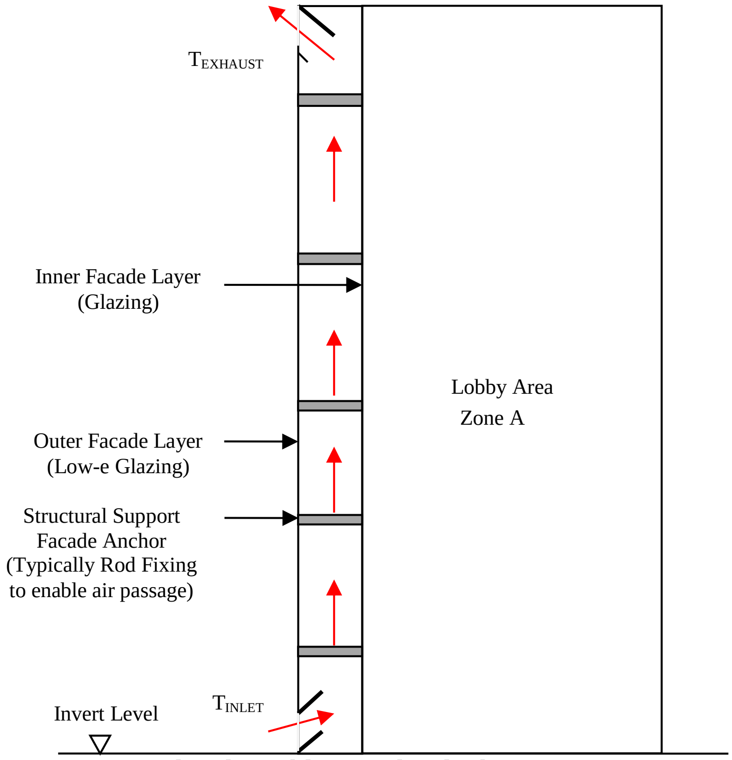


Figure 2.8- Ventilated Double Facade Block Diagram (Section View)

To further reduce solar heat gains into a space, ventilated double facade systems are employed using natural stack/wind effect (individual or combined) mechanisms to reduce the amount contributed into the atrium space. As detailed by Loncour et al., (2004), the next consideration is partitioning of the cavity, for example;

1. Depth of the façade which can be achieved by ventilated double windows;
2. Ventilated double facades, inner partitioned (full height) with opaque module i.e. internal shading device.

2.9.3 Critical Review of Annual Performance

Ventilated double façades are particularly effective as they encourage entrapment of solar heat by displacing the solar energy by natural means (convective air heat transfer) to the external environment, hence preventing large levels of solar heat gain entering the habitable space. Figure 2.9 below provides an indicative sectional cross-airflow arrangement from internal spaces to a double ventilated façade. This is a similar operation to solar chimneys, but is physically larger in comparison covering a complete façade and normally the main building entrance façade.

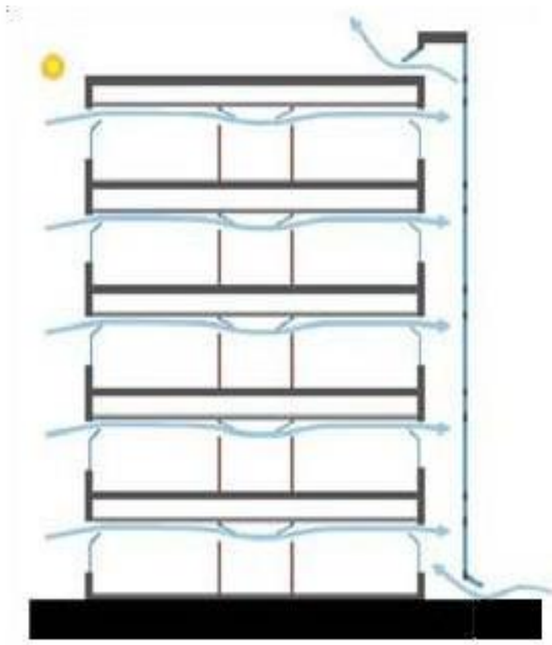


Figure 2.9- Cross-Airflow through an Office Building Using Double Ventilated Façade (Technical University Berlin and Pontificia Universidad Católica de Chile, 2012)

When reviewing these types of systems, Lieb (2001) states that the façade space is divided into two separate functions: solar shading and natural ventilation. The position of solar shading devices must not restrict airflow and day lighting. The size of the space is a contributing factor as smaller spaces heat up quicker. Lieb (2001) identifies the relationship between internal heat gains and window surface temperature as being proportional to each other: '*If sun shading is situated just in front of the inner façade and if the air space between the two is not optimally ventilated, the air in the front of the window can heat up considerably – an unsatisfactory phenomenon, regardless whether the windows are open or closed*.'

Research completed on an office building with ventilated double façades located in Santiago and Valparaiso, Chile comparing buildings with and without a ventilated double facade (VDF) passive ventilation system identified that: *'Simulations showed that double skin is not necessarily an effective strategy for energy efficiency* (Technical University Berlin and

Pontificia Universidad Católica de Chile, 2012).' Analysis of annual energy reduction is shown in Table 2.5 below.

Table 2.5- Cooling Demand to Building With and Without DS Façade (Technical University Berlin and Pontificia Universidad Católica de Chile, 2012)

Case	Santiago Cooling Demand kWh/M^2/Annum	Valparaiso Cooling Demand kWh/M^2/Annum
Case 1. All Windows (Double Skin (DS) and Building (B)) closed.	18.2	17.7
Case 2. Lower and upper DS windows opened. B windows closed.	12.2	11.4
Case 3. DS Windows open 24 hours. Unilateral ventilation 24 hours.	9.5	8.5
Case 5. DS Windows open 24 hours, Cross-nocturnal ventilation with 10% opening of B windows.	7.2	5.7
Case 6. Building without DS façade and with solar protection for north-orientated windows and nocturnal natural ventilation.	5.3	3.6

For examples of ventilated double facades (general case studies), refer to Appendix A.9.

2.10 Rainscreen Ventilated Façades

2.10.1 Description

Rainscreen facades are ventilated external cavities that protect the building envelope against external weathering, in particular rain. The second function provides protection against solar heat gains where the heat is conducted from the exposed outer board into the ventilated air cavity (natural). The façade can be applied to new and existing buildings comprising a weatherboard outer layer, central cavity air gap and insulation. The system is supported by a sub-frame and is available in different finishes such as cladded panels, bricks, ceramic tiles, sealed fibre board, reconstituted stone board and ceramic granite. This system also prevents interstitial condensation.

2.10.2 Design

Figure 2.10 below shows a basic cross-section of the rainscreen facade. The lower wall level is usually a hardened surface (damp course) such as brick, which can vary from 0.5 to 3 metres depending on the facade detail.

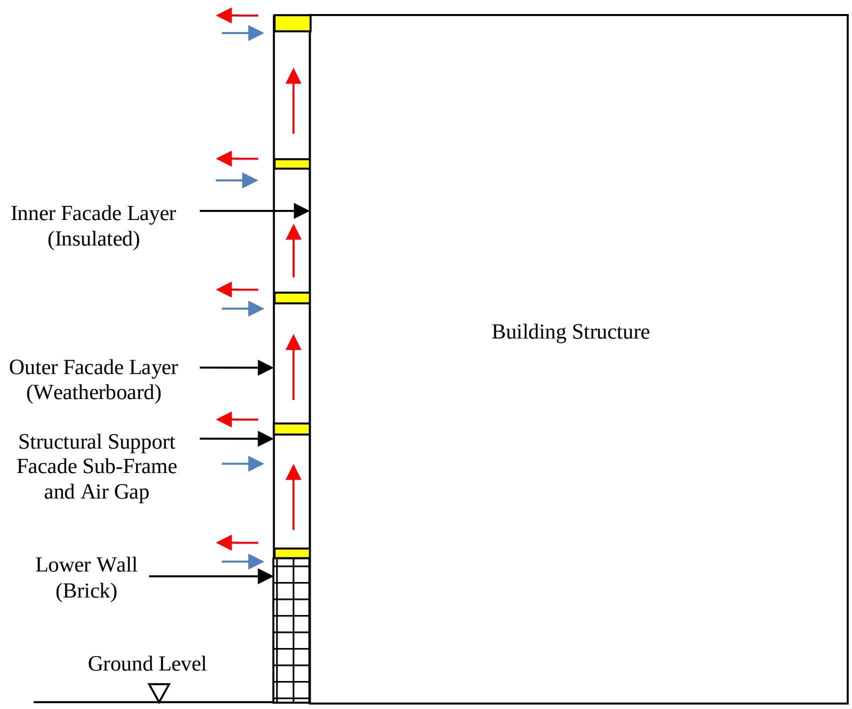


Figure 2.10- Rainscreen Facade Block Diagram (Section View)

The elevation is covered by the rainscreen facade with windows cut out of the weatherboard panels to allow sunlight penetration. Once insulation is applied to the outer wall of the building structure, rectangular weatherboards are applied to a steel frame with a specified cavity air gap and gaps between boards to allow natural air convection. The arrows in the Figure 2.9 show the airflow direction between the weatherboard air gaps and hot air rising upwards and out of the facade. The weatherboard is simply plywood with a PVC coating to prevent water absorption and panel mis-shaping (warping).

2.10.3 Critical Review of Annual Performance

Marinoscia et al. (2011) completed a study using rainscreen façades with a 24-cm air cavity that was dimensioned and fixed to a test building (2.89m wide, 2.89m long and 7.75m high) located in San Mauro Pascoli, Forli'Cesena, Italy. The tests were completed in March to assess implications of rainfall against thermal transmissivity. The structure had steel profiles and a wooden floor with the wall consisting of three layers: the external layer was stone cladding, then there was a 24-cm air cavity and then the rain screen cladding. As shown below in Figures 2.11 below, laminated board and insulation are provided to the external building façade allowing an air gap between the laminated board and insulation. The principle mechanism is to deflect rain water with the second function to reduce solar admittance through the wall structure. The air gap allows vertical air current (outside air at low-level inlets to high-level discharge outlets) to flow removing an amount of transmitted heat from the laminated board. This also helps reduce heat losses in the winter periods.

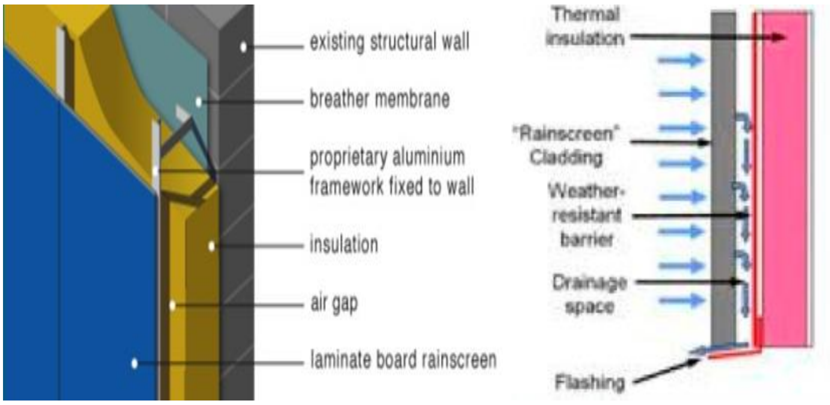
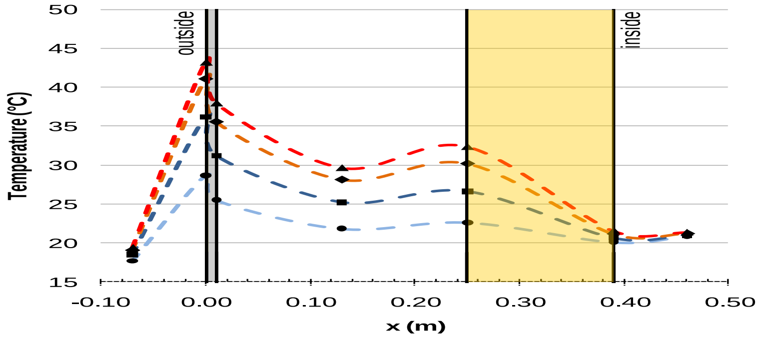


Figure 2.11- Rainscreen Façades 3D Graphic and Rainscreen Façades Cross-Section (Archiexpo, 2012)

From a dynamic modelling viewpoint, the air cavity (cavity back ventilation) requires a correlation to be derived to account for temperature difference (Marinoscia et al., 2011): *'Since the air cavity is being treated as a set of thermal zones, the heat transfer coefficients used by ESP-r for the inner surface of the air channel are the same as for room inner surfaces. These coefficients have been computed by using the Alamdari-Hammond correlations [20] as a function of the temperature difference between the surface and the room air (ΔT) and the surface height (H)':*

$$h_{c,I} = \left[\left(1.5 \cdot (\Delta T/H)^{0.25}\right)^6 + \left(1.23 \cdot (\Delta T)^{0.33}\right)^6\right]^{\frac{1}{6}} \qquad \text{Eq. 2.1}$$

The equation shows that, '*In the numerical simulation, it was verified that the results obtained by means of the airflow network model are very sensitive to the discharge coefficient C_d* (Marinoscia et al., 2011)*.'* This reinforces the point that discharge coefficients must be optimised according to the performance of the internal space. Adjustments via motorised air dampers could enhance airflow further by using dampers with high-level discharge coefficients. Figure 2.12 and 2.13 below shows temperature in relation to physical façade depth and incident solar radiation for calculated performance. The graph shows that as the solar gain increases during the day, the mid-air cavity gap has a lower temperature compared with outside ambient air temperature; the maximum value shown for solar radiation gain of 733W.m^2 indicates that the internal temperature converges (slight deviation) with other times/solar gains stated.



	Solar Radiation (W m^{-2})	Wind Speed (m s^{-1})	Air Cavity Velocity (m s^{-1})	Time (hh.mm)
—●—	462	0.68	0.37	10h30
—■—	596	1.69	0.11	11h30
—◆—	692	1.63	0.21	12h30
—▲—	733	1.44	0.16	13h30

Figure 2.12- Trend of the Average Values of the Measured Temperature and of the Air Cavity Velocity of the South Ventilated Wall for Different Hours (28th March 2010). Global Solar Radiation and Wind Speed Are Both Reported (Prevailing Wind Direction SW) (Marinoscia et al., 2011)

To provide empirical validation, Marinoscia et al. (2011) produced a graph to compare dynamically simulated values (ESP-r) against measured values which show a variance of approximately 2–3ºC, in particular between 02/01 and 06/01 and 10/01 and 11/01.

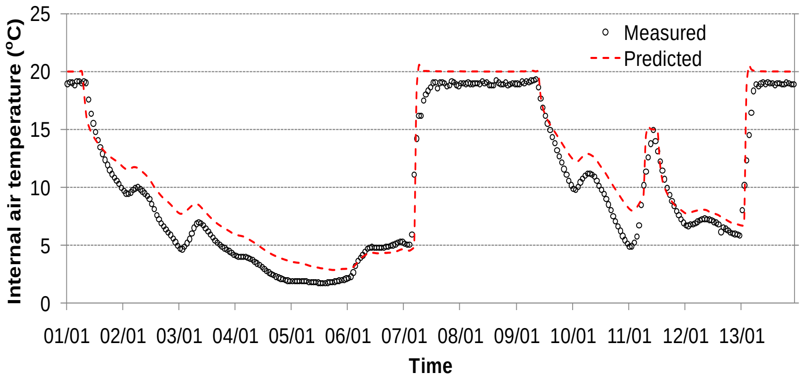


Figure 2.13- Comparison Between the Measured and Predicted Results of the Internal Air Room Temperature (Marinoscia et al., 2011)

It was concluded from the real-time and simulated results that if open ventilation grills are not provided at the top and bottom of the wall there is a large disagreement with experimental results, as the experimental data is strongly influenced by the orientation of the ventilated wall and increasing temperatures are part of exposure to higher solar gains. The air circulating within the cavity varies with larger levels of solar radiation (Marinoscia et al., 2011). From the simulated results, the ESP-r model underestimated external rainscreen surface temperature during night-time periods (absence of solar radiation) and overpredicted the degree of thermal insulation/inertia of the building. This also created uncertainties in thermo-physical properties of materials on the south façade.

For examples of rain screen façade (general physical application), refer to Appendix A.10.

2.11 Passive Downdraught Evaporative Cooling (PDEC)

2.11.1 Description

Passive downdraught evaporative cooling (PDEC) is the use of micronised water vapour sprayed into warm air in either a tower or high-level central atrium. Water is treated and stored locally for use when required. Water micronising control is particularly important as too much moisture content in the air increasing relative humidity and may cause rain.

2.11.2 Design

PDEC systems are designed by installing a number of water micronisers at a high level below the air inlet apertures. The tower is sized to suit the desired cooling load and airflow requirements. At the base of the tower is an automatic control damper and condensation drain. A water tank (chlorinated) can be positioned internally or externally to the building with an outlet pump set. This system uses natural mechanisms of water moisture absorption in dry air called latent heat of water vaporisation (2,260kJ/kg) creating a negative buoyancy effect where cooler air flows in a downward direction in central core areas of a building such as a central atrium (supply air plenum for natural ventilation). Water is injected at a high level via micronisers at typical rates of 6 litres per hour at 60µm, at a velocity of 30m/s at 60–70 bar, injected into air temperatures exceeding 24ºC. These quantities will vary depending on external air temperature, size of openings, internal heat gain and solar heat gains.

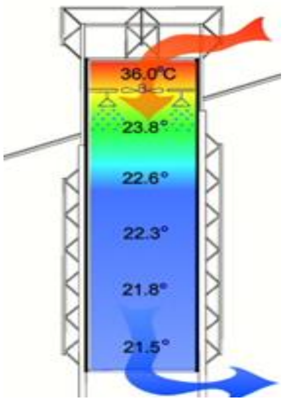


Figure 2.14- PDEC Airflow and Temperature Process
(Ben-Gurion University of Negev, 2012)

Figure 2.15 indicates how water vaporisation reduces upper level inlet air temperatures and creates negative buoyancy within the tower stack, the reverse of the natural ventilation process. The issues encountered are higher levels of humidity from the process with legionella bacteria growth and condensation, causing a real problem for structural integrity and human health.

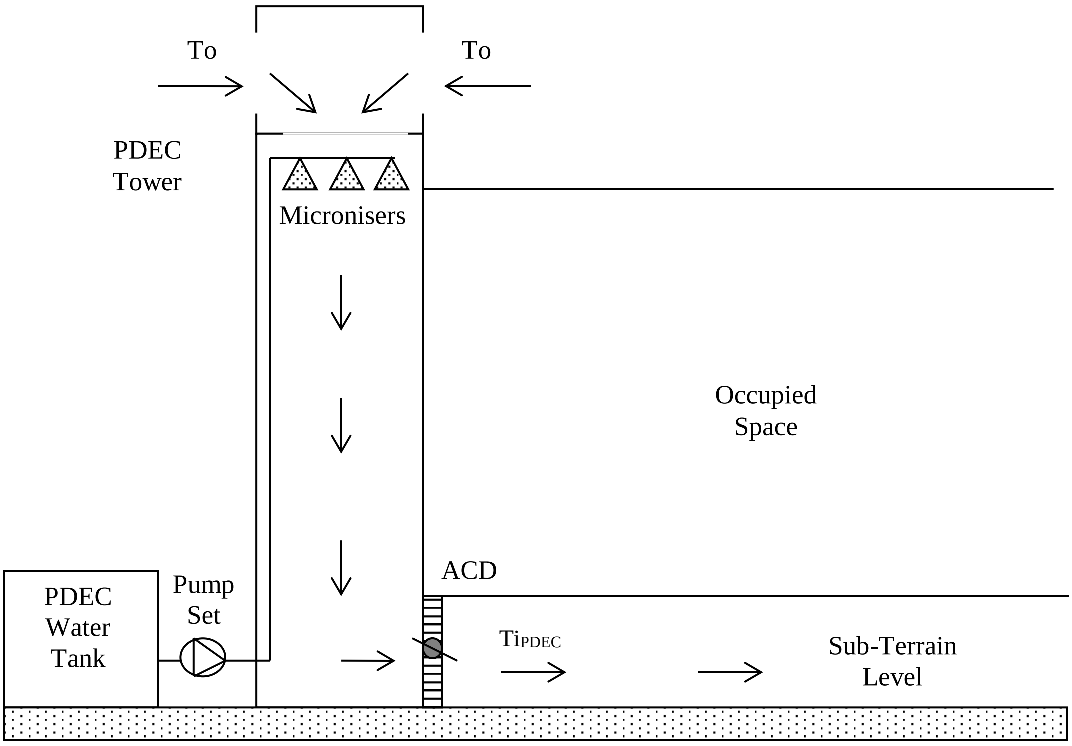


Figure 2.15- PDEC Parameters

As shown in Figure 2.15, vaporised water is absorbed into hot air making it denser and causing negative buoyancy within the tower. Figure 2.16 shows a section of basic operation principles for this PDEC tower system.

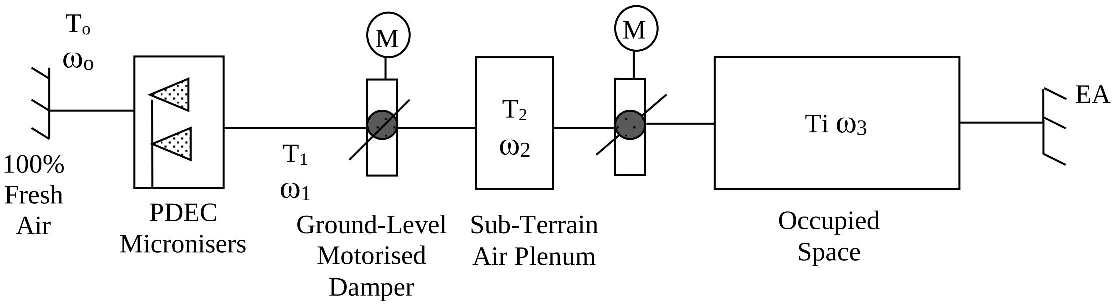


Figure 2.16- Line Diagram of PDEC Tower Systems

Table 2.6 below shows the design parameters for the PDEC system, as empirically tested by Bowman et al. (1998):

Table 2.6- PDEC System Parameters for MCA Design System (Bowman et al.,1998)

Microniser orifice Diameter (mm)	Compressed air pressure (Bar)	Water flow rate per hour (Litres)	Water spray delivery (microns)
0.2	70	6	1

2.11.3 Critical Review of Annual Performance

A case study, completed by Phillip (2011) to improve residential cooling (detailed in Figure 2.17) shows a significant difference between the base case, i.e. natural ventilation only, and final case of using a PDEC system. This graph indicates a peak temperature reduction between June and July of approximately 15°C where peak temperatures are 46°C for natural ventilation and 31°C for PDEC (approximate).

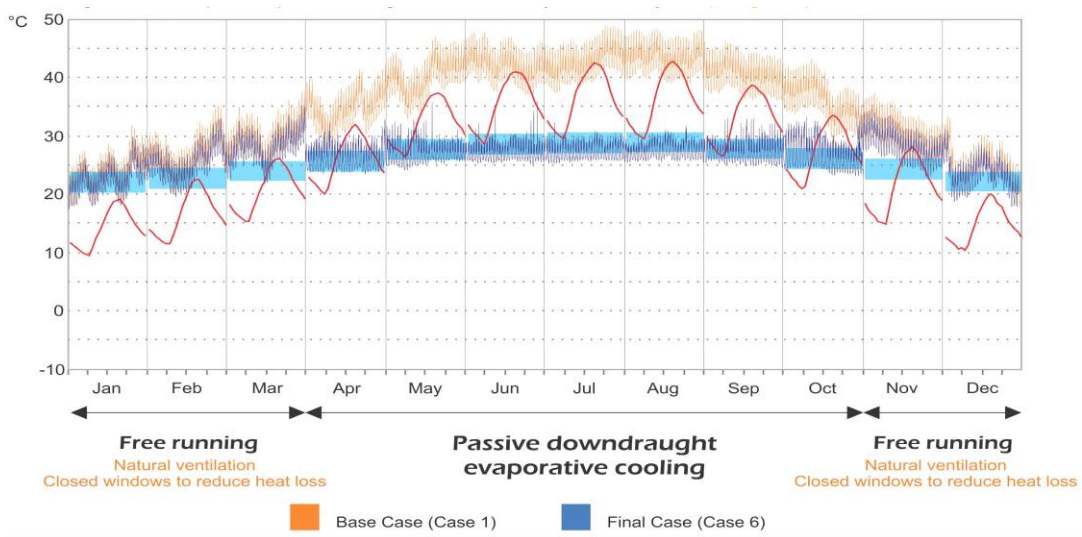


Figure 2.17-Annual Internal Temperature Profile of the Lounge Space (with and without PDEC system) (Phillip, 2011)

The graph in Figure 2.17 also shows a significant temperature reduction from the PDEC system and Phillip (2011) states: *'Apart from the cooling potential demonstrated in the study, it has the added advantages of a significant reduction in building energy consumption as well as CO_2 emissions.'* Phillip (2011) provides the following recommendations for PDEC systems:

- Cooling loads from equipment could be reduced even further if more efficient equipment and low-energy lighting are used within the building.
- PDEC systems have a huge potential for energy savings and there is scope for the introduction of renewable energy technologies (particularly solar energy) to offset the energy demands required to maintain operation of this system.

To show how effective PDEC systems are in terms of annual energy consumption, a study completed by Bowman et al. (1998) for commercial offices located in Seville, Spain and Catania, Italy, showed the following predicted energy savings (Table 2.7 below):

Table 2.7- Predicted Annual Cooling Energy Demand Using PDEC System (Bowman et al. 1998)

Parameter	Office Location: Catania, Italy	Office Location: Seville, Spain
Air Conditioning Annual Energy Cooling Load (KWh/M^2)	28.5	23.8
Air Conditioning Annual Energy Cooling Load with PDEC Support (kWh/M^2)	20.9	8
Percentage Saving for Each Location (%)	26	66

For examples of PDEC (general case studies), refer to Appendix A.11.

2.12 Earth Ducts

2.12.1 Description

Earth ducts are simple heat exchangers that transfer heat from external air to the ground via convective and conductive heat transfer mechanisms. Air is cooled down as it makes contact with the internal surface of the duct, which has a lower temperature, before entering its required destination within the air delivery plenum (sub-terrain) or occupied space. These ducts are large in diameter, around 900mm, allowing horizontal passage of air from an external ventilated column positioned at an appropriate distance away from the building. The airflow path should be as low resistance as possible as only natural ventilation is used. The aim of the earth duct is to reduce the incoming air temperature as much as possible by passive means. These also need drains to allow for condensed moisture from the air.

2.12.2 Design

The design of this passive system is relatively simple: select an earth duct and material type (clay or concrete) then determine the required depth and length of each earth duct. The horizontal length is important as the longer earth tubes, the greater the cooling capacity due to the increased contact surface area. The negative impact is the pressure drop, hence large diameter tubes with smooth internal surfaces are used. The earth duct column can vary in design but is usually about 2 to 3 metres and rectangular with large grills on all four orientations (N, E, S and W). This facilitates the effects of wind pressure and maximises airflow. On the opposite end, these can connect either into a sub-terrain level where air is supplied into an air handling unit as pre-conditioned or directly into a space controlled by dampers or part of a natural ventilation system (supply air element).

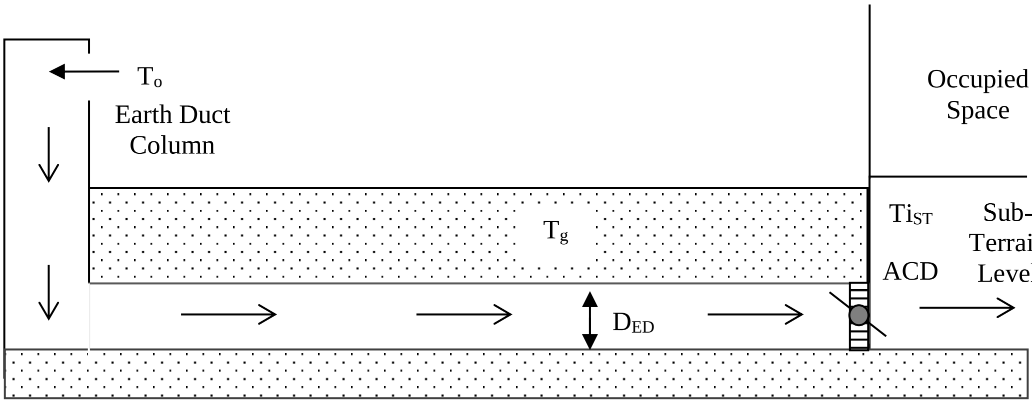


Figure 2.18- Earth Duct Parameters

Figure 2.18 above provides a diagrammatic cross-section of a typical earth duct and identifies the design parameters used. The main variables are earth duct diameter (D_{ED}), constant ground temperature at a given depth (T_g) and volumetric flow rate of air (m^3/s). Control of airflow can be achieved via an automatic control damper, which can be temperature-controlled and automated via BEMS. The thermal conductivity of the earth duct itself is also important but this depends on ground conditions (acidic, contaminated) and mitigating measures should be employed to avoid duct collapse and erosion. As the earth duct acts as a simple heat exchanger (external air to ground), the main parameters influencing the calculation are the external air temperature and convective heat transfer coefficient of the earth duct. Ground temperature has a thermal lag of approximately one month and ground temperature can average from 12ºC at 2 meters and vary from 8ºC to 9ºC at 15 metres (Building, 2013). Ideally, a greater duct depth means a greater rate of heat transfer but this is restricted by practical installation. Installation at these depths becomes problematic with costs and resources creating issues for construction teams. Factors such as volume of excavated soil/matter and time scales will make the decision to make the duct 15 metres deep questionable. This can be avoided as local ground temperature data for areas/provinces can indicate where ground temperatures stabilise. Another question is what is the maximum practical depth required to achieve the desired level of cooling?

2.12.3 Critical Review of Annual Performance

For Butterfield Business Park (Building, 2013), there was an expectation that a certain performance would be achieved: '*The expected energy savings over conventional air-conditioning systems are quite considerable. A typical fan-coil air-conditioning system can consume about 225kWh/m^2 a year for heating, ventilating and mechanical cooling. Atelier Ten believes the earth duct approach could bring the Butterfield complex down to 45kWh/m^2 annually. If phase two is fitted with thermal wheels, energy consumption could perhaps drop to 28kWh/m^2.'* This article was written at the project completion, which was during the autumn/winter period, and there is no data or published literature to state how the earth duct performed in the summer period.

Issues highlighted by the construction of this passive system in the United Kingdom lead towards the following design guidance (Building, 2013):

1. The ground temperature is stable at a depth of 2 metres at approximately 13^{o}C throughout the year.
2. Low air velocity (>2m/s) is optimal for heat transfer for ducts between 600mm and 700mm in diameter.
3. Earth ducts need to be at least 100 metres long for significant heat transfer to occur.
4. Turbulent air flow increases heat transfer by 3^{o}C to 8^{o}C for incoming air temperature range between -1^{o}C and 5^{o}C. This would impact the length, i.e. make it shorter in length.
5. Ribbed steel drainage ducts provide a higher surface area but sealing against water ingress is difficult.
6. Concrete drain sections should be porous to aid with supply air humidity control.
7. *'Labyrinths are more expensive than earth tubes, but payback can still be achieved within 10 years* (Building, 2013). *'*

A review of the application of earth tubes led this research to a simplified case study completed in 1993, where Bedales School (Hampshire, England) commissioned a new classroom and study block including a dormitory. The method of cooling was via natural ventilation means only to the auditorium and in order to satisfy the green brief earth tubes were used to cool incoming outside air supplied to spaces (summer time). *'Tube configuration is of four concrete pipes 50-75mm thick, 80meters long and 900mm diameter to be laid two meters apart. The air velocity modelled is 2m/s. This looks near optimal thermally, but cost studies have not yet been produced. The larger-diameter pipes provide a lot of surface contact area for heat transfer and are big enough to crawl through for maintenance. Some aspects, such as the slope of the pipes for drainage and concerns over legionella* (Evans, 1993)*.'* With regards to its potential cooling capacity, Evans (1993) stated that the total cooling capacity available was 50kW based upon an inlet air temperature of 20^{o}C maintaining a supply air temperature of 14^{o}C. The predicted heat gain for the space comprised 32kW from people (400@80W) and 25kW from lights in an evening performance, which means that there was 2kW additional heat gain to counteract. The secondary issue highlighted in Evans (1993) was a 50kW solar heat gain via the structure. This meant that the daytime period peak heat load was approximately 102kW. This highlights that earth tube ventilation cooling has the potential effect of reducing cooling loads by 51 per cent based on the above approximate figures. Empirical data would be necessary to back up this statement as this was not included as part of this analysis (Evans, 1993).

Sanusi et al. (2012) completed an investigation of earth pipe cooling technology as an alternative to air conditioning at International Islamic University (Gombak, Malaysia), in particular for hot and humid climates. Polystyrene pipes were buried 1 metre underground and the temperature drop between the pipe inlet and outlet was compared. *'In this work, air and soil temperatures were measured. At 1 metre underground, the results are most significant, where the soil temperature is 6*℃ *and 9*℃ *lower than the maximum ambient air temperature during wet and hot and dry seasons, respectively. A significant temperature drop was found* *in these pipes; 6.4°C and 6.9°C depending on the season of the year (*Sanusi et al., 2012).' The aim of this work was to optimise the depth of the earth tube, which was 1 metre, and to determine temperature reductions between the pipe inlets and outlets, which were shown to be significant.

For examples of earth ducts (general case studies), refer to Appendix A.12.

2.13 Summary

From this literature search, it appears that minimal research has been completed for calculating energy reductions for passive ventilation and cooling systems, which can be used by architects or building services engineers for similar type buildings. The passive systems highlighted only appear to have reviewed temperature reduction and only a small number show into basic analysis regarding annual energy consumption (quantitative data). A significant amount of work has been completed on individual passive systems using computational simulation and empirical validation for parameters such as temperature/pressure differentials, temperature analysis across thermal boundaries and optimal performance, but this still leaves the question about how passive measures would actually reduce monthly or annual mechanical ventilation and cooling energy for commercial buildings which is clear and concise at early design stages. Generally, it is difficult to identify current trends as no exact design guidance, strategy or calculation tools that are available or can be adopted.

To answer the questions raised in chapter 1 (section 1.2):

- ***What does existing literature provide in terms of design guidance, benchmarks and calculation methods for analysing annual energy performance of passive systems?*** Existing literature provides some basic design guidelines on how passive systems work detailing basic annual percentage reductions of mechanical ventilation and cooling energy. The analysis is limited to simulated/calculated values with regards to actual percentage reductions and no benchmarks appear to be available for passive system or combinations thereof. In some instance kWh/m^2 energy values are provided for specific buildings. Existing research on individual systems is completed to understand temperature reductions with some annual cooling energy analysis but this does not highlight how these can be combined together to further reduce annual energy consumption.

- ***How effective are passive systems in reducing external air temperature before it enters the building?*** Passive systems can be effective in reducing insolation and reducing external air temperature (conductive and convective heat transfer), but calculation methods cannot be readily identified.
- ***What are the key design parameters and limitations for each passive system in terms of practical application?*** Passive system parameters are detailed for each system with a metric but key design parameters are not clearly identified for improving passive system performance and how these can be combined together with HVAC or each other.
- ***What are the maximum ventilation and cooling potentials available for each passive system?*** Ventilation and cooling potentials are available for certain passive systems in terms percentage energy and temperature reductions including some analysis on annual energy values. This is not comprehensive enough to use for different buildings located in various climates.
- ***What is the total amount of HVAC energy saved when using passive systems?*** Some individual passive systems highlighted in literature show how HVAC energy can be saved but a like for like location of building cannot be easily analysed.

As discovered in the above, there is scope to develop this research by completing further for ventilation and cooling energy performance assessment leading to the development of passive system design guidance including performance assessment tools which would aid with the selection of passive systems in a desired climate together providing a quantitative reduction (kWh/m^2/Annum) for HVAC systems.

Chapter 3

Research Methodology

3.1 Introduction

This chapter sets out the research methodology for further energy performance assessment of passive system when incorporating with HVAC systems as required by aims and objectives set out in Chapter 1. The methodology was approached by modelling theoretical base case office building models using dynamic thermal simulations (DTS) located in four hot climates and fundamental analytical methods in order to quantify energy savings when applying passive systems. To achieve these objectives, new DTS building models are created to provide annual base case performance values for mechanical ventilation and cooling energy. Each passive system is analysed according to software capability and available analytical methods to determine percentage energy reduction for a given climate; which is then deducted from the base case models. This includes setting out development of new simplified design guidelines and integration strategies with new passive system energy assessment tools. The approach in this chapter explains how each passive systems energy performance is calculated with results for cooling load and energy compared against simplified theoretical building models (base case). The chapter includes research approach (3.2), base case theoretical commercial building model (3.3), passive system performance assessment (3.4), methods used in chapter 4 (3.5), methods used in chapter 5 (3.6), results analysis and PSEAT development (3.7), design guidance and strategies for passive system incorporation with HVAC system (3.8), research exclusions (3.9) and summary (3.10). Also described is the basis of design for building model creation, test of methodology, simulation tools used, analytical techniques used for performance analysis, climate selection and model verification. DTS and calculation methods are fully detailed for each passive system and developed to form a platform for new simplified design guidelines and analytical performance assessment. Flow diagrams for each passive system show work methods to achieving energy performance which is completed within Chapters 4 and 5.

3.2 Research Approach

It has been identified from existing research detailed in Chapter 2 that there is limited amount of knowledge for generic performance of passive systems with HVAC systems for commercial type buildings located in hot climates. Figure 3.1 flow diagram below shows an overview of this research methodology.

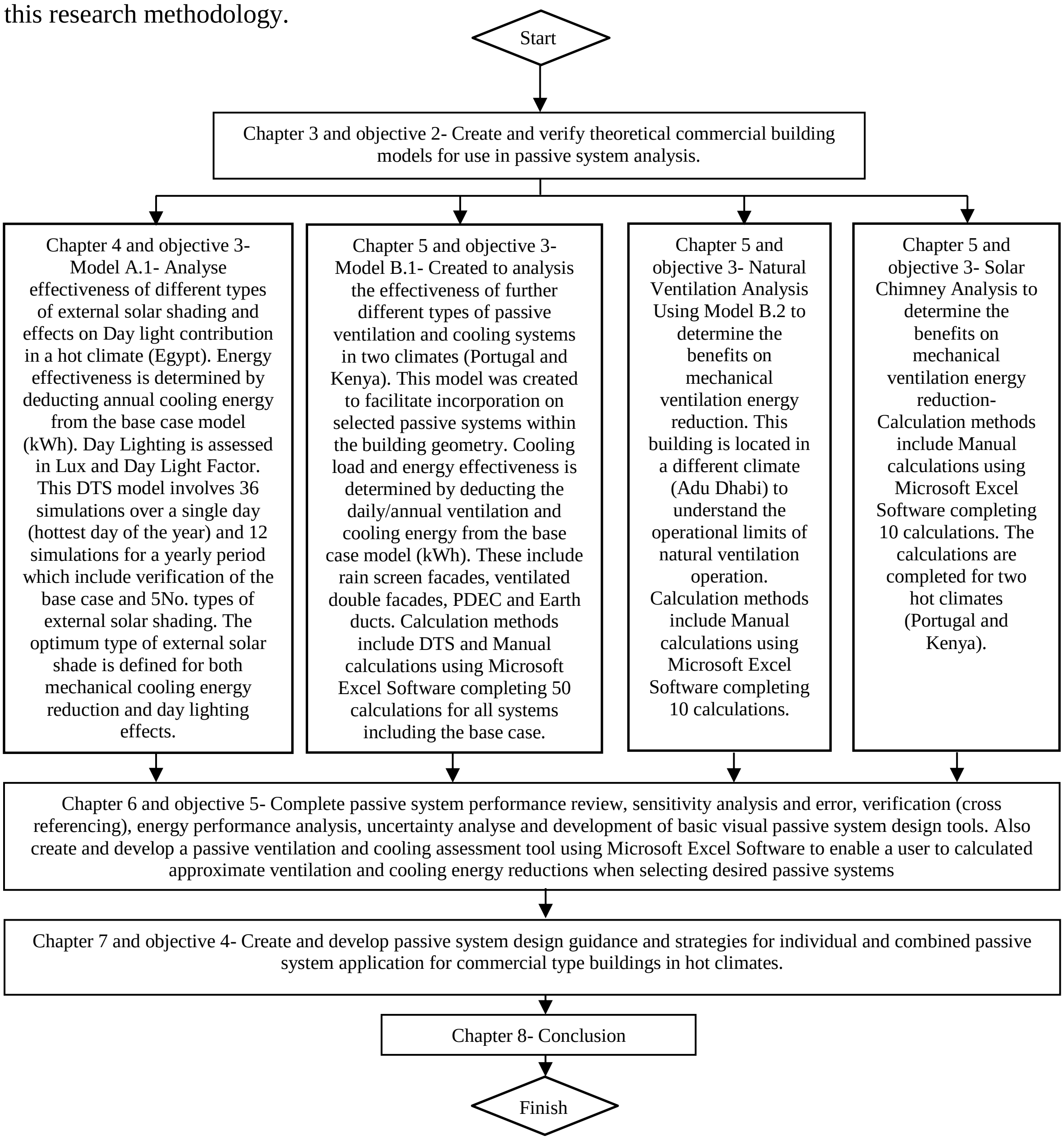


Figure 3.1- Overview Research Methodology Flow Diagram (Road Map)

The combination of these passive systems provides scope for closer examination and assessment. As shown in Figure 3.1 above, an overview of the research methodology is detailed and explains how ventilation and cooling capacities are determined. The depth of this research is shown in Chapters 4, 5 & 6 where performance of passive ventilation and cooling systems are comprehensively calculated using fundamental principles (Microsoft Excel Spreadsheets) or DTS and compared against verified base building models. The aim is to accurately calculate ventilation/cooling energy reducing potentials for each passive system and deduct from the base case model to obtain monthly performance data for different climates selected obtaining approximate percentage reductions identifying differences in performance values. Different climates are selected to provide a broad range of results and allow inter-comparisons to highlight any abnormalities.

3.3 Base Case Theoretical Commercial Buildings (Models)

3.3.1. Overview

Theoretical buildings have been created and based upon existing buildings in the basis of design (Appendix B). Appendix B details four buildings in total used as a basis of design for theoretical building model A.1, B.1 and B.2. For building model A.1, Vantage Point (Summerfield, 2014) and Rozenburg (Archinect Firms, 2014) buildings are described. For theoretical model B.1 and B.2, 1 North Bank (e-architect, 2014) and Verkerk group building (Zeospot, 2014) are described. These buildings use UK Building Regulations (HM Government, 2010a) as a basis of design in terms of thermal conductivity and air infiltration. The impacts of these values would increase cooling load proportionate to the amount of additional solar heat gain and warm air introduced to the internal office space. These new theoretical building models have a base case where a mechanical system is selected and simulated to determine monthly cooling loads and annual cooling energy consumption. The verification mechanisms for all models (Appendix C) are comparing DTS values for mechanical cooling energy performance (kWh/m^2) against current CIBSE (1999), CIBSE (2005), British Standard (2007) and 'benchmarks values' such as BSRIA (2003) and BSRIA (2009) to ensure values are not exceeded. For each passive system, performance values are generated and deducted from the base case models to determine effective reduction of cooling load and monthly energy consumption. These systems are analysed individually and comprehensively analysed in chapter 6.

3.3.2. Metrics for Mechanical/Passive Cooling Performance Analysis

For all theoretical commercial building models, metrics used (SI Units) are energy consumption (kWh), sensible cooling load (kW) and latent heat gains (kW). Sensible cooling load (kW) is analysed in greater detail as this factor has the greatest amount of change from these simulations.

3.3.3. DTS Analytical Techniques

For dynamic thermal simulation of building thermal loads per annum, finite differencing techniques embedded within the software tools (both software programs) have been employed via selected software with general equation shown below (Firth, 2009):

$$^{\theta}m{+}1{,}n = {}^{\theta}m{,}n\ (1\text{-}2K) + [^{\theta}m{,}n{+}1 + {}^{\theta}m{,}n\text{-}1]\ K_f \qquad \text{Eq. 3.1}$$

The above formula', also detailed in section B.2 (Appendix B), is used as basis for the mathematical models a basis for many computer simulation calculations (Software Engine). When using Design Builder software an option for conductive transfer method is available and reduces calculation time. The accuracy of the outputs is reduced by approximately 2-3% when initial simulations were completed. When DTS cannot be used due to software limitations, existing analytical methods will be used to calculate total cooling load potential for selected systems. The formulas used will be detailed further in later chapters.

3.3.4. Software Limitations

Existing energy performance assessment tools such as DTS provide dynamic thermal performance but do not provide a definitive performance assessment method for allowing simulation of passive systems annual cooling energy reduction against a base case model i.e.

dedicated applications for earth ducts, ventilated double facades, rain screen facade. Furthermore, DTS was not completed with co-simulation tools as existing online tools do not match the scope of this research in terms of parameters for reductions required for mixed mode mechanical ventilation and cooling energy performance. CFD tools are also available for finite element modelling (air flow and temperature distribution analysis) however these are not suited to the scope of this study as they cannot provide electrical energy performance values. There appears to be a significant amount of assumption with regard to the reliability of these results and parameters set can lead loads to be easily miss-interpreted or incorrect. This work aims to correct this problem by providing a clear direction/systematic guidance for passive systems and design thereof. Adding more systems such as PDEC and Earth ducts to DTS model is more problematic as direct specific model software applications are not available for modelling hence values obtained are questionable. Furthermore DTS software has many limitations with regards to the simulation of passive systems. These are identified below:

- Inability to control moisture content (g/g) for PDEC system
- Unable to provide buried earth duct conditions
- Inability to allow complex geometric (flexible) ventilation connections and within building geometry
- Rain screen facades cannot be truly simulated and have to be drawn as an extrusion volume with air dampers at the top and bottom of the simulated buoyant air flow

In order to create a passive system, the user must create a model using geometric shapes, windows, grills and openings. To clarify, items excluded from current DTS software packages are detailed below:

1. Dedicated applications for passive system design.
2. Low carbon design functionality and building adaptation.
3. Passive system parameter optimisation feature required.
4. Enhancement guidance for improving building energy performance.

5. Staged system performance analysis i.e. effects of adding additional systems to base case model.
6. Mixed mode ventilation and cooling control highlighting staged changeover limits.
7. Dedicated model functions for creating and optimising solar chimney, PDEC, earth ducts and double ventilated facades.

3.3.5. Modelling of Hot Climates

Location for theoretical building models (A.1, B1 and B.2) is paramount importance to this research and climate data effects underpins core outcomes within this research. The locations selected are detailed in Table 3.1 below. For more information on the origin of temperatures refer to Figure 2.1, Chapter 2. For average relative humidity, values available from ClimaTemps (2016).

Table 3.1- Climatic Characteristics

Location	Country	Climate Type (Figure 2.1)	Summer Time Climate Description	Max/Min Temperature (°C)	Annual Average Relative Humidity Range (%)
Aswan	Egypt	Dry	Hot Dry	45/17.7	26.2
Lisbon	Portugal	Mild	Hot Mild	27.9/8.2	70.8
Nairobi	Kenya	Tropical	Hot Humid	25.6/11	72.8
Abu Dhabi	United Arab Emirates	Dry	Hot Arid	42/11.8	61.3

Peak diurnal analysis, 29th July has been selected as records show this is currently the hottest day of the year for all areas and weather data will be average hourly temperature. The main weather characteristics used by selected weather files are (Exeter, 2016):

- *'Total irradiation on horizontal surface*
- *Diffuse radiation on the horizontal*
- *Daily mean wind speed*
- *Daily maximum dry-bulb temperature*

- *Daily minimum dry-bulb temperature*
- *Daily mean dry-bulb temperature*
- *'Infiltration number' (a function of wind speed and dry-bulb temperature)'*

For building model A.1 simulations, primary model input data which is weather data file is used for Aswan, Egypt weather year (EWY) files converted to 'fwt' by convention in IES VE, which is incumbent to the software. For building models B.1 and B.2, weather data used from Design builder software for Lisbon, Portugal, Nairobi, Kenya and Abu Dhabi, United Arab Emirates is hourly weather data sets TMY2 in the United States and TRY (CEC 1985) in Europe and are denoted as Energy Plus format hourly weather data has extension 'epw' by convention. The simulation time is 1st January to 31st December. These different climates will indicate how each will perform and determine the level impact on internal building conditions when using passive systems. Building Models are based on United Kingdom standards as detailed in section 2.4.5, Chapter 2. As defined by an article on weather data files (The Building Enclosure, 2016) The differences identified between the two weather data set (EWY and TMY2) is that the average period for gathering the data is longer for TMY i.e. single year from the 1948-1975 period of record where EWY is United kingdom based data sampling a 20 year period. It is difficult to identify what exact differences but an assumption could be TMY files would generate more accurate annual energy consumptions as temperatures and weather data are averaged over a greater time period.

3.3.6. Mechanical Ventilation and Cooling System Selection for Performance Assessment

Mechanical type ventilation and cooling systems are limited to the type of software and their respective pre-programmed templates. For each software application, system available is limited to generic systems, which are described below in Table 3.2 (Design builder, 2014 & IES VE 2013):

Table 3.2- Mechanical System Templates in Dynamic Thermal Simulation Software

Design builder (2014) Mechanical Template Available	IES VE (2013) Mechanical Template Available
Constant volume	Central heating using water radiators
Constant volume with DX	Generic Heating only- Electric Resistance
Duel duct VAV	Generic Heating only- other systems
Fan coil unit	Generic Heating and mechanical cooling
Heating and ventilation ducted supply + extract	Central heating using water: radiators
Hot water radiator heating, mixed mode with natural ventilation, local comfort cooling	Central heating using water: convectors
Hot water radiator heating, natural ventilation	Central heating using water: Floor heating
Hot water radiator heating, mechanical ventilation supply and extract	Central heating using air distribution
Natural ventilation-no heating/cooling	Other local room heater- fanned
Package direct expansion	Other local room heater- unfanned
Split + separate mechanical ventilation	Unflued radiant heater
Split no fresh air	Flued radiant heater
Storage heaters, natural ventilation	Multi-burner radiant heater
Underfloor heating natural ventilation	Flued forced-convection air heaters
VAV with fan-assisted terminal re-heat	Unflued forced-convection air heaters
VAV with heat recovery + outside air reset	Central heating using water radiators
VAV with heat recovery + outside air reset + mixed mode	Generic Heating only- Electric Resistance
VAV with outside air reset	Single duct VAV
VAV with terminal reheat	Duel duct VAV
-	Indoor package cabinet (VAV)
-	Fan coil systems
-	Constant air volume (fixed fresh air rate)
-	Constant air volume (Variable fresh air rate)
-	Multi-zone (hot deck/cold deck)
-	Terminal Reheat (constant volume)
-	Duel duct (Constant Volume)
-	Chilled Ceiling or passive chilled beams and displacement ventilation
-	Constant air volume (fixed fresh air rate)
-	Constant air volume (Variable fresh air rate)
-	Active chilled beams
-	Water loop heat pump
-	Split or multi-split system
-	Single room cooling system
-	Active chilled beams

The template provides system options for combining with natural ventilation or separately with natural ventilation as a separated option with both softwares using NCM database. Before completing design and DTS, it is important to select the correct energy efficient HVAC system which is suited to a particular building geometry and climate. For this research, simulated analysis was completed for a number of mechanical ventilation and cooling systems using DTS. Following DTS of various mechanical systems (building models B.1 & B.2), the most efficient cooling system was identified and used as part of this research which is split cooling (Direct expanding) with separate extract ventilation. The results shown in Appendix E rank mechanical systems in terms of annual energy performance. These systems show that energy consumption varies by <1% when comparing split cooling systems with separate extract ventilation and VAV with Outside Air Reset.

3.3.7. Building Model Verification

The theoretical buildings are verified against existing benchmarks and inter-compared with existing similar building types. Figure 3.2 below shows a flow diagram for verification.

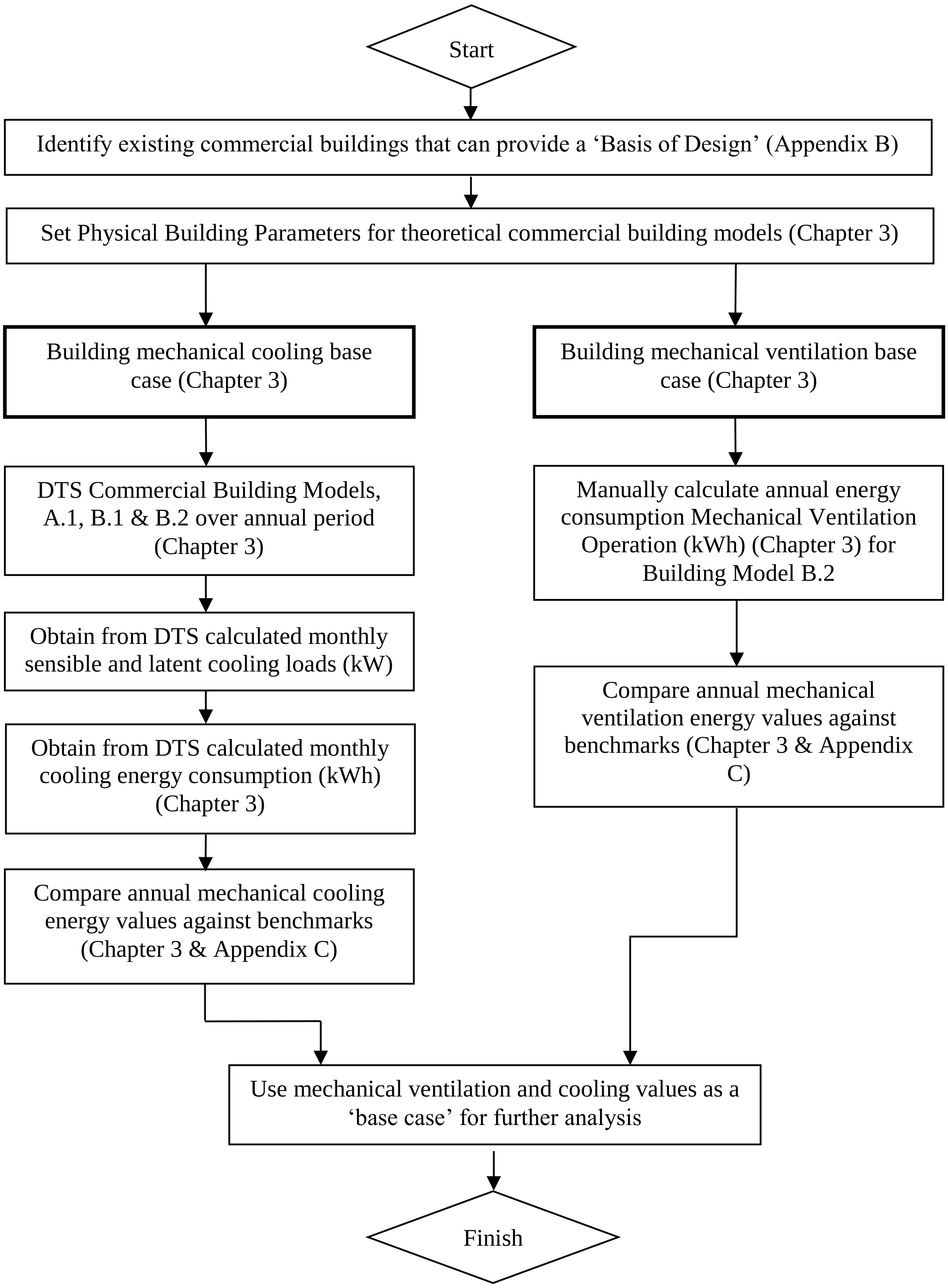


Figure 3.2- Theoretical Building Model Verification Flow Diagram

Figure 3.2 above, shows how the buildings are verified by comparing against country specific benchmarks and similar type commercial buildings in terms of mechanical ventilation and cooling energy consumption. For cooling energy benchmark verification, using Table C.1 in Appendix C, value for maximum cooling load are used to allow a maximum cooling energy benchmark value to be calculated based on an office floor area of 100 m^2 in summary Table 3.3 below:

Table 3.3- Mechanical Cooling Verification Benchmark (Calculated) Summary

Cooling Load ($100m^2$) based upon $87w/m^2$ (BSRIA Table C.1)	Calculated cooling energy kWh/Day based upon 9 Occupied Hours (kW x 9)-kWh/Day	Assumed Average days at 20 Days per Month-kWh/Month	Cooling Energy Per Annum Working Days x 10 Months (10 x 20)	**Maximum Mechanical Cooling $kWh/m^2/Annum$**	Table C.3 CIBSE Benchmark Values (Best Practice Offices)-$kWh/M^2/Annum$	Table C.3 ASHRAE Model Benchmark Values (Medium Offices)-$kWh/M^2/Annum$
8.7	78.3	1,566	15,660	**156.6**	128	117.54

The above calculated value for maximum cooling energy consumption alines with values detailed in Tables C.3, Appendix C. The manually calculated value is -compared with CIBSE and ASHRAE benchmarks and these do not directly compare. However, these values are also dependant on occupied hours which it appears a standard working week would be less than 45 hours. These benchmarks also assume a constant load (transient) where DTS allows for variances in building envelope heat gains (weather data). For this research, calculated values of maximum mechanical cooling energy are inter-compared with DTS models and provide similar correlation in terms of energy performance values. For mechanical ventilation verification against benchmarks, Table D.5 in Appendix D, shows best practice energy performance values.

3.3.8. Theoretical Commercial Building Models

A number of theoretical commercial buildings have been design and created, based upon energy performance benchmarks for model verification (Appendix D), to enable suitable integration and analysis of passive systems. The models are simple single floor type buildings with selected passive system added to its configuration, where possible. Models created will have similar building construction make up and operation parameters. The models created are detailed below:

- Model A.1 used in Chapter 4- Single Storey commercial building for External Solar Shading and effects on daylighting analysis.
- Model B.1 used in chapter 5- Single Storey commercial office building with south façade wall being completely glazed. This to facilitate analysis of ventilated double façade, rain screen façade, external solar shading, earth ducts and PDEC.
- Model B.2 used in chapter 5- Using building model B.1 located in a different climate to test extremes of high ambient air temperature, a natural ventilation and solar chimney.

To show which building relates to which climate, please see Table 3.4 below.

Table 3.4- Building Model and Climate

Location	Country	Theoretical Building Model
Aswan	Egypt	A.1
Lisbon	Portugal	B.1
Nairobi	Kenya	B.1
Abu Dhabi	United Arab Emirates	B.2

Different models have been created to suit the passive system type as well as bring in line with common buildings types as discovered in Appendix B (Basis of Design for theoretical commercial building models). For external solar shading analysis, this type of system is commonly applied to single windows (Appendix B.2). For multiple passive system the glazed facades need to be longer hence building model B (Appendix B.3) have a purely glazed south façade wall to allow ventilated double facades to be added. Other passive systems can easily added to building model B, as necessary. Different climates have been selected to assess the operational parameters of each of the passive systems. For example, Abu Dhabi has constant high dry bulb temperatures and assessment of natural ventilation operation in this environment test the time frame where this system will be effective before HVAC operation is required. For other systems such as rain screen facades and ventilated double facades, two climates have been selected to broaden the range of results and allow inter comparison of calculated energy reductions for mechanical cooling.

3.3.9. Base Case Building Model A.1

Based on typical buildings highlighted in Appendix B section B.2, Figure 3.3 below shows a single storey theoretical model 20x20m was created with a floor to ceiling height of 4.5m, designed as an open plan office. One elevation has three 4m x 2m windows and the north elevation has two wooden doors only. The construction is medium/light weight type.

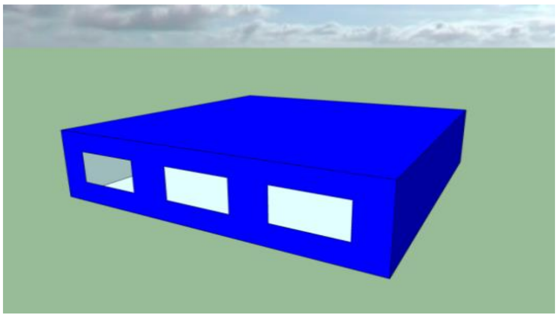


Figure 3.3- Model of Single Storey Commercial Building Under Study

The climate selected is detailed in Table 3.5 below which identifies the maximum temperature and minimum temperatures based on the height above sea level (World Meteorological Organisation, 2012).

Table 3.5- Climate Data for Hot Countries

Location	Altitude (m) Above Sea Level	Max. Temp. (ºC)	Min. Temp. (ºC)
Aswan, Egypt	194	45	17.7

Figure 3.4 shows annual temperature profile for maximum and minimum dry bulb temperatures using IES VE climate data (ASHRAE database).

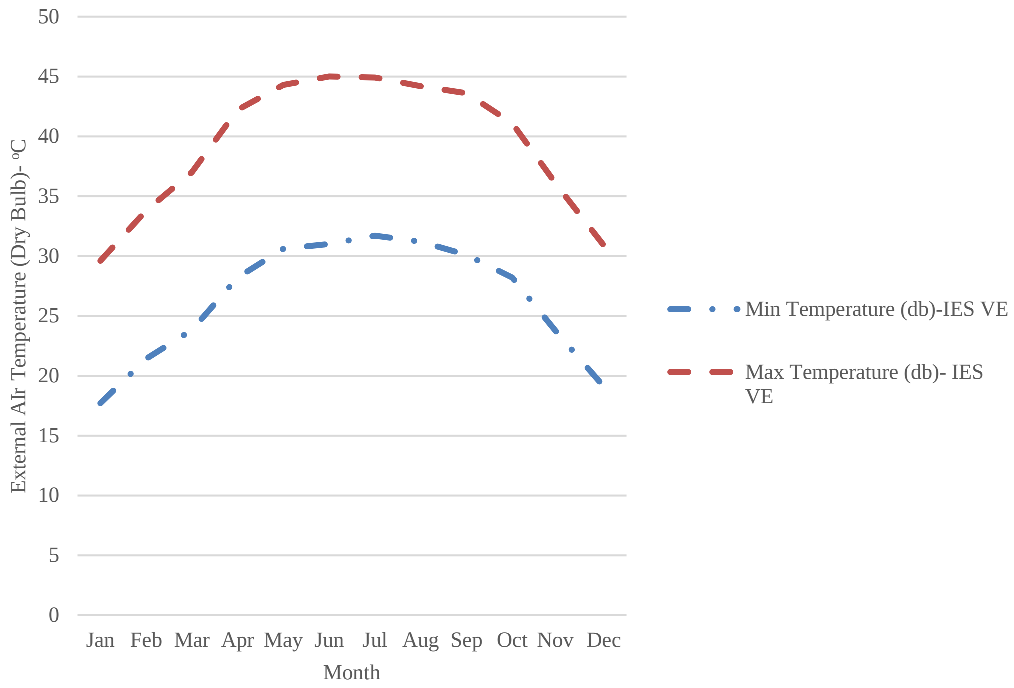


Figure 3.4- Annual Min/Max Dry Bulb Temperature for Aswan, Egypt

For this model, the theoretical commercial building is a simple square box with a flat roof enabling faster simulation times and modifications as necessary to ensure consistency of results. Standard building make up of materials have been made to ensure low U values are achieved and building is sufficiently air tight. For a comprehensive overview of all building materials used including their separate U values, ventilation permeability and heat gains (occupancy and equipment), building parameters are listed in Table 3.6 below:

Table 3.6- Building Model A.1 Parameters

Type	Description
External Walls	Outer Leaf Brickwork, Dense EPS slab Insulation, Concrete Block (medium density), Gypsum Plasterboard and Gypsum plastering- U value of 0.36W/m^2 K
Roof	Stone chippings, Felt/Bitumen Layers, Cast Concrete, Glass Fibre Quilt, Air Cavity and ceiling tiles finish Ceiling- U Value of 0.25W/m^2 K
Floor	Standard Ground, Brickwork (Hardcore), Cast Concrete, Dense ESP Slab Insulation (Like Styrofoam), chipboard and synthetic carpet- U Value of 0.25 W/m^2 K
Glazing	Low e Double glazing 6mm+12mm+6mm Pilkington K glass- U Value of 1.97W/m^2 K; Effective g-value 0.64
Doors	Wooden Doors (Pine) - U Value of 2.20 W/m^2 K
Air Permeability	0.25 Air Changes Per Hour
Ventilation	10 Litres/Second/Person.
Commercial building mechanical cooling set point for Indoor Conditions (Thermal Comfort)	23ºC
Internal heat gains are based on occupancy and lighting heat gains only	150W per person (combination of Sensible (90W) & Latent (60W)) and 12W/m^2 respectively (as a minimum).
Total occupancy	Allow 12m^2/person in usable space, 400m^2/12m^2= 34 people.
Occupancy Pattern	0800-1800. 50% occupancy 1200-1400.
Mechanical Cooling Fuel Source	Electrical
Artificial Lighting Design	56No. Thorn Lighting Line XS Tech 2x35W Suspended direct/indirect luminaires- 516lux (AL_1) at 0.85m above finished floor level. uniformity 68.5%. Total continuous Power Demand is 4.2kW including electronic ballast losses. Specific connected load: 10.50W/M^2=2.05W/M^2/100lux (Dialux Output). The luminaire quantity array is 8 x 7.

It is important to note that many existing older buildings are currently below this standard due to poor construction and low quality materials, this model provides a benchmark for building envelopes to achieve this level of embodied energy prior to application of passive systems. However, modern buildings (<10 year old) are constructed to achieve such values. Normally from a general point of view, mechanical cooling is sized to accommodate failing building fabrics i.e. over admittance of solar heat gains and infiltration. Unfortunately this is not stated in literature and is only an opinion of the author. Figure 3.5 below shows this models chiller energy consumption per annum using different building orientations when only one side of the building is glazed.

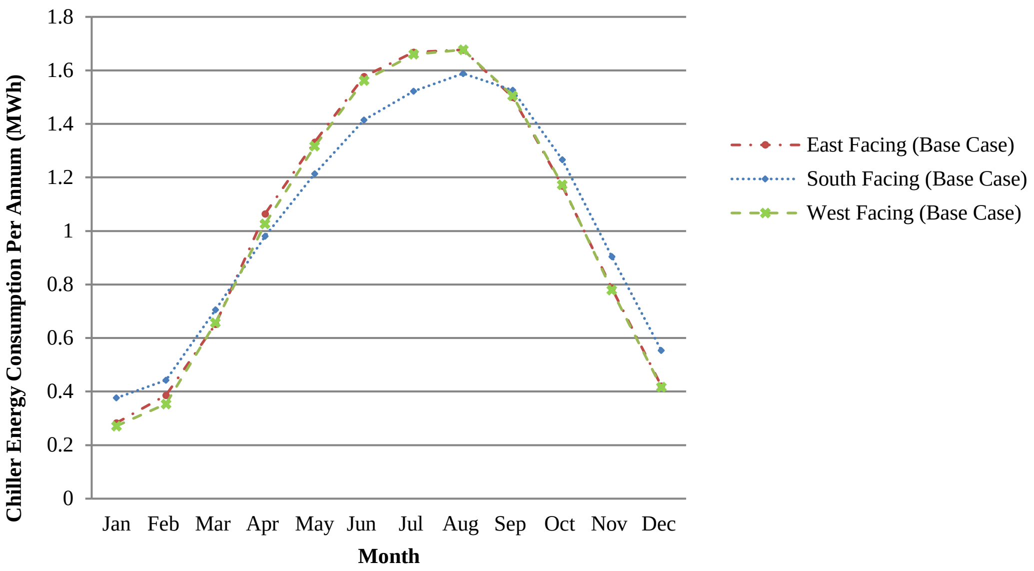


Figure 3.5- Base Case Mechanical Chiller Energy Consumption for Annual Period

Annual cooling energy consumption values for Building Model A.1 are calculated within DTS and compared against benchmark values identified in Appendix C; as shown in Table 3.7 below:

Table 3.7- Model Comparison against Standards

Orientation	Floor Area (M^2)	Carbon Emission Factor ($kgCO_2$/kWh)	Base case Model Annual Energy Consumption	Converted Carbon Emissions	Table 3.2 Benchmark Annual Energy Consumption	Benchmark Carbon Emissions	% Difference
		Grid Supplied Electricity	Electricity (kWh/M^2)	Fossil Thermal ($kgCO_2/M^2$)	Electricity (kWh/M^2)	Fossil Thermal ($kgCO_2/M^2$)	Electricity
East	400	0.517	31.28	16.17	156.6	80.96	-80.02
South	400	0.517	31.23	16.14	156.6	80.96	-80.05
West	400	0.517	30.99	16.02	156.6	80.96	-80.21

When comparing against benchmark values, the model cooling load is 80 percent lower than benchmark value in electricity energy consumption. This is due to the fact that there is only one set of windows for the DTS model. However, if windows were added to all elevations, the following results are detailed in the Table 3.8 below, where mechanical energy consumption appears to be more in line with benchmark values:

Table 3.8- Model Comparison against Standards for Windows on All Elevation

Floor Area (M^2)	Carbon Emission Factor ($kgCO_2$/kWh)	Base case Model Annual Energy Consumption	Converted Carbon Emissions	Table 3.2 Benchmark Annual Energy Consumption	Benchmark Carbon Emissions	% Difference
	Grid Supplied Electricity	Electricity (kWh/M^2)	Fossil Thermal ($kgCO_2/M^2$)	Electricity (kWh/M^2)	Fossil Thermal ($kgCO_2/M^2$)	Electricity
400	0.517	109.6	56.66	156.6	80.96	-30.01

3.3.10.   Base Case Building Model B.1

Based on typical buildings highlighted in Appendix B (basis of design) section B.3, a single height open office plan (theoretical model) has been created 20m (L) x 10 (W) x 3m (H). The south façade consists of a full height window 3m (H) x 19m (W). The East and West walls contain 3No. 2m (W) x 1.5m (h) and North wall contains double doors which are 2m (H) x 1.9m (W) and 2No. Windows 6m (W) x 2m (H). The building also has a flat roof. The graphic generated by the software is shown in Figure 3.6 below which shows the South façade view and second image indicate the building without the flat roof show highlighting the interior.

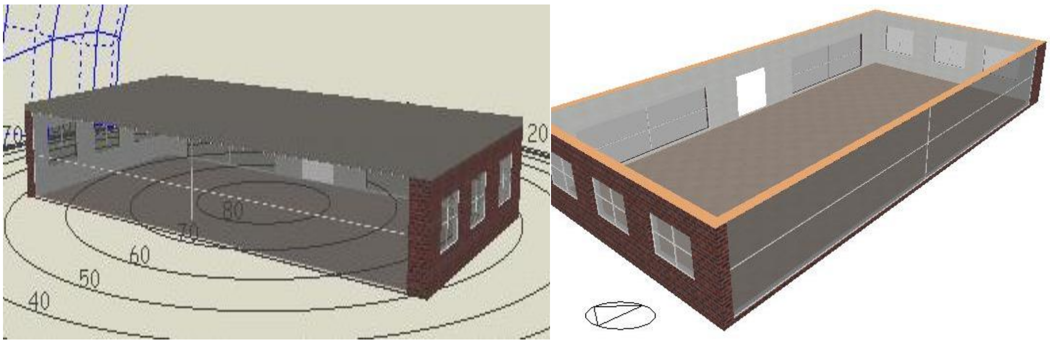


Figure 3.6 -South View of Office Building (Graphic) and South South West View of Office Building illustrating interior (Graphic)

The selected building locations selected is Portugal and Kenya. External temperatures (max/min.) are detailed below in Table 3.9 from Designbuilder software weather database.

Table 3.9- Climate Data for Hot Countries

Location	Height Above Sea Level(m)	Max.Average Temp (ºC)/(ºF)	Min. Average Temp. (ºC) /(ºF)
Lisbon, Portugal	95	27.9/82.22	8.2/46.76
Nairobi, Kenya	1,676.40	25.6/78.08	11/51.8

Figure 3.7 (Portugal) and 3.8 (Kenya) shows annual temperature profile for maximum and minimum dry bulb temperatures using Designbuilder climate data.

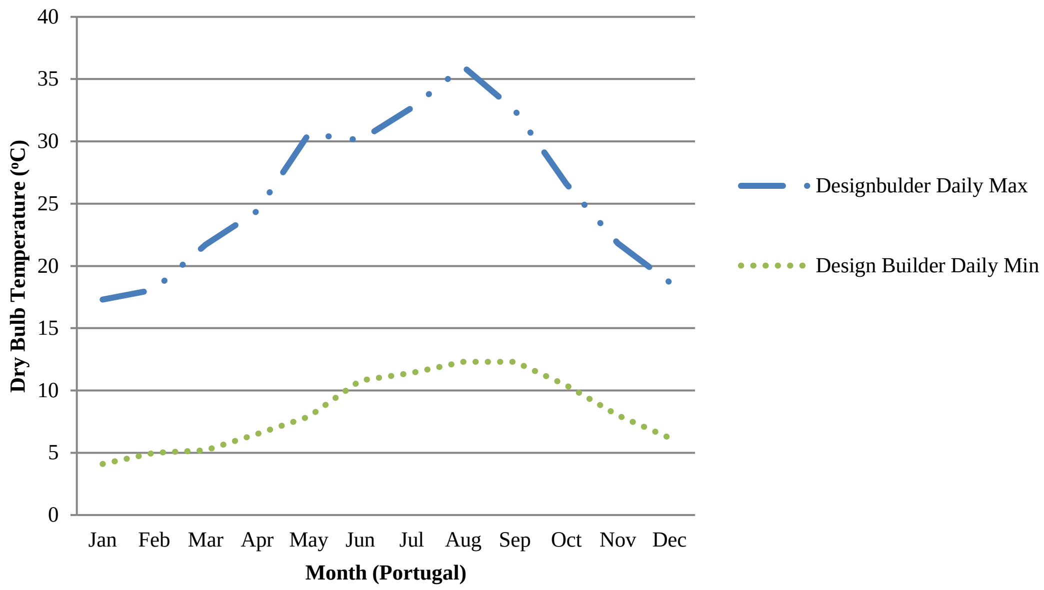


Figure 3.7- Annual Min/Max Dry Bulb Temperature for Lisbon, Portugal

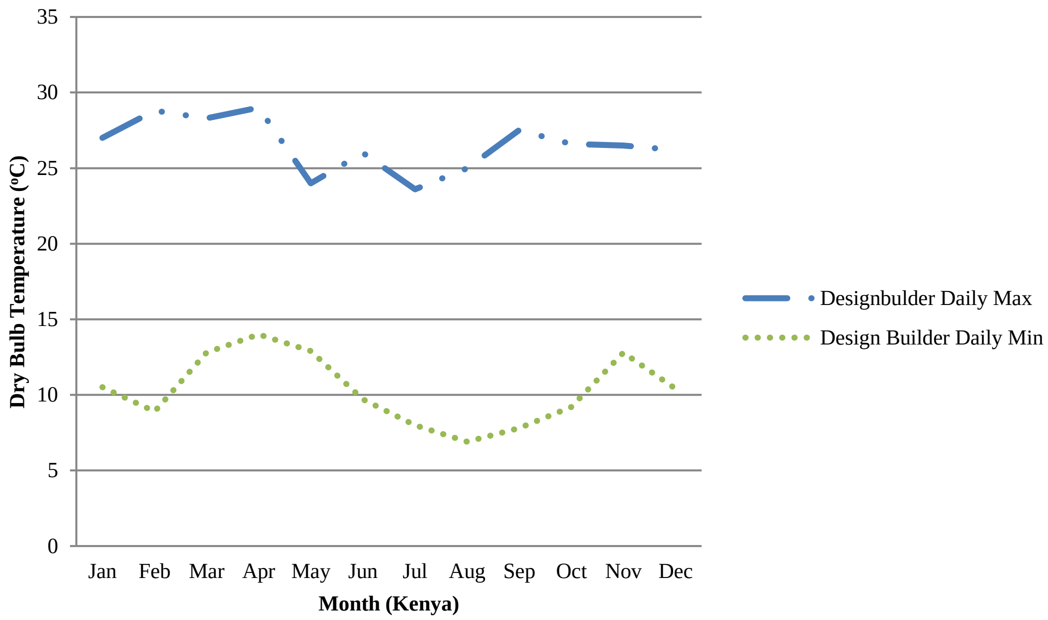


Figure 3.8- Annual Min/Max Dry Bulb Temperature for Nairobi, Kenya

For a comprehensive overview of all building materials used including their separate U values, ventilation permeability and heat gains (occupancy and equipment), building parameters are listed in Table 3.10 below:

Table 3.10- Building Model B.1 Parameters

Type	Description
External Walls	Brickwork, Outer Leaf (105mm), XPS Extruded Polystyrene (118mm), Medium Concrete Block (100mm) & Gypsum Plastering - U value of 0.25W/m^2 K
Roof (Flat)	Asphalt (10mm), MW Glass Wool (200mm), Air Gap (200mm), Plasterboard 13mm- U Value of 0.186W/m^2 K
Floor	Urea Formaldehyde Foam (200mm), Cast Concrete (100mm), Floor Screed (70mm) & Timber Flooring (30mm) - U Value of 0.176 W/m^2 K
Glazing	Pilkington North America Solar-E Arctic Blue (7.9mm), 12mm Argon Filled Gap & Pilkington North America Eclipse Advantage Clear (5.91mm)- U Value of 1.685W/m^2 K
Doors	Metal Framed Doors with Infill to match glazing- Pilkington North America Solar-E Artic Blue (7.9mm), 12mm Argon Filled Gap & Pilkington North America Eclipse Advantage Clear- U Value of 1.685W/m^2 K
Air Permeability	0.25 Air Changes Per Hour
Ventilation	Normal Operation (Base Case)- 10 litres/second per person Supply Air condition 12ºC Supply Air Humidity Ratio (g/g)- 0.08 Vents for Natural Ventilation- Large Grille (Dark Slates)- 0.5 Co-efficient of Discharge
Indoor Environmental Conditions (Summer Time Cooling)	Nominal Cooling-24ºC Cooling Set Back- 26ºC
Internal heat gains are based on occupancy and lighting heat gains only	Lighting – 12W/M^2 Occupancy Density- 10M^2/Person Activity- Light Office Work/Standing/Walking Computers 25W/M^2 Other Equipment- 0W/M^2 (Non Selected)
Occupancy Pattern	Weekdays Summer Design Day- 0700- 0% Occupancy, 0800 Hours- 25% Occupancy, 0900 Hours- 50% Occupancy, 1200 Hours- 100% Occupancy, 1400 Hours- 75% Occupancy, 1800 Hours- 50% Occupancy, 1900 Hours- 25% Occupancy, 2400 Hours- 0% Occupancy
Mechanical Cooling Fuel Source	Electrical

For the office building in each climate, simulations were completed to determine annual cooling load performance and annual cooling energy performance. Figure 3.9 shows sensible and latent DTS heat gains and plotted for each month. The graph shows that Portugal has higher sensible heat gains from March to November where Kenya has constant temperature due to location being higher above sea level. Latent heat gain as similar with Portugal indicating a slightly higher level June and October.

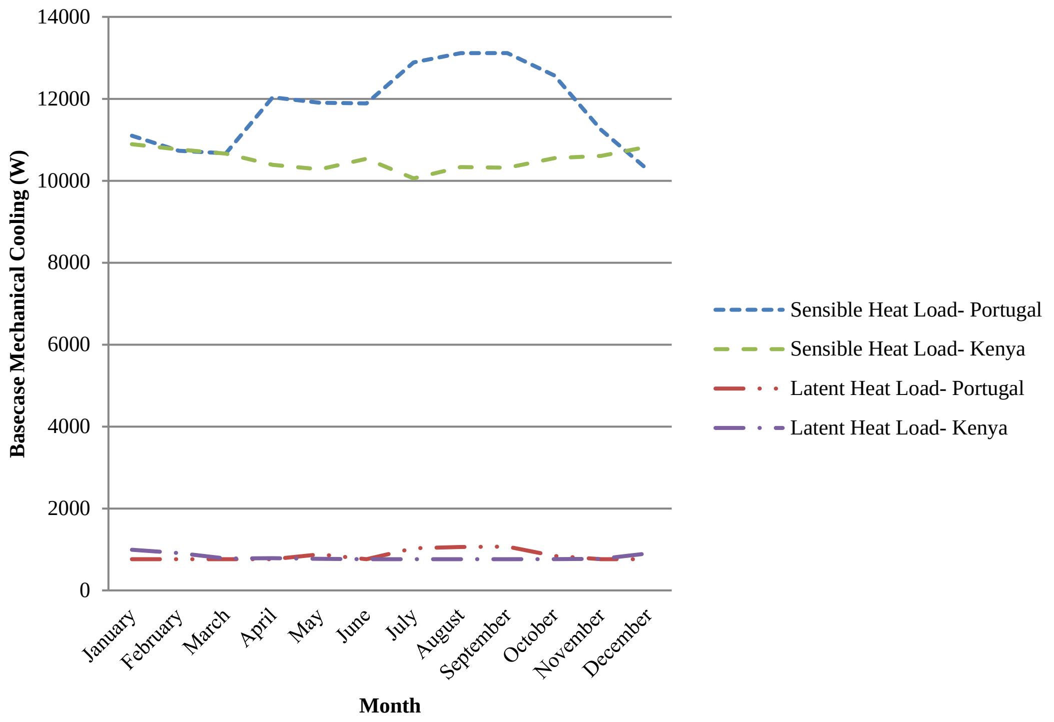


Figure 3.9- Base Case Cooling loads for Both Climates

Figure 3.10 below shows annual energy performance for cooling associated with each climate with Kenya climate indicating a greater value of 6.4%.

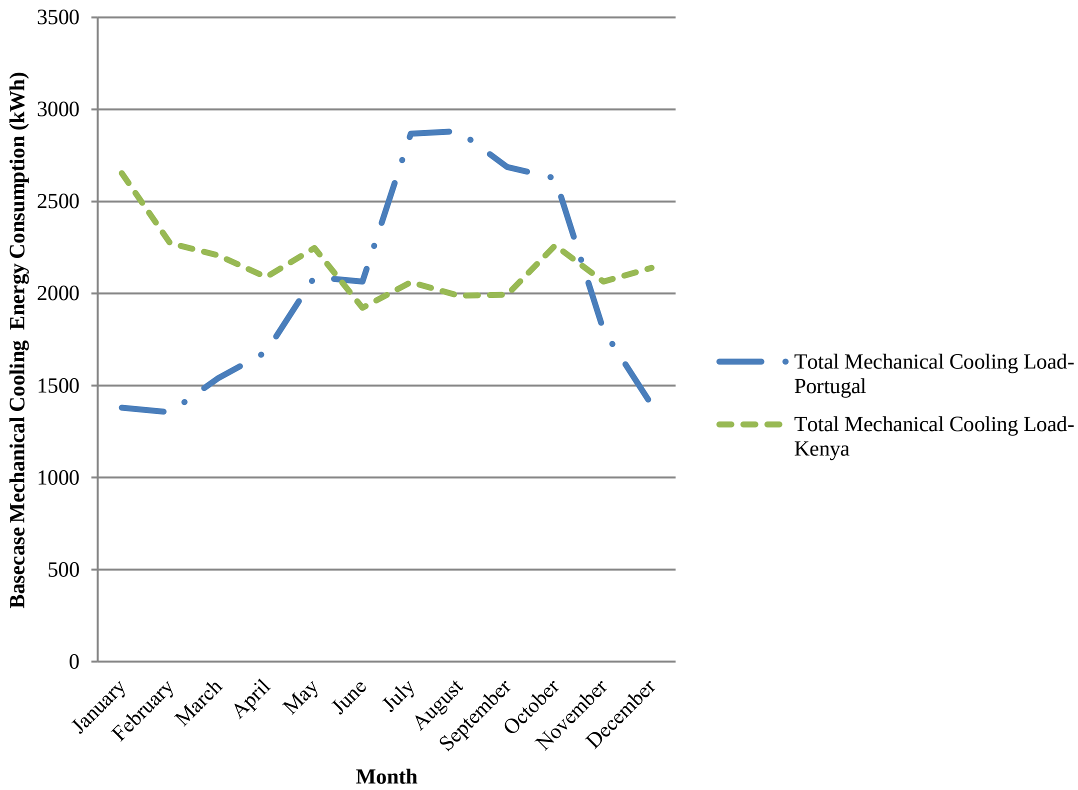


Figure 3.10- Base Case Mechanical Cooling Energy Consumption for Annual Period

Energy consumption for building model is detailed below in Tables 3.11 to 3.12.

Table 3.11- Model Comparison against Standards for Portugal

Floor Area (M^2)	Carbon Emission Factor ($kgCO_2/kWh$)	Base case Model Annual Energy Consumption	Converted Carbon Emissions	Table 3.2 Benchmark Annual Energy Consumption	Benchmark Carbon Emissions	% Difference
	Grid Supplied Electricity	Electricity (kWh/M^2)	Fossil Thermal ($kgCO_2/M^2$)	Electricity (kWh/M^2)	Fossil Thermal ($kgCO_2/M^2$)	Electricity
200	0.517	121.85	62.99	156.6	80.96	-22.19

Table 3.12- Model Comparison against Standards for Kenya

Floor Area (M^2)	Carbon Emission Factor ($kgCO_2/kWh$)	Base case Model Annual Energy Consumption	Converted Carbon Emissions	Table 3.2 Benchmark Annual Energy Consumption	Benchmark Carbon Emissions	% Difference
	Grid Supplied Electricity	Electricity (kWh/M^2)	Fossil Thermal ($kgCO_2/M^2$)	Electricity (kWh/M^2)	Fossil Thermal ($kgCO_2/M^2$)	Electricity
200	0.517	129.50	66.95	156.6	80.96	-17.30

When comparing against benchmark energy values, Kenya has an increased electrical energy consumption of 5.9 percent when compared to Portugal climate.

3.3.11. Base Case Building Model B.2

A different approach is taken for analysis of natural ventilation as operational time ($MV_{(t)}$) is of importance and understanding is required of how natural ventilation operation ($NV_{(t)}$) affects this time period. Using building model B.1 (geometry and building materials) in a different climatic location to test extremities of natural ventilation and mechanical ventilation operation and application in Abu Dhabi, United Arab Emirates (UAE). As this building is mixed mode ventilation operation, average dry bulb weather data exported from Designbuilder software and implemented in Microsoft Excel software to determine months that do not exceed pre-set temperature. The building location selected is Abu Dhabi, UAE, as this provides one global extreme of hot climate. Table 3.13 below shows maximum external temperature, minimum external temperatures, height above sea level and relative humidity.

Table 3.13- Climate Data for Hot Countries

Location	Height Above Sea Level(m)	Max. Tem (ºC)/(ºF)	Min. Temp. (ºC) /(ºF)
Abu Dhabi, UAE	27	42/107.6	11.8/53.24

The building ventilation strategy is mixed mode where base case HVAC operation temperature is set when internal air temperature exceeds 24ºC using 100 percent fresh air delivery. Parameters used for ventilation operation is detailed below in Table 3.13.

Table 3.14- Mechanical Ventilation System Parameters

Occupancy	Air Requirement (l/s/p)	Total (l/s)	Specific Fan Power (w/l/s)	Total SFP
15	10	150	2	300

HVAC operational time is detailed below in Table 3.15.

Table 3.15- Office Operational Hours

Hours of Office Start (Time)	Pre-cool Period Time (Hours)	Office Closing Start (Time)	Total office Hours for Day Time (Hours)
0800	1	1800	11

For each month, Figure 3.11 shows average daily dry bulb external air temperature for each month in Abu Dhabi. 100 percent fresh air is to be delivered via mechanical ventilation system.

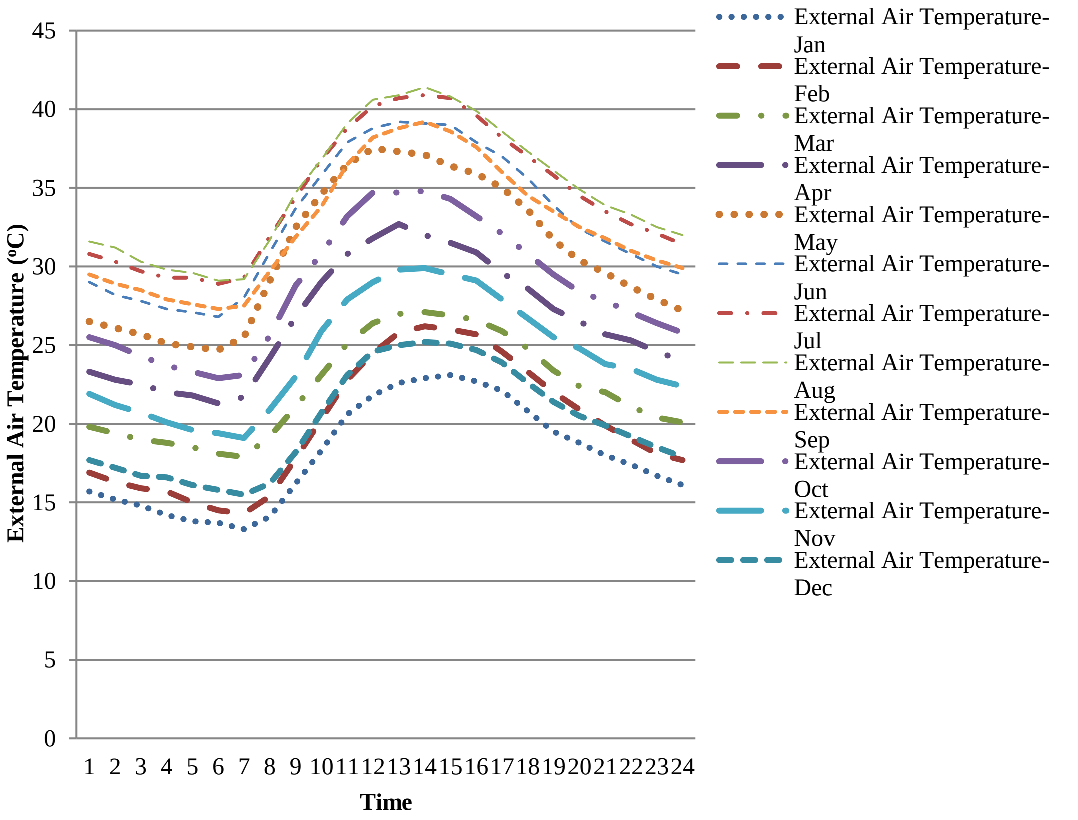


Figure 3.11- External Dry Bulb Temperature Profile for Abu Dhabi

Table 3.16 shows amount of energy required to maintain the internal occupied air space at 24ºC using full mechanical ventilation and cooling when external dry bulb temperature exceeds 24ºC and associated cooling load for full occupied hours (11 hours/day).

Table 3.16- Mechanical Ventilation & Cooling Operation

Month	AHU Specific Fan Power (kW)	Sensible Cooling Load (kW)	Latent Cooling Load (kW)	Total Cooling Coil Load (kW)	Mechanical Fan Energy (kWh)	Cooling Coil Energy (kWh)	Total Cooling Plant Energy (kWh)
January	0.30	10.03	1.02	11.05	75.9	2,796.55	2,872.45
February	0.30	10.05	1.02	11.07	66	2,435.68	2,501.68
March	0.30	10.07	1.13	11.20	66	2,463.73	2,529.73
April	0.30	10.32	1.19	11.51	72.6	2,785.22	2,857.82
May	0.30	10.42	1.37	11.79	72.6	2,852.47	2,925.07
June	0.30	10.38	1.37	11.75	69.3	2,714.55	2,783.85
July	0.30	10.52	1.51	12.03	75.9	3,042.86	3,118.76
August	0.30	10.49	1.52	12.01	69.3	2,773.58	2,842.88
September	0.30	10.59	1.50	12.09	72.6	2,926.75	2,999.35
October	0.30	10.47	1.35	11.82	75.9	2,990.67	3,066.57
November	0.30	10.41	1.23	11.65	66	2,562.45	2,628.45
December	0.30	10.06	1.10	11.17	56.1	2,088.09	2,144.19

For verification of building model B.2:

Table 3.17- Model Comparison against Standards for Abu Dhabi

Floor Area (M^2)	Carbon Emission Factor ($kgCO_2$/kWh)	Base case Model Annual Energy Consumption	Converted Carbon Emissions	Table 3.2 Benchmark Annual Energy Consumption	Benchmark Carbon Emissions	% Difference
	Grid Supplied Electricity	Electricity (kWh/M^2)	Fossil Thermal ($kgCO_2/M^2$)	Electricity (kWh/M^2)	Fossil Thermal ($kgCO_2/M^2$)	Electricity
200	0.517	162.16	83.8	156.6	80.96	+3.42

For mechanical ventilation energy, calculated values from Table G.4; outcome is detailed below in Table 3.18.

Table 3.18- Mechanical Ventilation Energy Comparison with Benchmark

Model B.2 floor Area (m^2)	Table E.4 -Calculated Fan Energy Consumption (kWh/M^2/Annum)	Benchmark Value Table C.5 for Best Practice Fan Energy Consumption (kWh/M^2/Annum)	% Difference
200	4.19	22	-80.90

3.4 Passive System Performance Assessment

In order to determine total reduction on mechanical cooling systems, analysis is completed in Chapters 4 and 5 to determine monthly cooling potentials for each selected passive system. Research detailed in this chapter substitutes existing steady state equations and develops the calculation methods for determining passive system cooling energy performance in terms of percentage reduction. In each case a passive system is added to the model and simulated/analysed accordingly. Current methods to calculate cooling performance are limited to existing research studies identified in chapter 2 and generic formulations stated in natural ventilation guidelines including institutional publications. The climatic operating parameters are identified and positive/negative impacts are critically assessed. Passive system performance assessment is particularly important during selection process. The level of passive cooling available is dependent on global location, external air temperature and diurnal solar radiation (insolation). In order to calculate effects on HVAC systems, the analysis can be sub-divided into actual temperature reduction, effects on mechanical cooling load and annual mechanical cooling energy reduction. For each passive system a new methodology and analytical assessment has been created specifically to solve these problems and provide theoretical commercial building examples to demonstrate passive system effects. The passive cooling systems selected for this analysis are as follows:

- External Solar Shading (SS) - Chapter 4, 5 and Appendix N
- Natural Ventilation (NV) - Chapter 5 and Appendix H
- Solar Chimney (SC) - Chapter 5 and Appendix I
- Ventilated Double façades (VDF) - Chapter 5 and Appendix J
- Rain Screen Façades (RSF) - Chapter 5 and Appendix K
- Passive Downdraught Evaporative Cooling (PDEC) - Chapter 5 and Appendix L
- Earth Ducts (ED) - Chapter 5 and Appendix M

3.5 Methods Used in Chapter 4

3.5.1 External Solar Shading DTS

Theoretical commercial building model A.1 located in Aswan, Egypt is used to complete this cooling load and mechanical cooling energy performance assessment. The selected shading device types detailed in Figure 2.6, Chapter 2 are selected for this analysis. These include; horizontal, angled, vertical and multiple angled external solar shading devices. These are simulated in DTS software and compared against a verified DTS base case building model. These are calculated for a 24 hour period with a 10 day solar gain lead in and is treated as unoccupied with not internal heat gains. The calculation time step is 10 minutes and on the hottest day of the year for this climate which is 29th July. All calculations are based on McAdams external convection model. This DTS involves 10 simulations for base case building model, 10 simulations for each form of shading type over a day time (hottest day of the year) and 10 simulations yearly period which include verification against other studies. For annual mechanical energy consumption, simulations are run over a yearly period from 1st January to 31st December for the base case and with this passive system. Day lighting is also compared for each elevation for each type of external solar shading and as a whole i.e. East, South and West Elevations. Fundamental calculation used for this analysis for calculated solar load per unit floor area in a space (CIBSE, 2006b) can be determined using the following equation:

$$\Phi_{SL} = (1/A_p) \sum (A_g\ \emptyset_S\ g_{Eff}) \qquad \text{Eq. 3.2}$$

Where A_p is the perimeter zone of the floor area; Ag is the net area of glazing in each element of the perimeter zone; $\emptyset_S$ is the external solar radiation for the particular orientation of the opening; and g_{Eff} is the effective g-value of the window and blind. For day lighting analysis, average daylight factor is calculated below (CIBSE,1999a):

$$DF = (Ei / Eo) \times 100\% \qquad \text{Eq. 3.3}$$

Where, Ei = illuminance due to daylight at a point on the indoors working plane units (Lux), Eo = simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky (Lux).

3.5.2 Analysis of External Solar Shading

As external solar shading methods is a vast subject, chapter 4 analyses the impact of common types of external fixed solar shading devices on building thermal loads and effects to daylight contribution into an office space. Investigations into the effectiveness of the solar shading for commercial buildings in hot climates in terms of solar heat gain reduction. This is realised by the following:

1. Effects of different types of window glazing where four different types of glazing with varying effective g-values are DTS for each elevation (East, South and West) and results inter-compared.
2. Effects of altering horizontal external solar shade over hang depth. DTS are completed to analyse effects of increasing the horizontal over hang depth (O_D) for East, South and West Elevations. Results are collated into percentage reductions for a shade depth (increments of 0.1m up to 1m) detailing effects of increasing O_D.
3. Effectiveness of Internal Blind at Peak Periods. A series of manual calculations are completed for the maximum amount of solar radiation in July. For each calculation, the blind will be closed in increments of 10 percent at different effective g-values for window glazing. For details of calculation refer to Appendix F.
4. Effectiveness of external light shelf. Manually calculate effects of solar heat gain transfer from light shelf mounted 50% of vertical height of the window. For details of calculation refer to Appendix G.
5. Dynamic thermal modelling simulation for a single storey exemplar theoretical commercial building located in a hot climate. Four types of external fixed solar shades are compared and analysed.
6. Determine the most effective method of fixed external solar shading in terms of cooling energy reduction.
7. Using most effective method, calculate impacts on mechanical cooling energy consumption and associated carbon dioxide production (electricity source).

This method of performance assessment is shown below in Figure 3.12 flow diagram below.

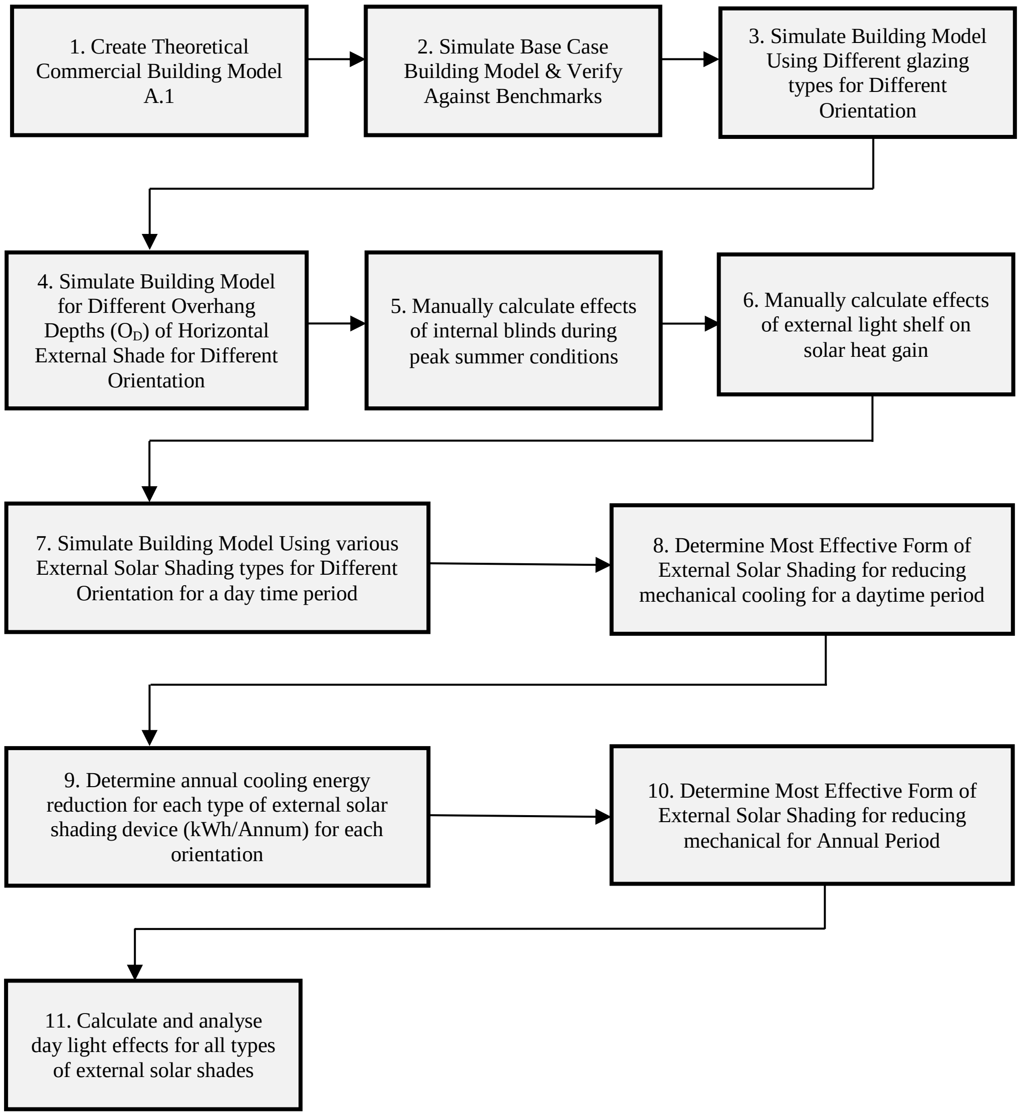


Figure 3.12- External Solar Shading Performance Assessment Methodology

3.6 Methods Used in Chapter 5

3.6.1 Natural Ventilation Approach

Base case model B.2 shows requirements of mechanical ventilation and cooling when external dry bulb air temperature exceeds 24°C. This section review the impacts of increasing HVAC set point increasing thermal comfort level from 24-28°C. For each temperature, the time period is taken from the graph and converted into energy (revised HVAC operation) for each month assuming 100 percent fresh air for both modes of operation. The time/temperature curve analysis method of performance assessment is shown below in Figure 3.13 flow diagram.

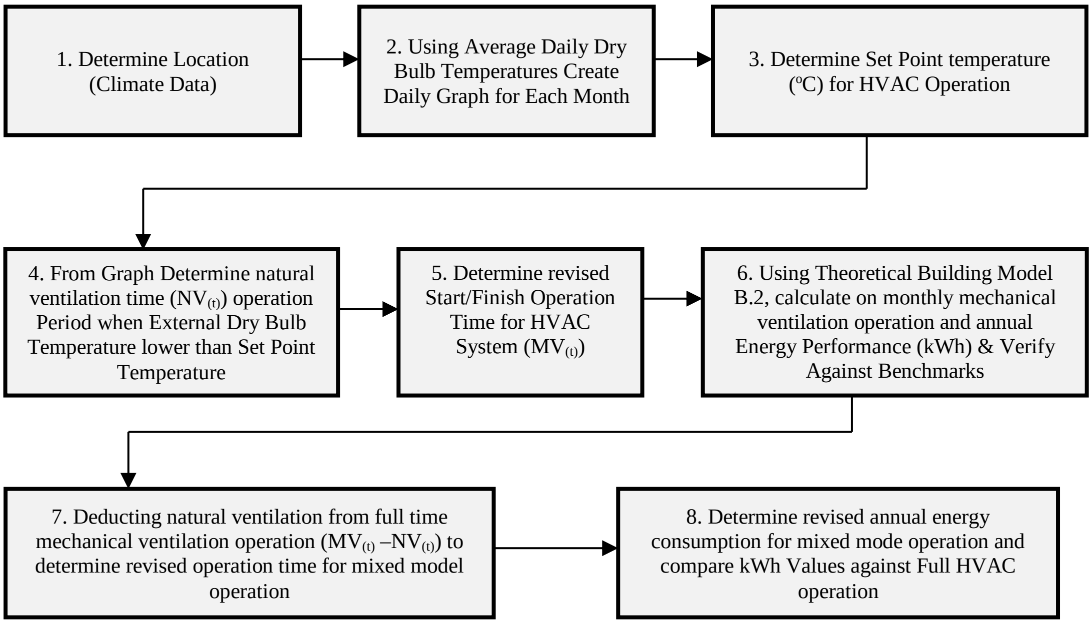


Figure 3.13- Natural Ventilation Performance Assessment Methodology

This flow diagram has been created to develop a new approach for assessing natural ventilation effects on reducing HVAC performance by approximating the operational time external dry bulb air temperature exceeds HVAC set point. The events identified in Figure 3.13 determine HVAC times of operation based upon mixed mode operations. The amount of energy saved by varying set points can be used to calculated ventilation and cooling energy consumption. For revised time period associated with ventilation system operations i.e. effects of reducing annual mechanical ventilation energy:

$$QV_{(t)} = MV_{(t)} - NV_{(t)} \qquad \text{Eq. 3.4}$$

Where; $QV_{(t)}$ is revised time to allow for mixed mode operations, $MV_{(t)}$ is full time operational time of mechanical ventilation system in hours and $NV_{(t)}$ is operational time of natural ventilation in hours. In order to calculate reductions in energy (Qe), the following formula applies:

$$Qe = QV_{(t)}\ P_{SF} \qquad \text{Eq. 3.5}$$

Where; Qe is the revised energy consumption for mixed mode operation (kWh_r) and P_{SF} is the specific fan power (W) or total fan power for complete building. For further calculation referred to as part of this work see Appendix H. For additional calculations methods used refer to Appendix B section B.3.

3.6.2 Solar Chimney Approach

With regards to cooling capacities of solar chimneys, increasing the air flow rate will improved thermal comfort, but may not solve the problem of cooling external supply air and minimising the usage of mechanical cooling plant. However, improving the air flow into the space can allow the set point temperature to be increased before HVAC operation is required. In terms of assessing energy performance using DTS climate data for Porugal and Kenya. This is to quantify air flow (l/s) impacts when introducing glazing into a natural ventilation stack can be achieved and dependent on a number of factors:

- Effective g-value of transparent surface of solar chimney.
- Solar heat gain to the chimney stack (Qsc)
- Mass flow rate of air (kg/s)

This method of performance assessment is shown below in Figure 3.14 flow diagram.

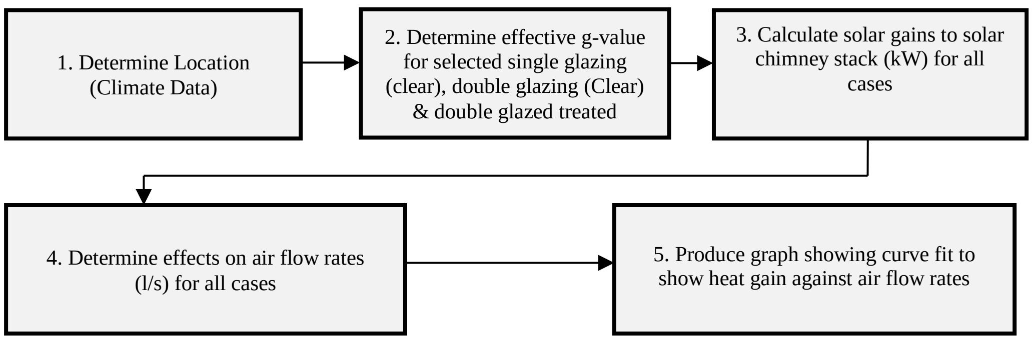


Figure 3.14- Solar Chimney Performance Assessment Methodology

This flow diagram has been created to develop a new approach for assessing solar chimney performance in terms of air flow rates from fundamental parameters (first principles). From initial climate selection through to analysing the effects on air flow with varying solar heat gains can be quantified in litres/second. Calculation parameters are similar to the natural ventilation calculations for calculating airflows and stack pressure drops but heat gain from the solar chimney requires correlating. The steady state (transient) heat gain to the stack (Q_{sc}) can be calculated using CIBSE (1999) and CIBSE (2006b) equations as the basis; substituting these existing equations to form a heat balance equation for solar chimneys:

$$Q_{sc} = \left\{ (1/A_p) \left(\sum A\, \varnothing S\ geff \right) \right\} - \left(\sum M_a\, C_p\, \Delta T \right) \qquad \text{Eq. 3.6}$$

Where; A_p is the perimeter zone of the exposed area/s; A is the net area of the opaque/transparent surface; $\varnothing_S$ is the external solar radiation for the particular orientation of opening; M_a is the mass flow rate of air (multiple outlets depending on rooms); C_p is the specific heat capacity of air; and ΔT is the mean air temperature at the stack inlet (extract from multiple rooms) and exhaust air temperature from the solar chimney (T_{Inlet} - $T_{exhaust}$) and geff is the effective g value for south-facing transparent/opaque surface. For airflow into and out of the chimney:

$$Ma = \frac{Q_{sc}}{C_{pa}\ \Delta T} \qquad \text{Eq. 3.7}$$

For performance data refer to Appendix I.

3.6.3 Ventilated Double Façade Approach

Introduction of a ventilated double façade (VDF) to a south elevation can capture and reduce solar heat gains. Traditionally this is installed to a south elevation to a long open plan space or reception/lobby area. The design of the façade is dependent on the outer glazing effective g-value and amount of air ventilating from low to high level. Thermal performance is calculated using formulas detailed in this section and uses building model B.1. The first set of results detail the effects of heat gain into the façade for two climates and second will review cooling load performance and annual cooling energy reduction. This method of performance assessment is shown below in Figure 3.15 flow diagram.

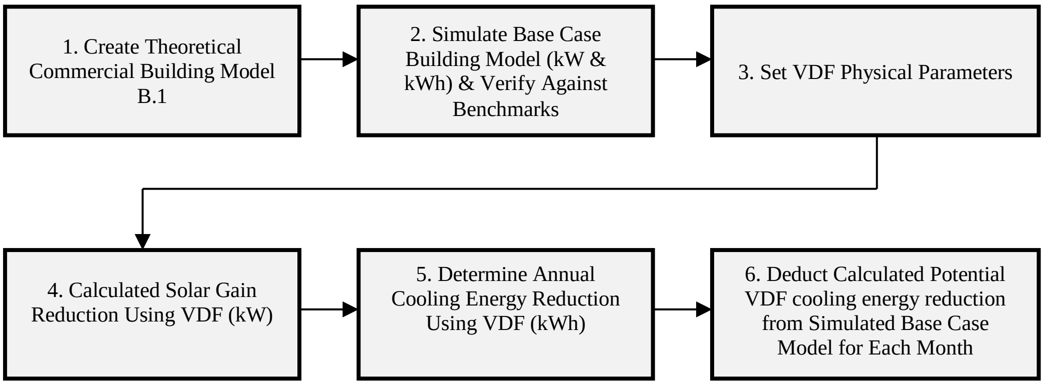


Figure 3.15- Ventilated Double Façade Performance Assessment Methodology

This flow diagram has been created to develop a new approach for assessing VDF performance and potential cooling effects using fundamental parameters (first principles). The flow of events from initial climate selection through to assessment of solar gain reduction into a ventilated double space (natural) is quantified in cooling load (kW) and converted into mechanical energy (kWh).

In order to calculate potential energy reductions, solar heat gains transfer within the ventilated double façade space (1) are calculated using existing equations CIBSE (2006b) and CIBSE (1999) which are substituted to create the following heat balance equation:

$$Q_{VDF} = \sum A_g \, \text{ø}_s \, eff_g + h_c \, M_a \, A_{fw} \qquad \text{Eq. 3.8}$$

Where: A_g is area of external facade glazing (m^2); ø_S is external solar radiation (w/m^2); eff_g is effective g value of glazing; h_c is heat transfer co-efficient of air (natural); Ma is mass flow rate of air (kg/s) and A_{FW} is area of facade wall. For cavity air temperature (T_{CA1}):

$$T_{CA1} = T_o - \left\{ \frac{Q_{VDF}}{C_{pa} \, M_a} \right\} \qquad \text{Eq. 3.9}$$

Where: T_o is outside air temperature (^oC); C_{pa} is specific heat capacity of air (1.2kJ/kg). For effective opening area of VDF (A_{eff}) (British Standards, 1991):

$$A_{eff} = (A_1 + A_2) \quad \frac{\varepsilon \sqrt{2}}{(1 + \varepsilon)\,(1+ \varepsilon^2)^{1/2}} \qquad \text{Eq. 3.10}$$

Where: A_1 is area of lower grill (Free area); A_2 is area of higher grill (Free area) and ε is A_1/A_2. The effective area of the façade opening shall be calculated where the inlet air entering the façade is on the same elevation as the exhaust outlet of the façade wall:

$$A_{fw} = (A1 + A2) \left(\frac{\varepsilon \sqrt{2}}{(1 + \varepsilon)\,(1+ \varepsilon^2)^{1/2}} \right) \qquad \text{Eq. 3.11}$$

Where ε is A_1/A_2. For mass flow rate of air (Ma) (British Standards, 1991):

$$Q = C_d\, A \left(\frac{2^{\Delta}P}{\rho} \right)^{1/2} \qquad \text{Eq. 3.12}$$

Where: Q is flow rate of air calculated as 14.89 l/s; P is pressure drop (Pa) and ρ is air density. For Resultant Heat gain through inner façade glazing using the corrected external air temperature (Q_{FG}) CIBSE (1999):

$$Q_{FG} = \sum U_g\, A\, (T_{CA1} - Ti) \qquad \text{Eq. 3.13}$$

Where; Ug is the thermal conductivity of glazing; A is area of glazing and T_i is internal air temperature. In order to make a comparison, a standard facade glazing calculation is completed, as show below: Eq. 3.14

$$Q_g = \sum U_g\, A\, (T_o - T_i)$$

These values are inter-compared to determine total reduction heat loss (Q_{TR1}):

$$Q_{TR1} = Q_g - Q_{FG} \qquad \text{Eq. 3.15}$$

For performance data refer to Appendix J.

3.6.4 Rains Screen Façade Approach

Rain Screen Façade is applicable for North, East, West & South elevations. The primary aim of a RSF is to protect the external wall from rain and secondary to reduce solar heat gains into the fabric. Using building model B.1, RSF solar performance is calculated and analysed for two different hot climates. The first set of results detail the effects of heat gain into the façade for two climates and second will review cooling load performance and annual cooling energy reduction. This method of performance assessment is shown below in Figure 3.16 flow diagram.

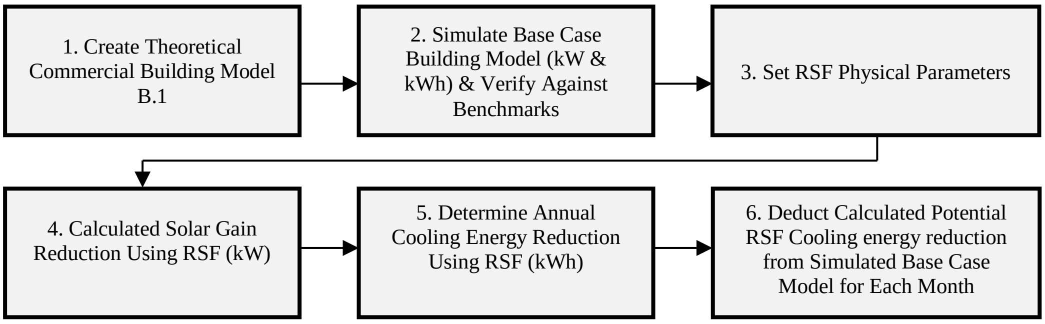


Figure 3.16- Rain Screen Façade Performance Assessment Methodology

This flow diagram has been created to develop a new approach for assessing RSF performance and potential cooling effects from fundamental parameters (first principles). From initial climate selection through to assessment of solar gain reduction to fabric (admittance) can be quantified in kilowatts and converted into kWh based upon occupation profiles. To calculate steady state heat gain into the facade cavity incorporating rain screen facades (Q_{RSF}), which is substituted using existing equations from CIBSE (2006b) and CIBSE (1999) basic heat loss equations has been adapted to create a new set of equations as detailed below:

$$Q_{RSF1} = \sum A_{rsf}\, ø_s\, eff_{gRSF} + h_c\, M_a\, A_w \qquad \text{Eq. 3.16}$$

Where; A_{rsf} is surface area of rain screen facade (m^2); A_w is surface area of building wall (m^2); $ø_S$ is external solar radiation (w/m^2); eff_{gRSF} is the equivalent effective g-value for rain screen façade weatherboard material (Appendix I); h_c is heat transfer co-efficient of air (natural) and Ma is mass flow rate of air (kg/s). To calculate cavity air temperature (T_{CA2}):

$$T_{CA2} = T_o - \left\{ \frac{Q_{RSF}}{C_{pa}\ M_a} \right\} \qquad \text{Eq. 3.17}$$

Where: T_o is outside air temperature (^oC); C_{pa} is specific heat capacity of air (1.2kJ/kg). For total fabric heat loss/gain (Q_{RSF2}):

$$Q_{RSF2} = \sum UA\ (T_{CA2} - Ti) \qquad \text{Eq. 3.18}$$

Where: U is thermal conductivity of wall ($w/m^2\ k$); A is area of wall (m^2); T_{CA2} is cavity air Temperature (^oC) and Ti is internal air temperature (^oC). In order to make a comparison, a standard wall calculation is completed, as show below:

$$Q_f = \sum U\ A\ (T_o - T_i) \qquad \text{Eq. 3.19}$$

These values are inter-compared to determine total reduction heat loss (Q_{TR2}):

$$Q_{TR2} = Q_f - Q_{RSF2} \qquad \text{Eq. 3.20}$$

For performance data refer to Appendix K.

3.6.5 PDEC Approach

Using theoretical building model B.1, an analysis is completed to determine the cooling potential of a PDEC system for each climate using maximum temperature for each month. The reason the maximum peak temperature is used and not the average maximum temperature is that this may not exceed 25^{o}C. For example in Kenya, the maximum average temperature is 24.5^{o}C (World Meteorological Organisation, 2014a) therefore minimal cooling effects can be calculated. Q_{PDEC} is calculated on the premise that maximum external air temperature for activated cooling will occur no more than 60 hours per month (3hours per day at 20 working days); this forms the basis of the annual PDEC cooling. This study uses a PDEC tower as this gives more control of supply air and enables other systems to interact effectively before supply air is delivered into an occupied space and control relative humidity (%RH). The energy reductions are based on the fact that there is no correction to relative humidity i.e. from 30 to

50 percent. This energy analysis is limited to not exceeding the relative humidity based upon specific enthalpy values at a given temperature/humidity. This method of performance assessment is shown below in Figure 3.17 flow diagram.

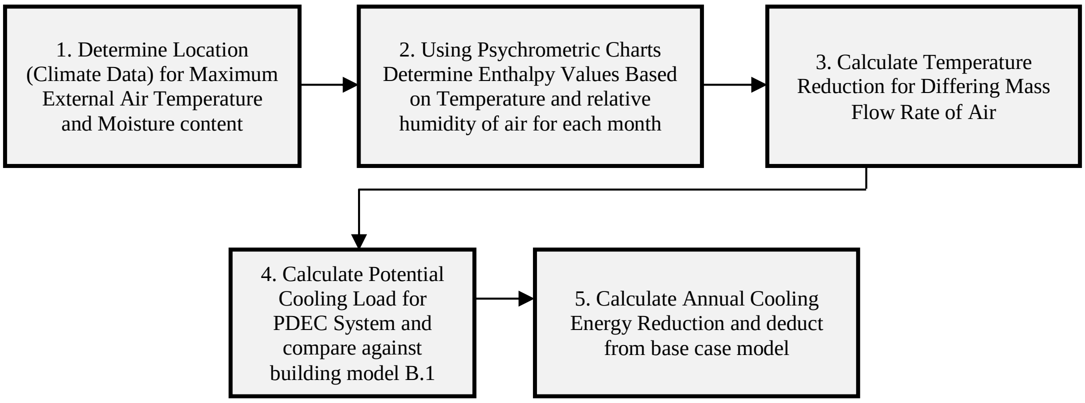


Figure 3.17- PDEC Performance Assessment Methodology

This flow diagram has been created to develop a new approach for assessing PDEC performance and potential cooling effects from fundamental parameters (first principles). From initial climate selection through to assessment temperature reduction using water micronisation and cooling potentials, which can be quantified in kilowatts, can be converted into kWh based upon occupation profiles. Typical parameters for system operation are detailed below in Table 3.19 below and details maximum environmental ranges to be expected from this system.

Table 3.19- PDEC System Parameters

External Temperature (°C) Range	Air Flow Rate (m/s)	Microniser Flow Rate (kg/s) Range	Relative Humidity (%) Range	Internal Heat Gains (kW) Range
26-45	0.5-1	0.001-0.01	30-40	1-20

The following equations identified as the method of calculating total cooling capacity of a PDEC system (Q_{PDEC}) (Cengel et al., 2008).

$$Q_{PDEC} = M_a (\omega_2 - \omega_1) hg \qquad \text{Eq. 3.21}$$

Where: M_a is the mass flow rate of air; hg is the enthalpy of water at the stated temperature; ω_1 is the moisture content of air at the inlet; and ω_2 is the moisture content of air at the outlet. For specific enthalpy of micronised vapour (Cengel et al., 2008):

$$hg = \frac{(h_2 - h_1)}{(\omega_2 - \omega_1)} \qquad \text{Eq. 3.22}$$

Where h is the enthalpy; and ω is the moisture content of the air. To calculate building cooling energy reductions when taking into account available PDEC cooling capacities:

$$Q_r = Q_{sim} - (Q_{PDEC}\, t) \qquad \text{Eq. 3.23}$$

Where: Q_r is revised building cooling energy consumption (kWh/Annum); Q_{SIM} is simulated building base case model for annual cooling (kWh/Annum) and t is estimated time of operation for PDEC system (hours). Background parameters and calculations are detailed in Appendix L for each of the following:

- Appendix Section L.2- PDEC System Parameters
- Appendix Section L.3- Effects of External Air Flow/Moisture Contents
- Appendix Section L.4- Available Cooling Capacities from PDEC system
- Appendix Section L.5- Daily Cooling Performance of PDEC System

The main results for cooling load and mechanical energy reduction are detailed in Chapter 5 section 5.6.

3.6.6 Earth Ducts Approach

Earth ducts can be used to assist cooling of hot air when natural ventilation strategies supplying 100% fresh air to an occupied space. The rate of cooling available depends on a number of factors such as air turbulence, thermal conductivity of earth duct material and below ground temperature. A performance assessment is completed to ascertain cooling potential for different types of earth duct material. The theoretical commercial building model B.1 is used for this analysis. This method of performance assessment is shown below in Figure 3.18 flow diagram.

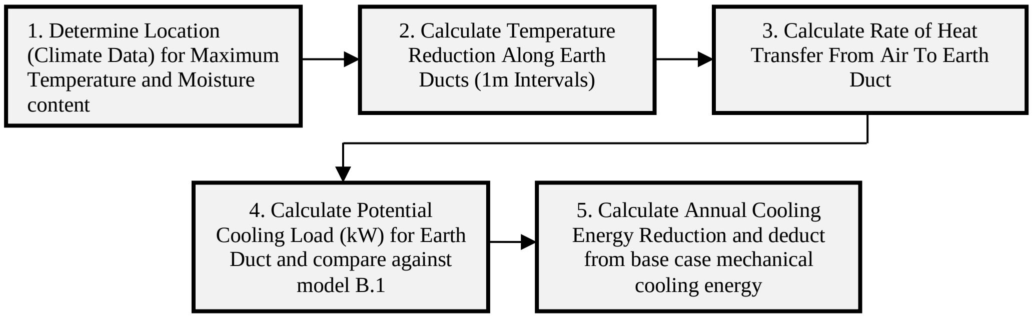


Figure 3.18- Earth Duct Performance Assessment Methodology

This flow diagram above has been created to develop a new approach for assessing earth duct performance and potential cooling effects from fundamental parameters (first principles). From initial climate selection through to assessment of cooling potential can be quantified in kilowatts and converted into kWh based upon occupation profiles. In order to calculate the rate of heat transfer to space (Q_t) (Cengel et al., 2008):

$$Q_t = \rho \ V \ h_c \ (T_i - T_o) \qquad \text{Eq. 3.24}$$

Where ρ is the air density; V is the volume of air; h_c is the convective heat transfer coefficient air; T_i is the air temperature in space; and T_o is the external air temperature. This can be re-arranged for air temperature from the earth duct outlet (Ti) (Cengel et al., 2008):

$$Ti = To - \left\{ \frac{Q_t}{\rho \ V \ hc} \right\} \qquad \text{Eq. 3.25}$$

The earth duct is categorised thermodynamically as an air to ground heat exchanger. To calculate the temperature profile for different types of materials, total surface heat loss from earth duct (Q_{ed}):

$$Qed = \sum_{i=j}^{n=10} qcir \qquad \text{Eq. 3.26}$$

Where; qcir is the heat loss at a point along the duct for a maximum of 10 points equal to n (one meter intervals). For heat loss through material to ground:

$$Q = \frac{\Delta T}{R} \qquad \text{Eq. 3.27}$$

Where; ΔT is the difference in temperature (°C); and R is the thermal resistance of the earth duct material. To calculate the earth duct wall's thermal resistance (Cengel et al., 2008):

$$Rwall = \frac{In\ (Do - Di)}{2\pi kL} \qquad \text{Eq. 3.28}$$

Where; D_o is the outer diameter; D_i is the inner diameter; k is the thermal conductivity; and L is the length. To calculate mass flow rate of air the following calculation applies (Cengel et al., 2008):

$$\text{Ma} = \frac{Q_{ED}}{C_{pa}\ \Delta T} \qquad \text{Eq. 3.29}$$

Where Ma is mass flow rate of air (kg/s); Q_{ED} is total potential heat loss from earth duct; C_{pa} is specific heat capacity of air (kj/kg) and ΔT is difference in air temperature between earth duct inlet and exhaust (°C). For pressure drop and turbulent flow formulae used in chapter 5 analysis, refer to section B.6, Appendix B and section M.3, Appendix M.

3.7 Passive System Results Analysis & PSEAT Development

3.7.1 Overview

This section provides details for further analysis on Chapter 4 and 5 results including sensitivity analysis and error, verification against published values (cross referencing), energy performance analysis, uncertainty analysis, developments of basic visual passive system design tools and development of Passive System Energy Assessment Tool (PSEAT). PSEAT is developed in Chapter 6 to aid with the detailed selection and performance assessment of passive ventilation and cooling systems for commercial buildings in hot climates. The aim of this tool is to allow building designers and low carbon building services engineers to complete an analytical assess total ventilation and cooling potential reductions for each passive system along with estimated annual energy reduction on mechanical cooling systems, carbon dioxide emissions, BREEAM assessment, life cycle costings and annual energy costs.

3.7.2 Sensitivity Analysis and Error

In chapter 6, the following is completed:

- Passive System Performance Review- This provides a visual tool in the form of a flow diagram using two new methods of calculation. Method 1 uses manual analysis based upon benchmarks against floor area to calculate basecase ventilation and cooling loads/energy consumption. Method 2 uses computational analysis (DTS) to develop base case ventilation and cooling loads for a building. Using this flow diagram, mechanical energy performance a reduction analysis can be completed and identifies minimum percentage reductions available for each passive system.
- Sensitivity Analysis & Error 1- Mechanical Cooling Performance of Base Case Model B.1- Approaches to weather data analysis includes weather data comparison, monthly average mechanical energy reduction and mechanical cooling energy data inter-comparisons.
- Sensitivity Analysis & Error 2- Verification Error of Passive System Performance Values – To inter-compare calculated values against published research has proven difficult as there is insufficient published energy performance data available to enable direct comparison for verification. Table 6.1 shows inter-comparisons of calculated and published values highlighting discrepancies.
- Energy Performance Analysis- To understand how passive systems perform with each other on a monthly basis, area performance graph have been created and explanation tables generated to identify which passive system have ideal operation in each month.
- Uncertainty in values- Discusses factors that affecting accuracy of calculated performance values.
- Development of basic visual passive system design tools.
- Development of passive system energy assessment tool (PSEAT).

3.7.3 Passive System Design Guidelines and Strategy

Prior to any analysis of the passive ventilation and cooling systems, pre-design works must be completed in an appropriate DTS software program. The strategy is detailed in Figure 3.19 below.

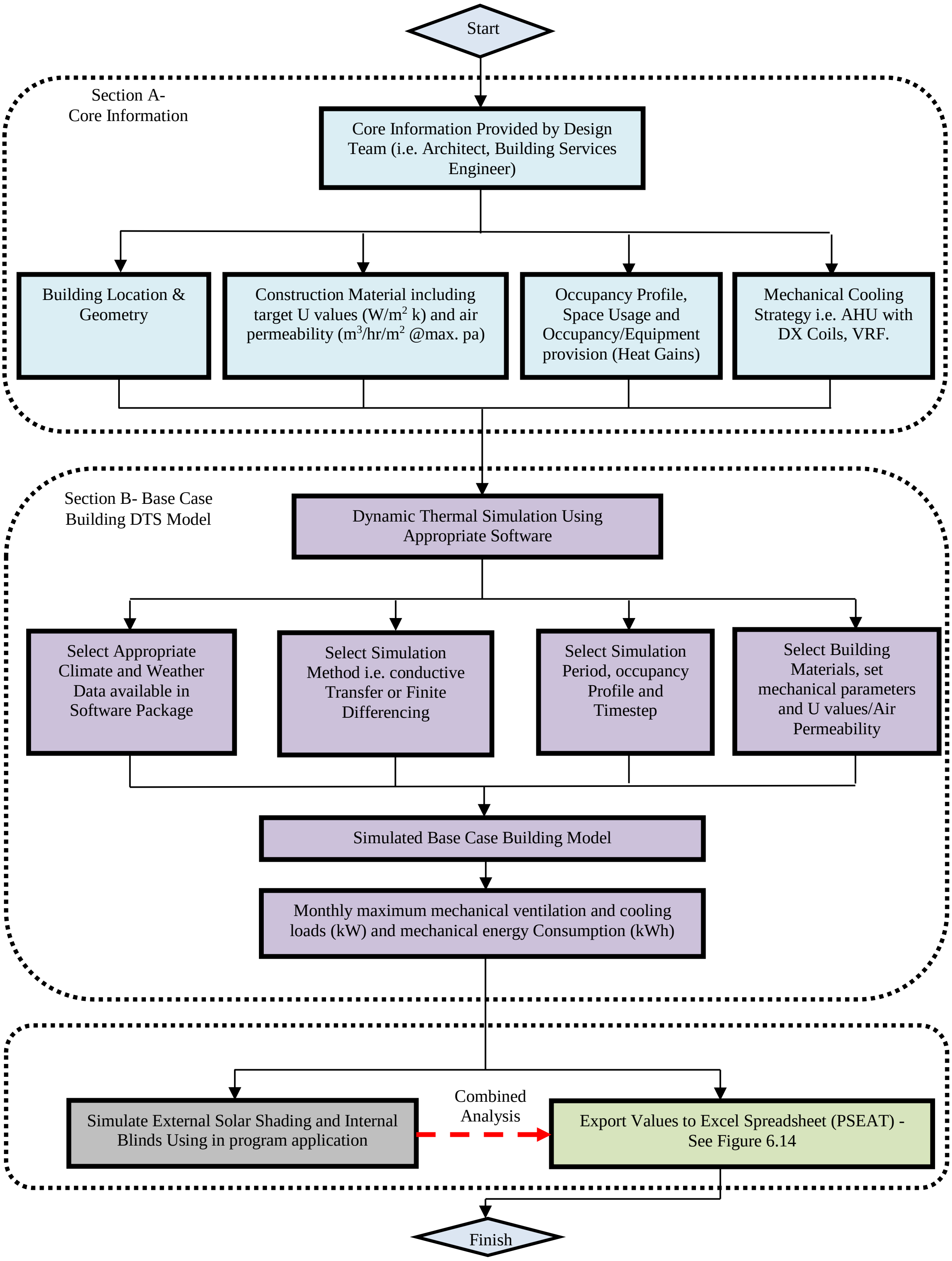


Figure 3.19- Pre-Design Works for Passive System Assessment

3.7.4 PSEAT Strategy

Figure 3.20 below shows passive system energy assessment tool strategy/process incorporating instructions, input information (section A), passive system performance calculations (section B) and parameter setting and results analysis (section C).

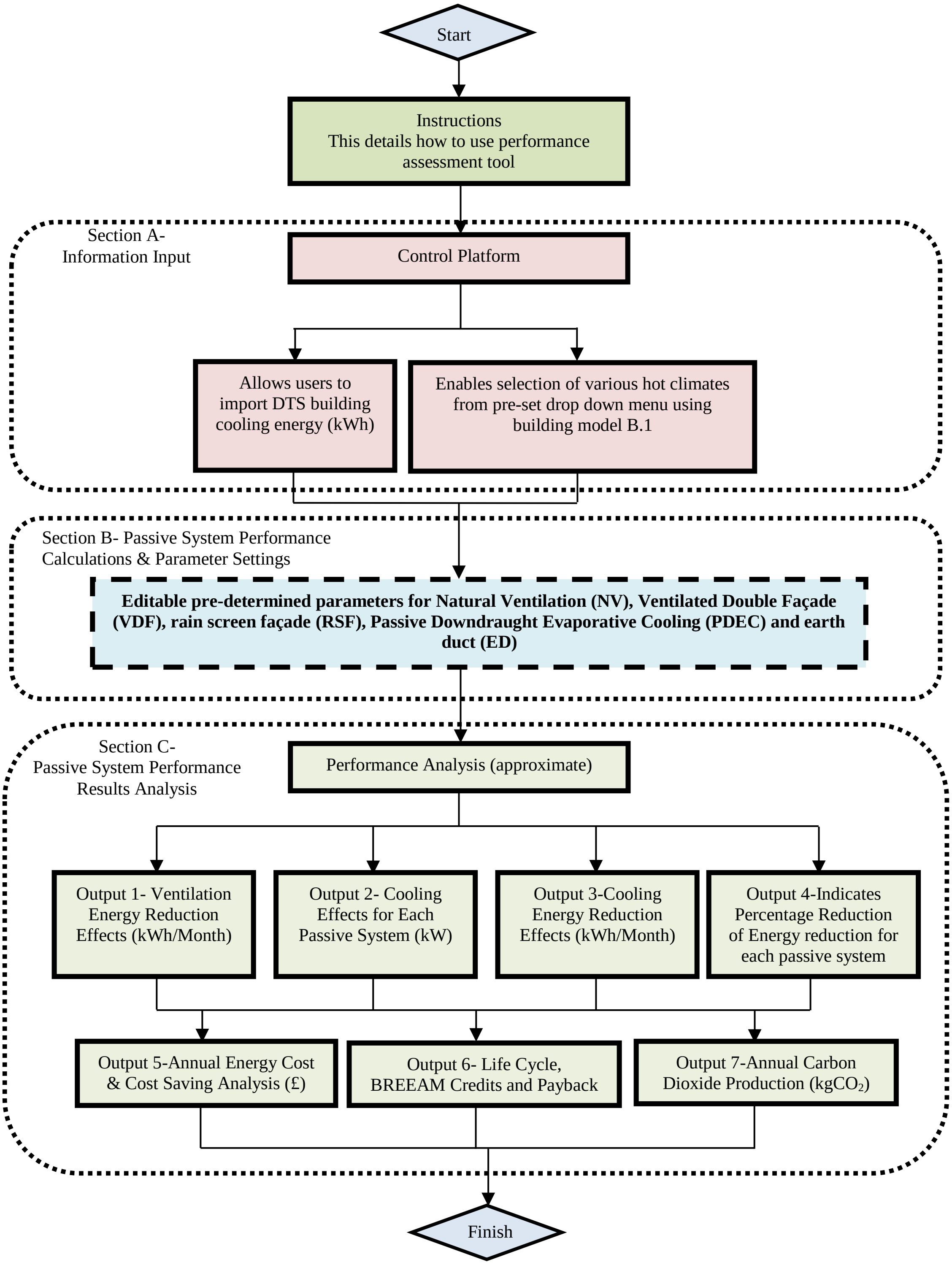


Figure 3.20- Performance Assessment Tool Flow Diagram

3.8 Design Guidance and Integration Strategies for Passive System Incorporation with HVAC Systems

The simplified passive system design guidance and integration strategies created for passive ventilation and cooling system design are detailed in Chapter 7 to enable architects and building services engineers to successfully design new commercial buildings setting out analytical parameters, practical applications and limitations. Figure 3.21 below shows the breadth of scope covered within this chapter and details key sections that form this new guidance.

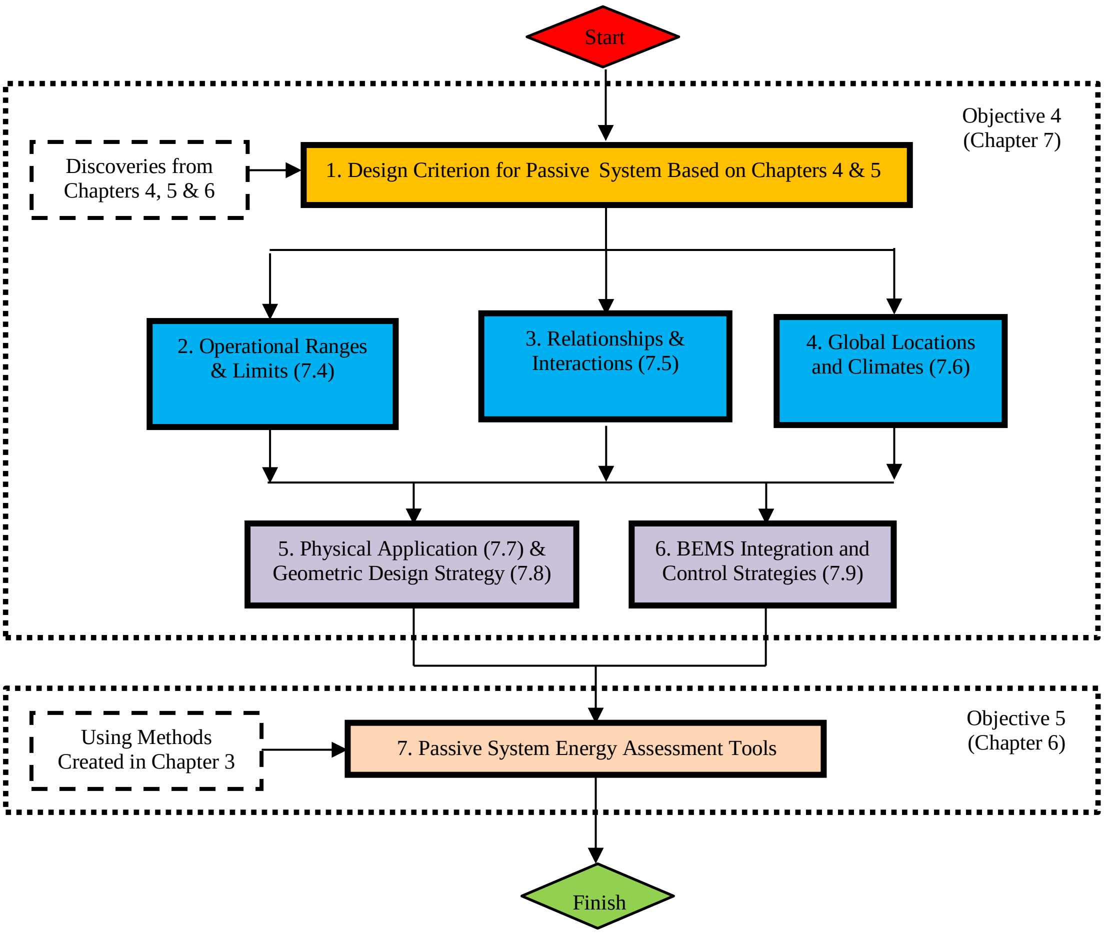


Figure 3.21- Flow Diagram of Passive Systems Design Guidance and Integration Strategy

Figure 3.21 shows how the design guidance and integration strategies are interconnected directed from discoveries made in previous chapters. This design guidance includes the following:

1. Passive ventilation and cooling design and strategies for combining with HVAC systems. Chapter 7 details the primary design considerations, passive system design incorporation strategy for relevant design stages i.e. RIBA stages and building information modelling.
2. Difficulties with passive system design.
3. Performance design guidelines and integration strategies.
4. Operational ranges and limits.
5. Relationships and interactions.
6. Global locations and climate.
7. Physical application.
8. Geometric design strategy.

The above points are expanded to provide detailed approach for implementation of passive systems and will recommend geometries, building materials and optimal operating conditions based upon discovered operating ranges (chapters 4 & 5).

3.9 Research Limitations and Exclusions

Building locations have been selected due to their external conditions in accordance with Chapter 1 definition of hot climate. What is not considered is impacts of Latitude i.e. what would be the effect if external solar shading was provided to the North Elevations. This is outside the scope of this research.

For building performance analysis, parameters are based upon HM Government (2010a) and (2010b) as these set a target benchmark for minimum building performance and standards in other countries (Building codes) have similar values. It is recognised these standards have been updated however these are used as a basis as this research commenced in October 2011.

A number of passive measures have been excluded from this research. These are trombe walls, phase changing materials (PCM), radiant cooling and radiant barriers. The impacts of these systems have been well research and implemented, without the need for further cooling energy consumption analysis. To further justify why these are excluded, statements below clarify for each:

i. Trombe wall as based on mass solar heat capture. This system is only suited for colder climates as these introduce heat into a space (new4old, 2013 and Torcellini & Pless, 2004).
ii. Phase changing materials are based on heat storage effects, rate of thermal change and storage is outside the scope of this research (Ghomeim, et al., 1991; Oyeleke, 2011 and Monodraught, 2011).
iii. Radiant cooling is classed as a mechanical type system therefore is not considered to fall within the category of passive system (Vangtook & Chirarattananon, 2007).
iv. Radiant barrier details that material location is important to minimise high infra-red solar effects and percentage reduction. Research into energy reductions is completed by others such as Fairey (1994) and Levins, et al (1986).

3.10 Summary

To summarise this chapter, this research methodology has been created to ensure clarity and structure to this study. The new passive system design guidance and integration strategies are detailed in chapter 7. This approach includes development of building base case models and analytical methods for passive system energy performance analysis. The results from the analysis completed in chapters 4 and 5 and are used as a platform for this contribution. The outcomes of this research focuses on satisfying aim and objectives set out in chapter 1.

Chapter 4

Effective Use of Solar Shading and Effects on Day Lighting

4.1 Introduction

This chapter analyses the effectiveness of available solar shading methods for internal space solar heat gain including impacts on internal office space cooling load and annual mechanical cooling energy consumption using theoretical building model A.1, which is located in a hot dry climate (refer to Table 3.1, Chapter 3). Use of EWY weather data files used in DTS software is described in 3.3.5. Effects of different types of external solar shades including analysis on day light contribution to determine impacts of day light penetration into internal office space. The purpose of this chapter is to provide analysis of different methods of solar heat gain reduction via windows such as different glazing types (4.3), external shading horizontal overhang depths (4.4), effectiveness of internal blind (4.5) and light shelf (4.6). In order to determine the most effective form of external solar shading (horizontal, vertical, angled and multi-angled), section 4.7 provides a performance analysis and identifies optimum type of external solar shade. Annual cooling energy effects from external solar shading devices is completed in section 4.8, to satisfy objective 3. Day lighting effects are analysed in section 4.9 for each type of external shading to determine which form has the greatest impact on reducing day light penetration into the open plan office space. For all analyses and calculations, research methods defined in Chapter 3 and Appendices B, F and G are used to determine overall results.

4.2 External Solar Shading Techniques

External solar shading was modelled using separate volume attached to the side of the main building in the DTS. The main external shading devices are horizontal high level overhang type (0.3m O_D), Vertical type (0.3m O_D) with four fins per window, single angled type (0.42m O_D) and Multi-Angled (0.42m O_D) with three shades per window. The depth of the overhang was increased for the angled and multi-angled shade by 0.12m to ensure a considerable impact when analysing lower solar azimuths. The shading device selected for this analysis is opaque, no thermal conductivity (0W/m^{2}k) for all scenarios. The selected shading device types below (Figure 4.1) are selected below based upon Windows & Daylighting (2013) and adopted accordingly. Figure 4.1 also shows the relationship between the overhand depth (O_D) and window height (W_h), where the greater O_D the greater the reduction of solar gains. The shading devices are angled at a maximum of 45 degree (cut off angle) (Lieb, 2001) and the effective window height (E_{wh}) is maximised (CIBSE, 2006b). Note that E_{Wh1} equals E_{Wh2} in this study.

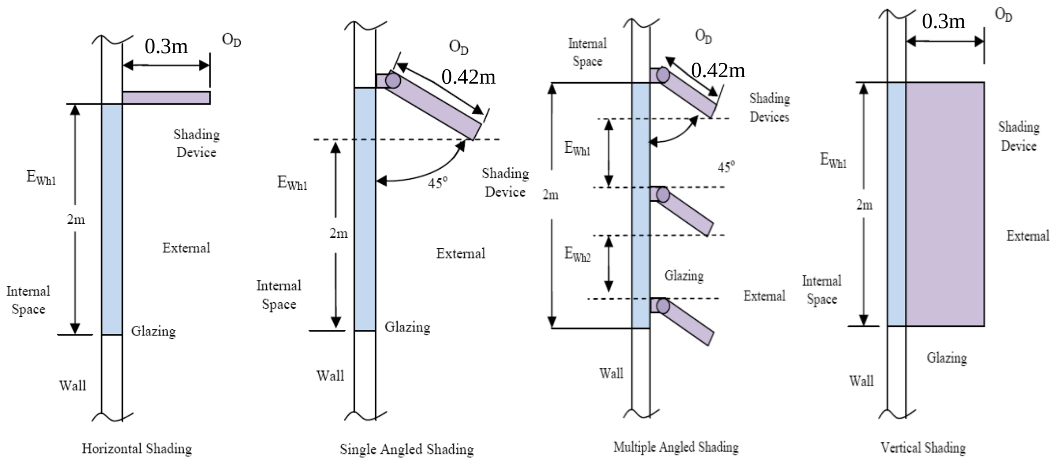


Figure 4.1- Common Forms of External Solar Shades

To show how these external solar shades were incorporated within building model A.1, Figures 4.2 and 4.3 graphically below shows how these formed part of DTS.

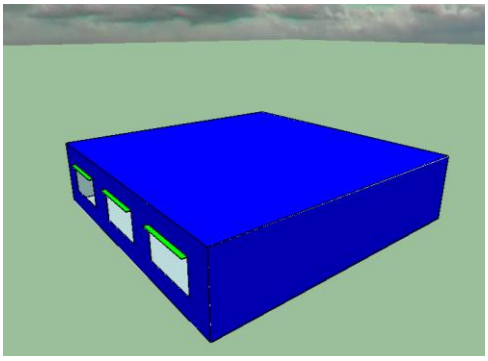
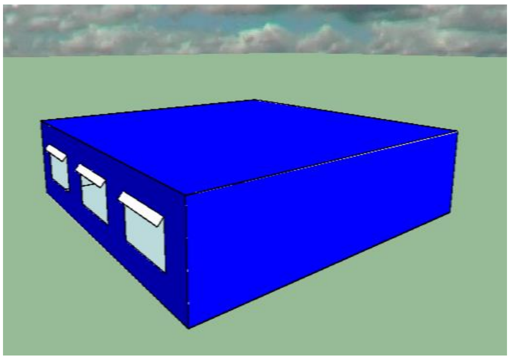



Figure 4.2- External Solar Shading for Windows
(Horizontal for Left and Angled for Right)

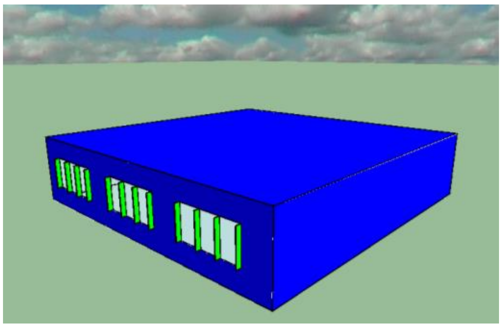
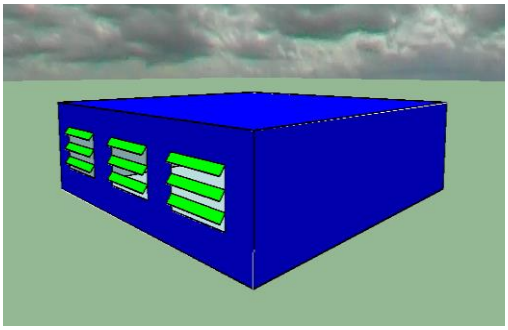



Figure 4.3- External Solar Shading for Windows (Vertical on Left Image and Multiple Angled on Right Image)

The methods for this analysis are detailed within section 3.5, Chapter 3.

4.3 Effects of Different Types of Window Glazing

This section analyses the impacts of varying different types of glazing on base case model A.1 and analysing impacts of varying window effective g-values. For this element of study, four different types of glazing are inter-compared as detailed in Table 4.1 below:

Table 4.1- Window Details & Properties

Glazing Type	Description	U Value (Including Window Frame)	Effective g-Value	Angular Dependence
A	Double Glazed-6mm + 12mm Argon + 6mm Inner (Steel Frame)	1.6	0.3993	Fensnel
B	Double Glazed- 6mm (Anti Sun)+ 12mm Argon + 6mm Inner (Steel Frame)	2.8598	0.4681	Fensnel
C	Single Glazed- 6mm Stopsol Clear (Steel Frame)	5.8824	0.5645	Fensnel
D	Double Glazed- 6mm + 12mm Air + 6mm Inner (Pilkington)-Steel Frame	1.9773	0.6406	Fensnel

Using theoretical building model A.1, DTS were completed for each orientation (East, South and West) to determine impacts of solar gains for each window type, as detailed in Table 4.1. Figure 4.4 below shows solar heat gain profile for each type of glazing on the East elevation for daytime period (hourly). Figures 4.5 and 4.6 show similar profiles for South and West elevations respectively.

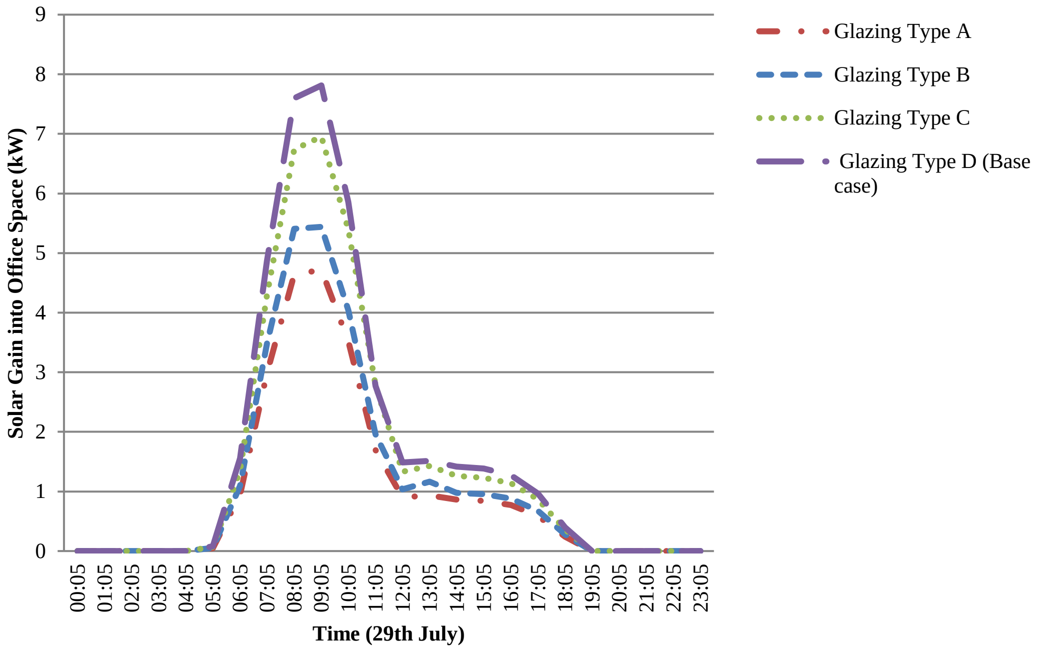


Figure 4.4- Solar Gains to Internal Space via East Elevation

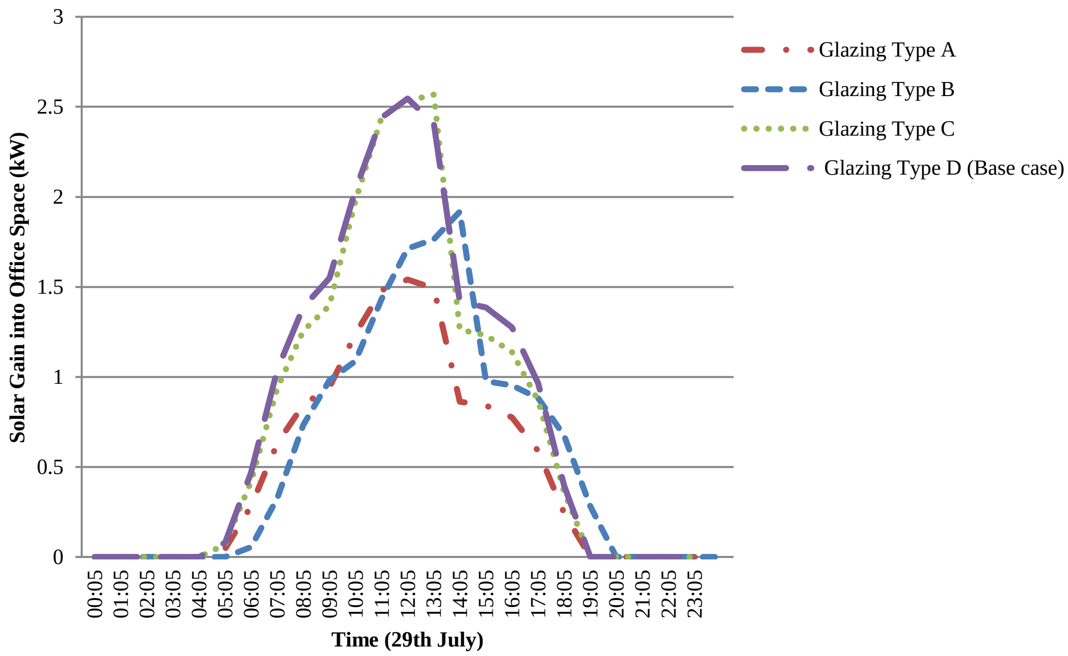


Figure 4.5- Solar Gains to Internal Space via South Elevation

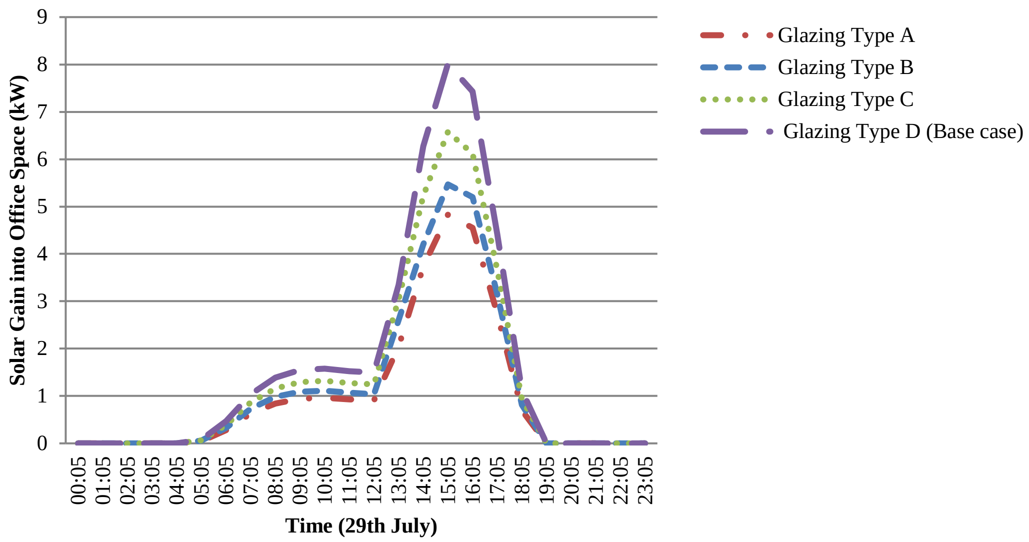


Figure 4.6- Solar Gains to Internal Space via West Elevation

The graphs above show that lowering effective g-value significantly reduces solar gains into the internal space where glazing type A is the most effective in all orientations and glazing type D being least effective, regardless of U value. For each building orientation, glazing type D is used as the base case and percentage reductions are shown in Figure 4.7. The bar graph shows that glazing types A and B are within 1 percent for each elevation. However, for glazing type C, has the greatest amount of reduction on West Elevation (16.44 percent). For East and South elevations, values vary by 5.12 percent.

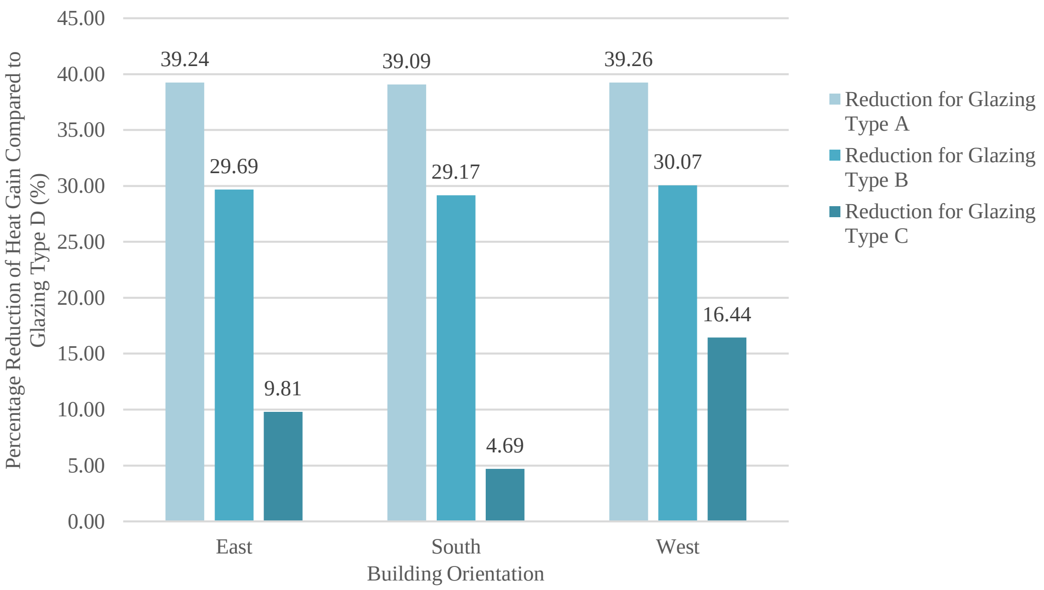


Figure 4.7- Solar Heat Gain Reduction For Different Types of Glazing
When compared to Glazing Type D

4.4 Horizontal External Solar Shade Over Hang Depth Analysis

This section analyses effects of reducing solar heat gain by changing the overhang depth (O_D) of a horizontal external solar shade from 0 to 1m. Using Theoretical Building Model A.1, DTS was completed increasing O_D by increments of 0.1m. Figures 4.8, 4.9 and 4.10 below show impacts for East, South and West orientations respectively. The graphs below show solar heat gain profile for a daytime period for each external solar shading depth.

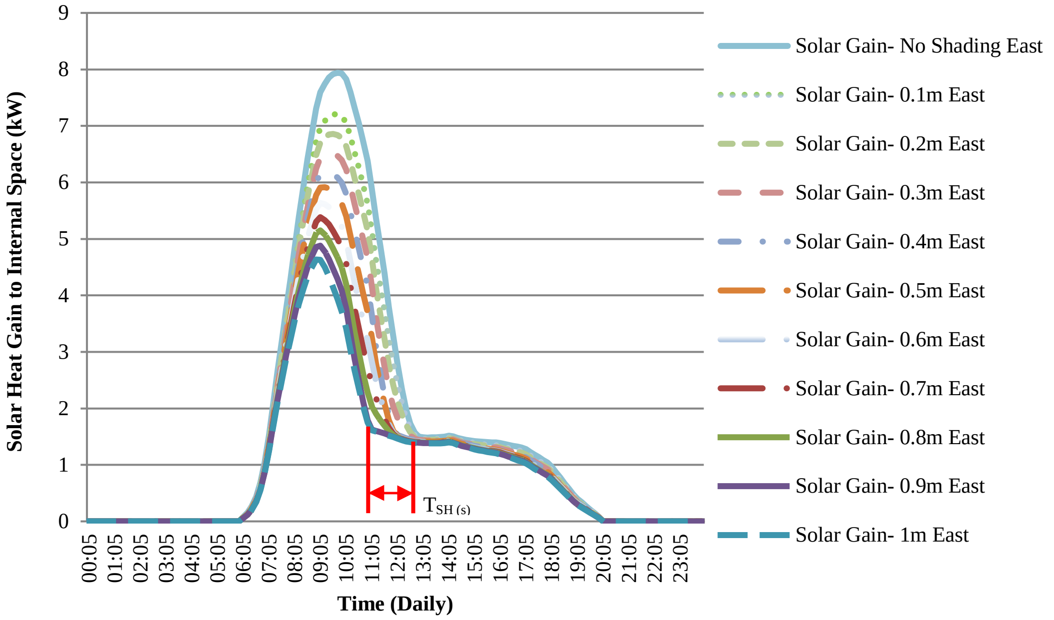


Figure 4.8- East Elevation Solar Heat Gains to Internal Space with Varying Overhang Depth

Figure 4.8 (East elevation) above shows there is a time shift ($T_{SH\ (s)}$) of cooling from 06:05 to 11:05, when O_D equal to or greater than 0.9m, hence mechanical cooling is required 2 hours later in the day. For best curve fit, polynomial analysis (6th Order) shows R^2 vary from 0.6774 (1m O_D) to 0.7013 (No Shading). Figure 4.9 and 4.10 below shows solar heat gain profiles for South and West elevations respectively.

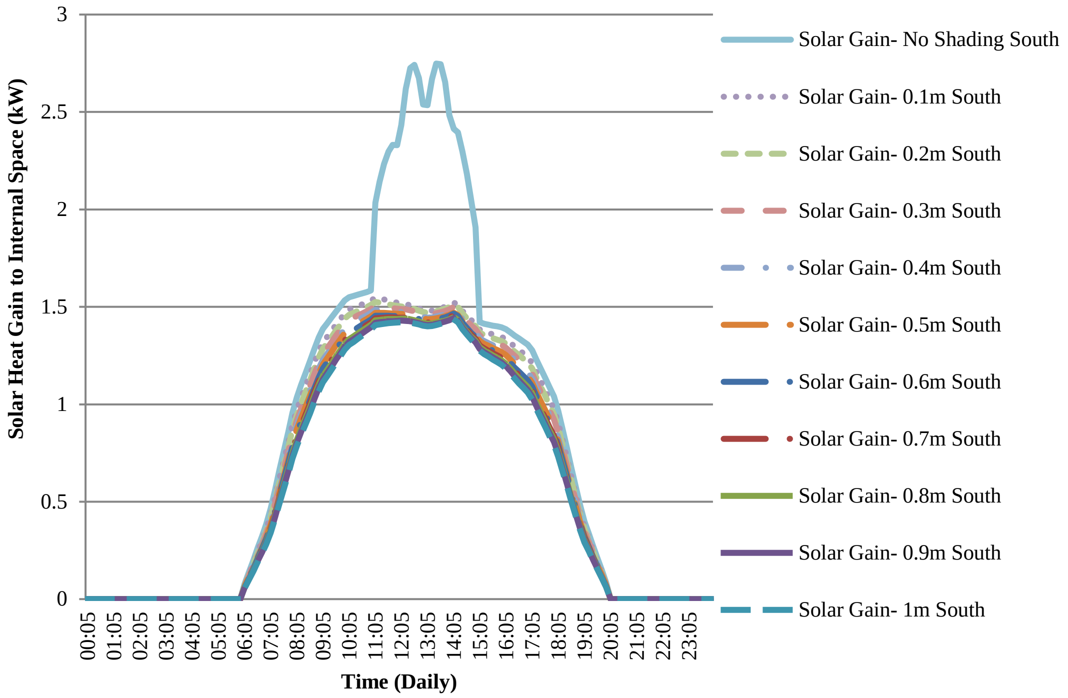


Figure 4.9- South Elevation Solar Heat Gains to Internal Space with Varying Overhang Depth

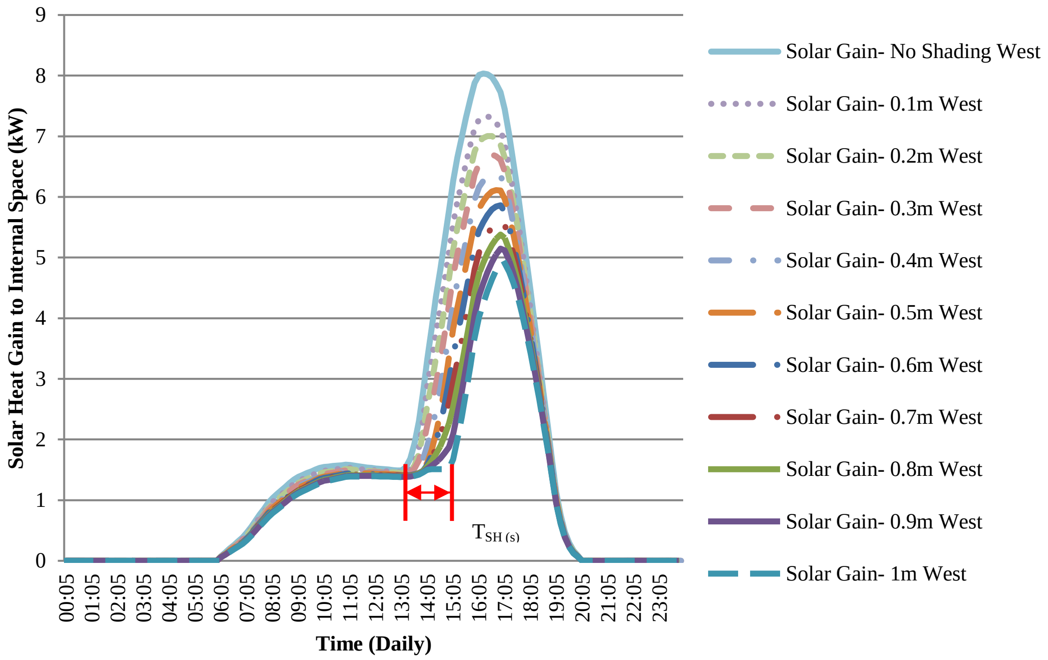
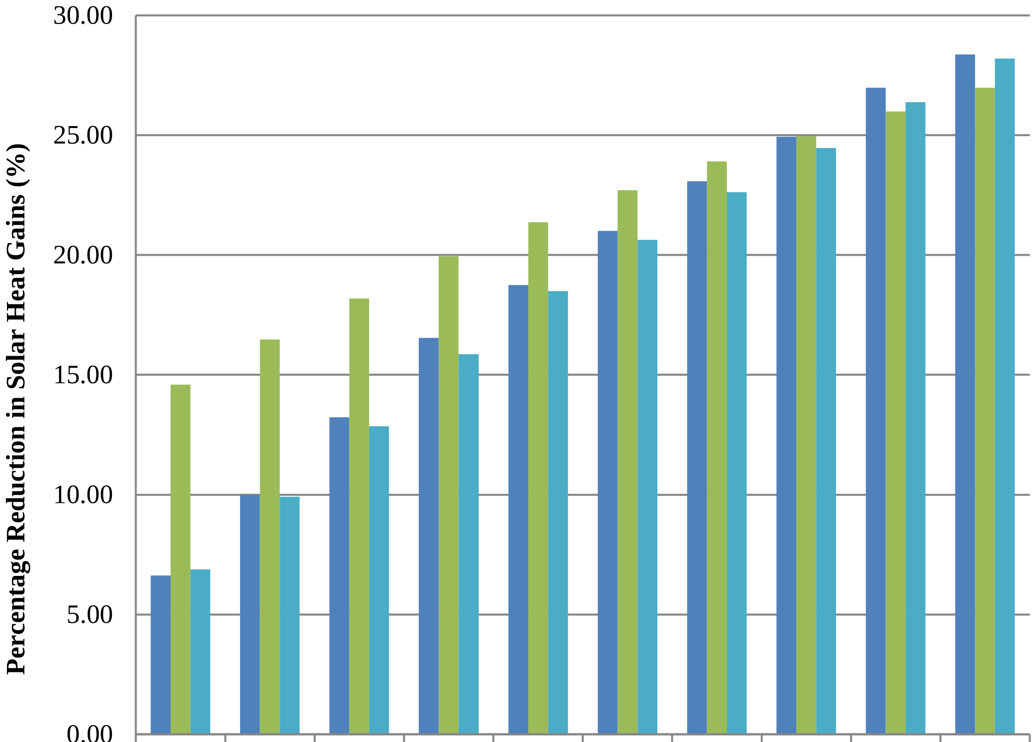


Figure 4.10- West Elevation Solar Heat Gains to Internal Space with Varying Overhang Depth

Figure 4.9 (South) shows a significant reduction for all shading depths throughout the daytime period with an immediate reduction from 2.8 to 1.6kW when using an O_D of 0.1m.

For best curve fit, polynomial curves (6th Order) shows R^2 vary from 0.9807 (1m O_D) to 0.9332 (No Shading). There is very minor differences in solar heat gain reductions between shading depths on this elevation. Furthermore, a time shift ($T_{SH\ (s)}$) is observed from 13.05, where reductions are available at 15:05, when O_D equal to or greater than 0.9m, hence solar cooling is required 2 hours later in the day. For best curve fit, polynomial analysis (6th Order) shows R^2 vary from 0.737 (1m O_D) to 0.7829 (No Shading). To summaries the effects of increasing the horizontal overhand depth, Figure 4.11 shows percentage reductions for each O_D at each elevation.



	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
East	6.63	9.98	13.22	16.54	18.75	21.00	23.08	24.94	26.98	28.37
South	14.60	16.47	18.18	19.95	21.36	22.70	23.91	24.96	26.00	26.98
West	6.87	9.91	12.85	15.86	18.49	20.63	22.63	24.47	26.38	28.19

Figure 4.11- Percentage Solar Gain Reduction at Varying Overhang Depth (O_D)

The above bar graph shows that where O_D is 0.1 to 0.7m, percentage reduction of solar heat gain is greatest for the South elevation. For O_D greater than 0.7m, percentage reductions appear to stabilise on all elevations between 1-2%. Furthermore, where O_D greater than 0.8m is more effective for East and West elevations.

4.5 Effectiveness of Internal Blind at Peak Summer Period

This section completes a fundamental calculation analysis to determine how effective the internal blind is at rejecting window solar heat gains externally. This analyses how closing the blind by increments of 10 percent of the window area can reduce solar heat gain into the internal space. Figure 4.12 provide an indicative section showing the relationships between internal blind and window and directional heat flows (arrows):

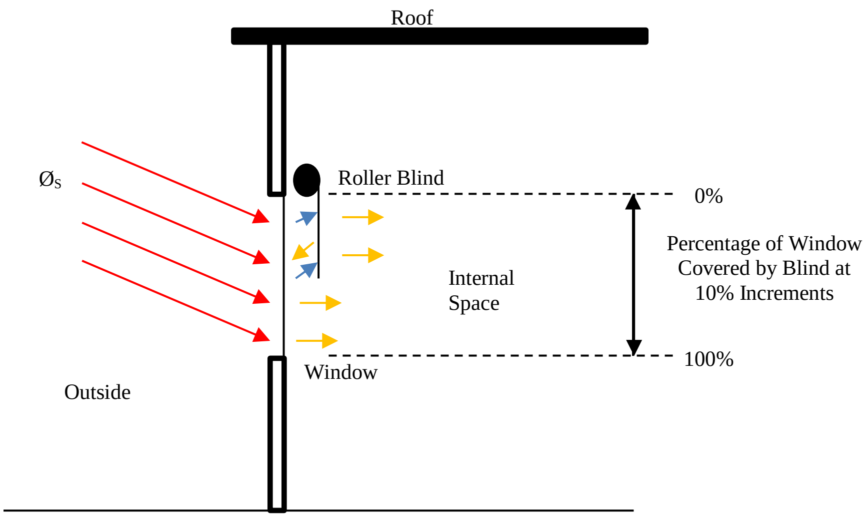


Figure 4.12- Building Section for Internal Blind Configuration

The manual calculation completed in Appendix F, using equations 3.2 and B.2, encompasses the following using fundamental heat transfer principles (convective and radiant):

- Maximum solar heat gain via glazing (Peak Period)- W/m^2
- Surface Temperature of Blind (T_b) based on transfer heat gains from glazing
- Irradiated heat transfer from Blind to Inner Glazing Surface
- Heat Transfer from inner glazing to outside air

The maximum solar radiation is based upon DTS weather data from IES VE software for July which is 1095.20 W/m^2 and maximum external air temperature 44.2^{o}C. By varying the internal blind height and effective g-value of glazing, a bar graph has been generated to show radiant heat transfer from the blind to external space at 10 percent increments (Figure 4.13).

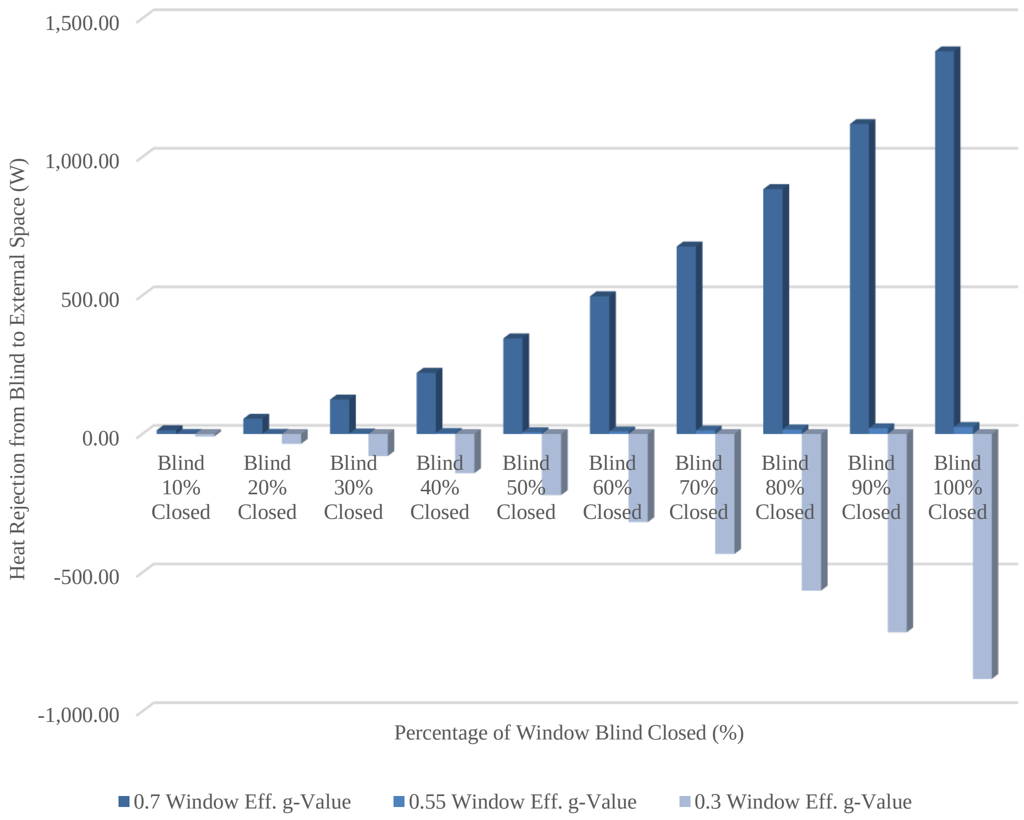


Figure 4.13- Heat Rejection from Blind to External Area

As the blind depth increases (lowering of blind over glazing), radiant heat transfer only increases when window effective g-value is equal to or greater than 0.55. Where effective g-values are less than 0.55, no heat is transferred externally and is absorbed into the internal space. The analysis shows that as blind height increases, solar heat gain reduction is proportional when using an effective g-value greater than 0.55. This figure shows that lower effective g-values have a higher thermal resistance of heat transfer effectively providing a higher thermal barrier for escaping irradiated heat.

4.6 Effectiveness of External Light Shelf at Peak Summer Period

This section analyses solar heat gain effects when utilising an external light shelf. Fundamental calculations are completed using heat transfer principles (radiant) to determine how the shelf reduces solar heat gains and how it's irradiated from the surface into the internal space. The horizontal light shelf comprises of steel frame edge and internal polycarbonate surface. Figure 4.14 below shows the light shelf position (50% of window elevation).

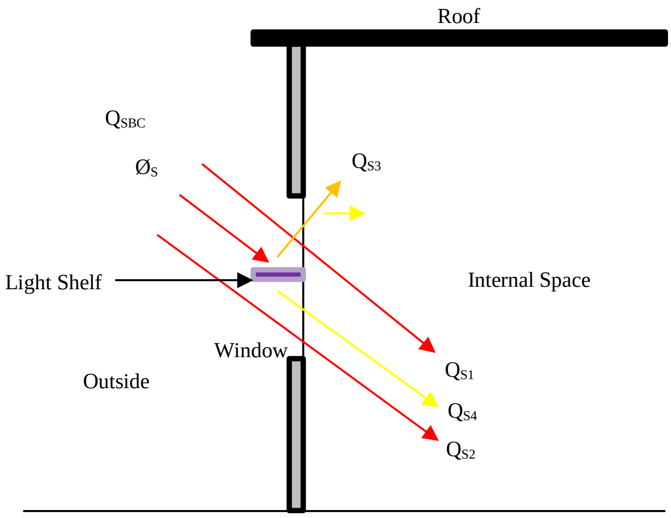


Figure 4.14- Building Section for External Light Shelf Configuration

Analysis completed in Appendix G, using equations 3.2 and B.2, shows that a 10.74% reduction is achieved at intermediate vertical positions when the light shelf is up to 10% distance from the lower sill. Additional analysis is completed to determine the effects of different materials used for light shelf, while understanding that these need to be as reflective as possible for maximise light transmission into the internal space. Figure 4.15 shows heat gain effects of different materials taking into account primary factors such as emissivity (ε) and conductivity's (k) for silver, aluminium, tungsten, steel, mild steel, new steel and polycarbonate. Other factors such as specific heat capacity, reflectivity and absorptivity are detailed below in Table 4.2 for each of these material from available information.

Table 4.2- Typical Material Properties

Material	Emissivity	Thermal Conductivity at 20°C (W/(m k)	Thermal Diffusivity (mm^2/s)	Absorptivity (Surface Colour Dependant)	Refractive Index (n)	Reflection Factor (%)	Specific Heat Capacity (kJ/kg k)
Source	Engineering Toolbox (2016b)	Engineering Toolbox (2014)	Netzsch (2017) & Holman, (2002)	Engineering Toolbox (2016c)	Refractive Index (2017)	Engineering Toolbox (2016d)	Engineering Toolbox (2016e)
Silver	0.02	429	165.63	***0.25 – 0.40***	0.5876	90 - 92	0.23
Aluminium	0.039	205	98.8	0.3	1.0972	65 - 75	0.91
Tungsten	0.04	174	-	***0.4 – 0.5***	3.5777	**65 - 75**	0.13
Steel, Carbon 1%	0.07	43	22.8	0.8	-	-	***0.49***
Mild Steel	0.2	43	22.8	***0.8***	-	-	0.49
New Steel	0.23	43	22.8	***0.8***	-	-	***0.49***
Polycarbonate (White Surface)	0.91	0.19	0.144	***0.25 – 0.40***	1.5848	-	1.2-1.3

For values highlighted (Red, bold and italics); these are estimated based on similar materials. Published values are currently not available from these sources. For the purpose of radiative heat exchange calculations, emissivity values are utilised from Table 4.2 in accordance with equation B.2 in Appendix B. Calculations are completed for the lower and upper light shelf surfaces. The polycarbonate has the greatest heat irradiated from the surface where metals have low values due to higher emissivity.

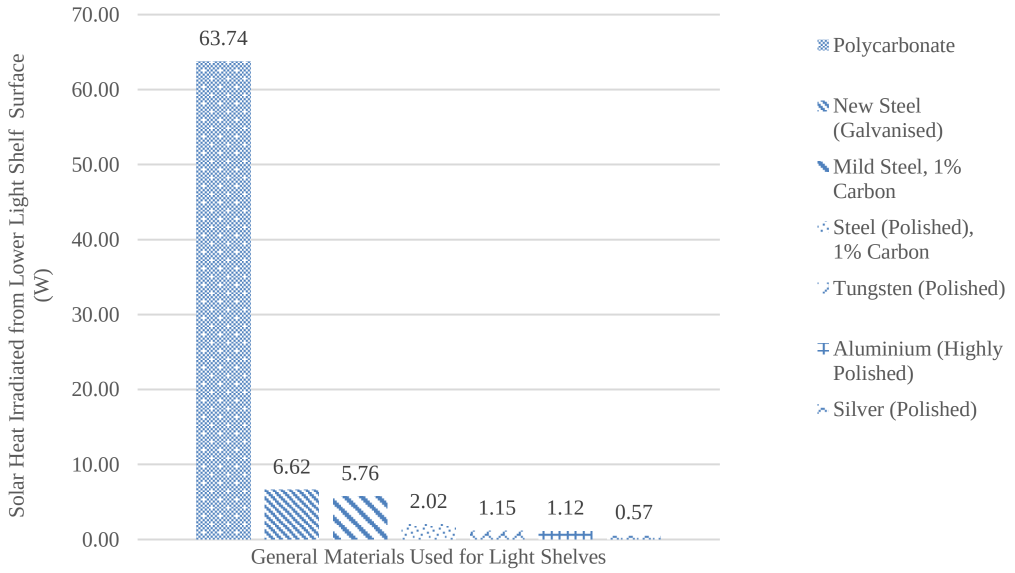


Figure 4.15- Lower Surface Heat Irradiation from Light Shelf

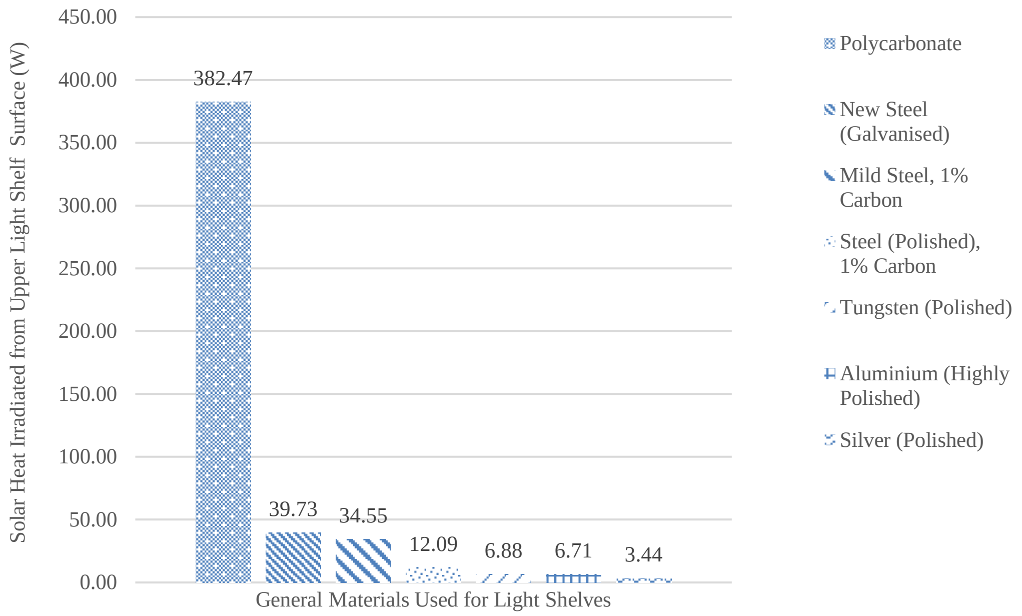


Figure 4.16- Upper Surface Heat Irradiation from Light Shelf

Figure 4.17 below shows the total solar heat gain reduction when using a light shelf including metallic surfaces which can reduce heat gains by average of 19.58 percent. Silver polished surface provides the highest reduction at 19.92 percent.

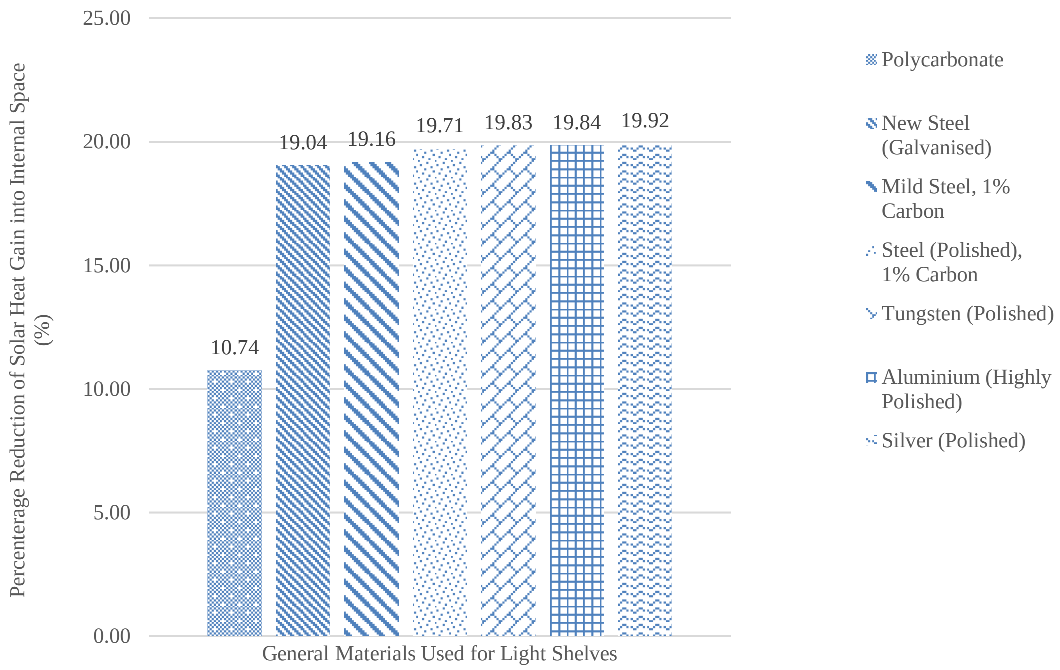


Figure 4.17- Total Solar Heat Gain Reduction Using Light Shelf

4.7 Effectiveness of Different External Fixed Solar Shading Devices for Summer Daytime Period

Dynamic thermal simulations were completed for each external wall elevation to determine thermal performance for each type of external solar shading devices as described in section 4.2. Effectiveness is defined as the total reduction of solar heat gain admittance into the office space via windows. Figures 4.18 to 4.20 show daytime solar heat gains (kW) for each type of shading and elevation. Figure 4.18 below shows solar heat gain effects on the South facing windows for each external shading case with the base case indicating the maximum amount of gain for a daily period for 29th July. The results of this shows that horizontal and angled have similar solar gain reduction performance (angled identifying greater reduction). Vertical shading indicates limited effectiveness, due to lack of shading at higher solar azimuths during midday periods. Multi-angled shading type being the most effective, providing the greatest reduction.

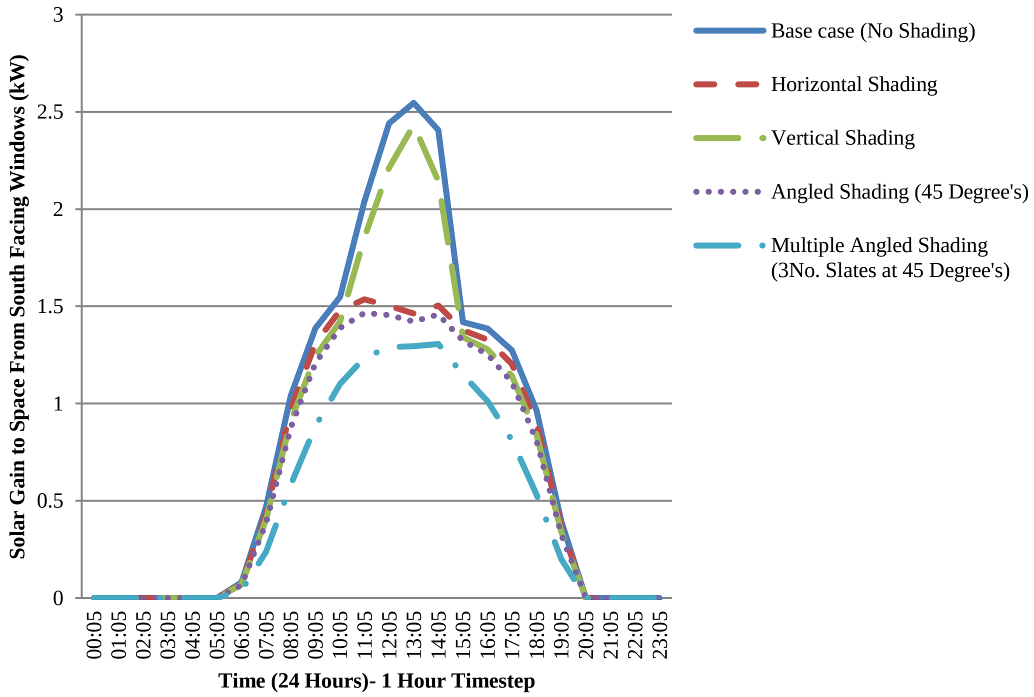


Figure 4.18- Solar Heat Gain for South Facing Windows/Shading (29th July)

Figure 4.19 below shows identical analysis has been completed for East facing windows showing the multi-angled shading solution being the most effective.

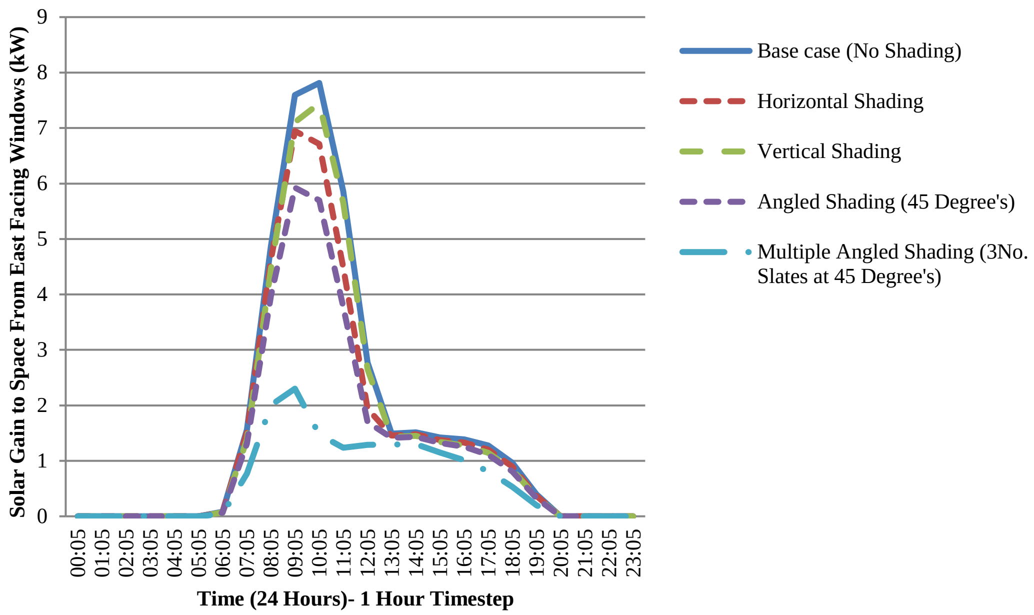


Figure 4.19- Solar Heat Gain for East Facing Windows/Shading

For West facing windows, the multi-angled solution provides the most effective solar gain reduction as shown in Figure 4.20. The curves are also similar to Figure 4.18 on the East Elevation.

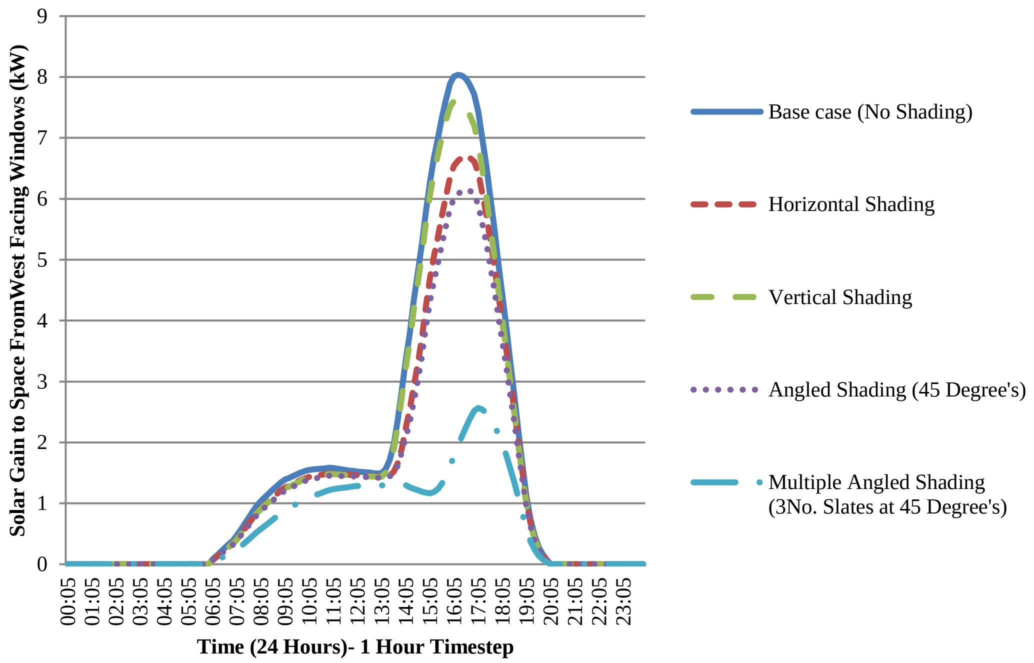


Figure 4.20- Solar Heat Gain for West Facing Windows/Shading

When comparing Figures 4.19 and 4.20, plotted results show that horizontal and angled external shading device on the East wall performs better than on the West wall; as graph peaks show greater magnitude. This is quantified by slightly higher heat gains to the West elevation and the graph peaks show a slight increase in solar heat gains. To provide an overview of the results for each elevation, Table 4.3 below highlights the percentage reductions of mechanical cooling load for each external solar shading methods.

Table 4.3- Diurnal Sensible Cooling Load Reduction (29th July)

Elevation	% Reduction Against Basecase-Horizontal External Solar Shading	% Reduction Against Basecase-Vertical External Solar Shading	% Reduction Against Basecase-Angled External Solar Shading	% Reduction Against Basecase-Multi-Angled External Solar Shading
East	8.71	7.94	17.72	46.20
South	15.15	10.42	21.40	41.16
West	8.33	8.19	17.42	46.53

Table 4.3 identifies that multi-angled external solar shading device is the most effective solution for all elevations when assessing solar heat gain reduction on hottest day of the year.

4.8 Annual Cooling Effects for External Solar Shading Devices

This section details impacts on mechanical cooling energy performance for each type of external solar shading over a yearly period. For each type of shading device, simulations are completed from 1st January to 31st December. Each external shading device is simulated for the year and orientation modified to suit (East, South or West). Total amount of simulations completed is 15 including base case (no shading). From DTS, values are exported and collated to determine chiller energy required for each month. For each orientations, bar graphs are produced showing chiller energy for each month showing energy reductions against the base case results. Figure 4.21 is East elevation, Figure 4.22 is South Elevation and Figure 4.23 West Elevation.

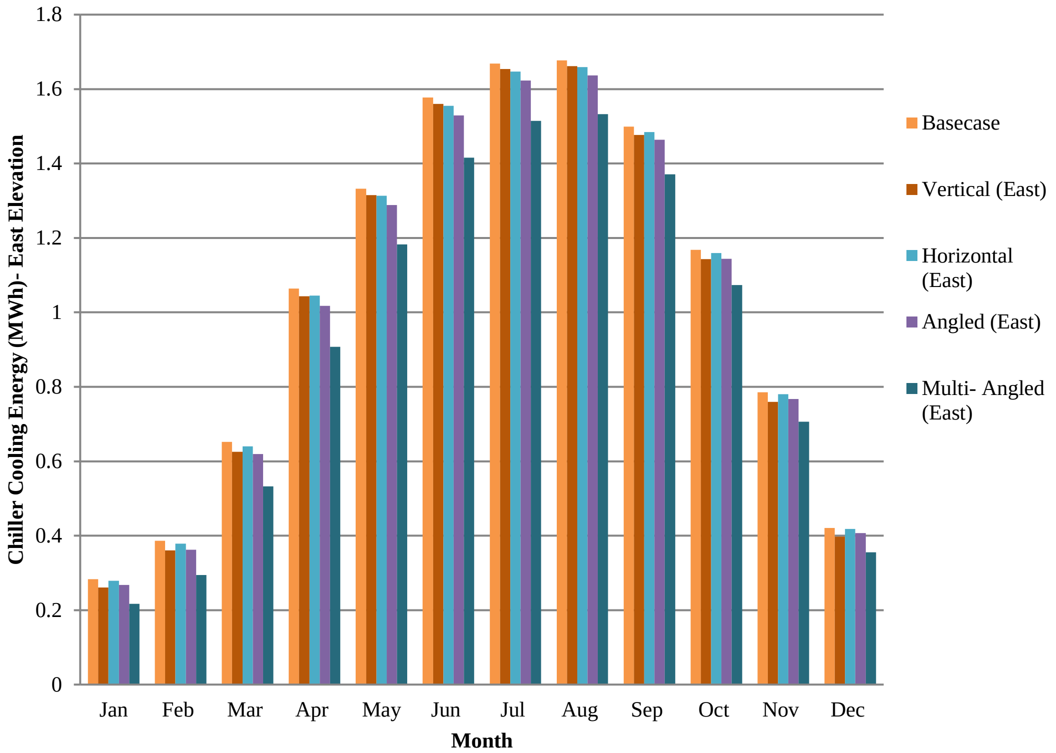


Figure 4.21- Building Model A.1 Chiller Energy Consumption for East Elevation

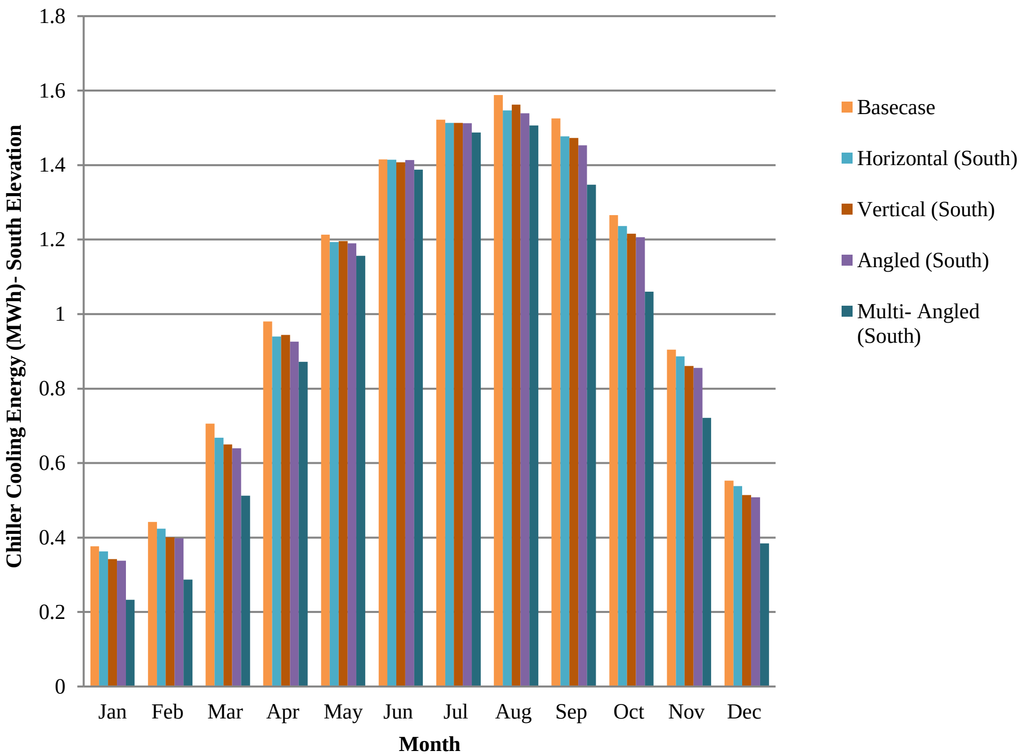


Figure 4.22- Building Model A.1 Chiller Energy Consumption for South Elevation

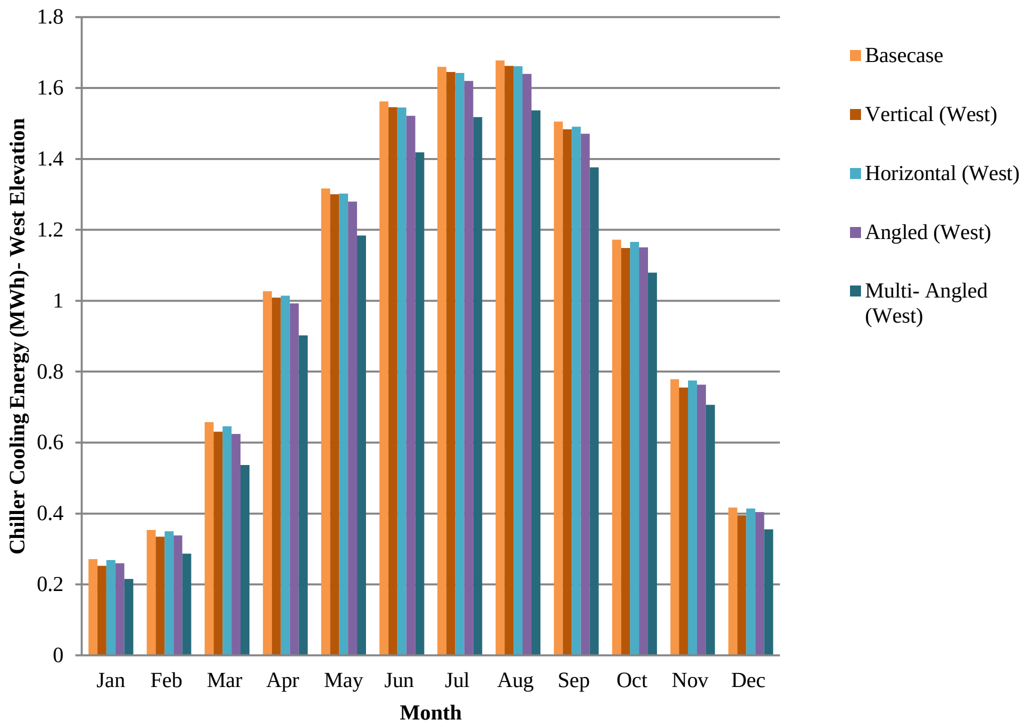


Figure 4.23- Building Model A.1 Chiller Energy Consumption for West Elevation

The above figures (4.21, 4.22 and 4.23) show that for each orientation multi-angles type shading devices are the most effective at reducing external solar gains. To understand chiller load percentage energy reductions for each shading type on each wall elevation, Figure 4.24 below summaries total amount of energy reduction available per year.

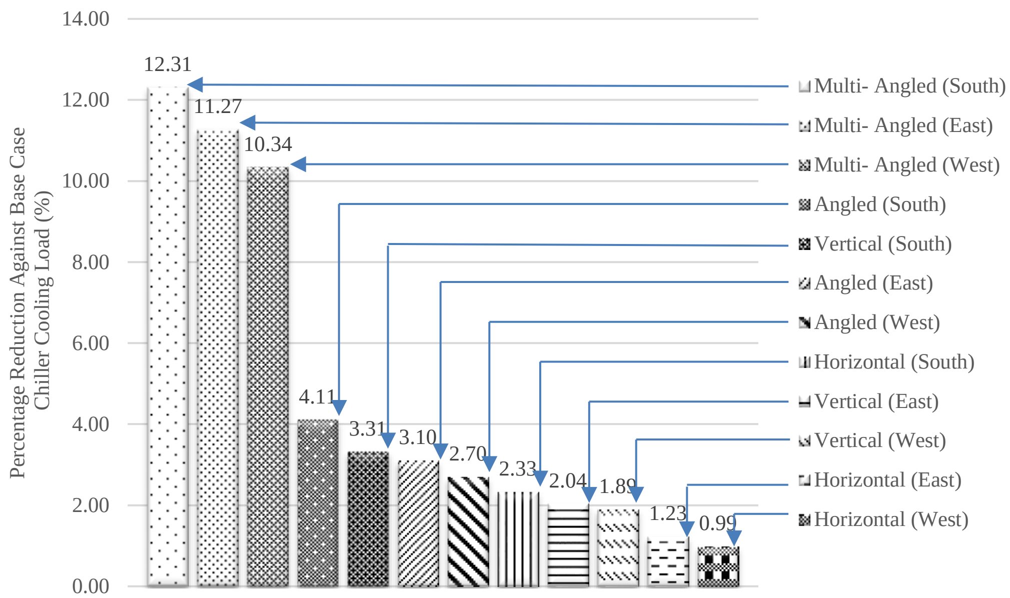


Figure 4.24- Percentage Reduction of Chiller Cooling Load for Each External Solar Shade Type and Orientation (East, South and West)

4.9 Effects of External Solar Shading Devices on Day lighting

Day light contribution can be significantly affected by external solar shading devices. This depends on the size, type, window coverage and angle of incidence. General design ethos and best practice means that this should be maximised as much as possible before glare becomes an issue (CIBSE, 1999a). The values for average daylighting levels can differ for each orientation with a desired daylight factor 5 required. Where daylight factor falls below 2, artificial lighting is required to maintain uniformity (CIBSE, 1999a). As recommended by CIBSE (2005), the minimum lighting level required for the task using computer screens only is 300 lux and computer screens including reading small text is 500lux at the working plane. The problem is there will be a considerable amount of glare (glare index >19) therefore the optimum solution should reduce external glare control below 19 (CIBSE, 2012b). Day lighting calculations have been completed for each type of solar shading using CIE clear skies weather data (section 3.3.3, chapter 3) and results are shown in Table 4.4 below. This table has been created to provide a direct comparison for all forms of external shading devices between maximum, minimum and average illumination levels (lux) against each other and benchmark set out by CIBSE (2005d) and CIBSE (1999a).

Table 4.4- Daylighting Comparison (South Elevation)

Type of Shading	Min. (Lux)	Max. (Lux)	Uniformity (Average)	Average (Lux)-DL_1	Average Design Light Level Bench Mark in Accordance with CIBSE LG7:2005 (PC Screen & Paper text)	% Average Daylighting Reduction from Shading Against Base Case	Average Calculated Daylight Factor	Minimum Average Daylight Factor in accordance with CIBSE LG10 :1999
Basecase (No Shading)	35.58	4810.71	0.08	463.81	500	-	1.9	2
Horizontal	35.71	4180.94	0.08	427.32	500	7.87	1.8	2
Vertical	29.43	4650.41	0.07	402.40	500	13.24	1.7	2
Angled	21.59	3285.23	0.06	337.62	500	27.21	1.4	2
Multiple Angled (3No.)	12.09	822.98	0.1	121.75	500	73.75	0.5	2

The results shown in Table 4.4 indicate there are higher levels of discomfort/disability glare from windows based on calculated maximum illumination levels i.e. >500 Lux. The optimum case solution is multi-angled shading as the maximum daylight calculated is reduced to 822.98 Lux. In all cases, artificial lighting is required to supplement day light contribution as the day lighting value is below 2 (CIBSE, 1999a). When considering lighting energy consumption, Table 4.5 shows calculated percentage reduction when comparing average artificial lighting (section 3.3.3, chapter 3) and daylighting illumination (lux) values (DL_1/AL_1).

Table 4.5- Artificial Lighting Energy Reduction for Each type of External Shading (South Facing Windows) When Maximising Daylighting Contribution

Type of Shading	Artificial Lighting Electrical Energy Reduction (%)
Base case Building Model (No Shading)	89.88%
Horizontal	82.81%
Vertical	77.98%
Angled	65.43%
Multiple Angled (3No.)	23.59%

Table 4.5 does not take into account uniformity and glare from the window panes. In reality, luminaire rows closest to the window should be provided with dimming controls in order to regulate lamp lumen output. Also the unified glare rating (UGR) must also be considered to prevent disability/discomfort glare; this is not necessary for this analysis as the external solar shading acts as glare control reducing the maximum lux level into the space. Luminaires to the rear of the room will still have to function at between 80-100% output to maintain illumination levels and uniformity; as the ingress of day light will be insufficient to illuminate the space (CIBSE, 1999a). Figure 4.25 below provides comparisons between all external solar shading device types for all different window. Excluding the base case model, the graph shows that the multi-angled shading has the lowest performance only providing a daylight factor of 0.5 for all elevations. Vertical shading is improved with higher daylight factor for the south facing glazing. Multiple angled shading is a slight improvement on vertical shading with improved daylight factor values for all elevations. Horizontal type shading provides the highest daylight values on all elevations. The higher daylight factors are desired and horizontal shading type provides the highest daylight factor for all elevations and orientations.

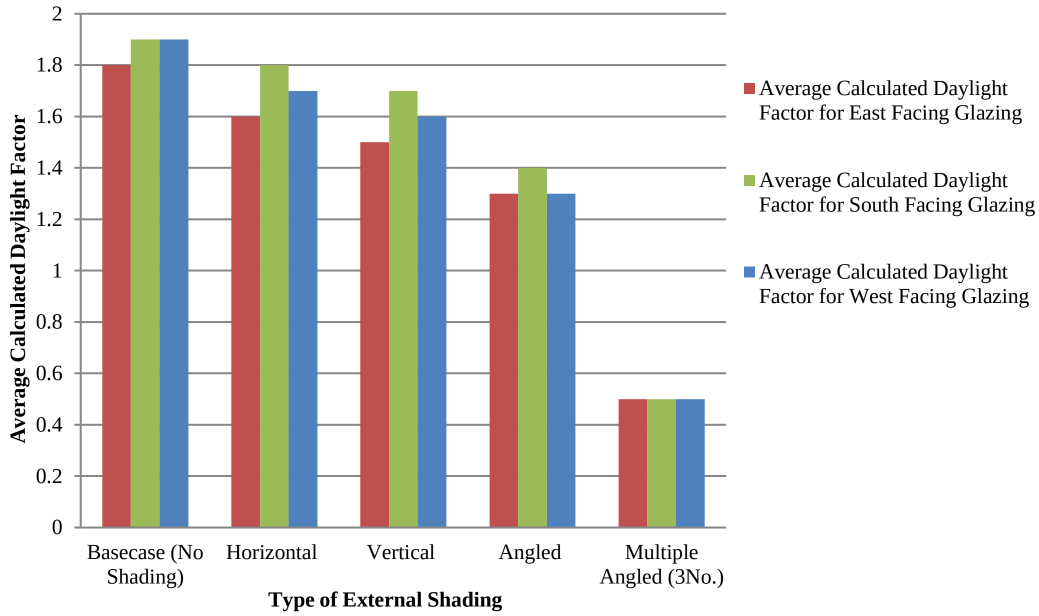


Figure 4.25- Average Daylight Factor for Various External Shading devices and Orientations (29th July)

The values for average daylighting levels differ for each orientation and all instances the daylight factor is below 2; hence artificial lighting is required to maintain required lighting levels and uniformity (CIBSE, 1999a). From Table 4.4, multiple angled shading provides a reduction of 73.75% and provides average daylighting level of 121.75 Lux. As recommended by CIBSE (2005b), the minimum lighting level required for the task (computer screens and reading small text) is 500lux at the working plane. The calculated daylight factor is reduced by 10% when compared to the base case model. Furthermore, this solution only reduces artificial lighting energy consumption by 23.59% when compared to others which offer a greater lighting saving. The problem encountered is that will be a considerable amount of glare (glare index >19) hence external solar shades would be recommended as glare control measure with internal blinds.

4.10 Summary

This chapter analyses solar heat gain reductions for different forms of external solar shading and proves methodology set out in section 3.5 (chapter 3) with regards to assessing potential mechanical cooling energy reduction for commercial building types (objective 3). This analysis includes mechanical energy reduction effectiveness of external solar shading devices, differing window glazing (effective g-value), internal blind (peak summer period), horizontal external overhang depth and light shelf in terms of solar heat gain contribution into an internal room. This chapter also determines impacts on daily mechanical cooling load and annual mechanical cooling energy reduction; identifying the most effective solution. The main finding from the generated results are detailed below:

- Window glazing (Type A) which is double glazed 6mm + 12mm Argon + 6mm inner and steel frame having an effective g-value of 0.3993 can reduce solar heat gains by 39.24 percent (East), 39.09 percent (South) and 39.26 percent (West) as detailed in Figure 4.7.
- Adjusting the overhang depth (O_D) on an external horizontal shading device greater than 0.7m has a stabilised increase of solar gain reduction by 1-2% hence there is minimal benefit by having this greater than 1m.
- Internal blinds are in-effective when summer period experience high solar radiation and high external temperatures when lowering effective g-value of external window. This means that glazing has a greater resistance for radiative heat from the blind to the external space, even when blind is 100 percent closed.
- For light shelves, use of different materials effects the amount of irradiated heat from both surfaces of the light shelf with polycarbonate being least effective. Ideal materials are metallic types due to lower emissivity values. Furthermore, there will be an element of reflection of solar heat into the external environment from the light shelf however this will be small amounts which would benefit from additional study.
- Results for both day time cooling load and annual energy reduction show that multiple angled shading is the most effective solution for commercial buildings in hot climates.

- For day lighting, when using multi-angled external shading devices which also acts as effective glare control for all elevations, an artificial lighting energy reduction of 23.59 percent can be achieved when compared with base case i.e. no external solar shading.
- As external solar radiation levels change i.e. the amount of reduction in heat gains via the window panes, there is a proportion relationship hence calculated percentage reductions will still equate to the whole cooling load contributed to the internal space with or without external solar shading.
- As discussed in section 3.3.5, use of TMY files may improve accuracy of results due to weather data averages taken over a longer period.

The main benefit of external solar shading is direct reduction of solar gains to the building, internal space via glazing and provides control of external day light (glare). The most effective form of external solar shading discovered in this chapter (multi-angled) is incorporated within theoretical building model B.1 in chapters 5 analysis. Chapter 5 completes analysis of natural ventilation, solar chimney, ventilated double facades, rain screen facades, passive downdraught evaporative cooling and earth ducts to calculate potential HVAC energy reductions. The results from these chapters are integrated within chapter 6 results analysis.

Chapter 5

Mechanical Ventilation and Cooling Energy Reduction Using Passive Systems

5.1 Introduction

This chapter analyses the effectiveness of natural ventilation, solar chimney, ventilated double facades, rain screen facades, passive downdraught evaporative cooling, earth ducts for space cooling load reduction and impacts on annual mechanical ventilation and cooling energy consumption using theoretical commercial building models B.1 and B.2. The purpose of this chapter is to determine the effectiveness of each passive system and rank accordingly (objective 3). Each section is broken down into overview, performance analysis and verification. Passive system effects on solar heat gains and external air temperature are expressed as temperature reduction (^{o}C), heat energy (kW), mechanical ventilation energy (kWh) and mechanical cooling energy (kWh). Overall energy reduction values are expressed as percentages to identify which is the most effective at lowering energy consumption. The majority of passive systems will be analysed using Model B.1; natural ventilation will be analysed using model B.2. The method defined in chapter 3 are used to determine overall results. The final performance results are shown using polynomial average trend analysis (R^2) and findings are summarised in Table 5.11. External solar shading is also incorporated within the overall results analysis based on discoveries made in Chapter 4.

5.2 Combining Natural Ventilation with Mechanical Ventilation and Cooling Systems

5.2.1 Overview

Using theoretical building model B.2 located in Abu Dhabi, a mixed mode ventilation and cooling strategy is used and analysis is completed. Mechanical system/natural ventilation operational time are determined from the sinusoidal behaviour of the external air temperature using time/temperature analysis, as detailed in Appendix H. Natural ventilation mode is in operation when external air temperature is less than the internal space set point temperature. Where external air temperature exceeds the set point temperature (24-28^{o}C), mechanical ventilation/cooling mode is in full operation. For example, actuation of natural ventilation external air temperature is below set point temperature (T_o<SP), once the set point temperature is exceeded, HVAC operation (T_o>SP) will activate. For mixed mode ventilation and cooling operation i.e. either mechanical or natural ventilation modes, energy consumption is revised accordingly as mixed mode system time periods change hourly hence operation is automatically adjusted accordingly via building energy management system (BEMS). The important factor is to determine operational times for both modes of operation, which are mechanical ventilation operational time ($MV_{(t)}$) and natural ventilation activation time ($NV_{(t)}$). The revised time can be determined ($NV_{(t)}$ – $MV_{(t)}$) and multiplied by mechanical system power (kW) which is revised hours of operation (Qe). This enables calculation of revised mechanical ventilation and cooling energy consumption when taking into account time of operation for natural ventilation. This is completed for both full time operation (base case) and mixed mode operation. Mechanical cooling operation is dependent on time operation only i.e. on or off above and below the BEMS set point temperature. These time/temperature curves are detailed in Appendix H for each set point temperature ranging from 24^{o}C to 28^{o}C. Sections for Appendix H are detailed below:

- H.2 Mechanical Ventilation Operation Period with a set point of 24^{o}C
- H.3 Mechanical Ventilation Operation Period with a set point of 25^{o}C

- H.4 Mechanical Ventilation Operation Period with a set point of 26°C
- H.5 Mechanical Ventilation Operation Period with a set point of 27°C
- H.6 Mechanical Ventilation Operation Period with a set point of 28°C

To explain how the revised mechanical plant time periods are derived, average temperature curves are produced for each month. Where curved line intersects with horizontal set point temperature line, mechanical ventilation time period can be determined above the set point line. Time period for natural ventilation can be determined below the set point line. Time periods for each mode are read from time/temperature graphs. These results are detailed in Tables for each set point temperature and equate to full working day.

5.2.2 Performance Analysis

Using base case mechanical ventilation and cooling energy results from Table 3.14 (chapter 3), Figure 5.1 below shows mechanical fan energy performance plots for each external set point temperature. These are based upon the hours associated with natural ventilation operation time ($NV_{(t)}$) which are deducted from mechanical ventilation operation time ($MV_{(t)}$). All plots are compared against the base case model i.e. full time operation of mechanical ventilation detailed in Figure 5.1 below (Brittle et al., 2016a). As shown in monthly energy profiles, increasing internal thermal comfort set point temperature has a significant impacts on reducing mechanical ventilation energy from February to April and October to December in Abu Dhabi. The graph also identifies that in all cases full mechanical ventilation is required from May to September as the external air temperature exceeds thermal comfort conditions.

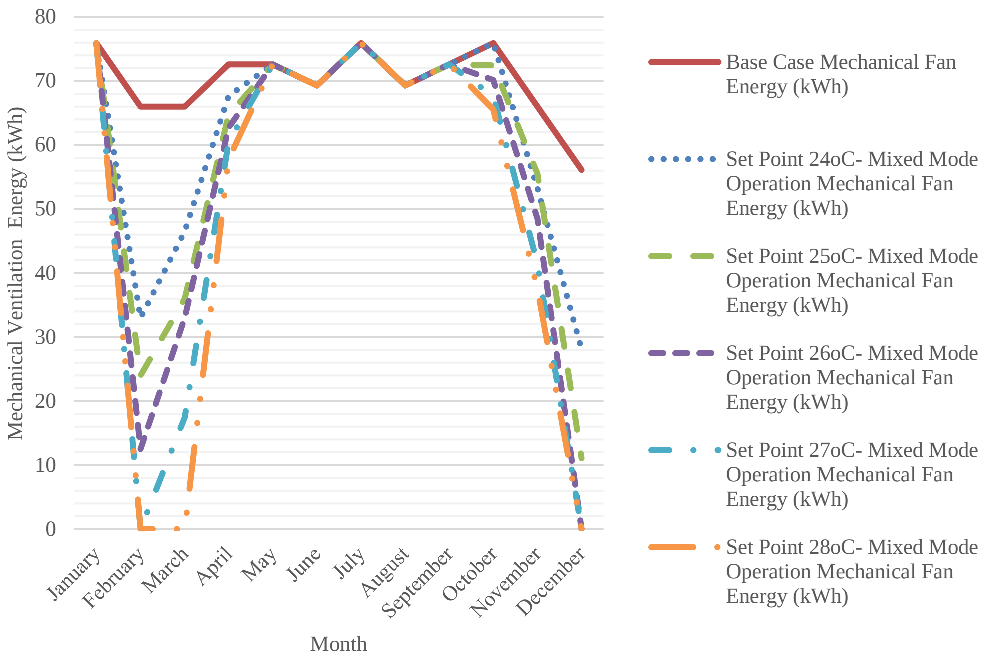


Figure 5.1- Mechanical Ventilation Energy Reduction Using Mixed Mode Operation

For mechanical cooling reductions, Figure 5.2 below shows similar profiles for the cooling with the same outcomes in terms of performance.

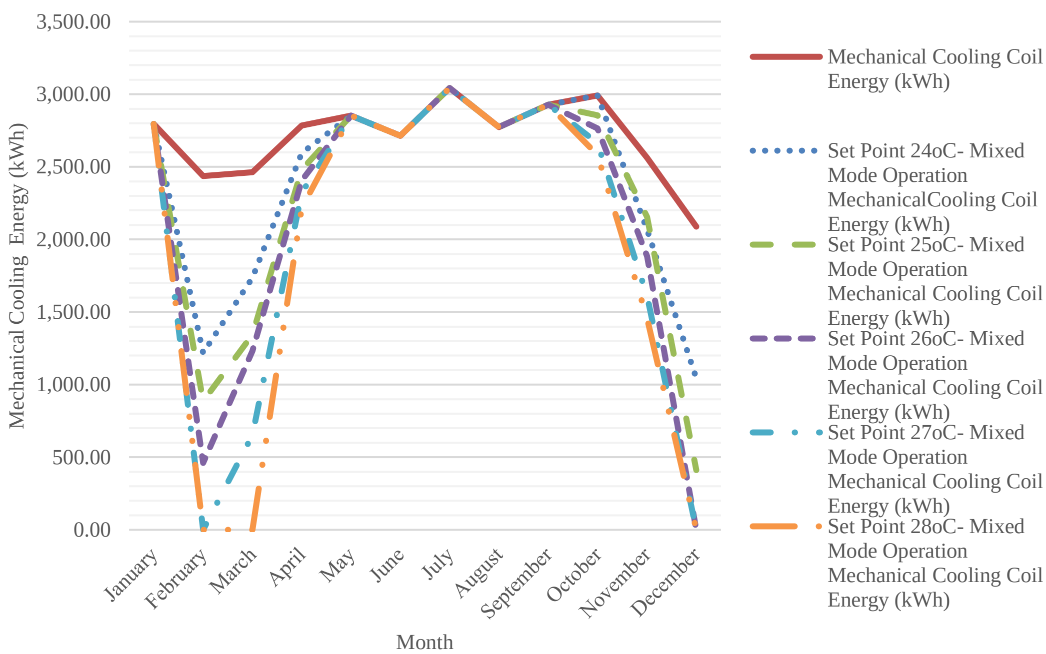


Figure 5.2- Mechanical Cooling Energy Reduction Using Mixed Mode Operation

For individual performance analysis in terms of maximum reductions available for mechanical ventilation, to supplement Figure 5.1, Table 5.1 below shows energy performance values calculated per month and percentage reductions available per annum.

Table 5.1- Energy Performance and Percentage Reduction Using Mixed Mode Ventilation

Month	Base Case Building Energy Consumption (kWh)	Internal Room Set Point Temperature (ºC) & Revised Building Energy Consumption (Mixed Mode Operation)				
		24	25	26	27	28
January	75.90	75.90	75.9	75.9	75.9	75.9
February	66.00	33.00	24	12.498	0	0
March	66.00	46.50	36	33	17.46	0
April	72.60	67.65	64.68	62.7	60.50	57.75
May	72.60	72.60	72.6	72.6	72.6	72.6
June	69.30	69.30	69.3	69.3	69.3	69.3
July	75.90	75.90	75.9	75.9	75.9	75.9
August	69.30	69.30	69.3	69.3	69.3	69.3
September	72.60	72.60	72.6	72.6	72.6	72.6
October	75.90	75.90	72.45	70.1523	67.62	65.55
November	66.00	53.22	55.5	48.498	41.46	37.5
December	56.10	28.05	11.0517	0	0	0
Totals	838.20	739.92	699.28	662.45	622.64	596.40
Percentage Reduction (%)	-	**11.73**	**16.57**	**20.97**	**25.72**	**28.85**

For mechanical cooling, Table 5.2 below shows energy performance values calculated per month and percentage reductions per annum to supplement Figure 5.2.

Table 5.2- Energy Performance and Percentage Reduction Using Mixed Mode Cooling

Month	Base Case Building Energy Consumption (kWh)	Internal Room Set Point Temperature (ºC) & Revised Building Energy Consumption (Mixed Mode Operation)				
		24	25	26	27	28
January	2,796.55	2,796.55	2,796.55	2,796.55	2,796.55	2,796.55
February	2,435.68	1,217.84	885.70	461.23	0.00	0.00
March	2,463.73	1,735.81	1,343.85	1,231.86	651.77	0.00
April	2,785.22	2,595.32	2,481.38	2,405.42	2,321.10	2,215.52
May	2,852.47	2,852.47	2,852.47	2,852.47	2,852.47	2,852.47
June	2,714.55	2,714.55	2,714.55	2,714.55	2,714.55	2,714.55
July	3,042.86	3,042.86	3,042.86	3,042.86	3,042.86	3,042.86
August	2,773.58	2,773.58	2,773.58	2,773.58	2,773.58	2,773.58
September	2,926.75	2,926.75	2,926.75	2,926.75	2,926.75	2,926.75
October	2,990.67	2,990.67	2,854.73	2,764.19	2,664.42	2,582.85
November	2,562.45	2,066.26	2,154.79	1,882.93	1,609.68	1,455.94
December	2,088.09	1,044.05	411.35	0.00	0.00	0.00
Totals	32,432.59	28,756.70	27,238.55	25,852.39	24,353.72	23,361.06
Percentage Reduction (%)	-	**11.33**	**16.01**	**20.29**	**24.91**	**27.97**

Analysing remaining set point temperatures (25-28ºC), occupied office time period for natural ventilation operation ($NV_{(t)}$) and mechanical HVAC operation ($MV_{(t)}$) are taken from graphs detailed in sections H.3 to H.6, Appendix H. The results from these are demonstrated for each set point temperature in Table 5.2 below. It is important to highlight the point that values calculated are on the assumption that cooling is on/off operation only dependant on time. As shown in time/temperature curves in Appendix H, above the intersect of internal set point temperature, full mechanical ventilation and cooling is in operation and this does not take into account thermal lag or temperature rise which switching between the two modes for the internal office space. It is also identified there is a slight difference in percentage energy reductions between Table 5.1 and 5.2 which are used in the summary Table 5.10. However, Table 5.3 below shows these combined as due to simultaneous operation hence the percentage is calculated from the total value when applied within PSEAT. The percentages expressed show the total amount of mechanical ventilation and cooling energy that can be saved when adopting this approach.

Table 5.3- Annual Mechanical Ventilation and Cooling Energy Reduction Using Mixed Mode Operation

Month	Base Case Building Energy Consumption (kWh)	Internal Room Set Point Temperature (ºC) & Revised Building Energy Consumption (Mixed Mode Operation)				
		24	25	26	27	28
January	2,872.45	2,872.45	2,872.45	2,872.45	2,872.45	2,872.45
February	2,501.68	1,250.84	909.70	473.73	0.00	0.00
March	2,529.73	1,782.31	1,379.85	1,264.86	669.23	0.00
April	2,857.82	2,662.97	2,546.06	2,468.12	2,381.61	2,273.27
May	2,925.07	2,925.07	2,925.07	2,925.07	2,925.07	2,925.07
June	2,783.85	2,783.85	2,783.85	2,783.85	2,783.85	2,783.85
July	3,118.76	3,118.76	3,118.76	3,118.76	3,118.76	3,118.76
August	2,842.88	2,842.88	2,842.88	2,842.88	2,842.88	2,842.88
September	2,999.35	2,999.35	2,999.35	2,999.35	2,999.35	2,999.35
October	3,066.57	3,066.57	2,927.18	2,834.35	2,732.04	2,648.40
November	2,628.45	2,119.48	2,210.29	1,931.43	1,651.14	1,493.44
December	2,144.19	1,072.10	422.41	0.00	0.00	0.00
Totals	33,270.79	29,496.62	27,937.84	26,514.84	24,976.36	23,957.46
Percentage Reduction (%)	-	**11.34**	**16.03**	**20.31**	**24.93**	**27.99**

The results show that adopting this method can achieve potential energy reductions ranging from 11.34 to 27.99 percent. However, a constant higher temperature greater than 25ºC will make the internal environment very uncomfortable for human occupation (British Standards, 2005) therefore the realistic values would a maximum set point temperature of 26ºC.

5.2.3 Verification

Verification proves somewhat difficult as many natural ventilation research conference papers, journal and books only review the performance of air flow, air temperature and heat gains. Inter-comparison of energy performance is difficult to empirically verify due to lack of readily available performance data with a bias building HVAC. This method of approximated time/temperature analysis is a solid and fundamental approach that provides calculated effects of natural ventilation on mechanical ventilation and cooling energy performance and operation. From this analysis, calculated monthly values can be used and compared against an actual building BEMS system (monitored outputs). This would also provide a benchmark how the building should be performing (future).

5.3 Solar Chimney Performance Analysis

5.3.1 Overview

A performance analysis is completed to determine the effects on air flow when converting a natural ventilation chimney into a solar chimney. This is completed by making the South side elevation to fully glazed surface. The variations of glazing used in this analysis include single pane clear glass, double glazed clear and double glazed treated (internal powder coating). For each month, solar heat gains are calculated using methods detailed in section 3.6.2, chapter 3 and parameters set out in Tables I.1 to I.3 in Appendix I. The calculated air flow effects of solar gain are analysed using linear regression for natural air flows within the chimney stack and determines which type of glazing that provides optimum air flow performance for two hot climates (Portugal and Kenya).

5.3.2 Performance Analysis

From available weather data, solar irradiance to the solar chimney's South facing vertical surface is based upon monthly peak values (maximum). For both climates, Figures 5.3 and 5.4 bar charts inter-compares different air flow rates for each month. A linear increase in air flow is observed for all months evenly for Portugal's climate as 57.14 percent for single glazing and 45.45 percent for double glazed.

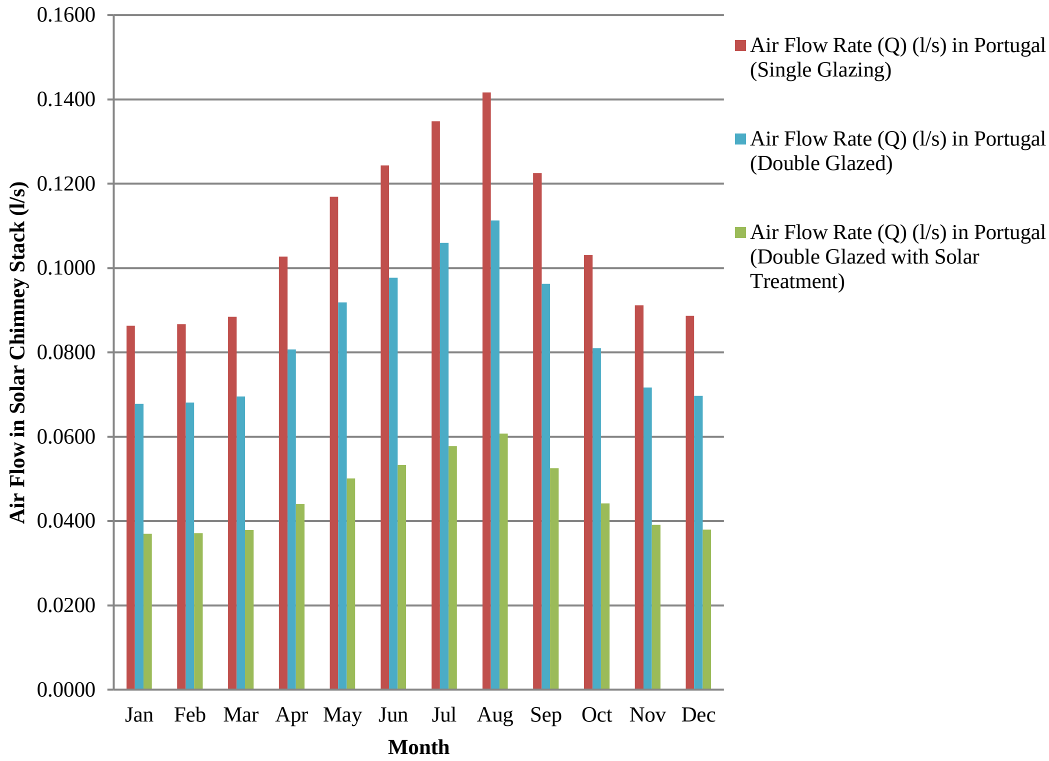


Figure 5.3- Monthly Air Flow Rates for Solar Chimney Performance in Lisbon, Portugal

Figure 5.3 shows that a maximum air flow of 14.16l/s (August) and minimum of 0.0863l/s (January) achieved when using single glazing. The double glazing has a slightly reduced performance. When adding a treatment to the outer pane of a double glazed window, this dramatically reduces solar irradiance into the inner chimney space hence reducing air buoyancy and air flow. Figure 5.4 below, air flow results are shown for Nairobi, Kenya. Similar reductions are observed in the bar graph when compared to Figure 5.3. For this climate, maximum air flow rate is 0.13l/s (February) and minimum air flow rate is 0.053l/s (July) respectively, when using single glazing.

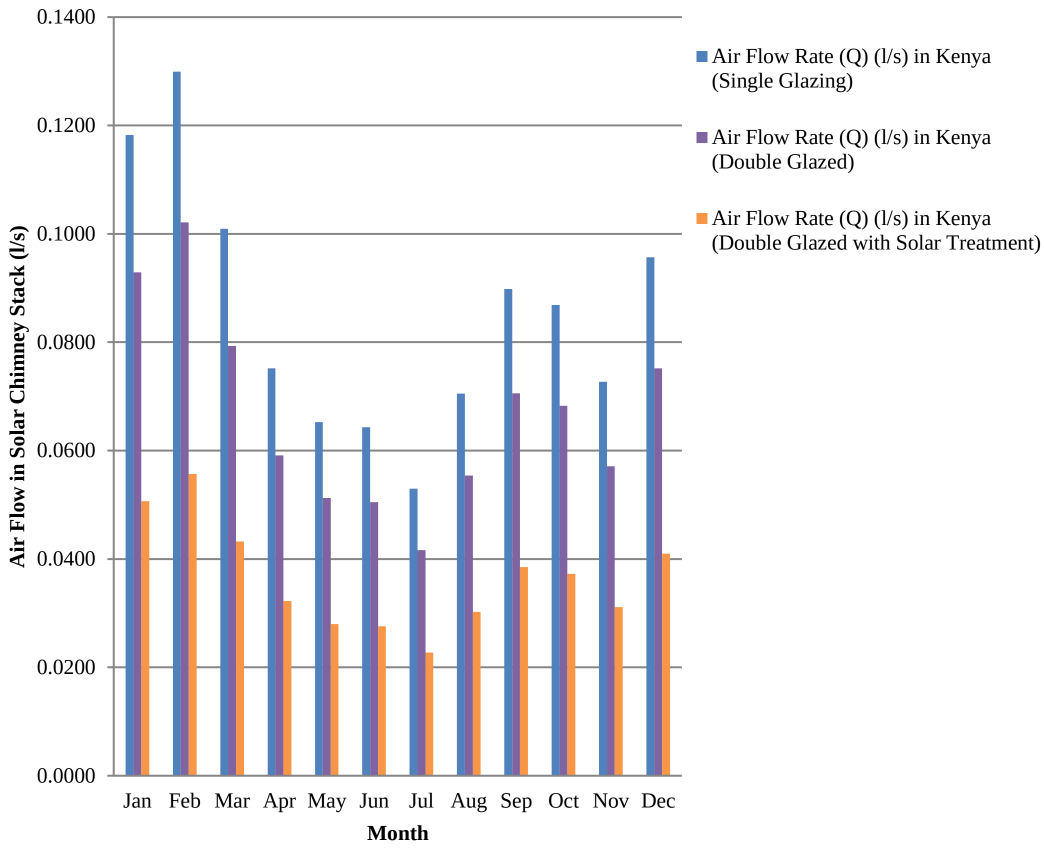


Figure 5.4- Monthly Air Flow Rates for Solar Chimney Performance in Nairobi, Kenya

In both climatic, single glazing provides optimum performance, with clear double glazed second and treated double glazed third. The higher effective g-value allows greater amounts of solar heat energy to penetrate solar chimney stack increasing its wall surface temperature and encouraging air buoyancy for exhaust natural air flow. Developing this analysis further in order to understand the relationship between solar heat gain into the solar chimney stack and effective g-value, Figure 5.5 below shows difference in solar heat gain (each climate) and changes in effective g-values. The graph identifies a rising linear profile (R^2=1) in both climates, however better performance is observed in Portugal. This proves that higher the effective g-value, greater solar heat gains are provided to the solar chimney.

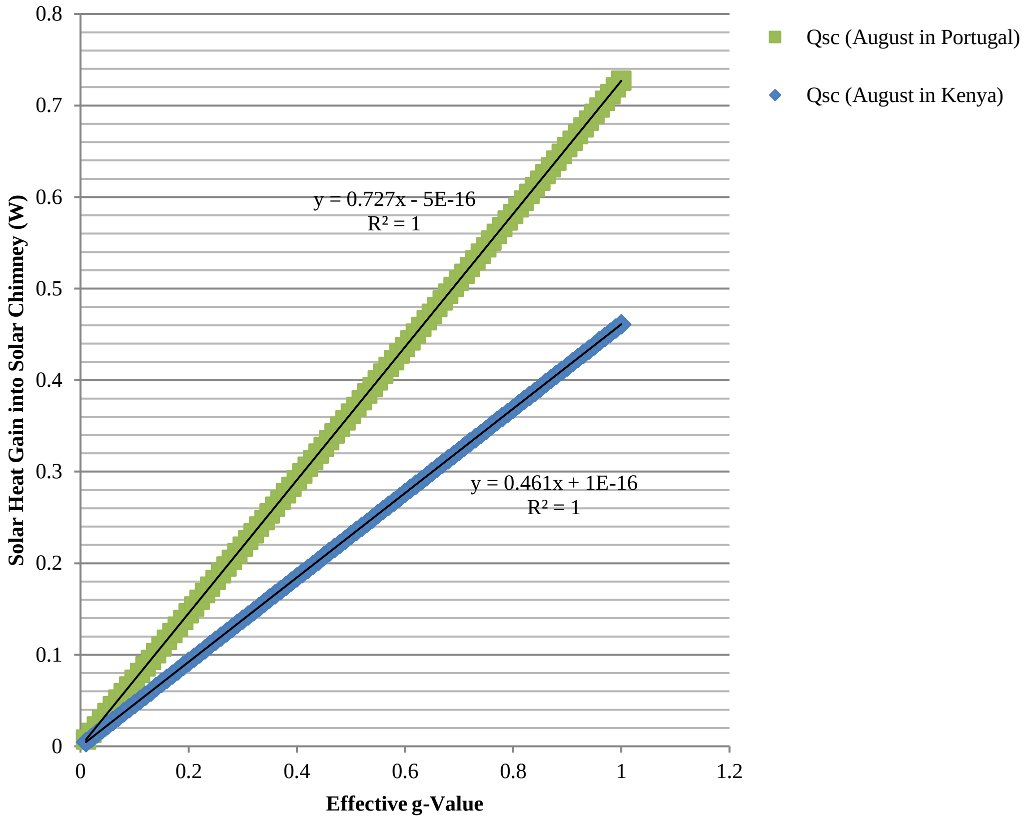


Figure 5.5- Solar Chimney Linear Regression Relationship Heat Gains to Effective g-Value (Portugal & Kenya)

To compare air flow rates with solar heat gains, Figures 5.6 (Portugal) and 5.7 (Kenya) below shows a comparison made from calculated solar heat gains and air flow rates. These line graphs shows the impacts on air flow when using these different types of glazing; analysed using linear regression (R^2). Again, similar to Figure 5.5, all plots show a rising linear profile and show how the air flow, within the solar chimney, increases proportionately with solar heat gain. For Portugal climate (Figure 5.6), clear single glazed and clear double glazed have a similar performance 0.31 and 0.4kW solar heat gain. The treated glazing does not interact with other linear plots and remains independent at the lowest scale of performance. For Kenya climate, all three linear plots interact with each other between the range solar heat gain of 0.17-0.21kW, all three types of glazing can perform achieving 0.05-0.06l/s. These graphs show there is a slight cross over in terms of performance between each glazing type.

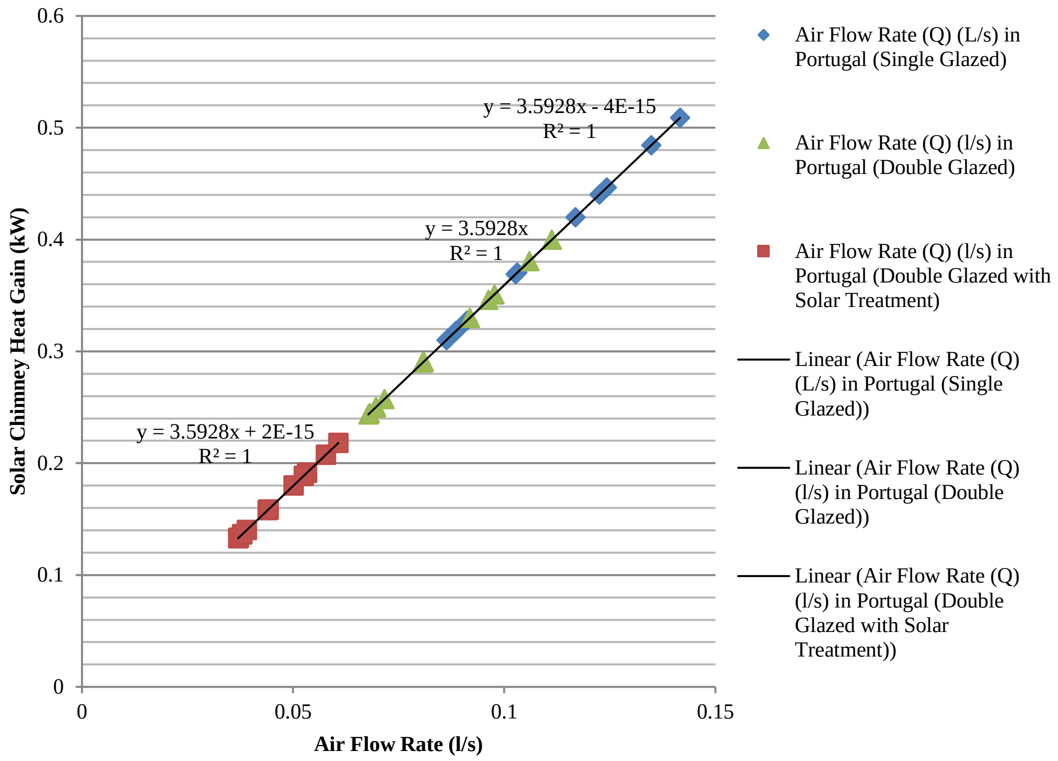


Figure 5.6- Solar Chimney Linear Regression Relationship Heat Gains to Effective g-Value for Portugal

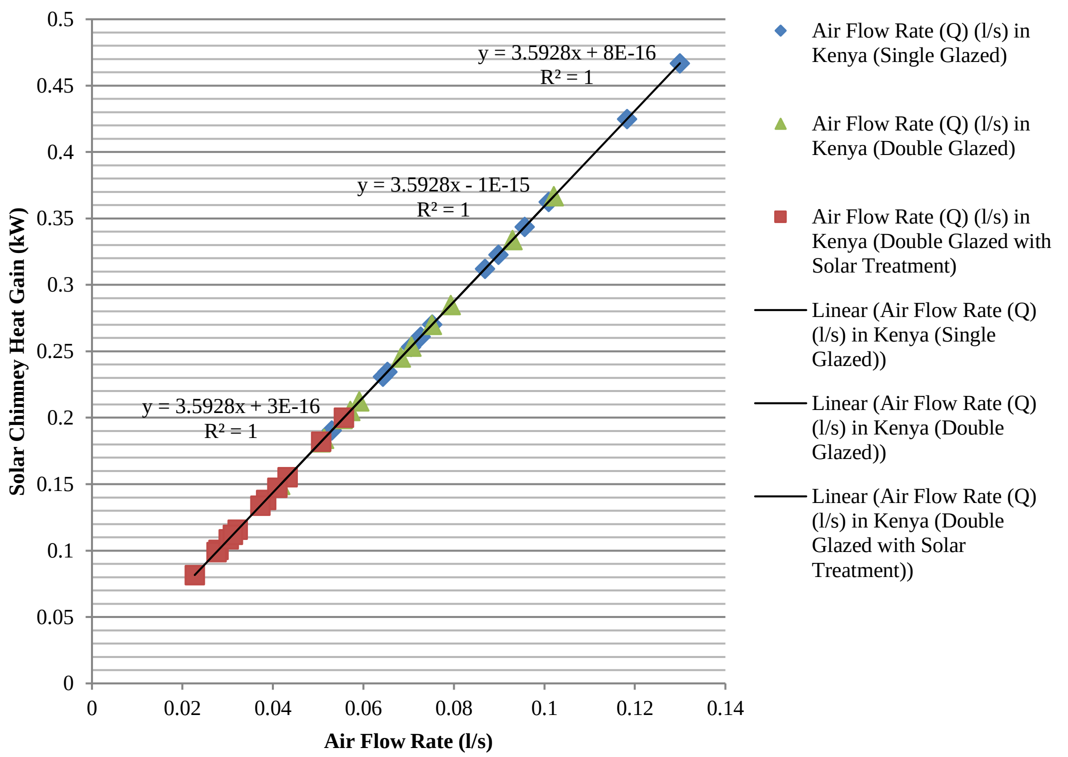


Figure 5.7- Solar Chimney Linear Regression Relationship Heat Gains to Effective g-Value for Kenya

Upon analysis of the two graphs (Figure 5.6 and 5.7), a higher air flow using clear single glazing is available in Portugal due to higher solar heat gains (irradiance) producing higher air flows within the solar chimney; providing improved performance when used in this type of climate.

5.3.3 Verification

This method has been created to analyse effects of different types of glazing in order to improve internal air flow within a solar chimney. This alternative analytical approach to performance analysis and verification is completed with inter-comparison of other research with regards to range of comparable air flows. As an example, existing research completed by Chatzipoulka (2011) in section 2.7.3, shows very low air flow rates ranging from 0 - 0.14 l/s. As identified in Figures 5.6 and 5.7, calculated air flow rates show values ranging from 0.0864-0.1416l/s (Portugal) and 0.053-0.13l/s (Kenya) which align with ranges highlighted in this study.

5.4 Ventilated Double Façade Performance Analysis

5.4.1 Overview

Using theoretical building model B.1, a performance analysis is completed on solar gain reduction via a ventilated double façade space (natural air flow) to the glazed South façade of this building model. This is quantified as solar heat gain (kW) and converted into mechanical cooling energy reduction (kWh). Analysis is completed by calculating the heat gain via the glazing using methods set out in section 3.6.3, Chapter 3 and parameters set out in Table I.1, Appendix I. The mechanical cooling (base case) calculation is then revised to take into account the effects of the ventilated double façade. Solar heat gain values are compared and detailed in section 5.4.2. Effectiveness of reducing mechanical cooling energy is also analysed in the section.

5.4.2 Performance Analysis

Figures 5.8 and 5.9 below show resultant outputs of solar heat reduction for both climates inter-comparing against standard glazing (Brittle et al., 2014a). As main variables are external dry bulb temperature and direct solar radiation, Figure 5.8 (Portugal) shows this system is most effective between months of March to November. The highest heat gain is shown to be in August and lowest direct comparable heat gain in April. Overcooling is experienced for months of January to March and November to December.

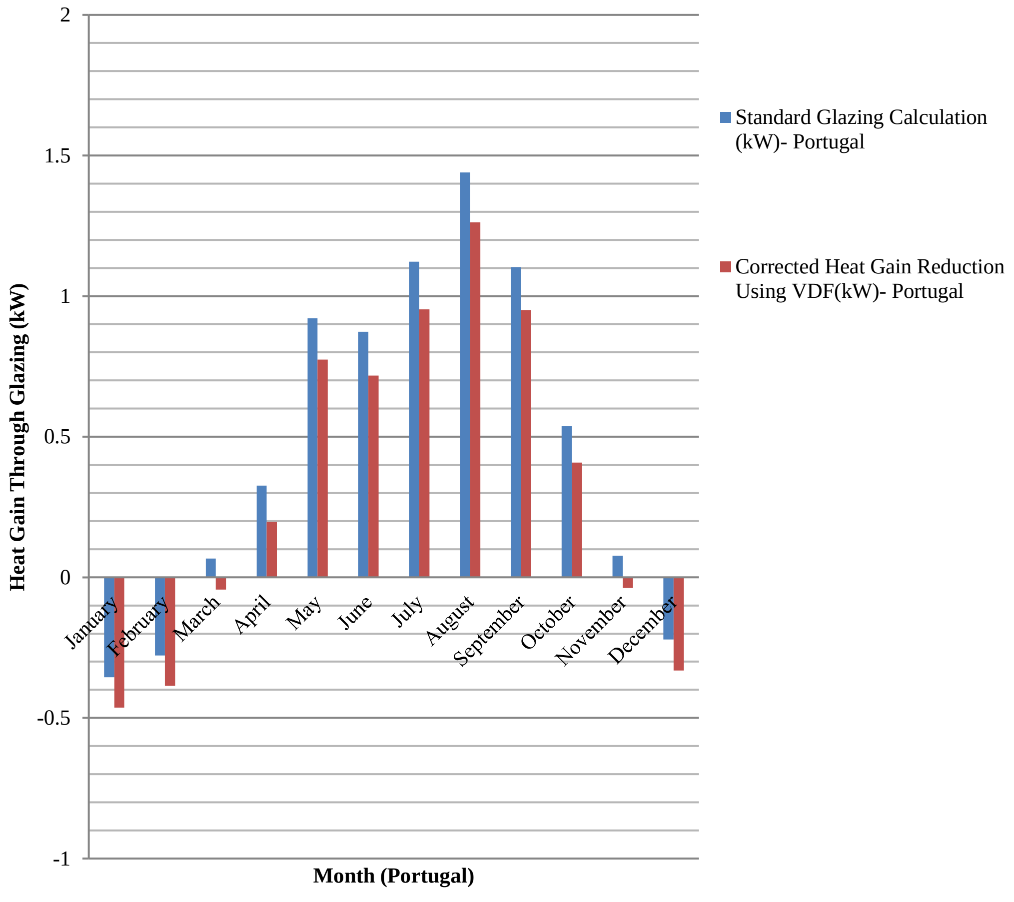


Figure 5.8- Heat Gain Analysis Comparing VDF Against Standard Glazed External Wall (South Facing) in Portugal

Figure 5.9 (Kenya) provides a similar pattern to Portugal climate and shows a consistent reduction in heat gains into the space. The most significant reduction, where external air temperature exceeds internal air temperature, between February and April.

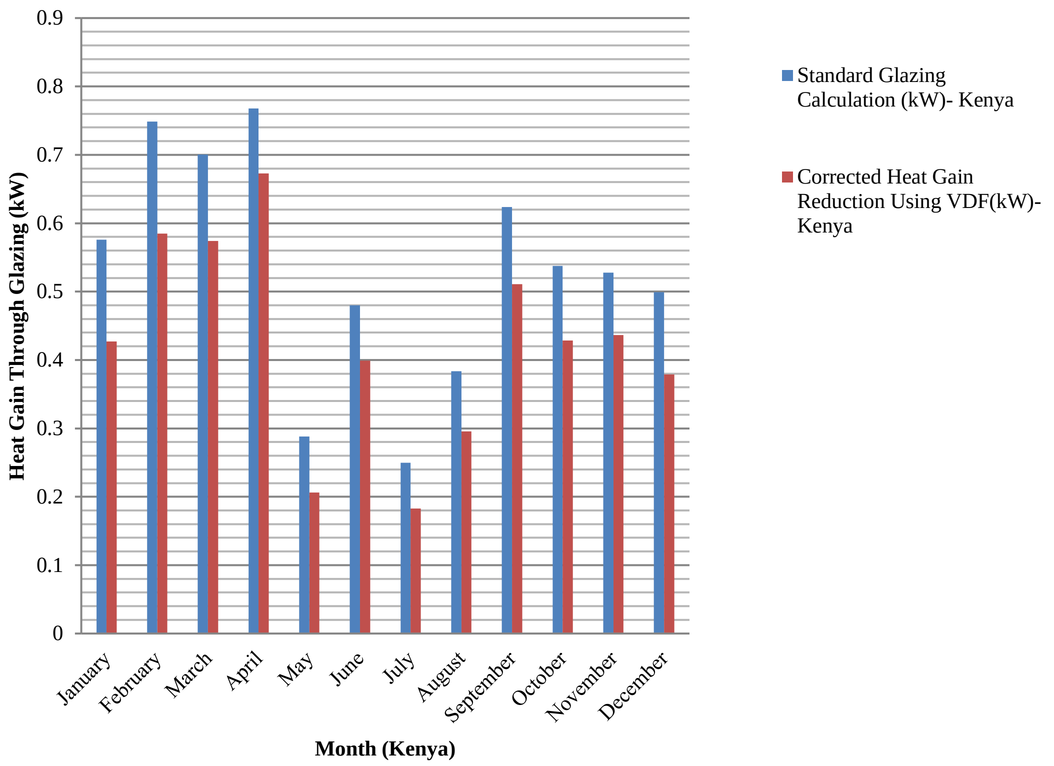


Figure 5.9- Heat Gain Analysis Comparing VDF Against Glazed External Wall (South Facing) in Kenya

To summarise performance of the ventilated double façade in different climates, graphs show these can have an effective impact on reducing solar heat gains; depending on the level of direct solar insolation on the South façade. The VDF cooling energy are deducted from the base case values to determine effective reduction in mechanical energy. The final energy reduction values are detailed below in Table 5.4. For each month a percentage reduction is shown (both climates), when both cases show the average energy reduction is only 2 percent. This is due to the fact that the amount of solar heat gain removed via façade only contributes a small amount compared to the overall space heat gain.

Table 5.4- Mechanical Energy Reduction When Using Ventilated Double Facades

System	Base case Cooling Energy (Portugal)	VDF Energy Reduction (Portugal)	VDF (Portugal) Deducted From Basecase	% Reduction against Base Case (Portugal)	Base case (Kenya)	VDF Energy Reduction (Kenya)	VDF (Kenya) Deducted From Basecase	% Reduction against Base Case (Kenya)
Month	Cooling Energy [kWh]	Cooling Energy [kWh]	Cooling Energy [kWh]	-	Cooling Energy [kWh]	Cooling Energy [kWh]	Cooling Energy [kWh]	-
January	1379.78	40.25	1,339.53	3	2653.79	55.32	2,598.47	2
February	1354.73	36.19	1,318.54	3	2273.94	54.94	2,219.00	2
March	1539.08	41.22	1,497.86	3	2207.93	47.06	2,160.87	2
April	1682.68	46.33	1,636.35	3	2088.48	34.09	2,054.39	2
May	2089.06	54.76	2,034.30	3	2247.77	30.47	2,217.30	1
June	2064.58	56.23	2,008.35	3	1922.29	29.09	1,893.20	2
July	2868.81	62.87	2,805.94	2	2061.28	24.74	2,036.54	1
August	2881.99	65.99	2,816.00	2	1987.68	32.88	1,954.80	2
September	2687.97	55.26	2,632.71	2	1992.78	40.57	1,952.21	2
October	2626.52	48.14	2,578.38	2	2261.3	40.51	2,220.79	2
November	1801.03	41.15	1,759.88	2	2064.2	32.80	2,031.40	2
December	1395.41	41.33	1,354.08	3	2139.84	44.60	2,095.24	2
Total	24,372		23,782	2	25,901		25,434	2

5.4.3 Verification

This method of analysing the performance of a ventilated double facade has been developed to determine effects on solar heat gains into the space and effectiveness of reducing mechanical cooling loads. Currently, there is a significant amount of research which has been completed to determine the approximate effects of VDF temperature reduction but there is very little information regarding available effects on whole building cooling energy performance, which makes this difficult for verification. As shown from the results, the performance diminishes with higher solar irradiance and dry bulb air temperatures. These findings also agree with the statement made in Technical University Berlin and Pontificia Universidad Católica de Chile (2012) that VDF is not necessarily an energy efficient strategy (Section 2.9.3, chapter 2) especially when considering capital build costs.

5.5 Rain Screen Façade Performance Analysis

5.5.1 Overview

Using theoretical building model B.1, an analysis is completed of solar gain reduction via a rain screen façade (weather boards), which is quantified solar heat gain (kW) and converted into mechanical cooling energy reduction (kWh). Analysis is completed by calculating the heat gain via weatherboard panels using the formulas set out in section 3.6.4, Chapter 3 and parameters set out in Appendix K. The calculation is then revised to take into account the effects of the ventilated cavity between the weatherboard and building envelope. Solar heat gain values are compared and detailed in section 5.5.2. Effectiveness of reducing mechanical cooling energy is also analysed in the section.

5.5.2 Performance Analysis

As shown Figures 5.10 and 5.11 below, rain screen façade are particularly effective in reducing conductive thermal heat gains through walls (Brittle et al., 2014a). When using external dry bulb temperature and direct solar radiation as main variables, this shows a consistent reduction in heat gain for all months in both climates, actively blocking direct solar heat gains. Figure 5.10 (Portugal) shows this system is most effective between months of July to August although a significant reduction is identified for all months. The greatest rate of heat gain reduction is shown in August and lowest direct comparable heat gain in April. For Portugal, overcooling is experienced between the months of January to February and November to December. Figure 5.11 (Kenya) provides a similar pattern to Portugal climate and shows a consistent reduction in heat gains into the space.

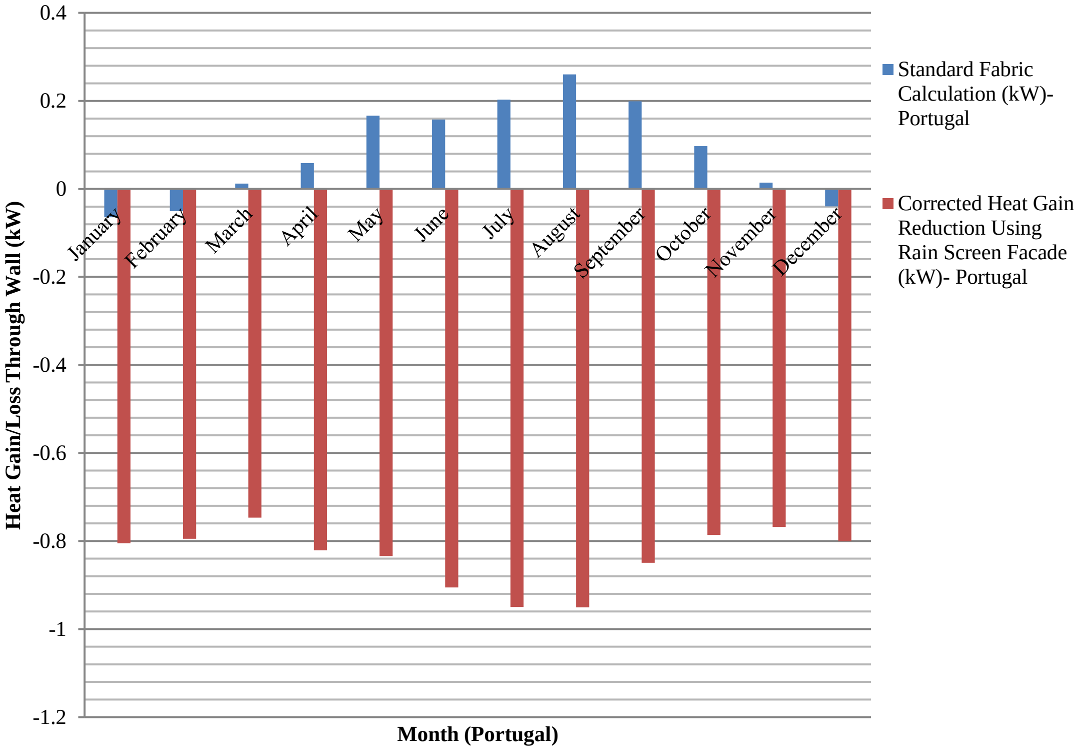


Figure 5.10- Wall Heat Gain Analysis comparing RSF against Standard Walls in Portugal

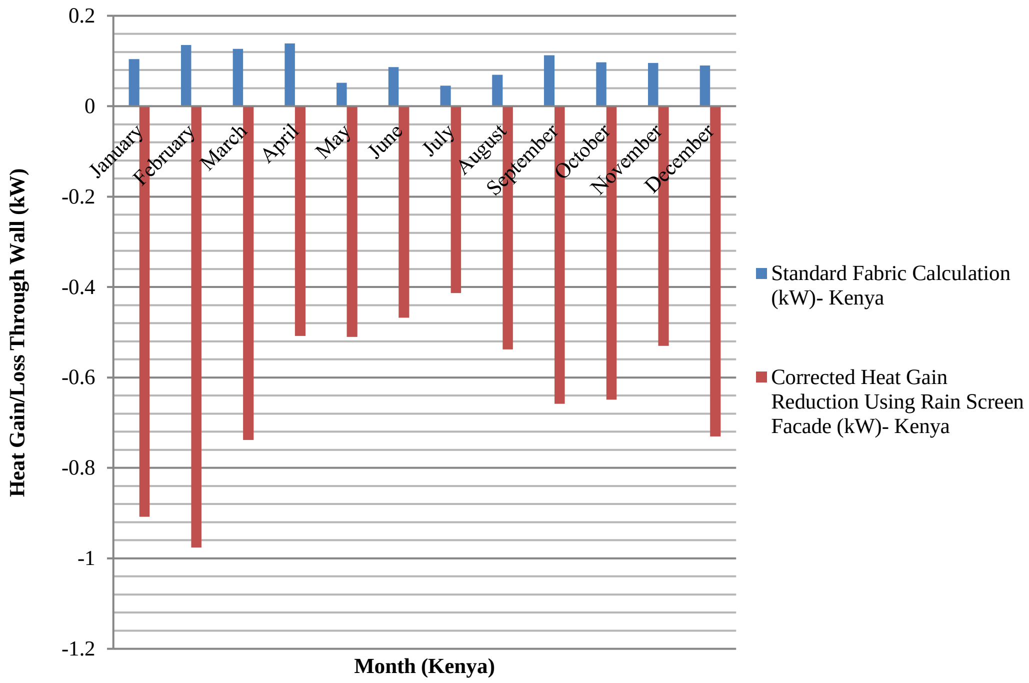


Figure 5.11- Wall Heat Gain Analysis comparing RSF against Standard Walls in Kenya

Final energy reduction values are detailed below in Table 5.5, which are calculated using mechanical energy performance values derived from DTS base case model B.1 allowing calculated RSF energy reductions to be deducted. In each month for each climate a percentage reduction is shown, where in Portugal values vary from 5 to 8 percent and Kenya 3-7 percent. From this analysis RSF perform better in Portugal i.e. more suited to Mediterranean type climates.

Table 5.5-RSF Annual Cooling Energy & Percentage Reduction

System	Base case (Portugal)	RSF Energy Reduction (Portugal)	RSF (Portugal) Revised Basecase	% Reduction against Base Case (Portugal)	Base case (Kenya)	RSF Energy Reduction (Kenya)	RSF (Kenya) Revised Basecase	% Reduction against Base Case (Kenya)
Month	Cooling Energy [kWh]	[kWh]	Cooling Energy [kWh]	-	Cooling Energy [kWh]	[kWh]	Cooling Energy [kWh]	-
January	1379.78	114.86	1,264.93	8	2653.79	156.86	2,496.93	6
February	1354.73	104.20	1,250.53	8	2273.94	155.60	2,118.34	7
March	1539.08	117.66	1,421.42	8	2207.93	134.09	2,073.84	6
April	1682.68	131.99	1,550.70	8	2088.48	97.01	1,991.48	5
May	2089.06	155.09	1,933.97	7	2247.77	87.17	2,160.60	4
June	2064.58	159.53	1,905.06	8	1922.29	83.13	1,839.16	4
July	2868.81	178.68	2,690.13	6	2061.28	71.04	1,990.24	3
August	2881.99	187.66	2,694.33	7	1987.68	94.10	1,893.58	5
September	2687.97	157.29	2,530.68	6	1992.78	115.62	1,877.16	6
October	2626.52	136.88	2,489.64	5	2261.3	115.63	2,145.67	5
November	1801.03	117.29	1,683.75	7	2064.2	93.80	1,970.41	5
December	1395.41	117.92	1,277.49	8	2139.84	127.16	2,012.68	6
Total	24,372		22,693	7	25,901		24,570	5

5.5.3 Verification

This method of analysing the performance of a rain screen facade has been developed to determine effects on solar heat gains via the building fabric effectively reducing mechanical cooling loads. For verification, an existing study completed by Marinoscia (2011) for test buildings located in Bologna, Rome and Palermo, energy demand for mechanical cooling reduced by 6-8% when using a rain screen façade. These values calculated results of 5-7% reduction fall within the range as detailed in Table 5.5.

5.6 PDEC Performance Analysis

5.6.1 Overview

Using theoretical building model B.1, a performance analysis is completed to determine cooling potential of a PDEC tower system for each climate, using maximum temperature for each month. This is completed using the methodology set out in section 3.6.5 (Chapter 3), PDEC system parameters set out in Tables L.1 and L.2 (Appendix L) and background calculations shown in Appendix L. This section completes assessment of monthly cooling loads and effects on annual mechanical energy performance. In order to calculate PDEC cooling energy potentials, background works completed are available in Appendix L, as detailed below:

- PDEC System parameters (L.2) - This section details PDEC system performance requirements.
- Effects of external air flow/moisture contents (L.3) - This section details maximum air moisture content of air at differing air flow rates as shown in Figure L.1.
- Available cooling capacities from PDEC system (L.4) - This section details total available cooling at a given relative humidity as shown in Figure L.4 using specific enthalpy calculations at a stated mass flow rate of air. This shows that higher cooling capacities are available at higher relative humidity's.
- Daily cooling performance of PDEC system (L.5) - This section details daily temperature reduction at different humidity's as detailed in Figure L.5.

From PDEC cooling capacities discovered in Appendix L.4, revised building cooling loads are calculated by deducting from base case model B.1 (Q_{SIM}- Q_{PDEC}) to determine overall mechanical cooling energy.

5.6.2 Performance Analysis

For base case cooling load comparisons against calculated PDEC cooling effects, Figure 5.12 below shows cooling loads for Qsim and Q_{PDEC} for a yearly period (Brittle et al., 2016c). The potential cooling form PDEC system (kW) is shown for each relative humidity (30%, 40% & 50%RH). The air flow rate is 0.5kg/s, which is used to identify minimum amount of cooling available.

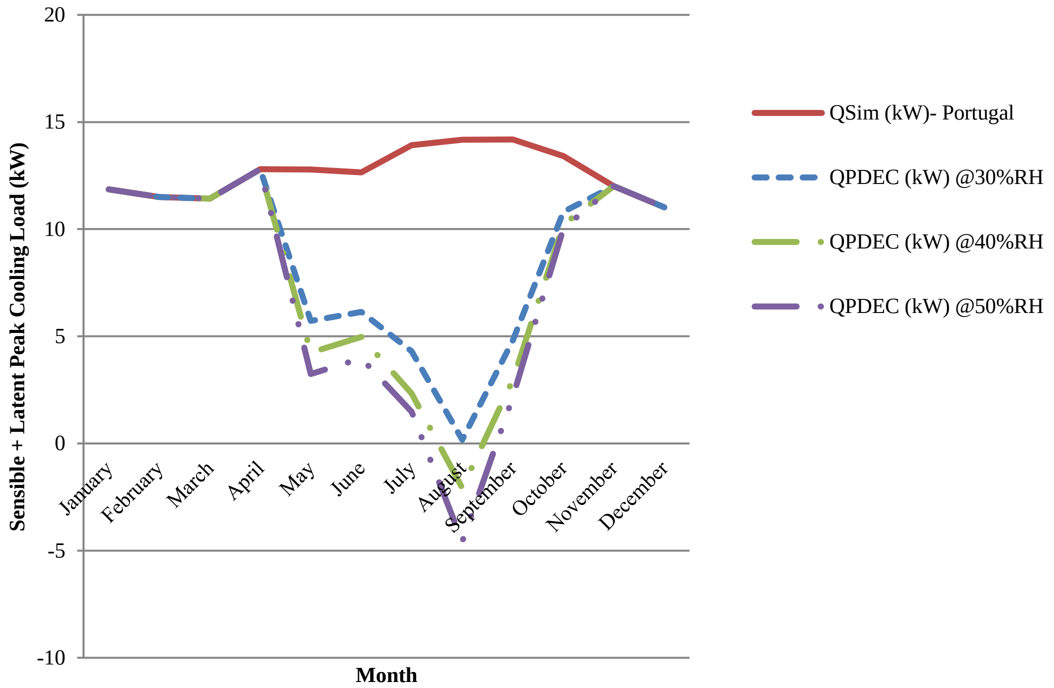


Figure 5.12-Effects of PDEC on Mechanical Cooling Load in Portugal

Figure 5.12 shows that if maximum temperature is maintained for the month, internal space cooling demand is dramatically reduced. For months of August to September, Q_{PDEC} matches the room cooling load provided the relative humidity is greater than 40%RH. For the months January, February, March, November and December, the maximum air temperature does not exceed 24ºC therefore the PDEC system is not required. Table 5.6 below show the percentage reduction available for each month and relative humidity (%).

Table 5.6- Monthly Cooling Load Reduction in Portugal

Month	% Cooling Load Reduction (Air 30% RH)	% Cooling Load Reduction (Air 40% RH)	% Cooling Load Reduction (Air 50% RH)
January	0	0	0
February	0	0	0
March	0	0	0
April	0	0	0
May	55	67	75
June	51	61	69
July	69	83	89
August	99	115	132
September	66	79	85
October	19	24	25
November	0	0	0
December	0	0	0

The maximum cooling reduction available is shown as 132% of the base case cooling load at 50%RH. Figure 5.13 shows cooling load reduction for Kenya. Although the profile is different to Portugal's, a similar amount of cooling is achieved based on the different humidity's. The maximum amount of PDEC system cooling is observed in April.

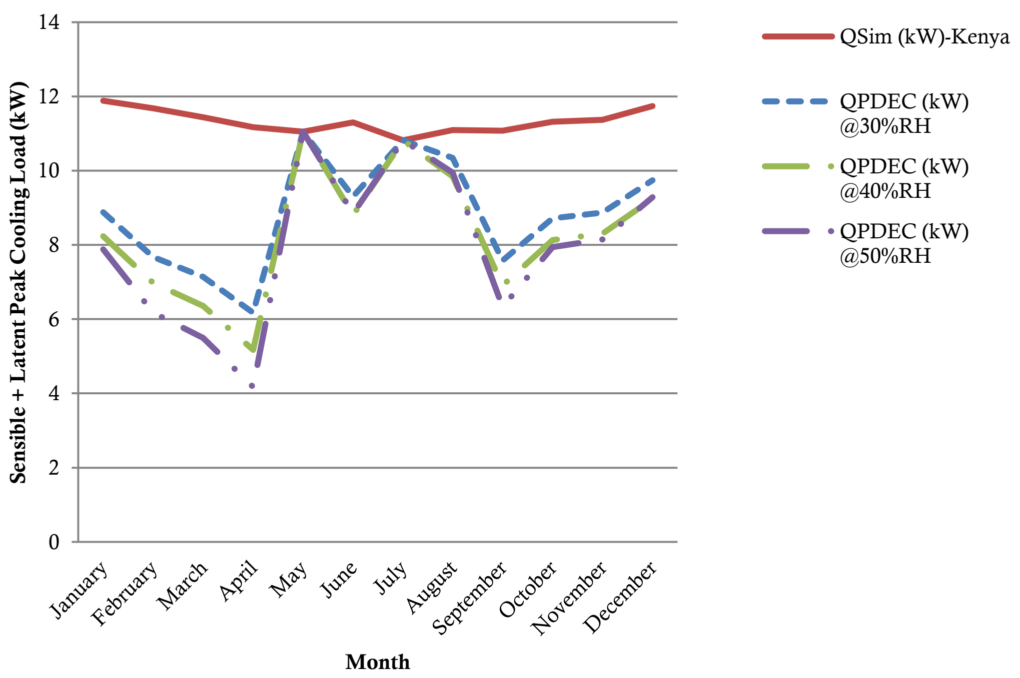


Figure 5.13-Effects of PDEC on Mechanical Cooling Load in Kenya

Table 5.7 below show the percentage reduction available for each month and relative humidity (%). The maximum amount of cooling available is shown as 63% at 50%RH in April.

Table 5.7- Monthly Cooling Load Reduction in Kenya

Month	% Cooling Load Reduction (Air 30% RH)	% Cooling Load Reduction (Air 40% RH)	% Cooling Load Reduction (Air 50% RH)
January	25	31	34
February	34	40	47
March	38	44	52
April	45	54	63
May	0	0	0
June	18	22	22
July	0	0	0
August	7	11	10
September	32	38	43
October	23	28	30
November	22	27	28
December	17	21	21

PDEC energy reduction (Q_{PDEC}) is calculated on the premise that maximum external air temperature for activated cooling will occur no more than 60 hours per month (3 hours per day at 20 working days); this forms the basis of the annual PDEC cooling. For mechanical cooling energy in Portugal, Figure 5.14 shows performance profile and comparison against the base case DTS model.

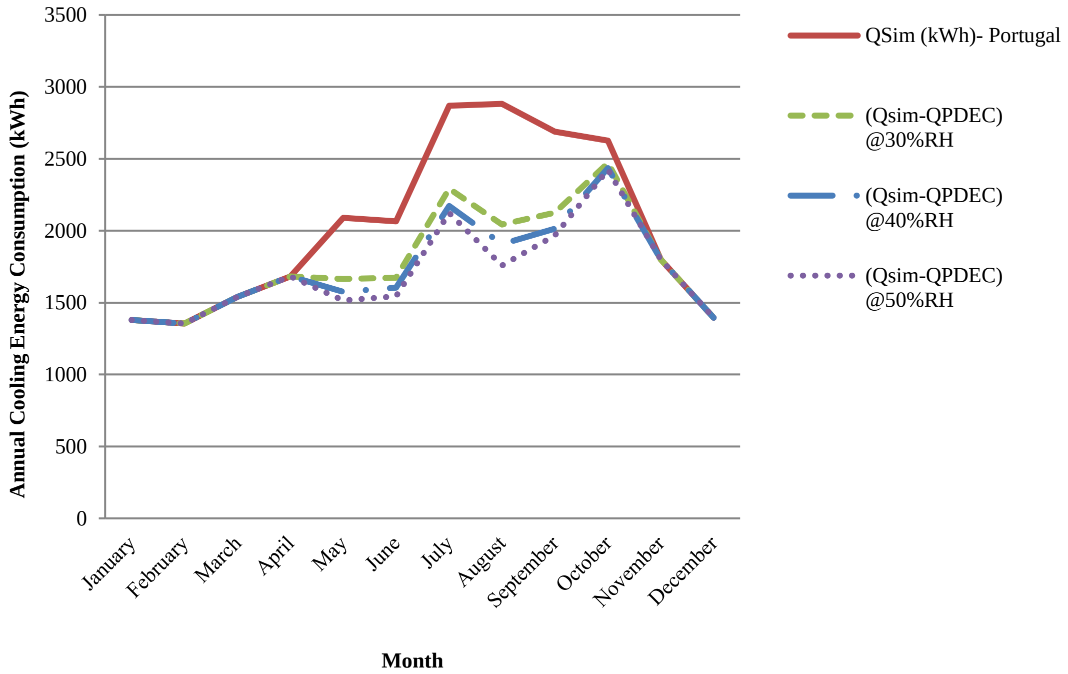


Figure 5.14- Annual Energy Consumption Analysis Using PDEC in Portugal

Figure 5.15 below shows mechanical energy performance for Kenya.

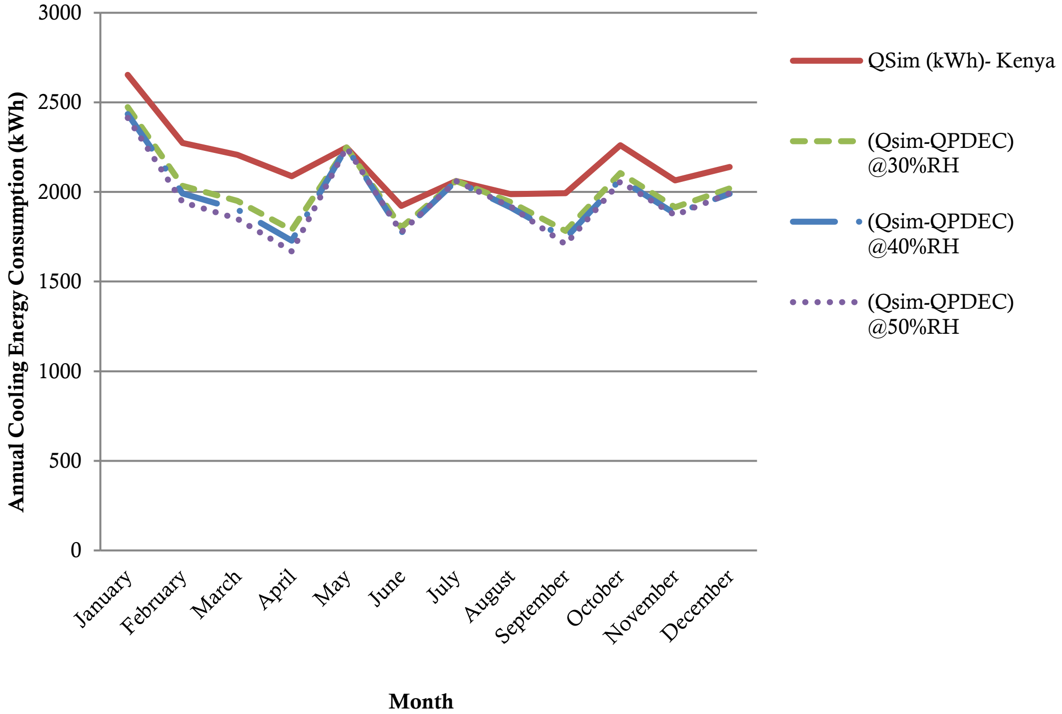


Figure 5.15- Annual Energy Consumption Analysis Using PDEC in Kenya

In both Figures (5.14 and 5.15), the cooling energy reduction at 50% humidity provides the optimum performance. For annual energy reduction, Table 5.8 below shows PDEC potential energy savings at varying humidity levels.

Table 5.8- Annual Mechanical Cooling Energy Reduction Using PDEC

Month	% Annual Cooling Energy Reduction (Air 30% RH)	Annual Cooling Energy Reduction (Air 40% RH)	Annual Cooling Energy Reduction (Air 50% RH)
Lisbon, Portugal	12.11	14.40	15.96
Nairobi, Kenya	6.87	8.37	9.23

The maximum value of reduction is 15.96% for Portugal and 9.23% for Kenya. This is due to the fact that Portugal has higher peak temperatures where a greater PDEC cooling capacity can be realised i.e. the higher the temperature the greater the rate of micronised water vapour absorption (latent heat of vaporisation). Furthermore, it is identified that there is a benefit of raising the humidity from 30 to 50 percent with this system provided higher air temperatures are achieved i.e. >24°C.

5.6.3 Verification

This approach analyses minimum potential PDEC cooling capacities that can be available at varying humidity's at a minimum air flow rate limiting relative humidity's to <50% RH. Verification of this study proves difficult for the following reasons:

- Existing research completed reviews higher humidity ratios i.e. >50%; hence greater cooling capacity's are observed.
- Mass flow rate of water in this study is limited to total amount of latent heat of vapourisation at a given temperature/air flow in order to limit relative humidity.
- Air flow rates are limited to 0.5kg/s.

In other research, greater cooling capacities can be achieved at higher relative humidity due to higher specific enthalpy's and greater air flow rates. This study shows a maximum cooling energy reduction 15.96% (Portugal) and 9.23% (Kenya). Existing research completed by Bowman et al., (1998) shows a total annual cooling energy reduction of 26% using multiple towers to spaces, as detailed in Table 2.7, Chapter 2.

5.7 Earth Ducts Performance Analysis

5.7.1 Overview

Using theoretical building model B.1, a performance analysis is completed to determine how earth ducts can reduce external air temperature in order to reduce mechanical cooling load and energy. Initial analysis is completed for four different types of materials which are generally used for earth ducts. These are inter-compared accordingly with regards to the individual performance of rate of heat loss and air temperature reduction. For Portugal and Kenya Climates, earth duct cooling load reduction is analysed with optimum air flow rates required to ensure minimum amount of cooling is achieved. This is quantified as temperature reduction along the earth duct (^{o}C), temperature loss through the earth duct (kW), optimum air flows to achieve rate of heat load (m^{3}/s). All cooling load reduction values are converted into mechanical cooling energy reduction (kWh) for each type of earth duct. Parameters used in this analysis are detailed in Appendix L.

5.7.2 Performance Analysis

Initial analysis is completed to determine surface temperature reduction for each earth duct type. In order to complete this, earth duct parameters used are detailed in section L.2, Tables L.1 and L.2 of Appendix L. This details all values used including thermal conductivity of earth duct material and earth duct geometry. Figure 5.16 below shows surface temperature of the earth duct against distance at one metre intervals (maximum length is 10 metres).

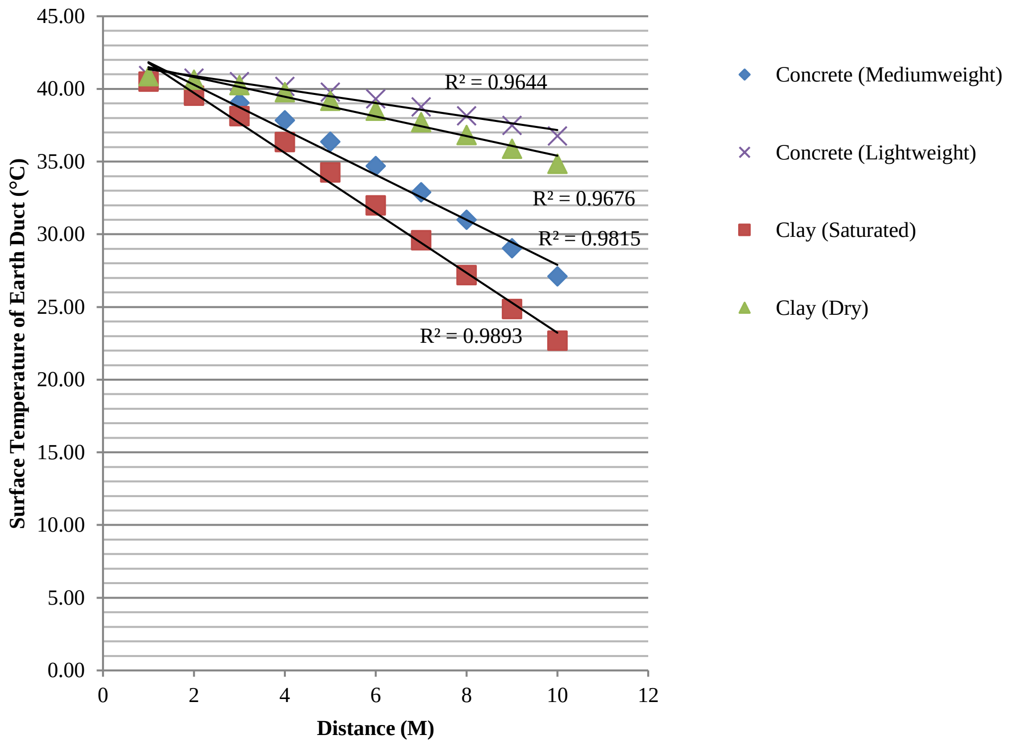


Figure 5.16- Earth Duct Temperature Profile

From Figure 5.16, maximum calculated temperature reduction are 4.24°C for lightweight concreate, 13.89°C for medium concrete, 6.14°C for dry clay and 18.33°C for dry clay (saturated). This analysis shows that the thermal conductivity of the earth duct material (k value) is an important factor. The greater the values (k), greater temperature reduction is observed.

For performance analysis of rate of heat loss from earth duct, Figure 5.17 indicates performance for each earth duct type. Although there is a continuous rate of heat load in all cases, dry clay (saturated) and medium concrete rates of heat loss reduce between 8 and 10 metres, have R^2 values of 0.7697 and 0.9178 respectively. Initially, in both cases, heat loss is high up to 7 metres, but depreciates after this point. This is due to the fact that the lower air temperature experience at this point provides a lower difference in temperature hence low rate of heat loss.

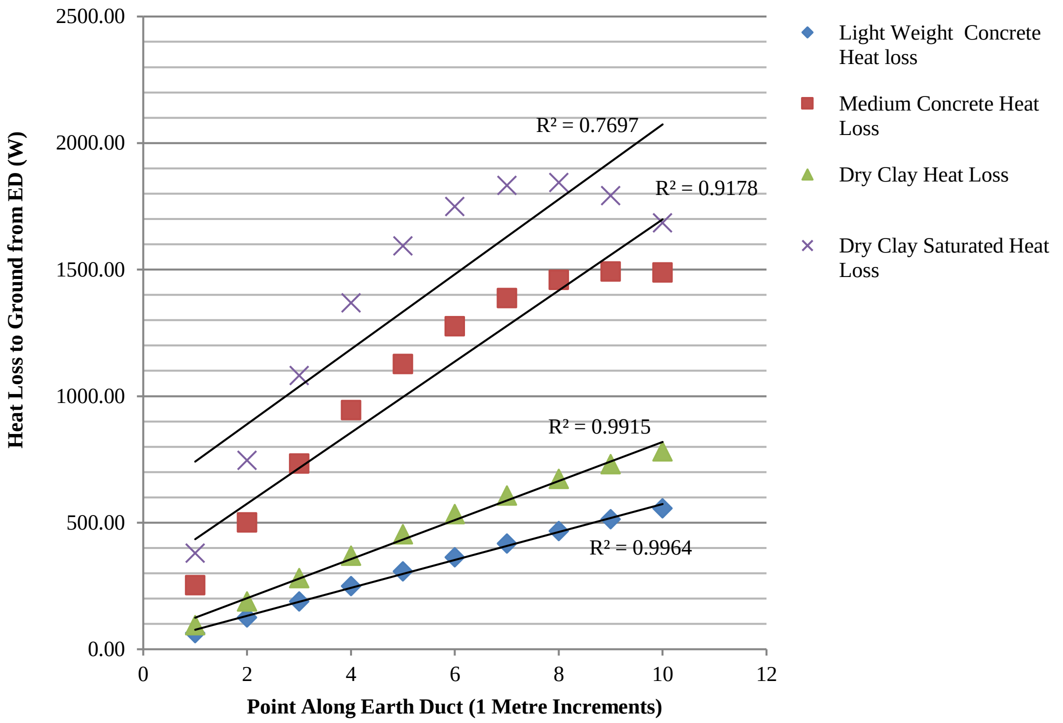


Figure 5.17- Heat Loss from Earth Duct to Ground Utilising Different Materials

Earth duct cooling loads are calculated for each climates and show maximum available cooling based upon the maximum average temperature. For Figures 5.18 (Portugal) and 5.19 (Kenya) below, show DTS base case model B.1 (Q_{sim}) provides a direct comparison for each earth duct type to discover yearly performance trends and optimum solution.

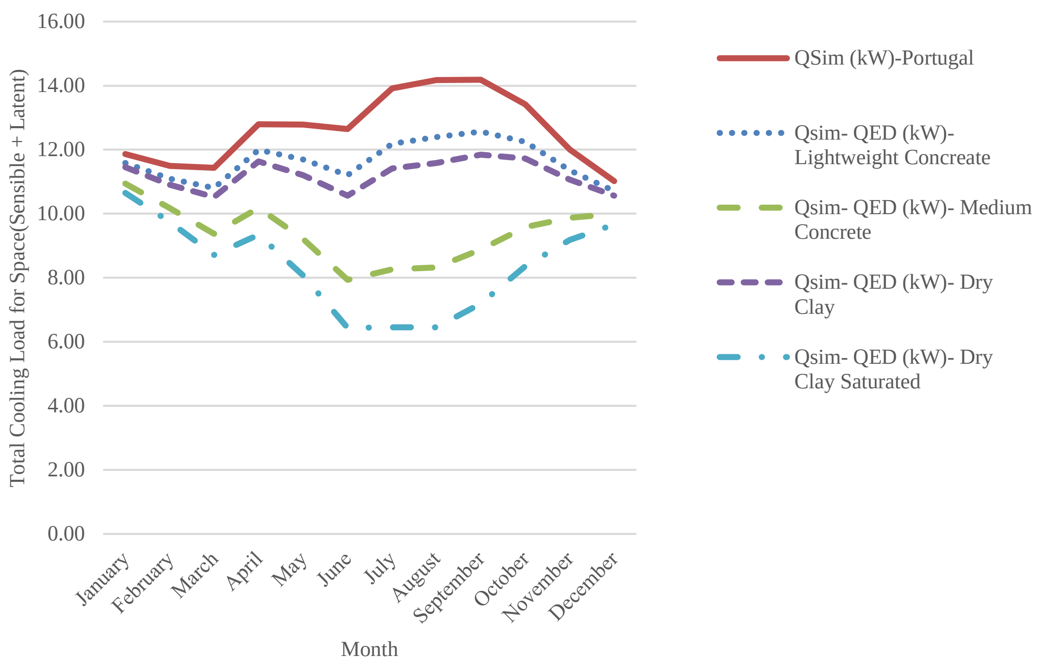


Figure 5.18- Earth Duct Cooling Load Reduction for Portugal

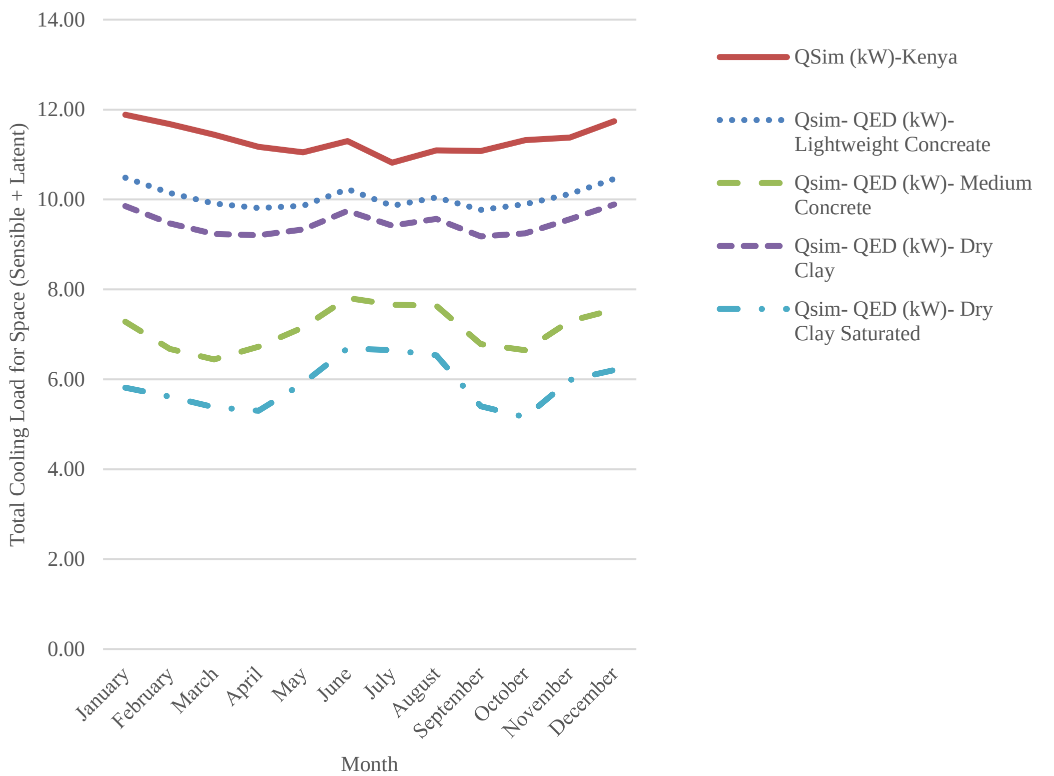


Figure 5.19- Earth Duct Cooling Load Reduction for Kenya

With regards to optimum air flow rates through duct to achieve the expected rate of cooling, Figures 5.20 (Portugal) and 5.21 (Kenya) are bar graphs indicating required air flow for each average maximum air temperature experience in a particular month.

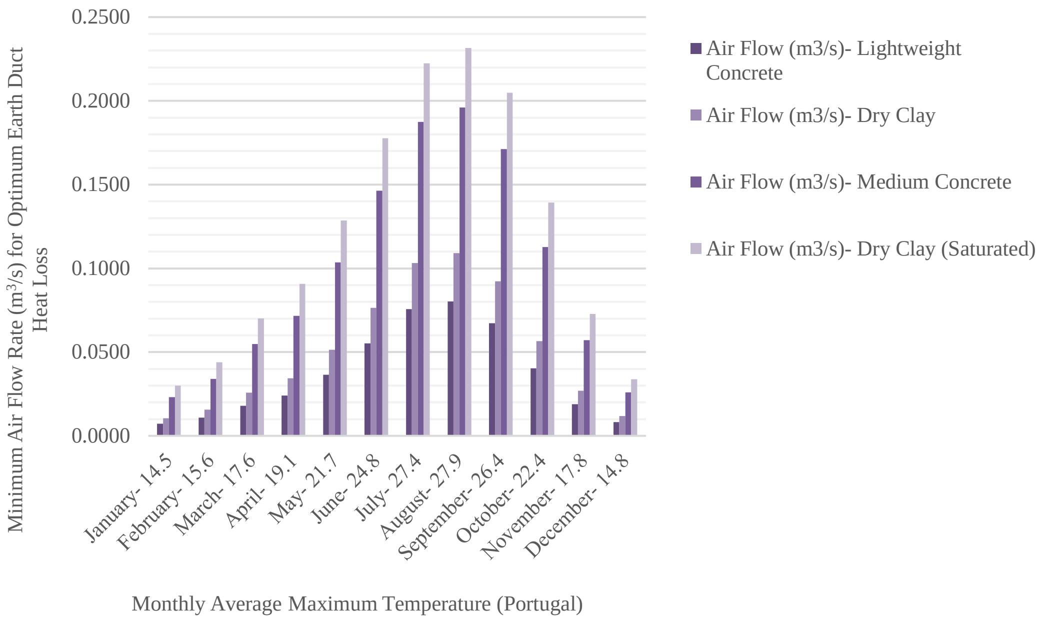


Figure 5.20- Optimum Air Flow Rates within Earth Ducts to Achieve Heat Loss Potential in Portugal

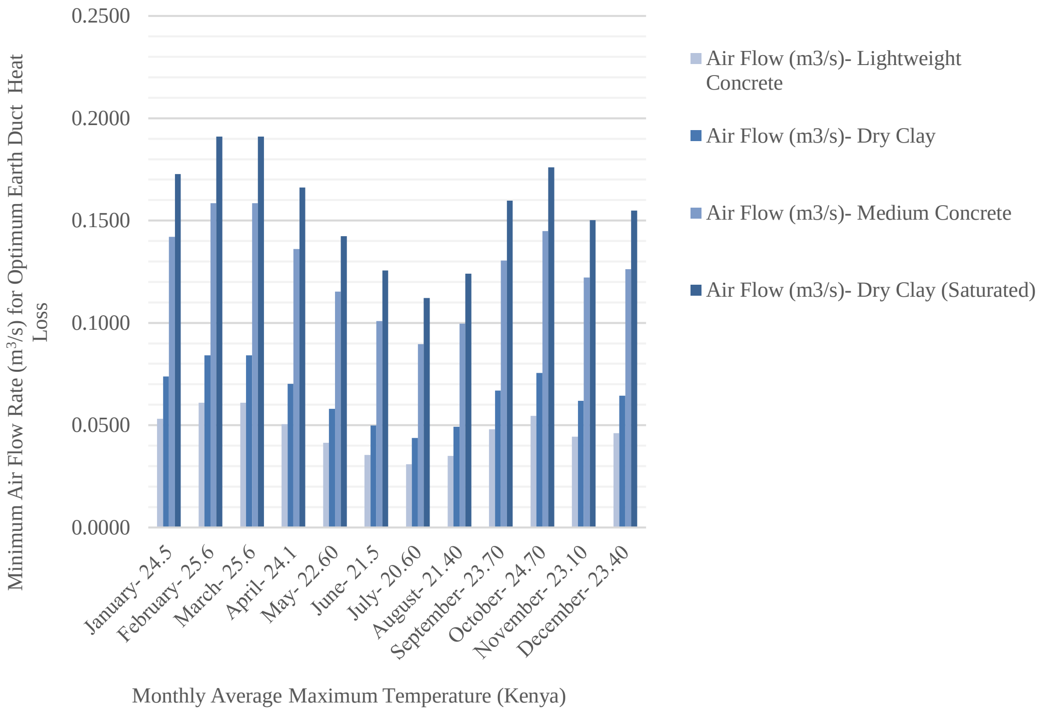


Figure 5.21- Optimum Air Flow Rates within Earth Ducts to Achieve Heat Loss Potential in Portugal

The results from Figure 5.18 and 5.19 show that dry clay (saturated) provides the greatest rate of reduction for both climates. The remaining materials performance is medium concrete (2nd), dry clay (3rd) and lightweight concreate (4th). These finding are linked to the thermal conductivity of the material i.e. low k values equals' lower rate of heat loss to ground. Upon review of air flow rates (Figures 5.20 and 5.21), higher air flow rates are required to achieve the greater rates heat transfer.

Annual mechanical cooling energy performance is detailed below for each climate and compare each earth duct type against base case DTS model B.1 (Q_{Sim}). This are show as Figure 5.22 for Portugal and 5.23 for Kenya.

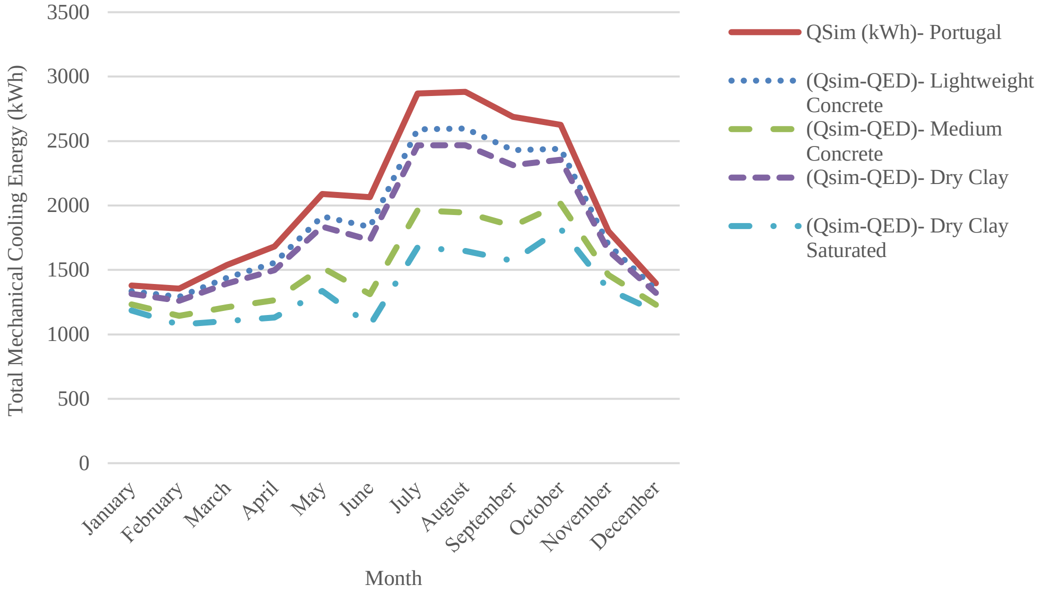


Figure 5.22- Earth Duct Annual Cooling Energy Performance in Portugal

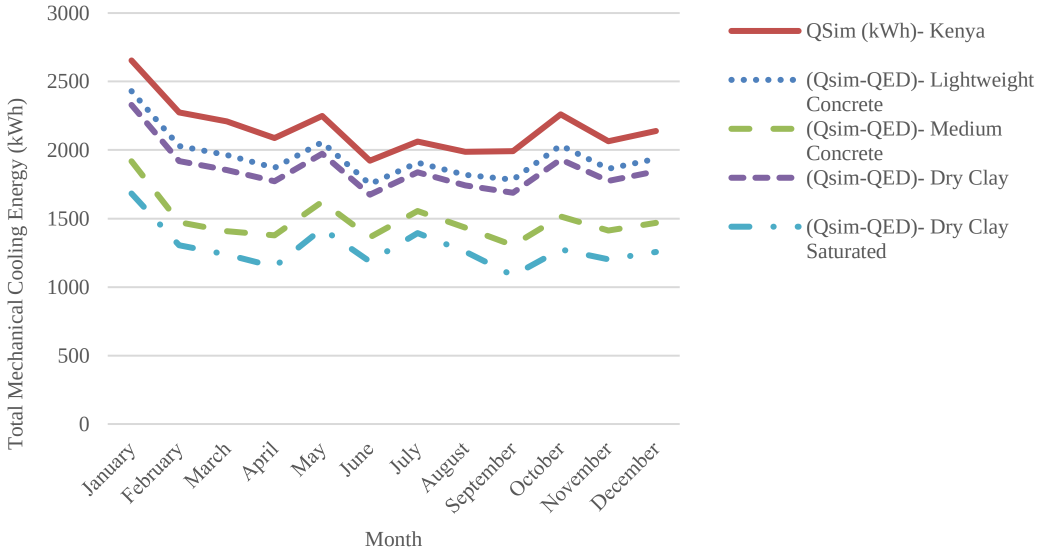


Figure 5.23- Earth Duct Annual Cooling Energy Performance in Kenya

Finding from these energy performance analysis show that earth ducts are particularly effective for hot climates providing a range of potential energy reductions for each type of earth duct, as detailed below in Table 5.9.

Table 5.9- Earth Duct Percentage Annual Mechanical Cooling Energy Reduction

Location	Annual Mechanical Cooling Energy Reduction (%) (Light Weight Concrete)	Annual Mechanical Cooling Energy Reduction (%) (Medium Concrete)	Annual Mechanical Cooling Energy Reduction (%) (Dry Clay)	Annual Mechanical Cooling Energy Reduction (%) (Dry Clay Saturated)
Lisbon, Portugal	7.81	25.60	11.33	33.78
Nairobi, Kenya	9.48	31.07	13.74	40.34

When assessing practical application for saturated clay earth duct, it is difficult maintain moisture levels at a sufficient level to maintain its level of thermal conductivity. However, when air is cooled from a high temperature, water vapour will condense onto the inner surface of the earth duct. This would provide some level of continuous moisture but cannot guarantee sufficient water moisture levels (g/g) or uniformity throughout the length of earth duct. This is also reliant of external relative humidity hence tropical climates would have greater levels of moisture when compared to a hot-arid climate, therefore this type of duct material may not be ideally suited to a hot-arid climate. Consideration should also be considered for beneath ground water supply system to earth duct to increase its thermal conductivity i.e. dry clay to dry clay saturated. Drainage should also be considered to remove excess water build up to prevent pooling of water.

In order to maintain maximum transfer of heat from air to earth duct, turbulent air flow is ideally suited to ensure maximum air contact with the surface. High wind velocities into the earth duct inlet with overcome difference in pressure (Δp) that exists in the system. Winder climates such are Canary Islands such as Tenerife and Fuerteventura, Spain, are ideal due to the constant sea breeze and hot climate. However, lower external air flows mean that the system reliant on stack effects which will only achieve air velocities based upon method of natural ventilation adopted and low resistance air passages provided throughout the building. When considering laminar and turbulent air flows within the earth duct, turbulent air flows are preferred to increase the rate of air contact with the surface of the earth duct. A calculation completed in Appendix M.3 (Table M.3) shows that the minimum air flow rate of 0.034053 m/s is required (laminar to turbulent) to ensure transition is achieved.

5.7.3 Verification

This approach analyses potential earth duct cooling capacity using temperature reduction across different earth duct materials. To verify against existing empirical studies as detailed on section 2.12.3, chapter 2, an expected temperature reduction from inlet air to outlet is approximately 3ºC to 8ºC (Building, 2013). In the same section, Sanusi et al., (2012) identifies that a 6.4ºC and 6.9ºC can be achieved depending on the time of the year using polystyrene pipes. Although the analysis completed does not take into account this material, equivalent temperature reduction values are calculated, as detailed in Figure 5.16 (4.24ºC, ***6.14ºC***, 13.89 ºC, 18.33ºC).

5.8 Summary

This chapter completes a comprehensive performance analysis for each passive ventilation and cooling system to determine its effectiveness and enable each one to be ranked accordingly, in terms of mechanical energy reduction (objective 3). For each particular passive system, cooling load analysis and energy performance assessment is completed to calculate effects on internal space cooling loads (kW) and annual mechanical cooling energy performance (kWh/month). These reductions determine available cooling capacity and deducted potential energy reductions from the DTS building base case models (B.1 & B.2). Using building model B.1, average performance trends using best curve fit are shown in Figures 5.24 and 5.25 below. For Portugal (Figure 5.24), between months of April to September, PDEC and earth ducts have better performance that all passive systems. Figure 5.25 (Kenya), excluding January, earth duct system has overall optimum performance in mechanical cooling energy reduction. This analysis also includes external solar shading which was dynamically thermally simulated (DTS) using Model B.1 for both climates and added to the Figures 5.24 and 5.25. This was calculated using optimum solution described in chapter 4 (multi-angled) and annual energy reduction values are 26% for Portugal and 14% for Kenya. Detailed effects of this external solar shading is analysed further in Appendix N.

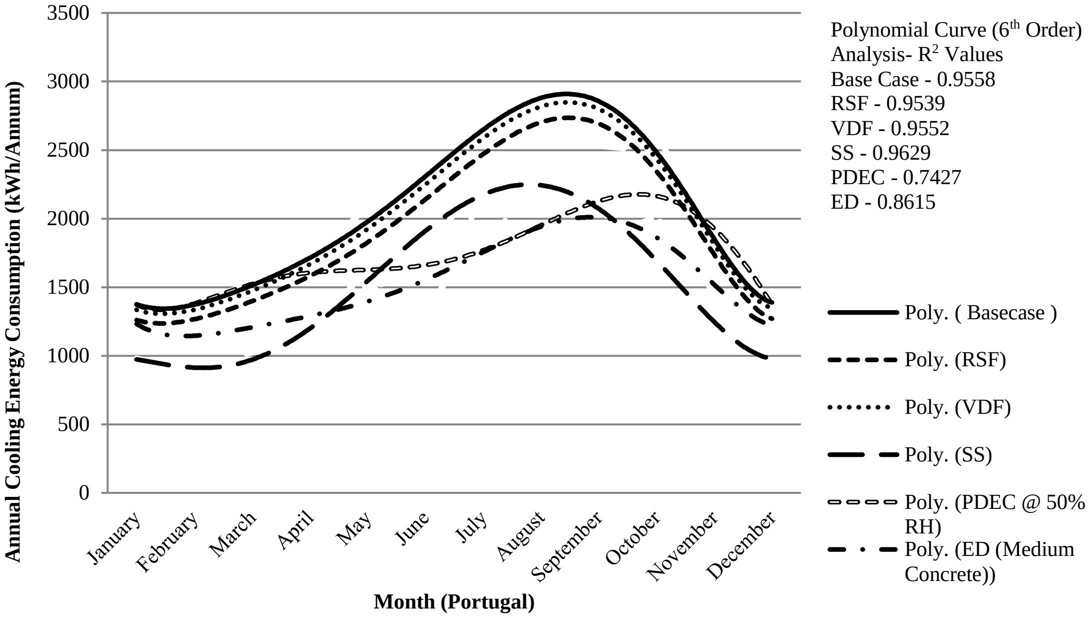


Figure 5.24- Average Annual Mechanical Cooling Energy Performance For Model B.1 Passive Systems Located in Portugal

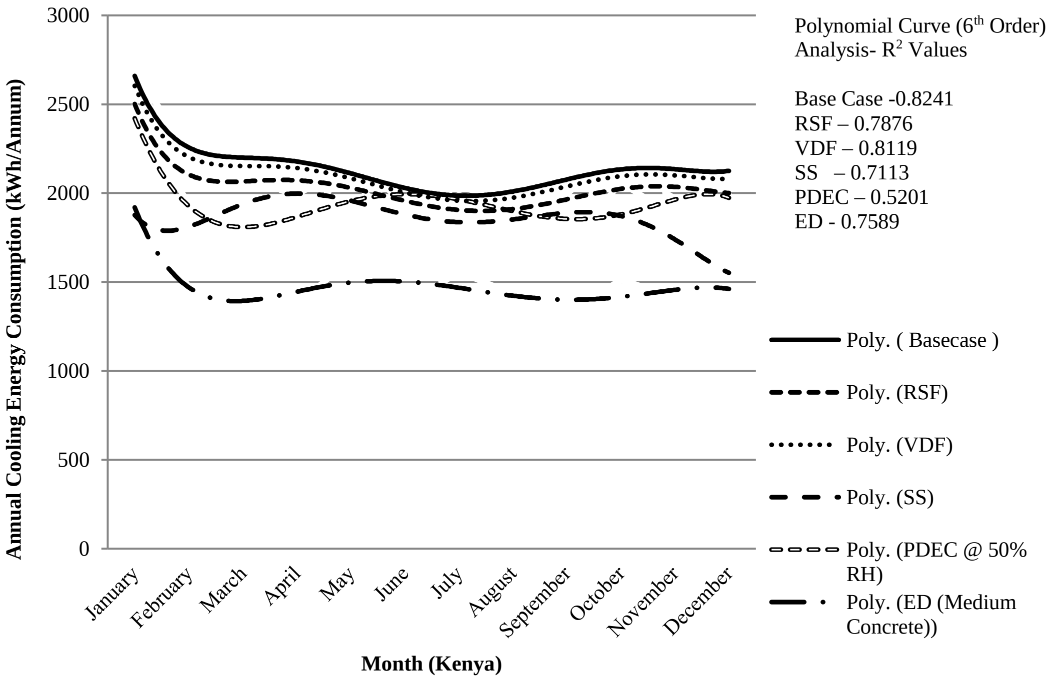


Figure 5.25- Average Annual Mechanical Cooling Energy Performance For Model B.1 Passive Systems Located in Kenya

Overall performance assessment completed highlights benefits of passive cooling aiding to support mechanical systems. In both theoretical commercial building cases (Models B.1 and B.2), there is a percentage reduction in cooling load, ventilation and cooling energy consumption in the selected hot climates. Table 5.10 below details the percentage energy reductions available (range) for each passive system, ranking each accordingly.

Table 5.10- HVAC Energy Reduction Using Passive Systems

Passive System	Rank	Percentage Reduction (%) in Mechanical Ventilation Energy (Range)	Percentage Reduction (%) in Mechanical Cooling Energy (Range)	Influencing Factor for Effectiveness
Earth Duct	1	-	7.81 – 40.34	Earth duct material thermal conductivity (K)
External Solar Shading (Table 4.4, Chapter 4)	2	-	16.18 – 27.04	Multi-angled shading is optimum solution
Natural Ventilation	3	11.73 to 28.85	11.33 to 27.97	Internal air temperature set point (ºC)
Passive Downdraught Evaporative Cooling	4	-	6.87 – 15.96	External humidity range (%RH)
Rain Screen Façade	5	-	5-7	Low weatherboard U-value
Ventilated Double Façade	6	-	2	Low effective g-value
Solar Chimney	7	None	None	High effective g-value

Table 5.9 identifies that earth ducts is the most effective as this has greatest potential range for cooling energy reduction per annum. These are ranked in terms of maximum available energy reduction. The reason natural ventilation is only rank 3rd is 28 degrees celcius puts thermal comfort at risk in terms of people's ability to adapt to their thermal environment (De (De Dear & Brager, 1998) and therefore a sensible assumption is that the internal office space should be maintained to 26 degrees set point in order to achieve benefits of electrical energy reduction i.e. 20.31 percent reduction per annum. This analysis also shows that a solar chimney is ineffective for reducing energy as this only enhancing stack effect and increases natural ventilation air flow rates. Influencing factors for effectiveness are shown in this table, where changing these will effect amount of energy reduction available in mechanical

ventilation and cooling. For example, having a low effective g-value on glazing for ventilated double façade will reduce direct solar heat gains into the façade cavity.

Significant findings from the chapter are as follows:

1. For natural ventilation, using time/temperature curves provides diurnal external temperature profile provides accurate time scales for assessing HVAC operation, when HVAC set points are exceeded i.e. switching from natural ventilation mode to HVAC mode.
2. Solar chimney only improves air flow and air change rates within an internal space hence there will be no additional benefit to cooling capacities or energy reductions.
3. Ventilated double façades in hot climates only provide a 2% reduction in mechanical cooling energy when compared to a building without this passive system.
4. Rain Screen façades should be interoperated as fabric heat gain reduction only, as this does not offer a complete building envelope solution i.e. cannot reduce heat gains to windows, doors, roofs and floors.
5. For PDEC system, environments with 50 percent relative humidity's provides slightly greater cooling capacities for PDEC systems due to increase specific enthalpy values. Increasing the mass flow rate of air would improve cooling capacities significantly.
6. Earth ducts materials (thermal conductivity) are a critical design element to consider, as this greatly affects the rate of cooling available.

These finding are used as a foundation for Chapters 6 and 7. These are incorporated within passive system design guidance, strategies and performance assessment tools. Chapter 6 will discuss and analyse in greater depth results obtained from this chapter including chapter 4. This includes a performance review, sensitivity analysis (weather data and verification error), energy performance analysis to understand these perform with each other on a monthly basis, uncertainty in values, and development of passive system energy assessment tools including PSEAT.

Chapter 6

Passive System Results Analysis & PSEAT Development

6.1 Introduction

This chapter analyses the results generated from chapter 5 to determine the level of uncertainty and errors that exist using this form of calculation method. The aim of this chapter to provide further in depth analysis of values calculated and analyse accordingly. This is required to ascertain level of accuracy and verification based upon values obtained from proceeding chapters 4 and 5. This is afforded by passive system performance review (6.2), sensitivity analysis and error 1- analysing weather data (6.3), sensitivity analysis and error 2- verification against publish values (6.4), energy performance analysis (6.5), uncertainty in values (6.6), development of basic visual passive system design tools (6.7) and development of passive system energy assessment tools (6.8) including PSEAT.

6.2 Passive System Performance Review

This section details logic created to determine annual energy reductions for mechanical cooling and ventilation systems when incorporating passive systems. To qualify percentages, these have been limited to the scope of theoretical building model B.1 and B.2 analysis. Thermal performance may be higher/lower if materials and parameters differ to the values set out in Table 3.8, Chapter 5. Impacts of improving thermal performance of the building envelope i.e. reducing amount of solar heat gain transferred into the space by increasing thermal mass, will impact the base case mechanical cooling energy consumption. There are two types of assessment methods are identified by this research (A & B) to calculate passive system energy reductions, as detailed below in Figure 6.1:

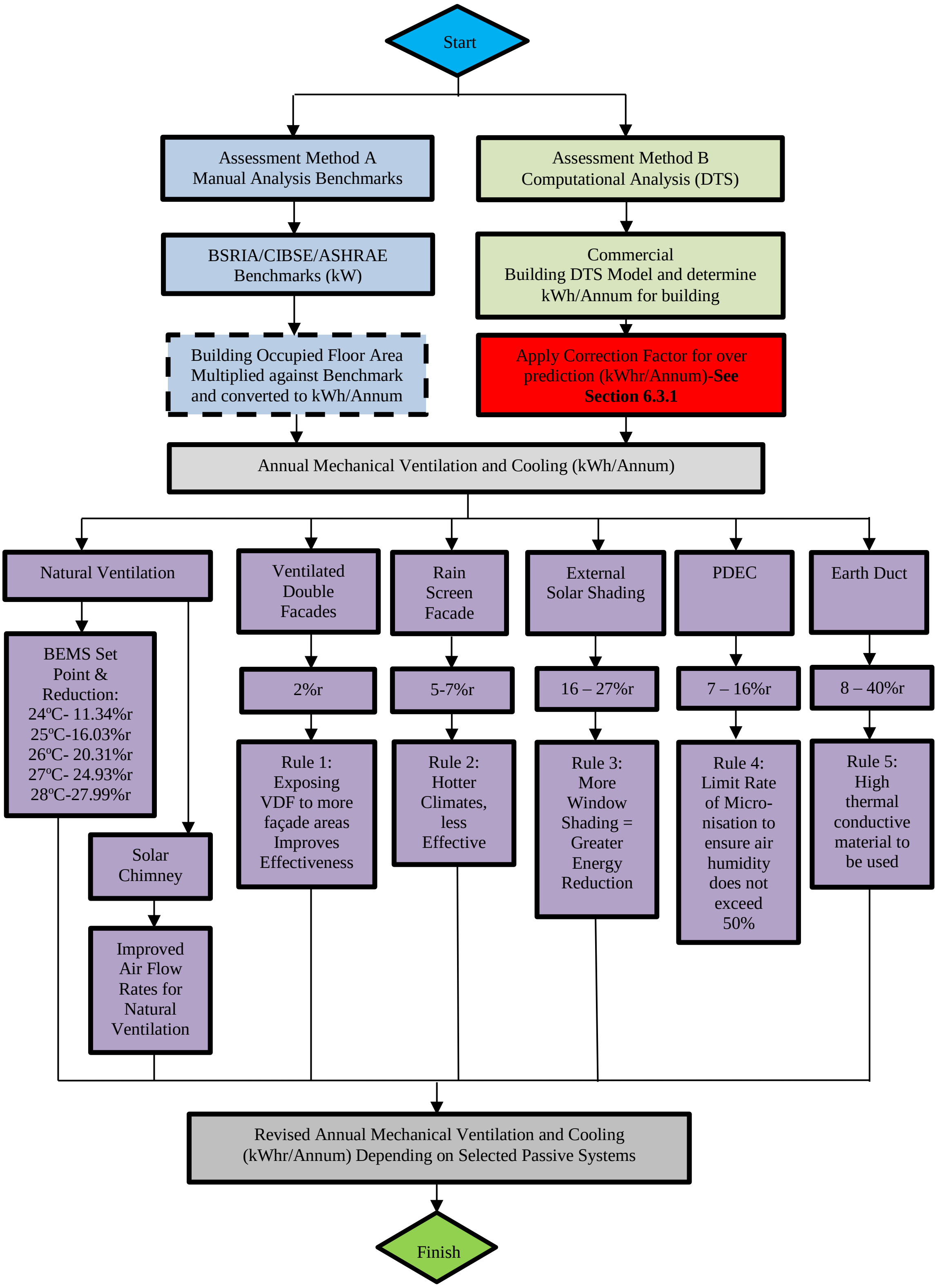


Figure 6.1- Passive Ventilation and Cooling Reductions Flow Diagram

Assessment method B will provide more accuracy as mechanical energy values are generated by specific climate conditions. For incorporation within PSEAT (section 6.8), these values are averaged between the two climates studied in Chapters 4 and 5.

6.3 Sensitivity Analysis 1- Mechanical Cooling Performance of Base Case Model B.1

6.3.1. Approaches to Weather Data Analysis

Errors have been identified is accuracy of the dynamic thermal model itself and weather data used (uncertainty). There are a number of passive system energy performance assessment methods generated as part of this research and an understanding of the level of error introduced is required. This includes the following:

- Weather Data Comparison (DTS Data verses WMO data)
- Monthly Average Mechanical Energy Reduction
- Mechanical Cooling Energy Data Inter-comparison (Building Model B.1)

The level of accuracy is dependent on the method adopted and is discussed later within this section.

6.3.2. Weather Data Comparison

For comparison of software weather data files and measured (published) average temperature values, weather data extracted from Designbuilder software was used for steady state analysis using monthly average dry bulb temperatures (maximum) and maximum monthly solar irradiance (W/m^2) in order to determine assessment of mechanical ventilation and cooling energy. Weather data averages incorporated within the DTS software do not appear as accurate as measured average data, hence error is introduced. As an example of this using building model B.1 weather data, Figure 6.2 (Portugal) and 6.3 (Kenya) below shows inter-comparison of Designbuilder temperatures (max/min) and measured WMO data (World Meteorological Organisation, 2014a, 2014b).

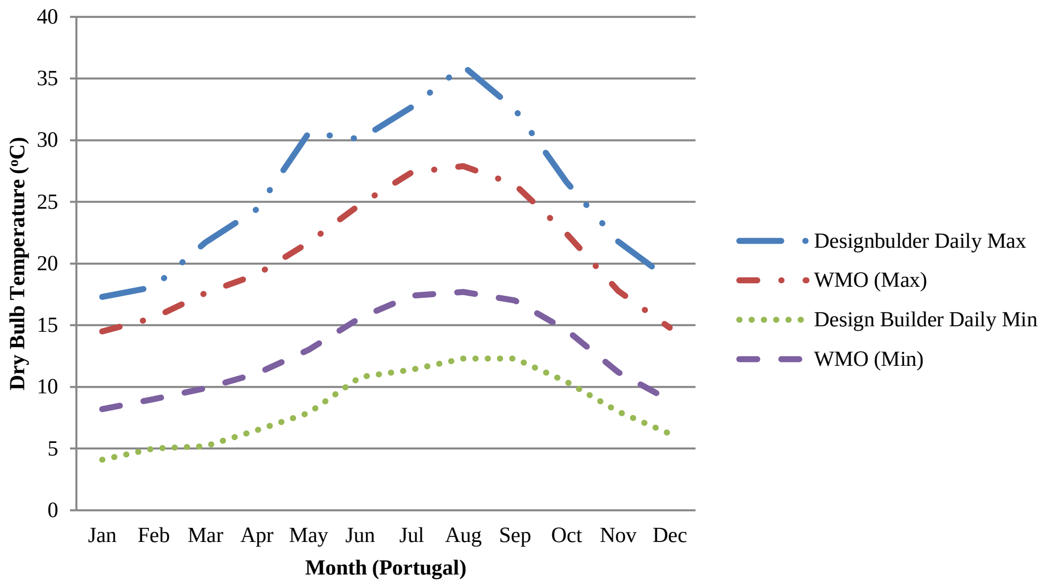


Figure 6.2- Inter-comparison of Portugal Average Dry Bulb Weather Data from Designbuilder and WMO

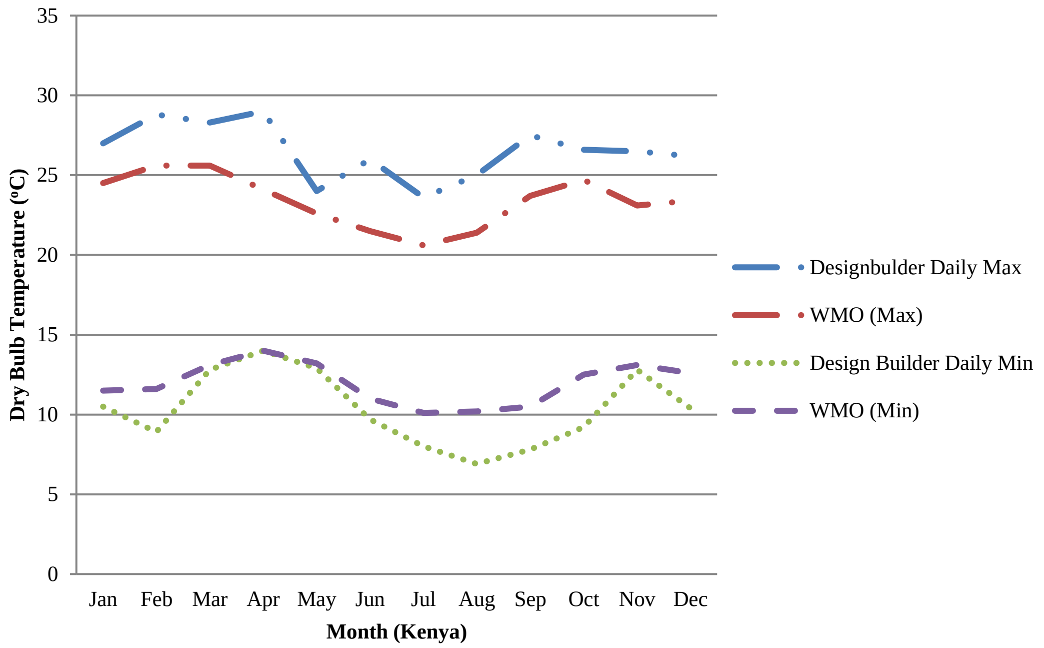


Figure 6.3- Inter-comparison of Kenya Average Dry Bulb Weather Data from Designbuilder and WMO

Analysis indicates that Kenya's Designbuilder software data over predicted error in monthly average dry bulb temperatures (ºC) by 14.45% (minimum) and 11.79% (maximum) per annum. The same is encountered for Portugal is 36.14% higher values for minimum dry bulb temperatures and 19.15% higher value for maximum dry bulb temperatures per annum. These values mean that there is a potential to reduce the base case energy model by 12-19% hence lowering total mechanical cooling demand. The variations are dependent on climate so cannot simply add a correction to apply to all locations.

6.3.3. Monthly Average Mechanical Energy Reductions

By calculating the difference between the maximum dry bulb temperatures from average WMO and design builder values, temperature differences, expressed as a percentage, are deducted from monthly base case mechanical cooling energy values produced in DTS. Figures 6.4 and 6.5 shows differences for each month. This highlights that deductions are not a clear 12-19% reduction as stated in 6.3.2. Kenya climatic data shows the greatest discrepancy.

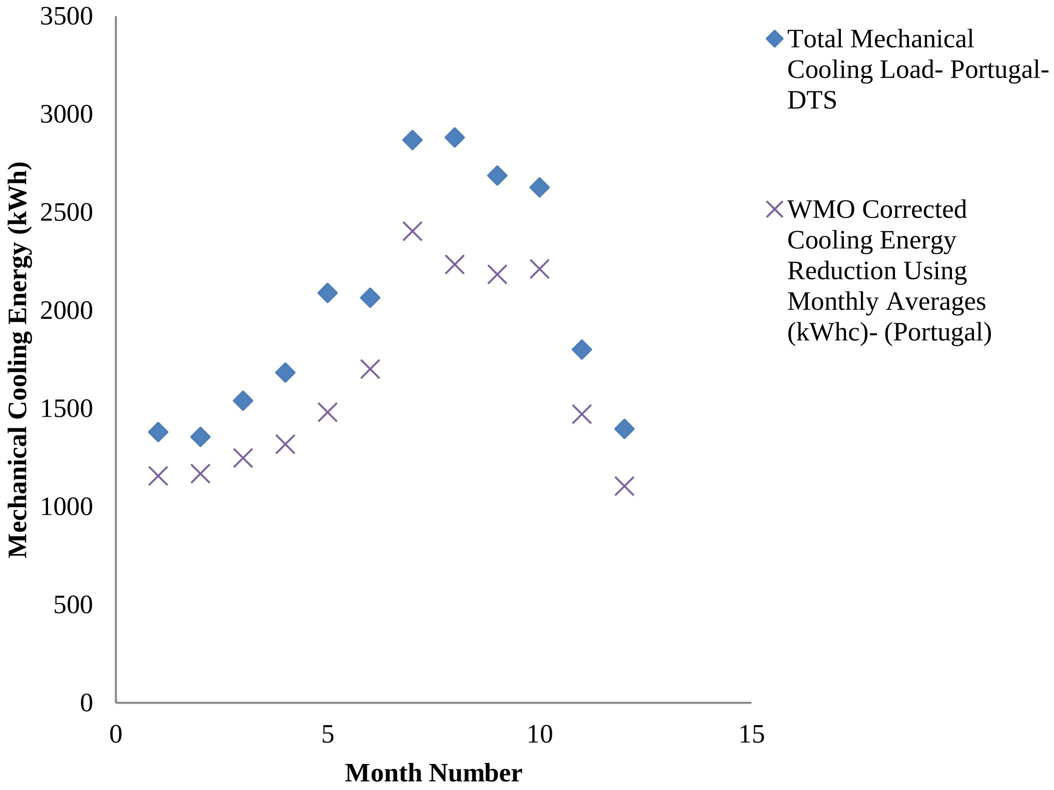


Figure 6.4- Base Case Model B.1 Mechanical Cooling Energy Performance Comparison for Portugal

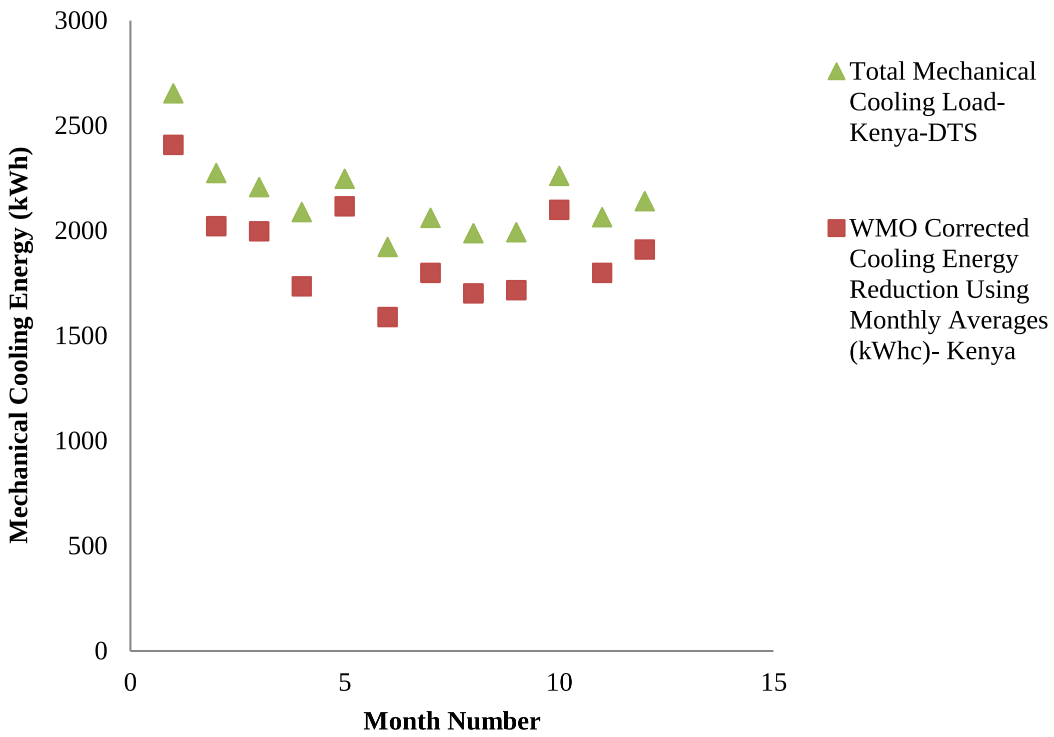


Figure 6.5- Base Case Model B.1 Mechanical Cooling Energy Performance Comparison for Kenya

Figures 6.4 and 6.5 provide information on how much discrepancy exists between DTS input data and WMO data. This identifies that when generating a base case model that a correction should be applied to the generated values for each month (as shown in Figure 6.1), assuming WMO data is more accurate.

6.3.4. Model B.1 Mechanical Cooling Data Inter-comparison

To understand the impacts on the mechanical cooling energy consumption for Building Model B.1 as described in sections 6.3.2 and 6.3.3, these values are re-calculated and shown in Figure 6.6 below for both Model B.1 Climates. Bar graphs shown in Figures 6.6 and 6.7 (below) show the simulated output (kWh/Annum), with overall corrected value using percentage correction for the year and corrected values using a monthly reduction. The results show that the level of accuracy increases by using monthly reductions.

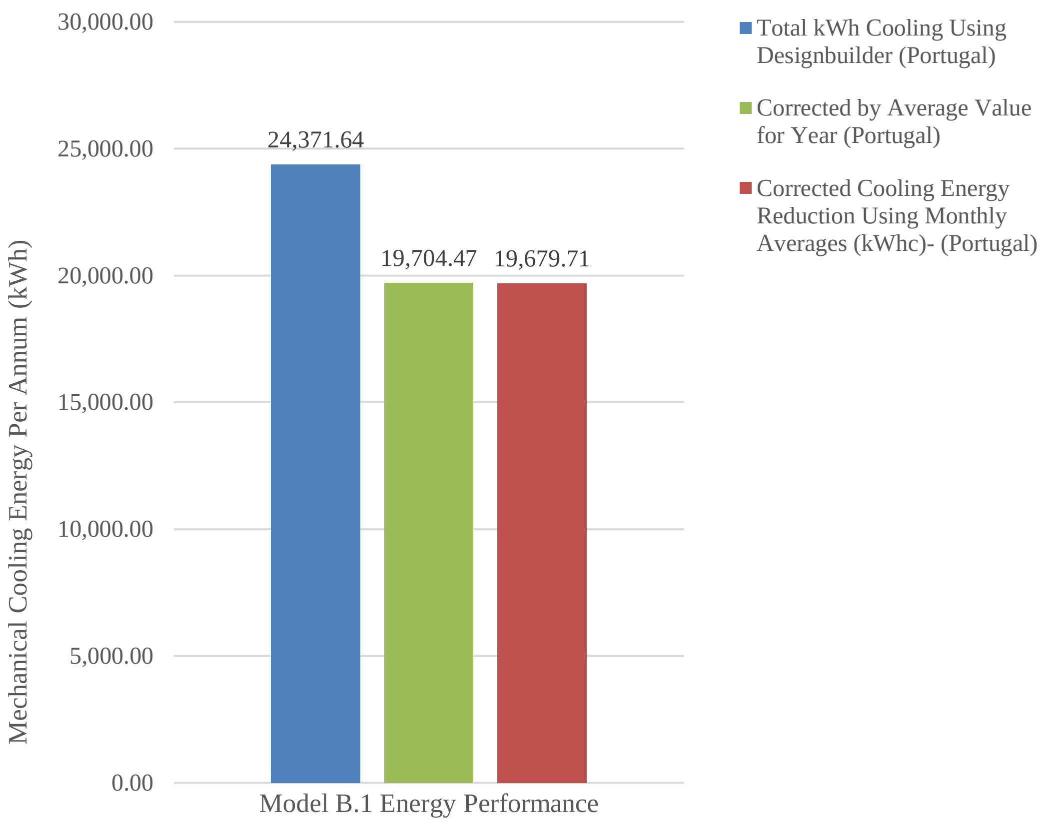


Figure 6.6- Base Case Model B.1 Mechanical Cooling Energy Performance Inter-comparison for Portugal

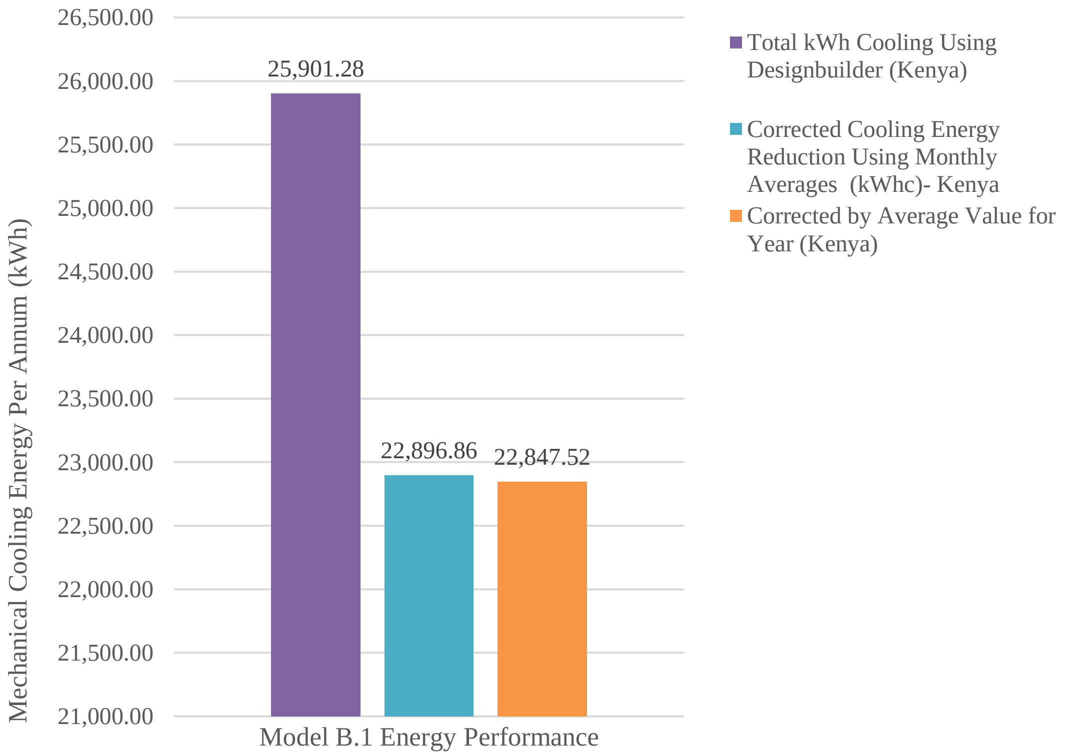


Figure 6.7- Base Case Model B.1 Mechanical Cooling Energy Performance Inter-comparison for Kenya

As shown in Figures 6.6 and 6.7, there are reductions when applying the corrections based upon the WMO average data, in particular in Kenya. For Portugal, both corrected values are within 0.012%. The analysis using monthly average values has more accuracy but average value for the year provide a similar result to 99.87 percent accuracy.

6.4 Sensitivity Analysis 2- Verification Error of Passive System Performance Values Against Published Values

6.4.1. Analysis of Values

To inter-compare calculated values against published research has proven difficult as there is insufficient published energy performance data available to enable direct comparison for verification of all passive systems. There appears to be conflicting values and unsubstantiated claims. The values calculated within Chapter 5 are a theoretical foundation to understand potential cooling capacities available for each system but more empirical work is required to close the gap in terms of real time performance figures.

Table 6.1- Inter-comparison of Calculated Reductions Verses Published Values

Passive System	Published Reductions (%)	Published Reference	Calculated % Values from Table 5.11, Chapter 5	Notes
Natural Ventilation	10-30	WBDG (2016)	11.73 to 28.85	Although values are similar, published claims are unsubstantiated
Solar Chimney	-	-	0	Unable to Source Published Values
External Solar Shading	32	Walliman and Resalati (2011)	27	Published value shows 5% greater reduction
Ventilated Double Facade	+56.5 & +68.4; 50	Technical University Berlin and Pontificia Universidad Católica de Chile (2012) & Designbuild-network, (2013)	2	Conflicting values where statements mean this system would reduce thermal performance. For Designbuilder (2013), the façade runs the complete length of the building hence greater reduction can be achieved.
Rain Screen Facade	-	-	5-7	Marinoscia (2011)
PDEC	26 & 66	Bowman et al. (1998)	6.87 – 15.96	Lower values are due to limiting time of operation, air flow (kg/s) and humidity to 50% RH.
Earth Ducts	-	-	7.81 – 40.34	Unable to Source Published Values

6.5 Energy Performance Analysis

To understand how passive ventilation and cooling systems works with each other, area graphs have been created for each climate (Figures 6.8 and 6.9). These outputs are based upon climate conditions as highlighted in section 2.2.1 (Chapter 2) and Table 3.1 (chapter 3). These graphs show performance profiles, on a month by month basis, indicating how each passive system performs with each other. Figures 6.8 and 6.9 show average annual mechanical cooling energy performance when assessing impacts on performance of ventilated double façade, rain screen façade, external solar shading, PDEC (<50 percent relative humidity) and earth duct using medium concrete. The base case is not show for clarity.

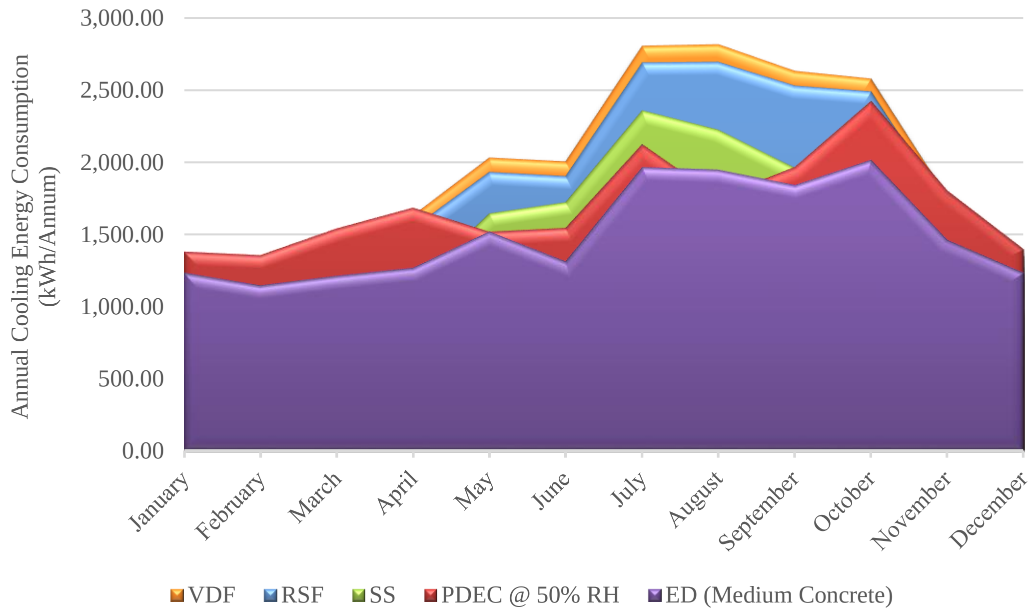


Figure 6.8- Average Annual Mechanical Cooling Energy Performance For Building Model B.1 Incorporating Passive Systems (Portugal)

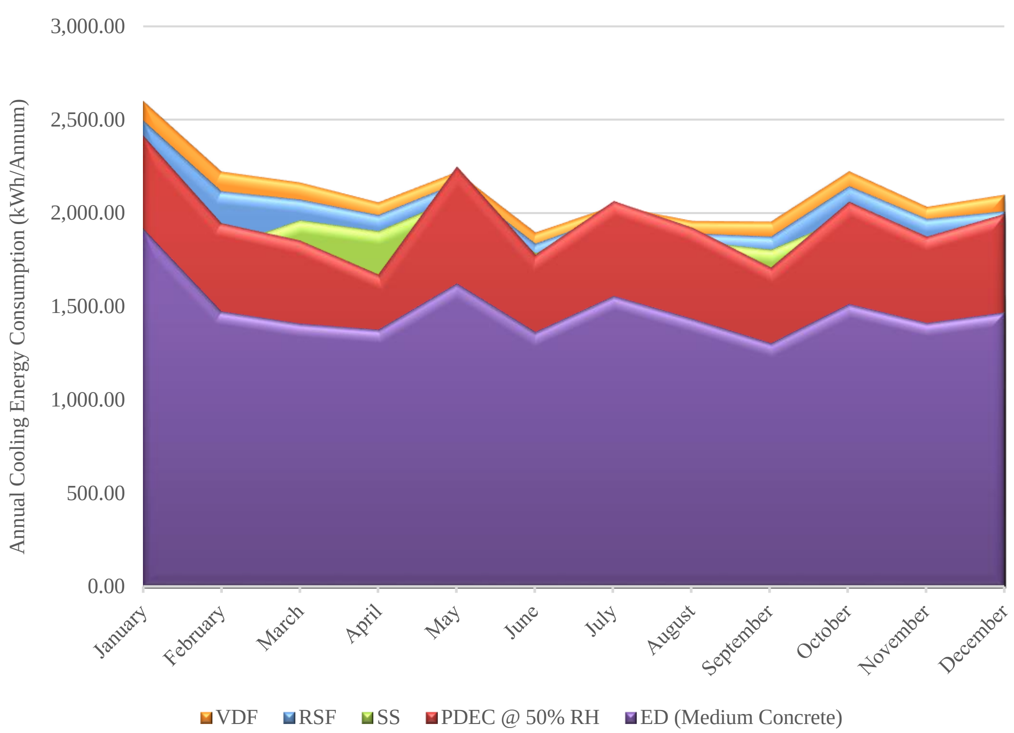


Figure 6.9- Average Annual Mechanical Cooling Energy Performance For Building Model B.1 Incorporating Passive Systems (Kenya)

It is identified that these graphs are difficult to interpret therefore Table 6.2 below provides a synopsis of the area graphs to identifying ideal monthly of passive system operation and which out performs each other.

Table 6.2- Operational Analysis of Passive Ventilation and Cooling Systems in Portugal

Passive System	**Month of Operation (Portugal)-See Figure 6.8**	**Outperformed By (Portugal)**	**Month of Operation (Kenya) -See Figure 6.9**	**Outperformed By (Kenya)**
ED	Jan-Dec	None	Jan-Dec	None
PDEC	Jan to July & September to December	ED	Jan-Dec	ED
RSF	Apr-Mid October	SS, ED & PDEC	Jan-May; June; August to December	SS, ED & PDEC
VDF	Apr-Mid October	RSF, SS, ED & PDEC	Jan-Dec	RSF, SS, ED & PDEC
SS	May-Mid Aug	ED & PDEC	Feb-May & September	ED & PDEC

In both climates, all passive systems perform in a similar manor with minor fluctuation between months due to differing average maximum temperatures.

6.6 Uncertainty in Values

The analysis completed in chapters 4 and 5 demonstrate that performance reductions can be calculated. However, verification shows there are elements of uncertainty with regards to accuracy of weather data and available empirical verification. Additional factors that affect accuracy of calculations are detailed below:

- Passive system calculations are based upon average maximum temperatures for each month. This means there is a possible over/under estimation of performance i.e. temperature may be different to average therefore error could be a difference $^{+}/\text{-}5^{o}C$.
- All energy performance calculations are based upon assumed hours of operation i.e. working hours.
- DTS is assuming perfect conditions i.e. no thermal bridging and building is simulated as a black box (mathematical). The level of accuracy to actual building performance is difficult to analyse due to lack of published data, hence reason for using bench marks for verification of base case building models.

6.7 Passive System Energy Assessment Tools

There is a limited avilability of simplified passive ventilation and cooling assessment tools that provide direct quantative energy reductions for HVAC system. For this research, it has been identified that simple graphs can be derived for natural ventilation performance analysis which can show an architect or building services engineer potential energy saving for different climates. For the assessment of natural ventilation and cooling performance against set point temperature based upon findings from Table 5.2 (Chapter 5), Figure 6.10 below shows a linear relationship between ventilation and cooling BEMS set point temperature. This includes annual energy saving for mechanical systems which are expressed as a percentage. As shown from linear regression R^2 values (0.6719, 0.9344 and 0.9953), varying linear relationships are identified. These reductions are calculated for Abu Dhabi, Portugal and Egypt.

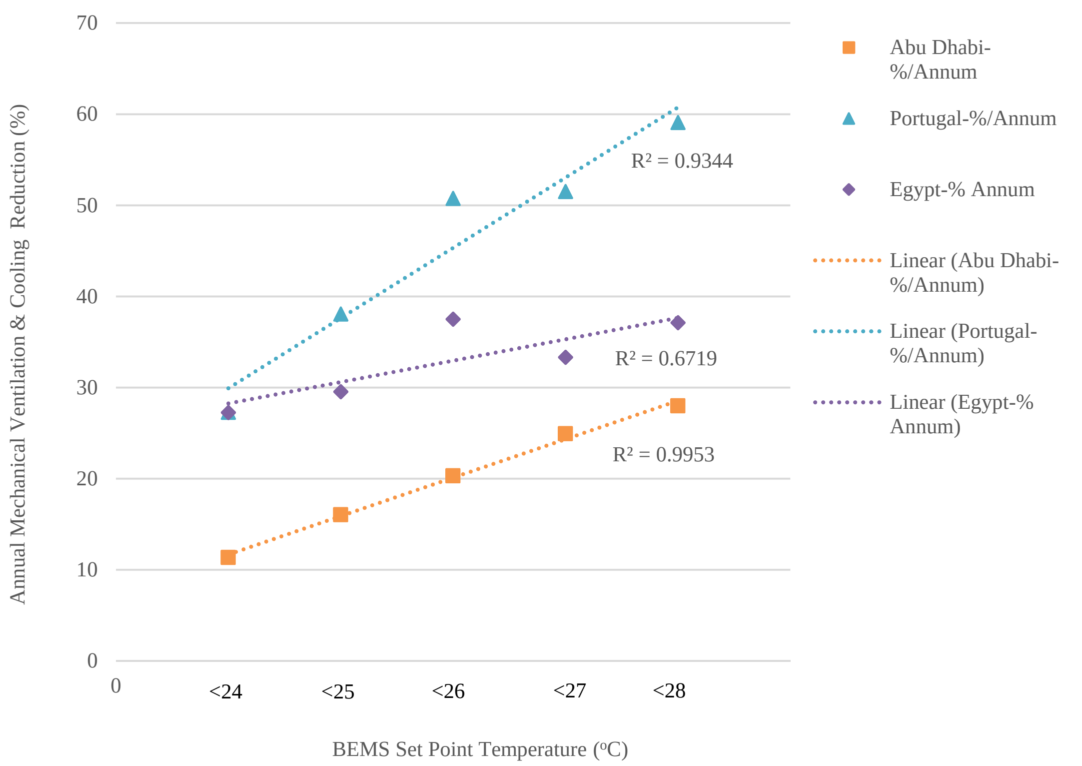


Figure 6.10- Percentage Annual Mechanical Ventilation and Cooling Energy Reduction against BEMS Set Point Temperature

As shown in Figure 6.10 above, increasing BEMS set point temperature increases potential energy savings per annum. This figure enables designers to approximate potential energy savings at concept design Stage (RIBA 2) to enable informed decisions on whether to adopt natural ventilation strategies when buildings are located in hot climates e.g. Abu Dhabi.

For analysis of average mechanical ventilation operational hours per day per month when incorporating natural ventilation strategies, Figure 6.11 (below) shows average hours of operations at a given set point for each month based on Abu Dhabi climate using building model B.2. The graph shows mechanical ventilation and cooling hours for specific BEMS set point temperatures ranging between 24-26°C. Full mechanical ventilation and cooling operation is show as full time operation for a typical daily period (11 hours per day). On x-axis, months are accompanied by average maximum temperatures to allow comparison against BEMS set point profiles. The y-axis shows revised operational time (hours) when deducting Natural Ventilation activation time ($NV_{(t)}$) from Full Mechanical Ventilation and Cooling Operation ($MV_{(t)}$).

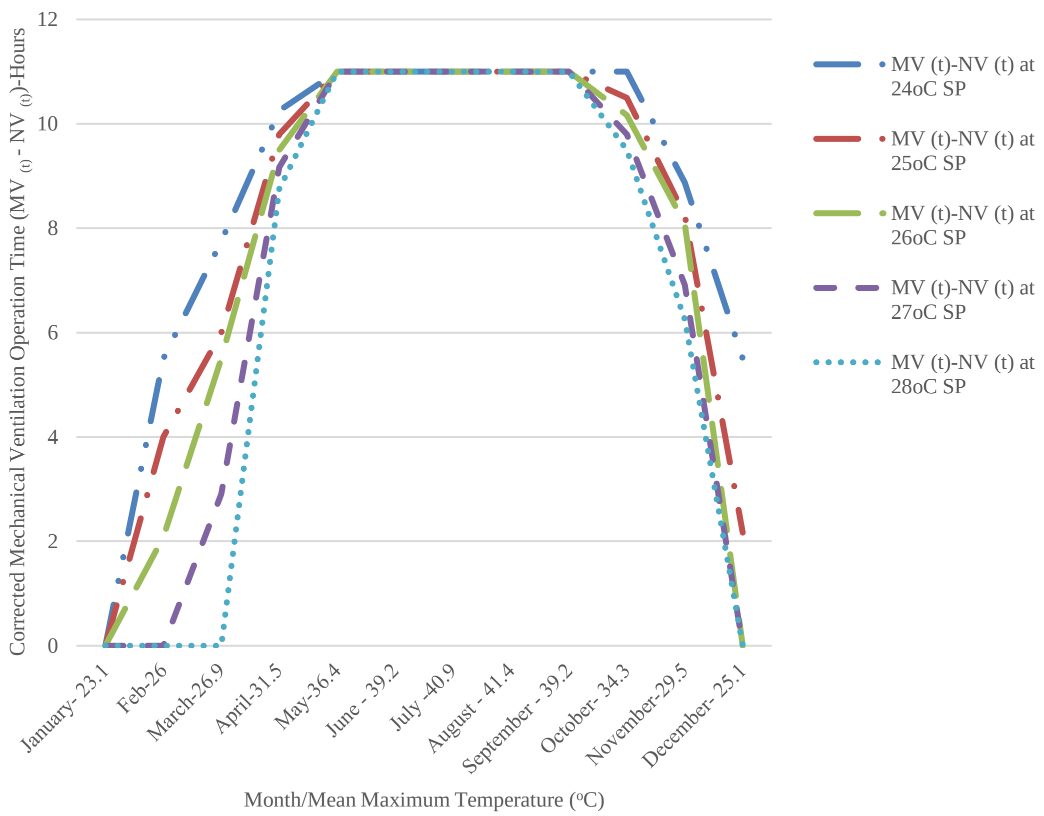


Figure 6.11- Hourly Operation of Mechanical Ventilation and Cooling Set Point Temperature/Average External Air Temperature Inter-comparison

This figure enables designers to determine average hours of operation when increasing the BEMS set point temperature to 26°C. However, higher set points would increase percentage of people dissatisfied (PPD) beyond 5 percent for indoor thermal comfort.

To summarise, these graphs (Figures 6.10 to 6.11) demonstrate minimal potential energy saving when increasing the internal BEMS set point temperature; encouraging natural ventilation activation. The main points highlighted are as follows:

- Percentage reductions can be readily identified for each climate as shown in Figure 6.10 when comparing to BEMS set point temperatures.
- Varying internal set point temperatures can be compared against monthly maximum temperatures (Figure 6.11)

6.8 Passive System Energy Assessment Tool (PSEAT)

6.8.1. Overview

As a by-product of this research, PSEAT has been created and developed to aid with the selection and energy performance assessment of passive ventilation and cooling systems for buildings as set out in Figure 3.20 (section 3.7.4, Chapter 3). As highlighted in 2.4.3, existing simplified design tools do not provide direct simple electrical energy performance assessment of combining passive systems with mechanical ventilation and cooling. The construction industry will benefit from an accessible tool which is available to a wider audience using a well-known and used platform, Microsoft Excel. The main purpose for PSEAT is approximating mechanical ventilation and cooling energy reduction using passive system percentages, determined in Chapters 4 and 5. These percentages are incorporated within a new Microsoft Excel workbook enabling a user (architect or building services engineer) to change the outputs based on pre-determined climates to affect overall outputs. These outputs include annual energy reductions (kWhr/annum), monetary energy savings (£), carbon dioxide emissions per annum ($kgCO_2$) using United Kingdom conversion factors for electricity, outputs per meter squared (m^2) and contribution to BREEAM credits.

6.8.2. PSEAT Microsoft Excel Workbook Programming

In order to complete simple deductions from base case cooling load using passive system percentages, PSEAT has been created using Microsoft Excel workbook incorporating existing embedded functions. A number of work sheets are created and interlinked to provide a platform for this tool. This has been created to enable simultaneous and instantaneous assessment of passive ventilation and cooling systems, calculating HVAC energy reductions per annum. This performance assessment tool is intended to be used at RIBA Stage 2 (Concept Design) using base case Building Model B.1 energy performance data as a basis these results (refer to section 3.3.11, Chapter 3) for building details). PSEAT is set up using commands LIST, VLOOKUP, CONDITIONAL FORMATTING and AUTOSUM to enable users to select various passive system combinations with background calculations being completed within the Excel workbook. Figure 6.12 shows inter-relationships of how these functions are used to produce outputs:

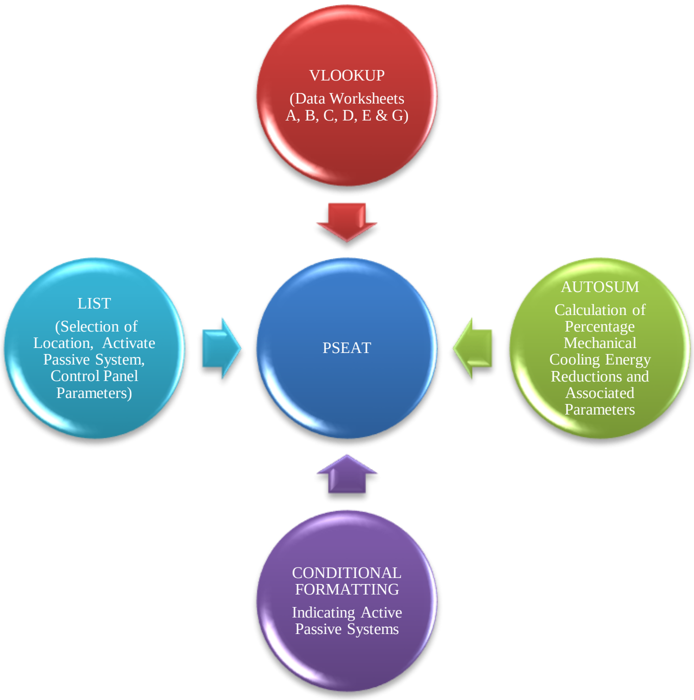


Figure 6.12- PSEAT Microsoft Excel Relationship Diagram

Furthermore, approximate values are calculated having a margin of error of +/-0-5 percent. This applies as percentages generated in chapters 4 and 5 are based upon average temperatures. Where greater accuracy is required, calculation methods identified in Chapter 3 should be adopted for a specific climate using appropriate data. For user control of PSEAT, the main control panel drop down menu's (embedded in each cell) can be used to select specific parameters highlighted in Chapter 4 & 5. Microsoft Excel workbook has been set up using multiple worksheets as defined in Appendix N. PSEAT is built with a percentage calculation tool for direct deductions when selecting each or a combination of passive systems. As an example, BREEAM Credits are selected on the basis that a feasibility study has been completed (excluding life cycle assessment). Furthermore, BREEAM exemplary level is ignored in this calculation (Reductions>30%) as detailed calculations and justification would be required for RIBA stage 4 (BREEAM, 2011). Figure 6.13 below shows the organisation relationships within PSEAT:

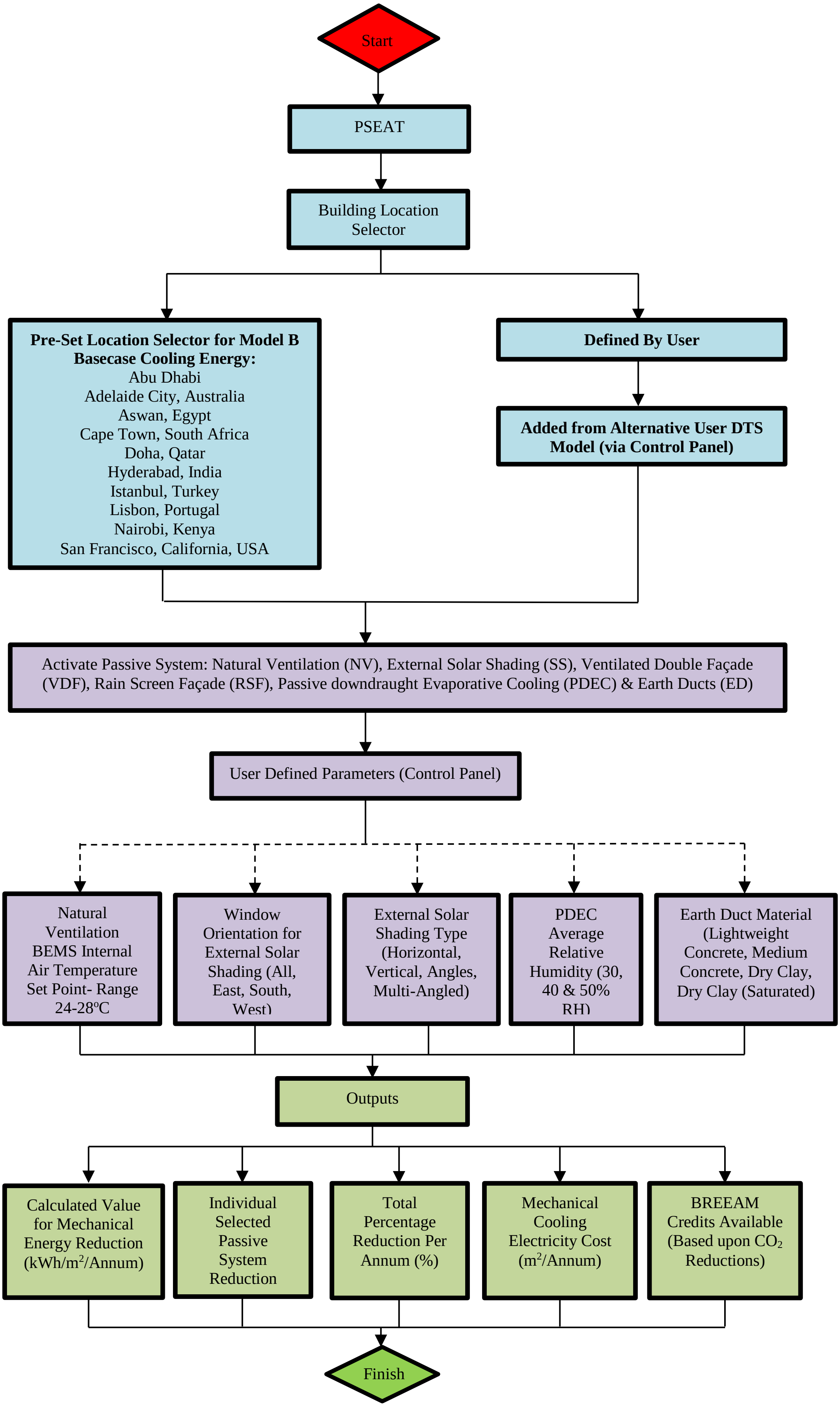


Figure 6.13- PSEAT Flow Diagram

Upon program testing, it was discovered that user defined energy performance from external DTS models annual energy outputs would be beneficial to broaden the range of building beyond Theoretical building Model B.1 hence defined by user function was added. Further development enables a benchmark values per metre squared to be generated which can apply to a wide range of buildings for similar climates. To refine PSEAT, additional outputs were added such as BREEAM Credits and comparison against cooling energy benchmarks. Details of PSEAT are included in Appendix N (Hard Copy) and O (CD ROM).

6.8.3. PSEAT Evaluation Outputs

Using theoretical building model B.1, calculations can be completed for each passive system for each climate type. As an example of this, Figure 6.14 below shows annual energy reductions calculated by PSEAT for various climates showing mechanical cooling energy consumption (kWh/Annum) for natural ventilation for a range of climates. This figure shows that as the set point temperature increases, mechanical cooling energy consumption decreases, indirectly proportional.

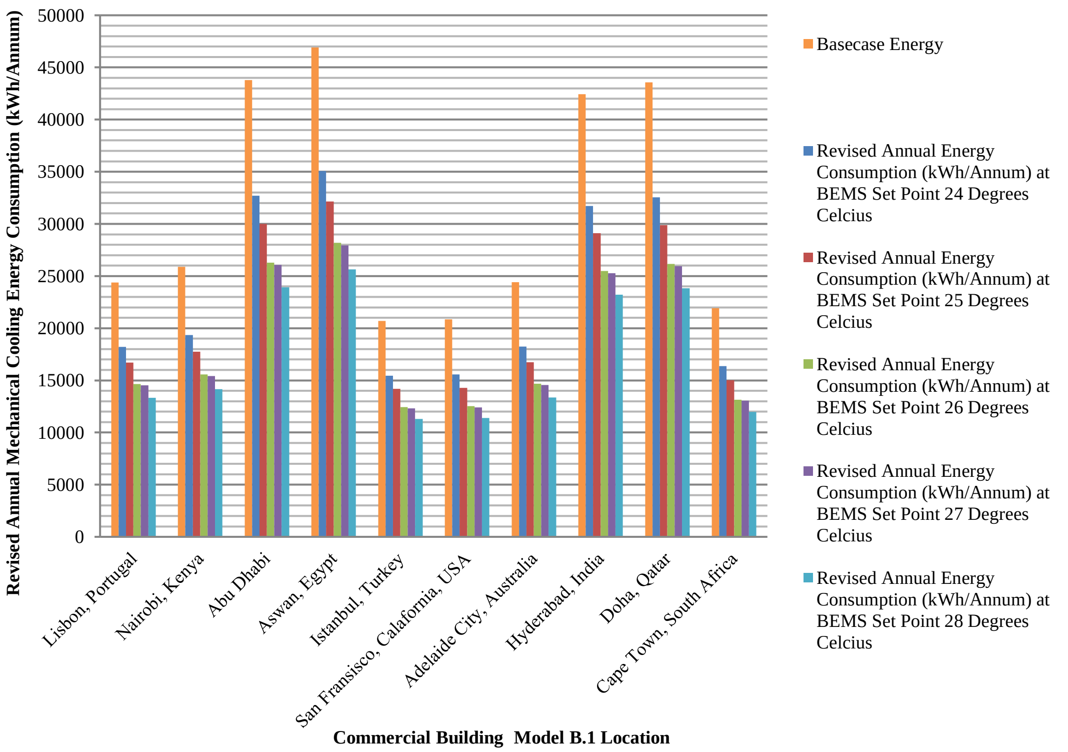


Figure 6.14- Approximate Mechanical Cooling Reduction Per Annum for Various Climates

Figure 6.15 below shows the same information but as energy per metre squared per annum.

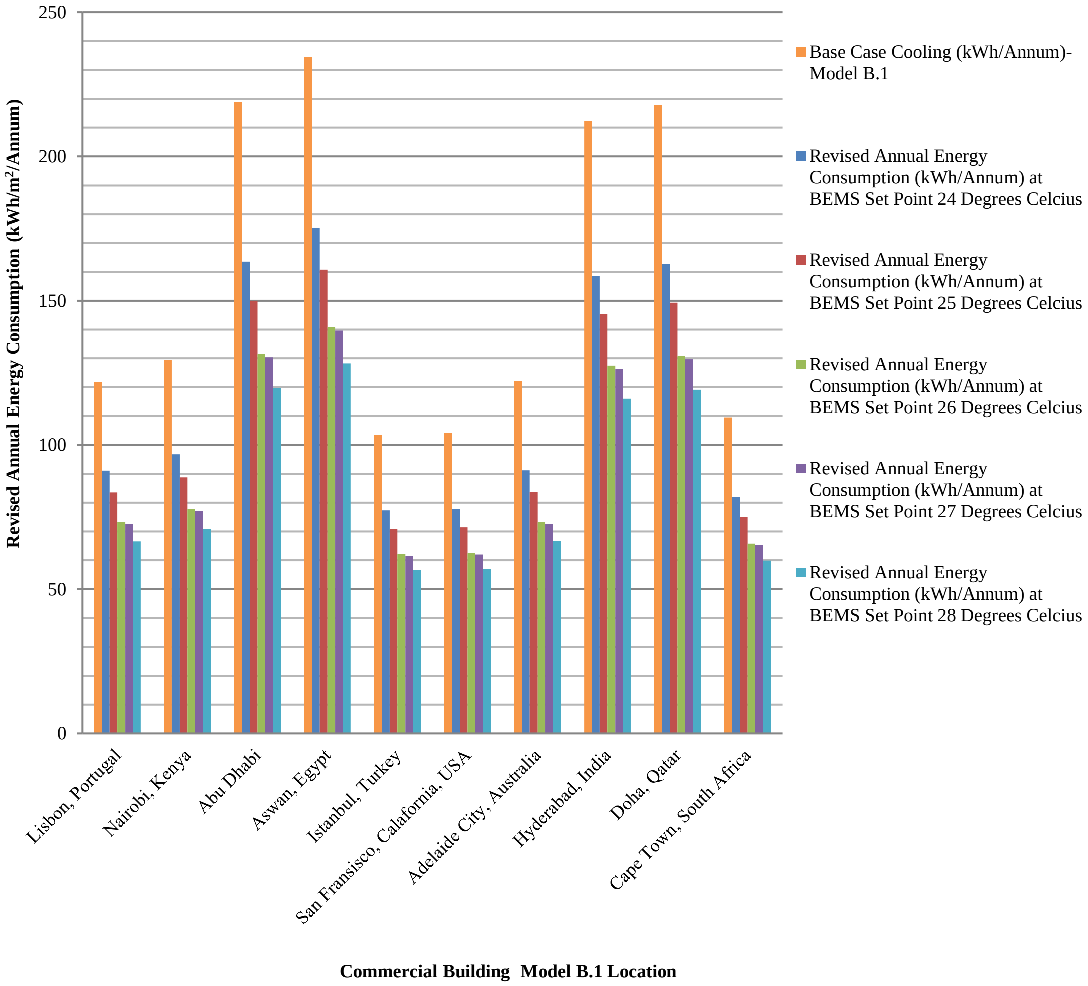


Figure 6.15- Approximate HVAC Reduction (kWh/m^2/Annum)

To demonstrate the full capability of the software, Figure 6.16 below shows each passive systems effect on mechanical cooling energy per annum for Hyderabad, India for building model B.1. Whilst Figure 6.16 shows external solar shading for all elevations (East, South and West), Figure 6.17 details the effects of external solar shading on varying external solar shading type for differing elevations.

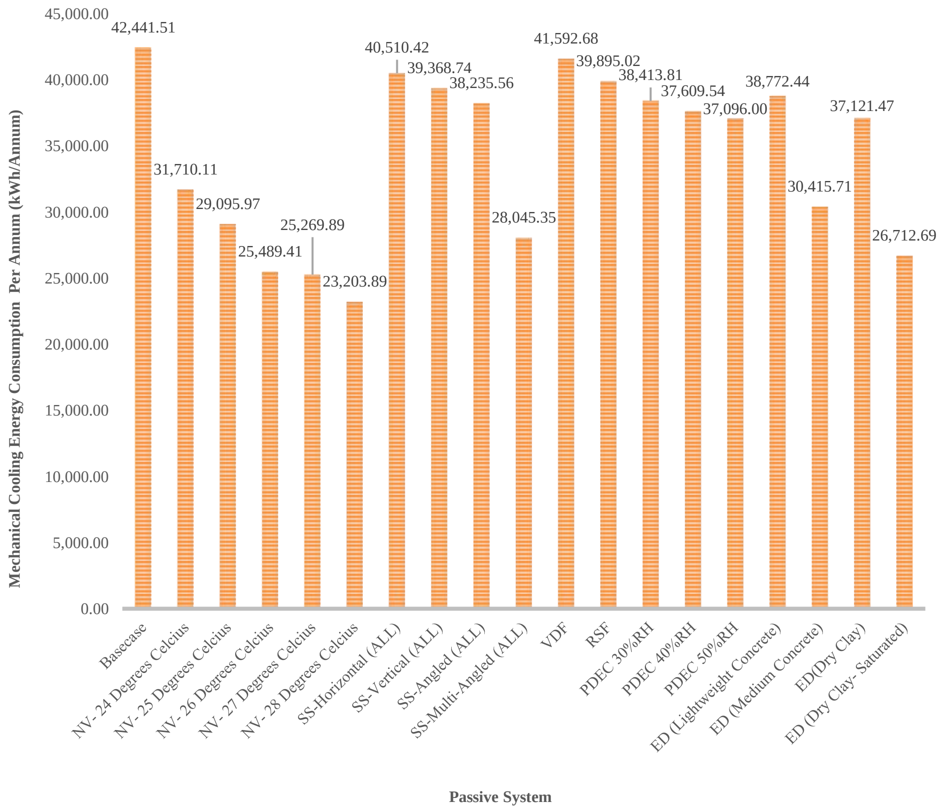


Figure 6.16- Approximate Mechanical Cooling Energy Reduction for Each Passive System for Hyderabad, India

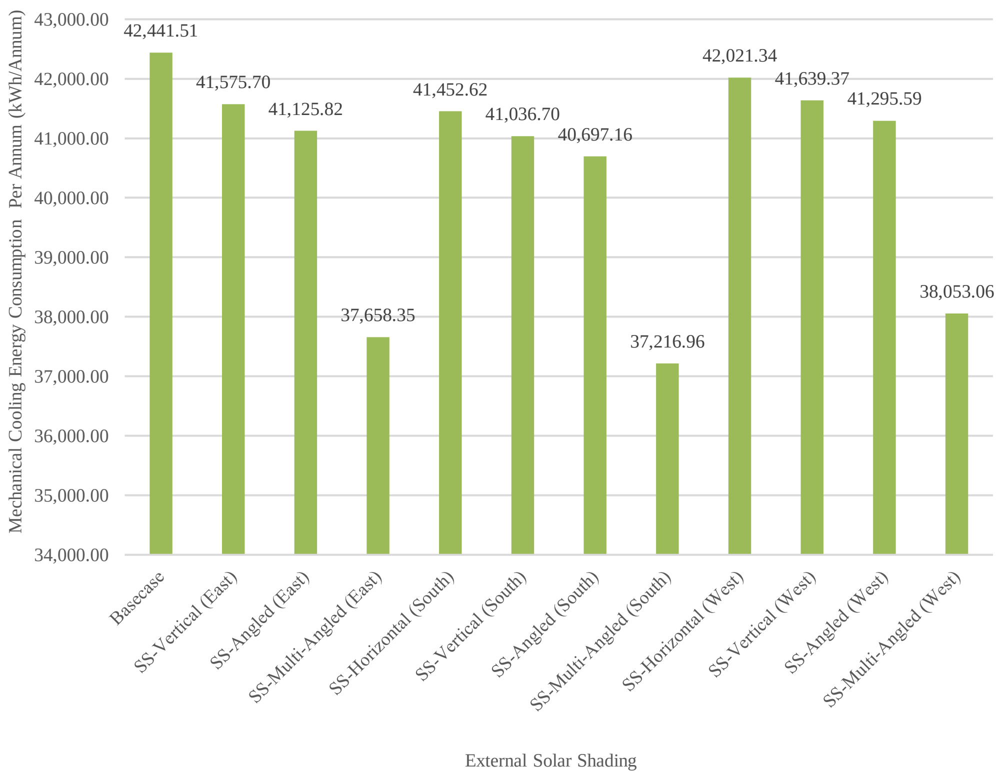


Figure 6.17- Approximate Mechanical Cooling Energy Reduction for Type of External Solar Shading for Hyderabad, India

6.8.4. PSEAT Functions and Limitations

Functions and limitations identified in this section include:

- PSEAT is not a validated tool in terms direct comparison with actual building energy performance values (*Limitation*).
- Ventilated double facades must be connected to all internal spaces in order for calculating approximate reductions (*Limitation*).
- Rain screen façade reductions apply when all building fabric (excluding windows, roof and doors) is provided (*Limitation*).
- This PSEAT tool does not allow for fabric thermal analysis, heat gain or heat loss analysis (*Limitation*).
- Further data worksheets are supporting data taken from Chapters 4 and 5 (*Function*).
- Data A is Base case Mechanical cooling data from Model B simulations; Data B is Natural Ventilation Data; Data C is External Solar Shading Data; Data C is PDEC Data; Data E is Earth Duct Data (*Function*).
- For graphical analysis of natural ventilation for cooling, Data F shows calculation results and a Graph A is a bar graph detailing these results and is incorporated within Chapter 6 (*Function*).
- For data B, C, D & E; averages are taken from calculated annual cooling energy reduction results detailed in Chapter 5 (*Function*).
- CO_2 conversion factors can be changed to suit carbon intensity of other countries (*Function*).

6.9 Summary

Main outcomes from this chapter are detailed below:

- Passive ventilation and cooling assessment tools can be derived for use in industry.

- Average weather data within DTS software requires correcting in line with WMO data (6.3).
- Verification of calculated passive ventilation and cooling system reductions (percentages) is difficult and existing published data is limited. Further issues are encountered when attempting to use benchmark values as $40W/m^2$ appears to limiting when further cooling potentials can be achieved in the methods highlighted in this research.
- Table 6.2 highlights which passive system has greatest level of effectiveness on a monthly basis.
- As detailed in 6.3.2, variations identified are dependent on climate therefore cannot be simply added as correction factor that can apply to all locations.

For a more integrated platform, PSEAT allows users to quickly calculate reductions in a simple program format which is available to a wider user group. Chapter 7 provides simplified design guidelines for this passive system design including integration strategies to complement this chapter.

Chapter 7

Passive Systems Design Guidance & Integration Strategies

7.1 Introduction

The purpose of this chapter is to provide simplified passive ventilation and cooling design guidance and integration strategies based upon research completed in earlier chapters highlighting all main aspects that influence passive system performance within mixed mode ventilation buildings. These systems are very complex and anticipated annual energy reduction are based upon steady state calculation methodology. Results from Chapter 5 identify percentage reductions that can be achieved. Chapter 6 highlights overall results available for each passive system and includes new tools for approximate performance assessment. This chapter focuses on the complete design process providing a range of techniques to identify ideal solutions and incorporate within the building design process (RIBA). This provides a simplified approach to each passive system and combinations thereof for mixed mode operation. This chapter includes discussions regarding difficulties with passive design (7.2), performance design guidelines and integration strategies (7.3), operational ranges and limits (7.4), relationships and interactions (7.5), global locations and climates (7.6), physical application (7.7), geometric design strategy (7.8) and BEMS integration and control strategy (7.9).

7.2 Difficulties with Passive System design

Problems and difficulties identified for these passive systems design are detailed below:

- Engineers knowledge and skills are limited to mechanical systems design and basic natural ventilation implementation based on guidance set out in British Standards (1991).
- Understanding which passive systems can be ideally located (globally).
- Understanding of basic building integration within building geometry for individual and multiple systems.
- Basic control guidelines and how these will interface with a HVAC system.

Techniques have been developed to provide a clear approach aiding with passive ventilation and cooling system selection and design. This chapter provides a simplified and novel approach to design processes as an aid to architects and building services engineer at early design stages (RIBA Plan of work 1, 2 & 3), which are fully accessible.

7.3 Incorporation with RIBA Plan of Work and Practical Application

The aim of this section details how these new design guideline can be incorporated within RIBA plan of work. This also identifies processes to be used during the building design process including limitations of existing design tools and practical application.

7.3.1. Incorporation with RIBA Plan of Work

Buildings can be designed to encompass multiple variations of HVAC systems and must be considered with the RIBA plan of work. For each stage of the plan, Figure 7.1 shows passive system integration that can be adopted from RIBA stages 1 to 4. Concept design (RIBA Stage 2) is the most important as this is where key decisions are made by the design team, effectively fixing internal geometry. For each stage, a feedback loop occurs that directly provides critical information about the selected passive system and its performance, aiding the decision making process.

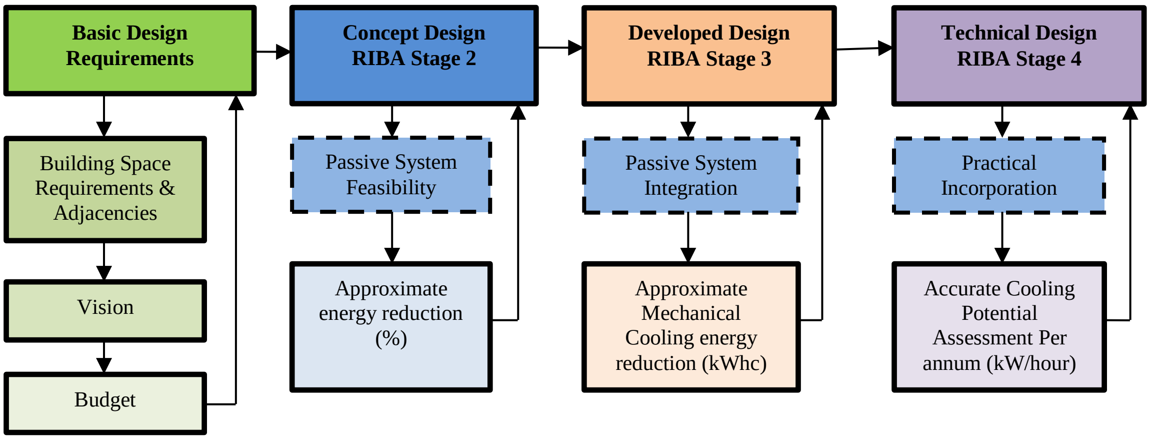


Figure 7.1 – Passive System Design Incorporation within RIBA Plan of Work

For more detailed design strategy of this stage, Figure 7.2 below shows major considerations required to incorporate these passive systems. These include; selection of a suitable passive system, potential mechanical power reduction, budget implications and annual mechanical ventilation and cooling energy saving, as well as life cycle costing.

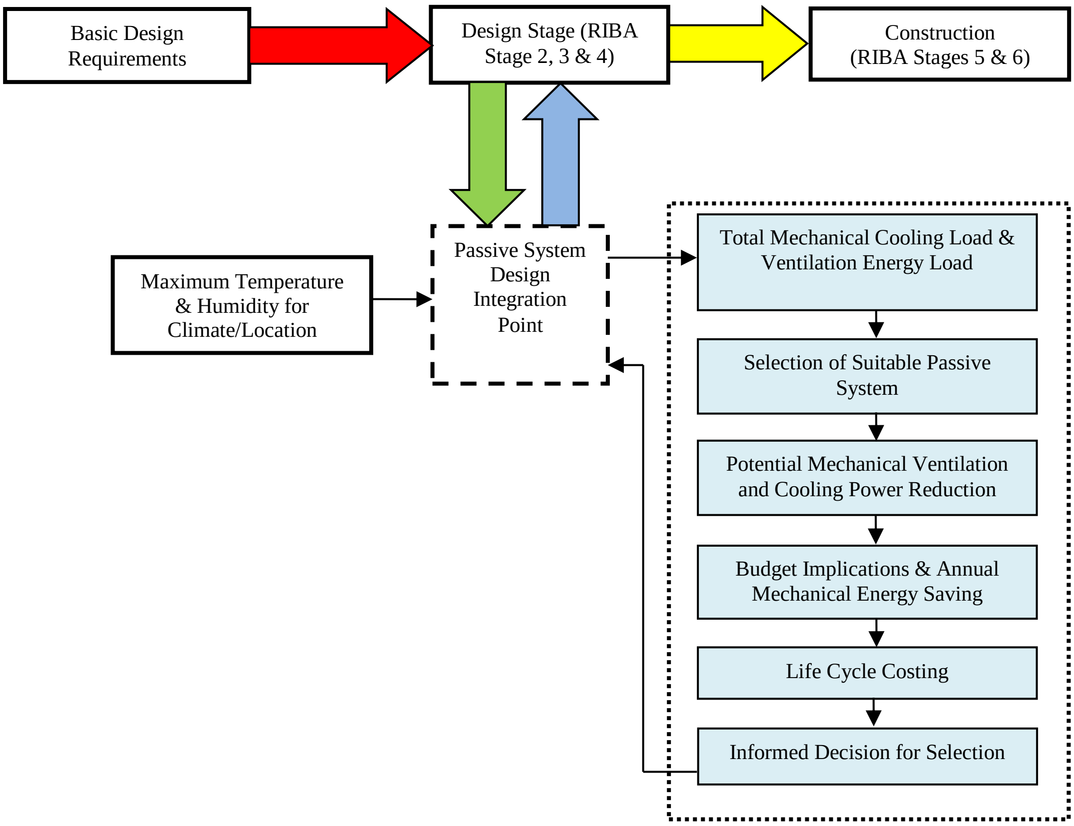


Figure 7.2- Passive System Design Management Flow Diagram (Brittle et al., 2014b)

In order to achieve credits towards BREEAM accreditation for new or existing commercial buildings, which are identified in section 2.4.7 (Chapter 2), main element that would benefit from passive systems is Energy 1 (Ene 1), where a maximum of 4 credits are available provided a feasibility report is completed. Selecting correct passive systems to support HVAC operation is crucial. It is extremely important that the correct strategy is adopted and future performance is anticipated. Passive systems identified have specific selection criterion and care must be given to existing climatic data within the selected global region, as this will have greater impact towards which passive system is selected and its approximate performance. Key drivers for passive system performance are local weather conditions i.e. average temperature, average solar insolation, local wind effects and humidity. These will determine selection and combinations thereof. The aim is to select the most effective passive systems while taking into account capital expenditure, payback (life cycle costing) and carbon emissions.

7.3.2. Existing Design Tools for Passive System Implimention

To achieve accurate assessment of each of these passive systems, complex calculations are required to determine maximum solar gains and solar air temperature effects. Scope for modelling complex passive system is limited. In order to create a passive system (solar chimneys, ventilated double facades, rain screen facades, PDEC and earth ducts), the user must create a model using geometric shapes, windows, grills and openings. To clarify, items missing from DTS are detailed below:

1. Dedicated applications for passive system design.
2. Low carbon design functionality and building adaptation to facilitate passive system integration.
3. Passive system parameter optimisation feature required.
4. Enhancement guidance for improving building energy performance.
5. Staged system performance analysis i.e. effects of adding additional systems to base case models.

6. Mixed mode ventilation and cooling control highlighting staged changeover limits.
7. Dedicated model functions for creating and optimising solar chimney, earth ducts, double ventilated facades and rain screen facades.

The integration of passive systems with mechanical ventilation and cooling systems has major benefits of actively reducing annual energy consumption as demonstrated in case studies in this research (chapters 4 and 5).

7.3.3. Practical Application of Passive Systems

For practical applications and limitations for passive systems:

- Natural Ventilation & Solar Chimneys- Practical application is provided in the form of external high-level stacks to enable exhaust air to flow and absorb maximum solar gains via heavy weight construction i.e. dense high thermal storage capacity materials. Limitation is building geometry as specific configurations are required i.e. rising supply air plenum such as full height atrium connecting all spaces to a sub-terrain level where air is delivered.
- Passive downdraught evaporative cooling- high level water micronisers installed as per details in section 2.11.2, chapter 2. Ideally positioned adjacent incoming control air supply to maximise rate of water absorption to air. Major limitation is legionella treatment and humidity control.
- Ventilated Double Facades- Practical Application double glazed space encompassing an internal void (100-800mm depth) using low-e double glazing and suitably sized high and low level louvres. Ideally these should be sealed during winter conditions. Limited application to front of buildings and entrances.
- Rain Screen Facades- Practical application for all wall surfaces to have weatherboard provided to protect against rain and direct solar gains with an exposed to air gap of 25-100mm. limitations is that this can only be applied to opaque surfaces i.e. excludes glass facades and windows.

- Earth Ducts- Practical application involves conductive robust materials such as lightweight concrete ducts to be buried at 2 metres (minimum) below ground level with large internal diameter for maximum turbulent airflow (increase air to duct surface contact) encouraging maximum heat transfer to ground. Limitation identified is that sub-terrain level is required to terminate and evenly distribute air.
- External Solar Shading- Practical application is fixed external shades normally 50-500mm provided in either angles, horizontal, vertical or multiple angles positions. Limitations are restriction of daylight contribution.

7.3.4. Additional Considerations

Additional considerations that apply to passive system process are size of building and building thermal weight. These parameters have minimal consequence as the size and weight of the building only effects base case mechanical and cooling energy model. A larger building would naturally have a greater demand and percentage reductions for these systems would be a percentage of the total energy demand. For building weight, light weight buildings will allow much more solar gain hence greater energy demand would be required to counteraction solar heat gains. Ideally medium to heavy weight buildings are ideally considered for these system to provide more control of these solar gains.

7.4 Operational Ranges & Limits

The operational ranges for each passive system are detailed within this section identifying ideal climates for optimum operation based upon the findings from Chapters 2, 4 and 5.

7.4.1. Natural Ventilation

There is a broad range where humans are tolerant (heat). This is dependent on how accepting individuals are to higher internal air temperatures. As calculated in Table 5.2, chapter 5, higher external air temperatures lead to a reduction in mechanical cooling energy, particularly in summer months. However, provided average external air temperature does not exceed BEMS set point i.e. <24ºC, natural ventilation activation can offer higher energy savings. Although higher mechanical ventilation and cooling energy savings are calculated in climates such as Abu Dhabi (Model B.2), internal air temperatures become intolerable for human occupants beyond 26ºC hence these savings may not be realised. For climatic location, this would have major benefits would be locations such as Portugal, Spain and France as lower average external air temperatures are experienced. Furthermore, low average humidity should be a consideration and limited i.e. <55%RH. In climates such as Abu Dhabi and Egypt, higher temperature extremes encountered meaning natural ventilation actuation times would be limited to early mornings and late evenings. During peak times i.e. 10am to 3pm, full mechanical ventilation and cooling would be recommended. However, in winter periods, particularly in climates like Sweden, Norway and England, supply air into buildings using natural ventilation will require mechanical pre-heating to 19ºC, via terminal re-heat batteries, in order to increase to thermal comfort temperature and increase buoyancy to overcome pressure differential caused by the internal building layout. This is very inefficient as energy savings of natural ventilation operation in the summer are diminished in the winter due to increased mechanical heating energy.

7.4.2. Solar Chimney

Similar to natural ventilation, benefits of increasing air flow enhancing room ventilation and indoor air quality. However, this does not solve issue of reducing higher natural air temperature (supply). Solar chimneys are ideally more suited to cooler climates where the benefit of increasing natural ventilation stack solar heat gains via high effective g-value glazing encourages air flow as part of the stack/wind effects overcoming internal pressure resistances. When comparing the effectiveness is Portugal and Kenya (Model B.1) in terms of maximum air flows (Figures 5.3 and 5.4, chapter 5), Portuguese climate displays higher internal air flow rates when using higher effective g-values for glazing, hence a hotter climate with greater solar radiative heat gains providing optimum performance.

7.4.3. Ventilated Double Facade

Ventilated double facades are limited by physical constraints of the building as designers need to ensure multiple internal spaces are integrated on any given elevation. Furthermore, annual mechanical cooling energy reductions are very low when compared to capital cost. This should be comprehensively analysed at early design stage. The system does not appear to be limited to a particular climate type but can perform better when effective g-value is lower hence minimising solar heat absorbed by VDF hence lowering amount of heat gains to be naturally ventilated i.e. reducing façade cavity temperature sufficiently to prevent excessive heat transfer into the internal space.

7.4.4. Rain Screen Facade

This system can be applied in almost all circumstances provided the building is not fully glazed e.g. The Shard, London (The Shard, 2015). The rain screen façade weather board can have the benefit of being retrofitted to existing buildings reducing fabric solar heat gains. Ideally suited to hotter climates, a 2% higher reduction can be achieved when the higher temperatures and solar heat gains are experienced; see Table 5.4, Chapter 5.

7.4.5. External Solar Shading

External solar shading can be applied to all external windows and can be aesthetically blended into the façade wall. Greater depth of horizontal external solar shading enables a solar gain time shift by 2 hours (from 0.4 to 0.9 metres), see Figures 4.8 and 4.10, Chapter 4. Horizontal shading can eliminate approximately 2kW daily for south facing glazing. Different external solar shade types, can also be ranked accordingly in terms of effectiveness (Highest to Lowest): Multiple Angled Shading (1), Angled Shading (2), Vertical Shading (3) and Horizontal Shading (4). As detailed in section 4.9 (Chapter 4), summarising selection of external solar shades has a fundamental impact on day lighting contribution into internal spaces. These do, however, provide a good form of day light glare reduction. Optimum day light factor observed when using horizontal type shading achieving a daylight factor of 1.8 on South elevation.

7.4.6. Passive Downdraught Evaporative Cooling (PDEC)

For PDEC, Humidity control (ratio) is particularly important when using water evaporation systems. Condensing water vapour in office environments is undesirable and measures should be taken to control the rate of water vaporisation hence controlling internal relative humidity (<50%RH). As stated in CIBSE (1999a), acceptable external air moisture limits for vaporisation range between 40-50 percent relative humidity depending on the type of climate. Tropical climate types PDEC is not as effective with higher relative humidity's limit available cooling capacities. In terms of using a PDEC system, this is limited to hotter dryer air applications due to better latent heat of vaporisation and water must be treated to avoid the transfer of legionnaire's disease via airborne particles.

7.4.7. Earth Ducts

These systems are particularly reliant on prevailing winds to overcome pressure differences through air inlet dampers. These also need to maintain turbulent air flow to maintain maximum possible air contact with earth duct wall maximise convective and conductive heat transfer mechanisms. Best practices in industry now attempt force draft, via extract air handling units, maintaining supply air flow through earth ducts when natural ventilated stack and wind effects cannot be relied upon. Selection of high thermal conductive materials and consideration of buried depth are also key values to ensure maximum heat exchange to ground. The primary driver for location is the temperature at a specific depth below ground level. This will ultimately determine how much heat can be transferred i.e. greater ΔT is required to maximise performance.

7.5 Relationships and Interactions

When combining passive building ventilation and cooling, building designs naturally become more complex and passive systems need to assist the mechanical ventilation and cooling ventilation strategy. To incorporate passive systems within a building, it is important to identify design application of each passive system type and correctly integrate within a building structure. This would be based upon estimated anticipate building performance. The main passive system for mixed mode operation is natural ventilation. The advantage of supplying natural ventilation air into spaces has many energy saving advantages on reducing specific fan power, cooling/heating loads for supply air and providing 100% full fresh air into spaces. To illustrate how all considerations can be combined into a single process, Figure 7.3 below shows the inter-relationships of all main external parameters identified in this study.

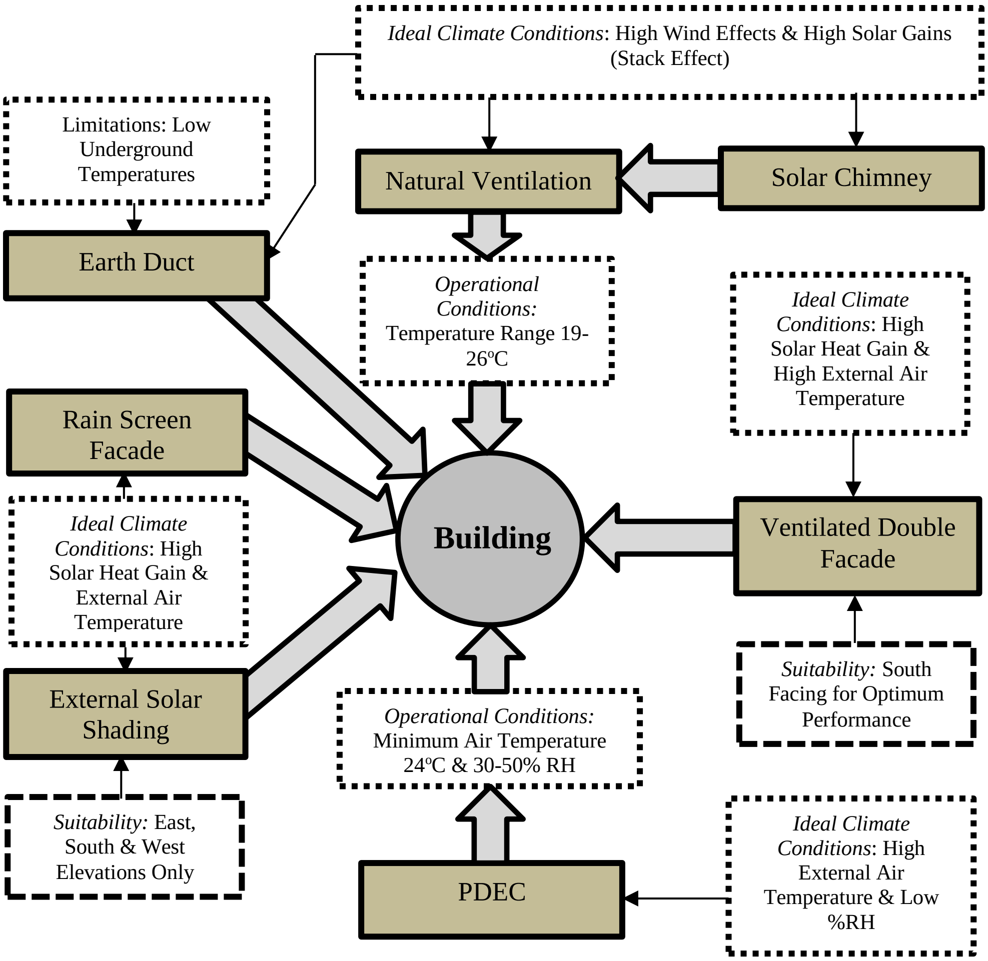


Figure 7.3- Inter-relationships of Passive Systems and External Conditions (Brittle et al., 2016b)

The above diagram shows internal ambient air temperature has a comfort range between 16-26ºC. Building energy performance is mainly reliant upon external conditions and HVAC is design to deliver requisite design conditions, as and when required. Internal spaces that are not deemed as continually occupied, such as entrance foyers, circulation spaces, passive systems can be incorporated and used depending on the architectural configuration. Entrance foyers can adopt ventilated double facades and atriums adopt PDEC (high level). As shown in Figure 7.3 above, the main parameters parameters include high wind effects, solar heat gains (irradiance), high average external air temperatures, ground temperatures and relative humidity. The ranges of these parameters is particularly important as this decides which passive system is ideally suited to a particular climate. Combining these systems together can be complex as architectural/structural restrictions take precedence in terms of space planning and structural engineering. Furthermore, aesthetic considerations are major driving factor. Passive system effectiveness is dependent on the following:

- Low ground temperatures to ensure greater rate of heat exchange between earth duct
- Solar chimney is directly linked to natural ventilation.
- Low relative humidity is required to enable PDEC system to introduce micronised water without increasing levels outside range i.e. greater than 50 percent.
- Ventilated double facades should be on the South Façade of a building to ensure optimum solar heat gain capture. This should cover a larger area as physically possible.
- External solar shading are suitable for East, South and West.
- Rain screen facades can be applied to all elevations to prevent wall damage from rain, direct solar heat gains (East, South and West only) and high dry bulb temperatures.
- Higher wind pressures are desirable for effective operation of natural ventilation systems and earth duct i.e. to overcome stack/duct pressure drops.

7.6 Global Locations & Climate

The main environmental considerations for design of these passive systems is external dry bulb temperature, external humidity and solar irradiance per annum. These parameters affect all calculations in DTS hence local Test Reference Year (TRY) or Design Summer Year (DSY) should be selected using appropriate software. These conditions have a profound effect on how well each of these passive systems will performs as only narrow limits apply before mechanical ventilation and cooling are required. An example of this would be natural ventilation, which would be difficult to operate is hot arid climates as there is only small time frame in the morning and late afternoon where air temperatures achieve thermal comfort levels.

In order to provide guidance on which systems are suitable for a given location, Figure 7.4 below shows suitable locations for each passive ventilation and cooling system. This uses an outline world map from Clker (2015) in conjunction with Table 7.2 (below). Climates are identified as: BLUE spot means mild climate with average temperature band within human thermal comfort limits; RED spot means high average dry bulb temperatures with relative humidity averaging 50 percent; Orange spot mean high average dry bulb temperatures with high relative humidity greater than 50 percent and purple means extremely hot climate i.e. average air temperature exceeds 35ºC.

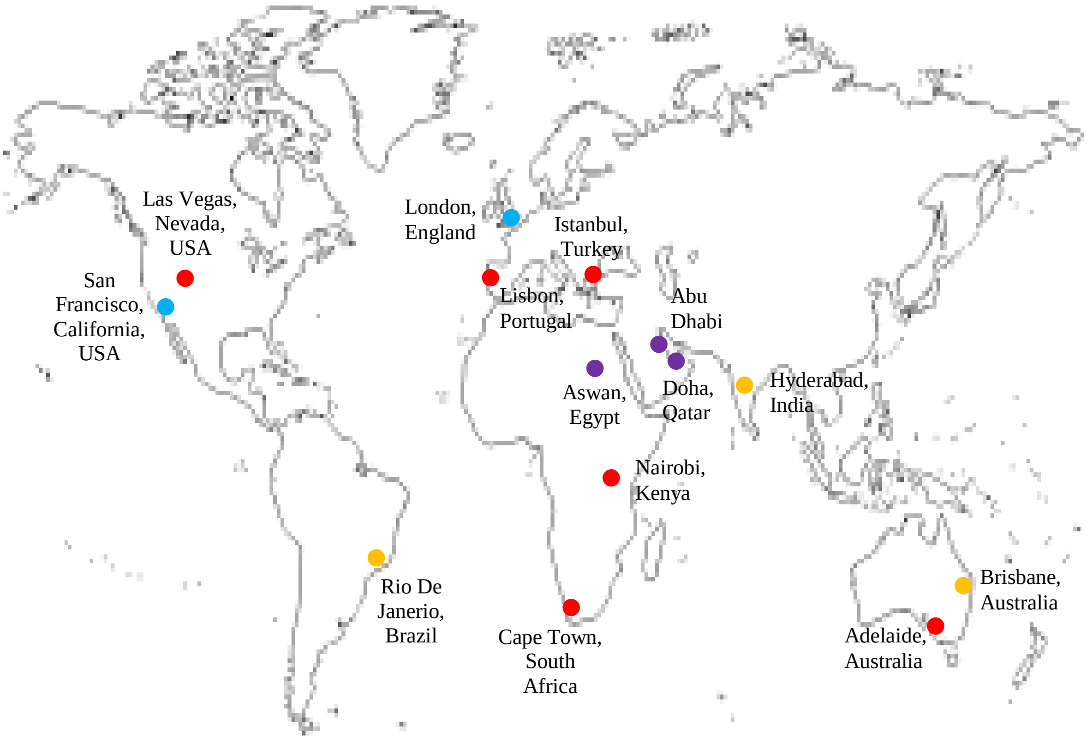


Figure 7.4- Global Locations Using Clker (2015) World Map (Brittle et al., 2016b)

Table 7.1 below identifies most suitable passive systems for the locations identified in Figure 7.4. Ideal passive systems are indicated due to highest probable effectiveness for each location shown.

Table 7.1- Ideal Global Locations for Passive Systems (Brittle et al., 2016b)

Passive System	**Ideal Location**			
Natural Ventilation	●	X	●	X
Solar Chimney	●	X	●	X
External Solar Shading	●	●	●	●
Ventilated Double Facade	●	●	X	●
Rain Screen Facade	●	●	●	●
Passive Downdraught Evaporative Cooling	●	X	●	●
Earth Duct	●	X	●	●

The colours indicate which passive systems are suited to that environment. The cross means that the passive system is not ideally suitable for the climate hence not recommended for use. The selection is based upon highest probable effectiveness. As an example, external solar shading is suitable for all types of climate. In cities such as Brisbane, Australia, due to high relative humidity, PDEC would be unsuitable due to low levels of water moisture absorption into air. It is important to note that winter conditions have an adverse effect, for example, in United Kingdom; power-heating types (heater batteries) would be required.

For incorporation into a design process, Figure 7.5 flow diagram below shows a detailed design strategy that can be adopted for implementation to support RIBA plan of work stages 2 or 3 (RIBA, 2014). Upon initial design process, selection process of passive system can be completed, should these be desired and identifies considerations required at each stage of incorporation.

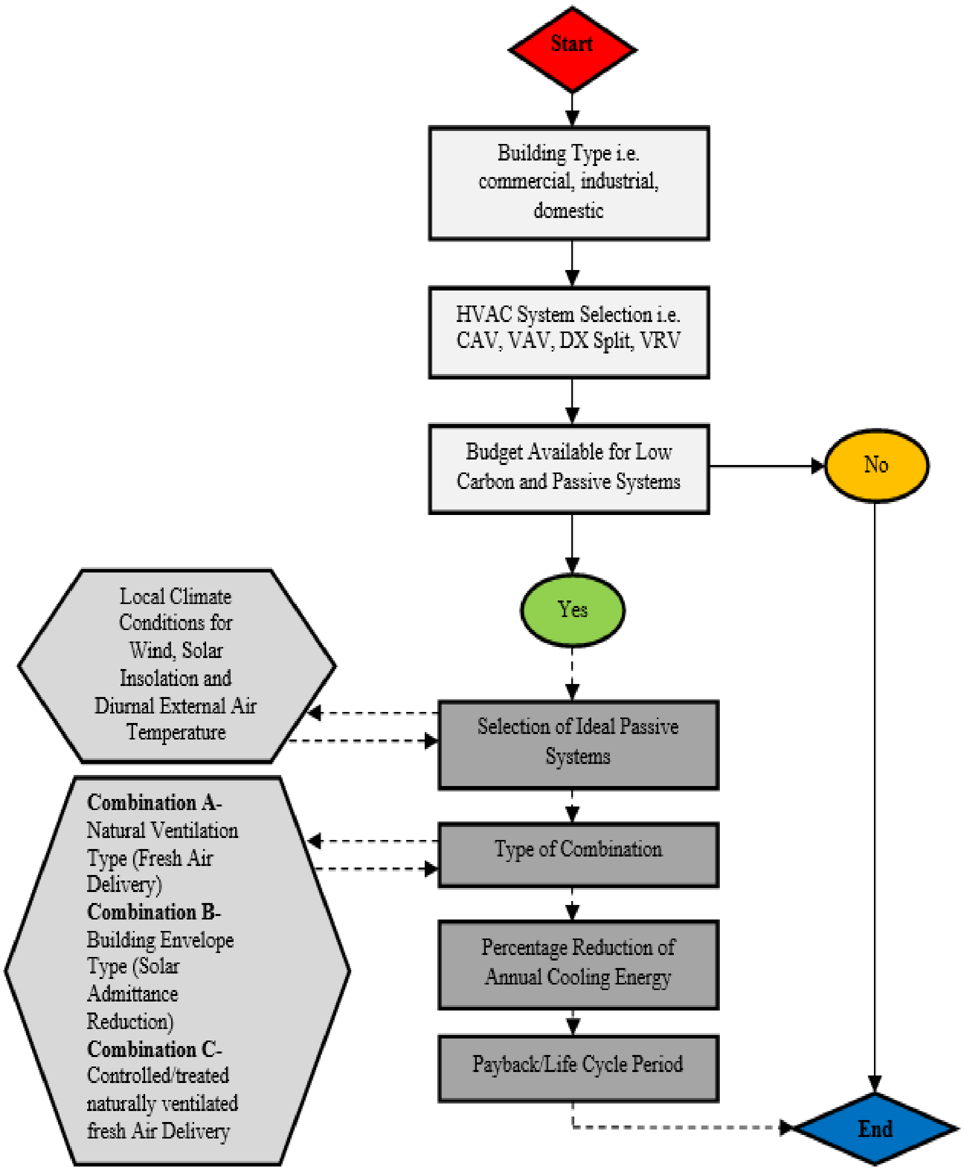


Figure 7.5- Application of Combining Passive Systems Methodology Flow Diagram (Brittle et al., 2016b)

As shown in Figure 7.5 above, parameters include high wind effects, high solar heat gains, high average external air temperatures, low underground temperature and low relative humidity. The ranges of these parameters is particularly important as this decides which passive system is ideally suited to a particular climate.

7.7 Physical Application

Physical application of each passive system is complex and costly, requiring a significant amount of project planning and expertise as detailed in Chapter 2. In order to achieve the percentage reductions shown in Table 5.9, Chapter 5 a greater amount of design is required. For each passive system, physical application, limitations and recommendations are detailed below in Table 7.2:

Table 7.2- Passive System Selection Guidance Table

Passive System	Feasible Application	Limitations	Recommendations	Metrics (Variables)
Natural Ventilation	All Spaces	Complex Geometry, Capital Cost Increase, air flow limited by wind	Building to be provided with low level sub-terrain labyrinth to act as sensible heat store	Natural Ventilation Temperature difference (ΔT) dependent on external air temperature (T_o)
Solar Chimney	All Spaces provided with natural ventilation	Complex Geometry and Structural Reinforcement	Glazing pane (High effective g-value) or opaque surface (High Emissivity)	Q_{SC}-Solar Chimney Heat Gain in Watts (W)
External Solar Shading	External Windows (East, South and West)	Additional structural support; daylight reduction	Effects on daylight should be considered as not to reduce daylight factor below 2	Q_{SS}- Solar Heat Gain in Watts (W)
Rain Screen Facades	All Exterior Facades	Aesthetics and impact withstand limited	Weatherboard layer will have to be reinforced to prevent warping	Q_{VDF}- Ventilated Double Façade Heat Loss (-) in Watts (W)
Ventilated Double Facades	Front Facades and Entrance Foyers	Deep void space required in entrance foyers	Deep facade void depth required for maximum efficiency	Q_{RSF}- Rain screen Façade Solar Heat Gain in Watts (W)
Passive Downdraught Evaporative Cooling (PDEC)	High Level Atriums or PDEC Towers	High internal humidity, risk of legionella's disease and increased water consumption..	Limited to external relative humidity (<50%RH)	Microniser Flow Rate (kg/s) and Humidity Ratio (Δx). Q_{PDEC} PDEC system heat reduction in Watts (W)
Earth Ducts	Sub-Terrain Labyrinth Connections	Air flow limited by wind and internal stack effect	Adaptive control strategy to be employed with natural ventilation and large ducts required to minimise pressure drop	Q_{ED}- Earth Duct Heat Loss to ground in Watts (W)

7.8 Geometric Design Strategy

For each passive system strategy, conditions and parameters must be determined i.e. buildings internal geometry, plant provision and space, occupancy and envelope thermal mass. To successfully integrate, airflows must be balanced and deliver identical air volumes in both operations. Impacts on building configurations are particularly important when incorporating any type of passive systems. The internal building layouts need to be organised to ensure most efficient method of cooling by natural means. Potential configurations (simplified) for natural ventilation are shown below in Figure 7.6; ventilation stack (S) and central atriums (CA).

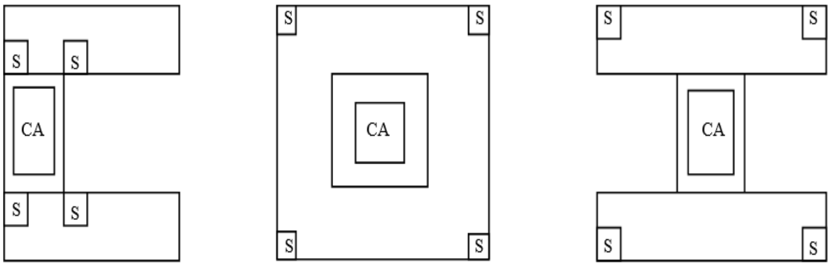


Figure 7.6- General Configuration for Building Incorporating Natural Ventilation-
C shape, Square shape & H shape respectively (Brittle et al., 2016b)

Natural ventilation and mixed mode building studied by Krausse et al (2007) and Svensson (2011) identified that common configuration should in square shape building methodology provides an effective method of air distribution. This configuration can be implemented by the ability to connect spaces allowing low resistance passage of air, from sub-terrain level via a central atrium (air delivery plenum) to stack discharge outlets. This provides a platform for adding additional systems to minimise solar gains via the building fabric (admittance). A potential concept layout are shown below showing the relationship to the building envelope in Figure 7.7 below. In addition, a section the concept building section detailed below in Figure 7.8.

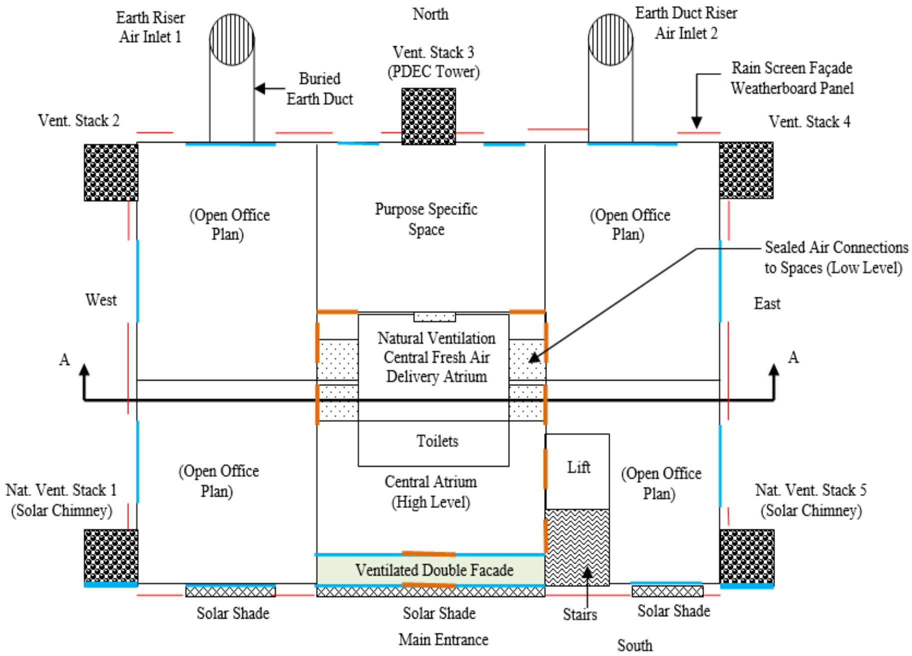


Figure 7.7- Basic Theoretical Combined Passive System with Natural Ventilation Ground Floor Block Diagram (Plan View) (Brittle et al., 2016b)

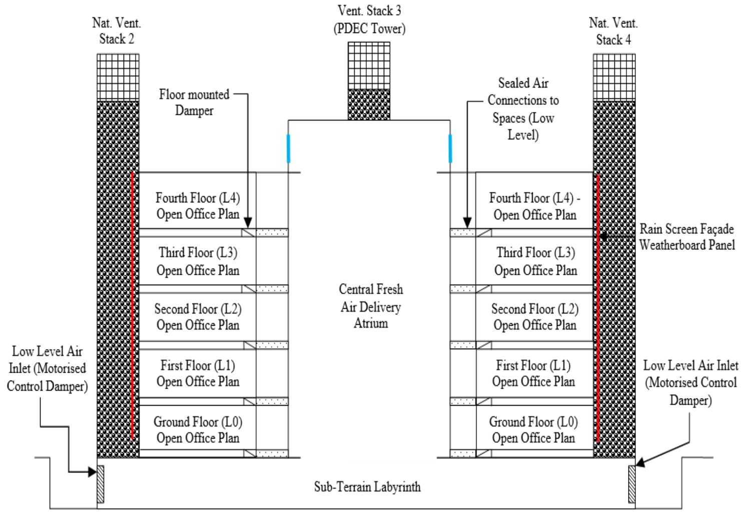


Figure 7.8- Section A-A Building Block Diagram (Sectional View) (Brittle et al., 2016b)

7.9 BEMS Integration & Control Strategy

In typical mixed mode buildings, HVAC systems consist of centralised plant using variable air volume (VAV) or constant air volume (CAV) incorporation cooling coils from secondary cooling plant. In normal operation, this equipment remains on standby, as passive systems will be in operation, until internal environmental design parameters fail and mechanical ventilation and cooling is required. Passive system operation can be complex to control and requires sophisticated pre-set values and programming to maximise benefits of each and every passive system before HVAC operation is required. In its simplest form, Figure 7.9 shows basic control strategy.

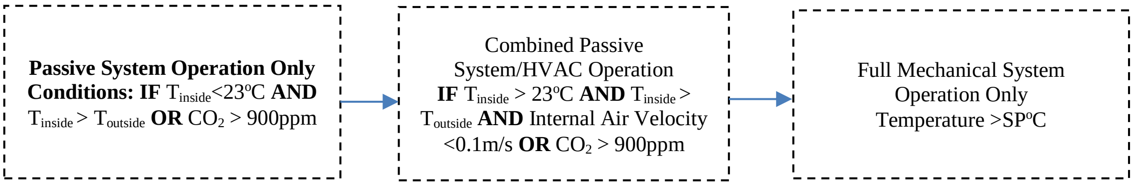


Figure 7.9- Passive System Control Strategy for Building Operation

Using combinations of passive systems which allow manual or electronic control, Figure 7.10 (below) details simply how each system can contribute before HVAC is required. Rain screen facades and external solar shading are not included as these are termed as fixed systems without control variation, once installed.

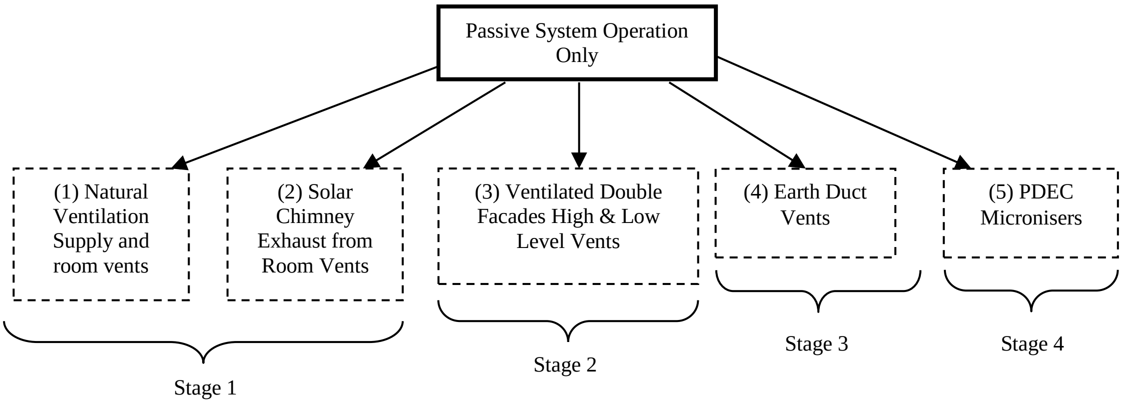


Figure 7.10- Passive Systems Staged Control Strategy

Figure 7.10 passive system 'switching on' sequence of operation strategy which is dependent on external environmental conditions and internal heat gains. In order to maximise effectiveness of each passive system, these must be brought in at various stages mainly driven by external air temperature. For stage 1 operation, natural ventilation can be considered stage 1 operation providing 100% fresh air to spaces assisted by solar chimneys provided the minimum air temperature is 19°C. As daily external air temperatures increase along with solar radiation, Stage 2 can activate high and low level outlets to the ventilated double facades.

Stage 3 operation would can provide more cooling capacity, via below ground level, using earth ducts where larger volumes of cooler air is required. Stage 4 operation adopts a PDEC system dependant of percentage relative humidity and would benefit from external air temperatures exceeding 24°C. Figure 7.11 below show basic inter-relationship between Passive Systems & HVAC operation using 100% fresh air.

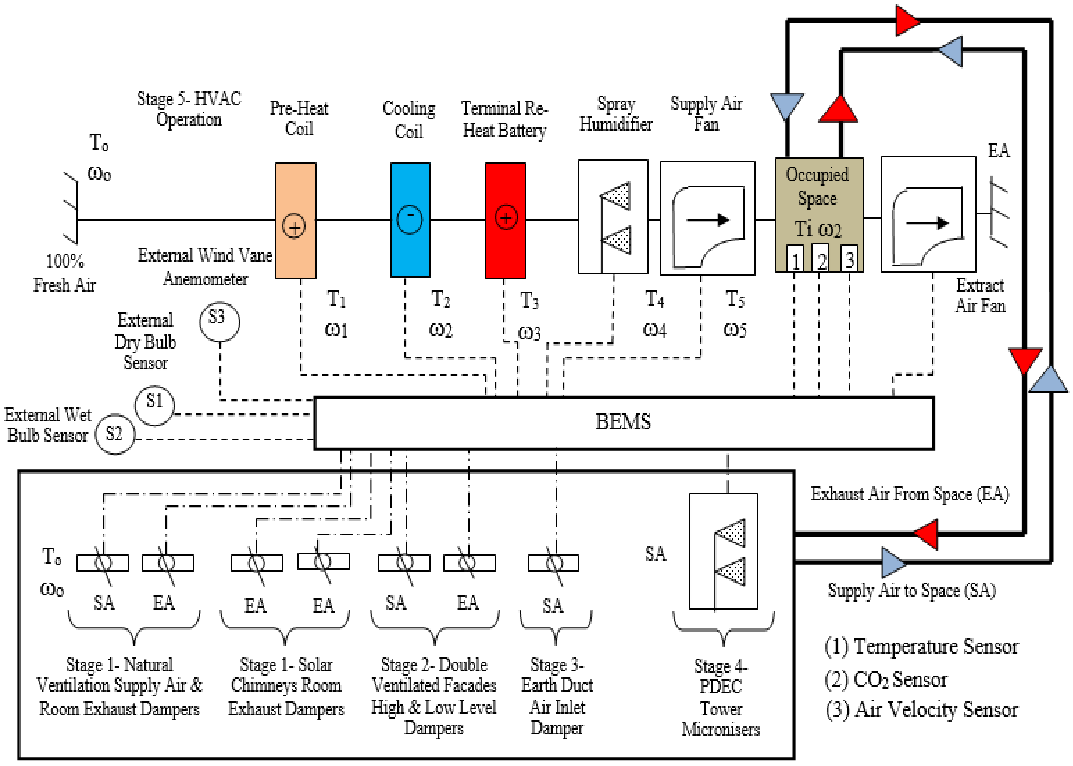


Figure 7.11- Mixed Mode Ventilation & Cooling Relationship with BEMS System (Brittle et al., 2016b)

In Figure 7.11, main component parts are identified for the main air handling unit as pre-heat coil, cooling coil, terminal re-heat battery, spray humidifier, supply air fan and extract air fan. Under normal operation, air handling units will control occupied space environment. Incorporating passive systems into the HVAC strategy shows physically separate connections to the occupied space. These systems all have basic airflow control dampers controlled via BEMS system.

The operation depends on the internal environment and these systems activation in stages as simultaneous operation may lower internal temperature outside comfort conditions. In the first instance, natural ventilation (stage 1 operation) will provide 100% fresh air to spaces assisted by solar chimneys (southern ventilation stacks). Stage 2 control temperature via ventilated double facades and stage 3 provide more cooling capacity where are can be supplied via earth ducts only. Stage 4 would be very high temperature (>30ºC) using PDEC tower system to cool supply air to spaces, via natural ventilation system. Stage 5 is full HVAC operation deactivating all passive systems. The pre-programmed conditions identified, can also cause different passive systems to operate until the external air threshold exceeds passive system limits.

In normal operation, natural ventilation and passive systems will ventilate the spaces based on discussed parameters. Upon the requirement for change over i.e. stage 5 operations (HVAC), all dampers will actuate closed and mechanical system will take operation. Programming of BEMS is crucial to determine system state and when stages should be switched in before full mechanical operation is required. Variations of this system can include re-circulating air for full mechanical operation and night-time air/heat purging. BEMS has overall control in these types of buildings and monitors internal air conditions including dry bulb temperature (ºC), carbon dioxide levels (ppm) and air velocity (m/s). When the space is occupied, the control system will change over the HVAC operation when pre-programmed thermal comfort limits are exceeded.

7.10 Summary

This chapter provides passive ventilation and cooling design guidance and integration strategies building upon existing literature and analytical research completed in chapters 4, 5 and 6 as required by objective 4. Using this chapter along with Figure 6.1 (Chapter 6) or PSEAT, practicing architects and building services engineers have an effective design resource for accelerated selection and application enabling calculations to be completed without the need for complex analysis or prior knowledge of passive ventilation and cooling systems.

Chapter 8

Conclusion

The aim of this research is to investigate how existing passive ventilation and cooling systems design and operation strategies can be improved to reduce mechanical ventilation and cooling energy consumption for office buildings in hot climates. This chapter presents the conclusion to this research and details how effective passive ventilation and cooling systems are at reducing mechanical ventilation and cooling for office buildings in hot climates. The research aim and objectives are answered in this chapter detailing how each are satisfied. Discoveries from previous chapters are described detailing major findings of this research. The original contribution to new knowledge is also justified.

8.1 Review of Objectives

This section completes a review of the research objectives set out in section 1.3 (chapter 1). Each one identifies if goals are achieved identifying significant issues.

As required by objective 1, a comprehensive literature was completed (chapter 2) for existing passive ventilation and cooling techniques including case studies identifying how these are currently incorporated within buildings. The main conclusions from literature review shows that minimal research has been completed for calculating energy reductions for passive systems and highlights these have been reviewed temperature reduction with only a small number showing basic analysis regarding annual energy consumption (quantitative data). This identifies that further research scope for investigating potential energy reductions for each passive system. There is also limited design tools available which leaves scope for passive system tool development.

Objective 2 was completed by the development of theoretical building base case models. This is realised via buildings models A.1, B1 and B2 using all available industrial software and verified against energy benchmarks, as detailed in Chapter 3. These building models are fundamental foundation for this research work and enabled assessment of passive system energy reductions and their associated percentage reductions calculated in chapters 4 and 5.

Objective 3 identifies approximate passive ventilation and cooling energy reductions available per year, as detailed in chapters 4 and 5. This was achieved by generating percentage reductions based upon calculation methodology set out in chapter 3. The approach was developed using analytical steady state techniques enabling percentage reductions to be calculated and deducted from the monthly base case energy consumption (building models A.1, B.1 and B.2). Ranges of percentage reduction for each passive system were derived and attempted to be verified against published values, which has proved difficult.

Objective 4 is achieved by development of simplified passive system design guidance and integration strategies for individual and combined passive systems for office type buildings in hot climates (chapter 7). This details discussion regarding difficulties with passive design, performance design guidelines and strategies, operational ranges and limits, relationships and interactions, global locations and climates, physical application, geometric design strategy and BEMS integration and control strategy.

Objective 5 is realised by the development of Figure 6.1 and Passive System Energy Assessment Tool (PSEAT), as detailed in Chapter 6. PSEAT is a simplified design tool using Microsoft Excel software enabling wider audience within the consulting industry to make fast and simple calculations without the need to use complex software; a by-product of this research.

8.2 Test of Hypotheses

Following completion of this research, tests of the hypothesis are completed below:

Hypothesis 1: As shown in in the results in Chapters 4 and 5, using methods developed in research methodology (chapter 3), mechanical ventilation and cooling loads are reduced by approximating potential energy reductions for passive ventilation and cooling systems.

Hypothesis 2: Chapter 7 details simplified passive system design guidelines and integration strategies base upon research completed in previous chapters in line with objective 4. These can be used immediately within the construction industry.

8.3 Main Research Findings

The main findings from this research are as follows:

1) Calculated percentage reductions identifying energy savings when using passive systems with mechanical ventilation and cooling systems; these are detailed in Figure 6.1. These reductions are based analytical methods developed in this research (chapter 3) and can be applied to similar type buildings.
2) Average weather data within DTS software requires correcting in line with WMO data (section 6.3.4, chapter 6), assuming this data is more accurate.
3) Verification of calculated passive ventilation and cooling system reductions (percentages) is difficult and existing published data is extremely limited. Further issues are encountered when attempting to use benchmark values as $40W/m^2$ appears to limiting when further cooling potentials can be achieved in methods adopted by this researched.

4) Table 6.2 highlights which each passive system has greatest level of energy effectiveness per month.

5) As detailed in 6.3.2, variations identified are dependent on climate so cannot simply add a correction to apply to all locations.

6) Research methodology set out in Figure 3.1 is proven in chapters 4 and 5 can be applied to construction industry in order to calculate approximate ventilation and cooling energy reductions at desired RIBA design stage.

7) A new passive system energy assessment tool (PSEAT) is generated, as a by-product of this research. This is a simplified calculation tool on an accessible platform to assist architects and building services engineers in order determine annual energy reductions for office buildings.

8.4 Justification of Original Contribution to Knowledge

There are limited simplified design and calculation tools available for passive ventilation and cooling systems. In a practical sense, architects and building services engineers do not have design tools or skills available to enable an accelerated assessment for implementation of these passive systems. At later design stages, these passive systems are ruled out (omitted) from the design process, as benefits cannot be fully understood or assessed. These passive system are highly complex and relying on marginally predictable external environmental conditions. This makes designs complex, expensive and high risk, especially when attempting to guarantee building energy performance for hot climates. The construction industry is reliant on calculation tools to verify their design decisions and provide a backup on individual’s expertise, in terms of design justification and corporate liabilities. This is important in order to avoid miss-leading clients, avoid contractual disputes or compromise design intent. These passive system design guidance, integration strategies and performance assessment calculation tools provides industry with a simplified and applicable design tool to enable confident assessment of passive ventilation and cooling systems, based upon this research which is fully transparent.

8.5 Research Critique

This research work has been completed by adapting existing fundamental equations to identify temperature reductions and solar heat gain encountered by each passive ventilation and cooling system using maximum average temperatures and peak average temperatures, as appropriate. With the exception of natural ventilation and solar shading studies completed in this research, daily sinusoidal impact of external air temperature and solar radiation variations is not explored for the remaining passive system hence hour by hour operation of mechanical ventilation and cooling needs to be explored as part of a separate optimisation study. Average weather data values are effective for determining maximum cooling potential of each passive systems but these may under or over predict actual percentage reduction available for a given climate. Optimisation of these percentages for mechanical ventilation and cooling energy saving could be completed as future research in order to understand how long a temperature/solar radiation is maintained hence making these percentages more accurate and increase/decrease operational times for these passive systems. Furthermore, this research does not consider the impacts of latitude. If considering building locations South of Earths Equator, building orientation is an important factor for consideration, for example, external solar shades will require DTS to identify optimum locations for appropriate window elevations i.e. North, East and West.

8.6 Recommendations for Industry

This research can be used immediately within construction industry and following items can be applied for use by architects and building services engineers:

a. Simplified passive system design guidelines and integration strategies developed can be used to assess impacts of each passive system in terms of building design and location. Furthermore, this enables ease of passive system design application at RIBA Plan of Work stages 2, 3 and 4.

b. Energy performance assessments can be completed to understand the impacts on mechanical ventilation and cooling when applying a passive system strategy for mixed mode ventilation office building operation, in particular buildings located in hot climates. The PSEAT program allows a direct interface into industry as a *'ready to use'* tool.

8.7 Future Works

The following research objectives are suggested for future research works:

a) Optimisation of influencing factors for effectiveness as identified in Table 5.9.
b) Optimisation analysis for passive system operation times.
c) Create simple passive system algorithms (percentage reductions) for incorporation within existing industry DTS software.
d) Clearly this work applies to a bespoke building configuration and can benefit from assessing the impact of being applied to various other types of buildings.
e) Developing PSEAT in Microsoft Visual basic or C++/C# software to enhance user platform and improve presentation in line with common industry software.
f) Integrate calculation methodology within existing DTS software's.
g) Integrate design guidance and application strategies within ASHRAE/CIBSE guides.
h) Enhance BREEAM assessment guidelines for credits using passive system strategies.
i) Incorporate with BEMS logic control strategy based upon Figure 7.12 (Chapter 7).

References

Actual (2015) 'Advanced Climate Technology: Urban Atmospheric Laboratory- Snoozing in the Heat'. Available From: http://www.actual.ac.uk/2014/07/24/snoozing-in-the-heat/ [accessed: 8 March 2015]

Archiexpo (2012) 'Rain Screen Facades'. Available from: http://pdf.archiexpo.com/pdf/lusorochas/rainscreen-ventilated-facade/51519-71536-_2.html [Accessed: 6 July 2012]

Architecture Today (2013) *'Book: Cultural alignment.'* Available From: http://www.architecturetoday.co.uk/?p=20055 [accessed: 23 September 2013]

Ahuja, R & Rao, V.M (2005) *'Natural Cooling of Residential Buildings in Hot-Dry Climates'*. Vol.6, NOS, 1-2 (2005). I.I.T, Roorkee, India.

Archinect Firms (2014) *'Office in Rozenburg by Sputnik'*. Rotterdam, Netherlands. Available from: http://archinect.com/sputnik/release/office-building-in-rozenburg-by-sputnik [accessed: 20 November 2014]

Axley, J.W (2001) 'Application of Natural Ventilation for U.S. Commercial Buildings: Climate Strategies & Methods Modeling Studies.' Available From: http://www.seedengr.com/Climate%20Suitability%20Metric.pdf [accessed 12 December 2016]

Ansys (2016) *'Ansys.'* Available From: http://www.ansys.com/?gclid=CNTxj7y9-9ACFQaVGwodGI0Jtw [accessed 17 December 2016]

Barnard, N. Concannon, P. Jaunzens, D. (2001) *'Modelling the Performance of Thermal Mass'*. Information Paper IP6/01. London, UK. BRE Publishing.

Bahadori, M (1984) 'An improved design of wind towers for natural ventilation and passive cooling.' College of Architecture and Environmental Design, Arizona State University, Tempe. Pergamon Press Ltd. Arizona, USA

Ben-Gurion University of Negev (2012) *'Energy and climate in desert architecture'*. Israel. Available From: http://www.bgu.ac.il/CDAUP/energy.html [accessed: 6 July 2012]

BB101 (2006) *'Building Bulletin 101, Ventilation of School Buildings'*. Version 1.4, ISBN 011-2711642, England, UK.

British Standard (2005) *Ergonomics of the Thermal Environment- Analytical Determination and Interpretation of Thermal Comfort Using Calculation of PMV and PPD Indices and Local Thermal Comfort Criteria*. BS EN ISO 7730:2005. London, UK.

British Standard (2007) *Ventilation for Non-Residential Buildings. Performance Requirements for Ventilation and Room Requirements.* BS EN 13779: 2007. London, UK.

British Standard (1991) *'Ventilation principle and designing for natural Ventilation.;* BS 5925:1991 Incorporation Amendment No. 1. London, UK

BREEAM (2011) *'BREEAM New Construction Non Domestic Buildings Technical Manual'*. SD5073-2.0. BRE Global Ltd. Watford England. Available From: www.breeam.org/breeamGeneralPrint/breeam_non_dom_manual_3_0.pdf [accessed 27 April 2015]

BSRIA (2003) *Rules of Thumb Guidlines for Building Services*. 4th Edition. London, UK.

BSRIA (2011) *Rules of Thumb Guidlines for Building Services*. 5th Edition. London, UK.

BSRIA (2009) *Blue book*, London, UK

BSRIA (2016) *'Soft Landing.'* Available From: https://www.bsria.co.uk/services/design/soft-landings/ [accessed 17 December 2016]

Bowman, N.T, Lomas, K.J, Cook, M.J, Eppel, H, Robinson, D, Ford, B, Diaz, C, Wilton, M, Badano, E, Bombardi, F, Fransis, E, Galata, A, Lanarde, P, Belarbi, R, Rodriguez & Alvarez, S (1998) *'The Application of Passive Downdraught Evaporative Cooling (PDEC) to non-domestic buildings' .De Montfort University, United Kingdom.*

Building (2013) *'Earth ducts supply fresh air to Luton office village'.* Available From: http://www.building.co.uk/earth-ducts-supply-fresh-air-to-luton-office-village/3119333.article [accessed 15 September 2013]

Building (2016) *'Passivoffice: First UK office to reach Passivhaus standards.'* Available From: http://www.building.co.uk/passivoffice-first-uk-office-to-reach-passivhaus-standards/5007596.article [accessed 17 December 2016]

BSRIA (2013) *'Model demonstration project - Butterfield Business Park.'* Available From: https://www.bsria.co.uk/news/article/butterfield/ [accessed 15 September 2013]

Building (2014) 'On air: BSkyB's naturally ventilated studios: Change of Air. Available From:

http://www.building.co.uk/Journals/Graphic/m/o/p/proj1.jpg [accessed 24 October 2014]

Brittle, J. P, Eftekhari, M.M & Firth, S.F (2013) *'Mechanical cooling energy reduction for commercial buildings in hot climates: Effective use of external solar shading incorporating effects on daylight contribution.'* 13th Conference of International Building Performance Simulation Association, France.

Brittle, J. P, Eftekhari, M.M & Firth, S.F (2014a) *'Mechanical cooling energy reduction for commercial buildings in hot climates: effectiveness of combined passive systems.'* Building Simulation and Optimization BSO14, University College London, London

Brittle, J. P, Eftekhari, M.M & Firth, S.F (2014b) *'Combined passive system selection strategy for low carbon commercial buildings.'* Zero Carbon Buildings Today and in the Future, Birmingham City University, Birmingham, England, UK.

Brittle, J. P, Eftekhari, M.M & Firth, S.F (2016a) *'Mechanical ventilation & cooling energy versus thermal comfort: a study of mixed mode office building performance in Abu Dhabi.'* 9th Windsor Conference: Making Comfort Relevant, Cumberland Lodge, Windsor, England, UK

Brittle, J. P, Eftekhari, M.M & Firth, S.F (2016b) *'Mixed mode ventilation & cooling in commercial buildings: concepts for passive system integration.'* Zero Carbon Buildings Today and in the Future, Birmingham City University, England, UK

Brittle, J. P, Eftekhari, M.M & Firth, S.F (2016c) *'PDEC tower cooling energy performance assessment using specific enthalpy calculation methodology.'* IBPSA Building Simulation & Optimisation, Newcastle University; Newcastle, England, UK

The Building Enclosure (2016) *'Climate Data for Building Simulations.'* Available From: https://builtenv.wordpress.com/2014/02/27/climate-data-for-building-simulations/ [accessed 18 December 2017]

Chatzipoulka, C (2011) *'The Potential use of solar chimneys in urban multi-story buildings in Greece'*. Cardiff University. Conference Paper, Arup, London. Conference Paper, Arup, London.

Cengel, Y.A. Turner, R.H & Cimbala, J.M (2008) *'Fundamentals of Thermo-fluid Sciences'*. Third Edition. McGraw Hill Publishing. New York, USA.

Chadderton, D.V (2004) '*Building Services Engineering.* Fourth Edn.' Spon Press Taylor & Francis Group

Carboun (2013) *'A Damascus School Revives Traditional Cooling Techniques'*. Available From: http://www.carboun.com/tag/solar-chimney/ [accessed 15 September 2013]

Coolvent (2016) *'Coolvent The Natural Ventilation Simulation Tool by MIT.' Available FromL* http://coolvent.mit.edu/ [accessed 17 December 2016]

CIBSE (2016) *Guide A: Environmental Design.* London, England

CIBSE (2005a) *Guide B: Heating, Ventilation, Air Conditioning & Refrigeration.* London, England

CIBSE (2005b) *Technical Memorandum 36: Climate Changes and the Indoor Environment. Impacts and Adaptation.* London, UK

CIBSE (2005c) *Applications Manual 10: Natural Ventilation in Non-Domestic Buildings*. London, UK

CIBSE (2005d) '*Lighting Guide 7: Office Lighting*'. London, England.

CIBSE (1998) *Applications Manual 11: Building energy and environmental modelling.* London, UK.

CIBSE (2006b) *Technical Memorandum 37: Design for Improved Solar Shading Control.* London, UK

CIBSE (2002) *Technical Memorandum 29: HVAC Strategies for Well Insulated Airtight Buildings*. London, UK.

CIBSE (2008) '*Technical Memorandum 46: Energy Benchmarks.* London, UK

CIBSE (2009) *Guide H: Building Controls.* London, England

CIBSE (2012a) *'Guide F: Energy efficiency in buildings.'* London, UK.

CIBSE (2012b) *'SLL Code for Lighting'*. London, UK

CIBSE (2000) *'Applications Manual 13: Mixed Mode Ventilation'*. London, UK

CIBSE (1999a) *'Lighting Guide 10: Daylighting and Window Design'*. London, England.

CIBSE (2013a) '*Technical Memorandum 52: The Limits of Thermal Comfort: Avoiding Overheating in European Buildings'* London, UK

CIBSE (2013b) *'Technical Memorandum 54: Evaluating operational energy performance of buildings at the design stage.'* London, UK

Clker (2015) *'World Map 2 clip art.'* Available From: http://www.clker.com/clipart-9213.html [accessed: 7 July 2015]

Climate Data (2016) *'Climate-Nairobi.'* Available From: http://en.climate-data.org/location/541/ [Accessed: 12 December 2016]

Climate and Weather (2016) 'Climate and Weather.' Available From: http://roble.pntic.mec.es/rmac0040/climateandweather.html#Climate [Accessed 17 December 2017]

ClimaTemps (2016) *'Climate and Temperatures.'* Available From: http://www.climatemps.com/ [Accessed 18 December 2017]

CHAM (2016) *'PHEONICS Software- CFD'* Available From: http://www.cham.co.uk/phoenics.php [accessed 17 December 2016]

De Dear, R. J. Brager, G.S. (1998) *'Developing an Adaptive Model of Thermal Comfort and Preference'*. Volume 104 Part 1, Ashrae, USA. Available From: http://escholarship.org/uc/item/4qq2p9c6 [Accessed: 13 October 2011]

NewLearn (2016) 'CLEAR-Comfortable Low Energy Architecture.' Available From: http://www.newlearn.info/packages/clear/thermal/buildings/building_fabric/properties/time_lag.html [Accessed: 17 December 2017]

Department of Trade and Industry (2004) *'Our Energy future- Creating Low Carbon Economy'*. Technical Report TSO, England, UK.

Designbuild-network (2013) *'Loyola University Information Commons and Digital Library, Chicago, Illinois, United States of America.'* Available From: http://www.designbuild-network.com/projects/loyola/loyola2.html [accessed 16 September 2013]

Douglas, J.F & Matthews, R.D (1996) *'Solving Problems in Fluid Mechanics'*. Pearson Publishing. Volume 1, 3rd Edition.

Designbuilder (2014) *'Designbuilder.' Available From http://www.designbuilder.co.uk/* [accessed 2 January 2014]

Diakin (2016) *'Diakin.'* Available From: http://www.daikin.co.uk/ [Accessed: 17 December 2017]

Evans, B (1993) *'Ventilations Using Earth Tubes'*. The Architects Journal C1/SfB (R) 52, England, UK.

ENoB (2011) *'Energon passive office building'* Germany. Available From: http://www.enob.info/en/new-buildings/project/details/energon-passive-office-building [Accessed: 26 April 2013]

Engineering Toolbox (2013) *'Humidity Ratio of Air'*. Available From: http://www.engineeringtoolbox.com/humidity-ratio-air-d_686.html [Accessed 24 September 2013]

Engineering Toolbox (2014) *'Thermal Conductivity of Materials'*. Available From: http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html [Accessed 15 December 2014]

Engineering Toolbox (2016a) 'Cooling and Dehumidifying Air.' Available From: http://www.engineeringtoolbox.com/cooling-dehumidifying-air-d_695.html [Accessed: 17 December 2017]

Engineering Toolbox (2016b) *'Emissivity Co-Efficients.'* Available From: http://www.engineeringtoolbox.com/emissivity-coefficients-d_447.html [accessed 18 December 2016]

Engineering Toolbox (2016c) *'Solar Radiation Absorbed by Materials'* Available From: http://www.engineeringtoolbox.com/solar-radiation-absorbed-materials-d_1568.html [accessed 18 December 2016]

Engineering Toolbox (2016d) *'Light Material Reflection Factors.'* Available From: http://www.engineeringtoolbox.com/light-material-reflecting-factor-d_1842.html [accessed 18 December 2016]

Engineering Toolbox (2016e) *'Specific Heat of Metals.'* Available From: http://www.engineeringtoolbox.com/specific-heat-metals-d_152.html [accessed 18 December 2016]

e-architect (2014) *'1 North Bank – Sheffield Architecture, Yorkshire, England.'* Available From: http://www.e-architect.co.uk/leeds/sheffield-office-building [accessed: 26 March 2014]

European Environment Agency (2016) 'Global and European Temperatures.' Available From: http://www.eea.europa.eu/data-and-maps/indicators/global-and-european-temperature-1/assessment [Accessed: 17 December 2017]

Eurima (2016) 'U-Values in Europe'. Available From: http://www.eurima.org/resource-centre/facts-figures/u-values-in-europe.html [accessed 17 December 2016]

EDSL (2016) *'EDSL TAS.'* Available From: http://www.edsl.net/main/ [accessed 17 December 2016]

Energy Plus (2016) *'Energy Plus.'* Available From: https://energyplus.net/ [accessed 17 December 2016]

Flahiff, D (2009) *'The Mode-Gakuen Spiral Towers: a New Twist on School Design'*. Available from: http://inhabitat.com/mode-gakuen-spiral-towers-by-nikken-sekkei/ [Accessed: 13 September 2013]

Francis, M (2011) *'Investigating Passive Cooling Techniques in the Summer Season in Abu Dhabi'*. University of Cardiff. Conference Paper, Arup, London.

Ford, B (2002) *'Passive Downdraught Evaporative Cooling (PDEC) applied to the Central Atrium Space within the New Stock Exchange in Malta'*. WSP Environmental. United Kindom.

Fellows, R. & Liu, A. (2003) *Research Methods for Construction.* 2nd Edn. Blackwell Publishing

Fairey, P. (1994) *'Radiant Energy Transfer and Radiant System in Buildings'*. Florida Solar Energy Centre Publication DN-6, Florida, USA. Available From: http://harmonyfl.com/lih/documents/eh245.pdf [Accessed: 03 January 2012]

Firth, S. (2009) *'Advanced Thermal Modelling: Introduction to Building Simulation.* ' [Power point Slides] Lecture Handouts. Loughborough University. 20 March.

Flaktwood (2016) *'Flaktwood.'* Available From: http://www.flaktwoods.co.uk/ [Accessed: 17 December 2017]

Ghoneim, A.A, Klein, S. & Duffie, J.A (1991) *'Analysis of Collector-Storage Building Walls Using Phase-Changing Materials'*. Solar Energy Vol. 47, No. 3, Pergamon Press, USA.

Groenhout, N. & Partridge, L. (2010) *'Optimisation of Passive Ventilation Design for Public Assembly Building in a Tropical Climate'*. Ecolibrium, Forum Paper.

Greeno, R. (1997) *'Building Services, Technology and Design'*. Harlow, England. Pearson Longman

Gov.uk (2016) *'Energy performance certificates.'* Available From: https://www.gov.uk/buy-sell-your-home/energy-performance-certificates [accessed 17 Decmber 2016]

Homes in the Earth (2013) *'Earth Tube Design'*. Available From: http://www.homeintheearth.com/tech_notes/earth-tubes/earth-tube-design-for-earth-sheltered-homes/ [accessed 15 September 2013]

Hyvfirinen, J & Karki, S (1996) *'Building Optimisation and Fault Diagnosis Book'*. IEA Annex

HM Government (2010a) *Amendments to Approved Document and Compliance Guide. Non-Domestic Building Services Compliance Guide.* The Building Regulations. England, UK.

HM Government (2010b) *Approved Document F: Means of Ventilation.* The Building Regulations. England, UK.

HM Government (2016) 'The Building Regulation 2010 Conservation of Fuel and power Approved document L2A. L2A Conservation of fuel and power in new buildings other than dwellings.' 2013 Edition Incorporating 2016 amendments. England, UK. Available From: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/540328/BR_PDF_AD_L2A_2013_with_2016_amendments.pdf [Accessed: 17 December 2017]

Holman, J.P. (2002). Heat Transfer (9th ed.). McGraw-Hill.

IPCC (2007) *'Climate Change 2007- Impacts, Adaptations and Vulnerability: Contribution of Working Groups II to the Fourth Assessment Report of the IPCC'*. Cambridge University Press, Cambridge, England.

IPCC (2007) 'Climate change 2007- The Physical Science Basis: Contribution of Working Group I the Fourth Assessment Report of the IPCC. Cambridge Press, Cambridge, United Kingdom.

International Standard (2007) *Building Materials and Products- Hygrothermal Properties- Tabulated Design Values and Procedures for Determining Declared and Design Thermal Values.* ISO 10456:2007.

International Standard (2007) *Building Components and Building Elements- Thermal Resistance and Thermal Transmittance Calculation Method.* ISO 6946:2007.

Iqbal, I & Al.Homoud, M (2007) *'Parametric Analysis of alternative energy conservation measures in an office building in hot and humid climates'*. Elsevier. King Fahd University, Dhahran, Saudi Arabia.

IES VE (2016) *'Integrated Environmental Solutions.'* Available From: https://www.iesve.com/ [accessed 17 December 2016]

IES VE (2010) *ApacheSim Calculation Methods 5.9.* Integrated Environmental Solutions Ltd, Ireland.

IPMA (2016) 'Normais Climatológicas - 1981-2010 (provisórias) - Lisboa, Geofísico.' Available From: http://www.ipma.pt/pt/oclima/normais.clima/1981-2010/012/ [accessed: 12 December 2016]

Just Facades (2013) *'Airtec glass rain screen'.* Available From: http://www.justfacades.com/airtec_glass_rainscreen.php [Accessed 23 September 2013]

Krausse, B. Cook, M. Lomas, K. (2007) *'Environmental Performance of a Naturally Ventilated City Centre Library'*. Energy & Building 39 (2007) 792-801, De Montfort University, Leicester, UK: Elsevier.

karmatrendz (2014) 'Verkerk Group Office Building'. Available from : http://karmatrendz.wordpress.com/2011/01/08/verkerk-group-office-building-by-egm-architects/ [Accessed 20 November 2014]

Lomas. K.J. Fiala, D. Cook M.J. Cropper, P.C (2004) *'Building bioclimatic charts for non-domestic buildings and passive downdraught evaporative cooling.'* Building and Environment 39 (2004) 661 – 676. Elsevier Ltd. London, UK.

Loncour, X. Deneyer, A. Blasco, M. Flamant, G. Wouters, P. (2004) *'Ventilated Double Facades Classification & illustration of façade concepts'*. Belgian Building Research Institute, Belgium.

Lieb, R-D (2001) *'Double Skin Facades'*. Pretel Verlag, Stutgard, Germany.

Levins, W.P. Karnitz, M.A. Knight, D.K. (1986) *'Cooling Energy Measurements of Houses with Attics Containing Radiant Barriers'*. Oak Ridge National Laboratorys, Tennessee, USA. Available From: http://repository.tamu.edu/handle/1969.1/6871 [Accessed: 03 January 2012]

Levolux (2012) Available From: http://www.levolux.com/L_case_studies/TTPCom.htm [Accessed: 6 July 2012]

Levolux (2013a) 'Levolux gets a First in One of a Kind Design'. Available From: http://www.levolux.com/L_case_studies/lancaster_university.htm [accessed 15 September 2013]

Levolux (2013b) 'Case Studies TTPCom.' Available From: http://www.levolux.com/L_case_studies/TTPCom.htm [accessed 16 September 2013]

Loyola University Chicago (2013) *'Richard J Klarchek information commons'*. Available From: http://www.luc.edu/ic/index.shtml [accessed 16 September 2013]

USGBC (2016) 'Leadership in Energy and Environmental Design.' Available From: http://www.usgbc.org/leed?gclid=CPOvmf-g-9ACFQ2ZGwodzqICbg [accessed 17 December 2016]

Michler, A (2010) '*World's Most Sustainable Broadcasting Studio Unveiled in the UK*'. Available from: http://inhabitat.com/arup-unveils-the-worlds-most-sustainable-broadcasting-studio/ [Accessed: 13 September 2013]

Monodraught (2011) 'Cool Phase'. UK. Available From: http://www.cool-phase.com/overheating.htm [Accessed: 2 December 2011]

Martin, A.J (1996) Control of Natural Ventilation, Technical Note TN11/95

Marinoscia, C. Strachanb, P.A. Semprinia, G. Morinia G.L. (2011) *'Empirical validation and modelling of a naturally ventilated rainscreen façade building'*.Università degli Studi di Bologna, Italy & University of Strathclyde, Glasgow, Scotland, UK

Marinoscia, C (2011) 'Dynamic Thermal Performance of Building Components and Application to the Experimental and Theoretical Analysis of a Ventilated Facade.' Universita di Bologna. Available From: amsdottorato.unibo.it/3556/1/PhD_thesis_C_Marinosci.pdf [accessed: 26 January 2014]

My Modern Met (2014) 'Modern Architecture - Mode-Gakuen Spiral Towers: Nagoya, Japan.' Available From: http://www.mymodernmet.com/profiles/blogs/modern-architecture [accessed: 24 October 2014]

Mitsubishi Electric (2016) *'Mitsubishi Electric Air Conditioning.'* Available From: http://airconditioning.mitsubishielectric.co.uk/Pages/default.aspx [Accessed: 17 December 2017]

Muehleisen, R.T (2014) *'Simple Design Tools for Earth-Air Heat Exchangers.'* Argonne National Lab, Argonner, Illiois, USE. Available From: https://www.researchgate.net/publication/269096337_Simple_Design_Tools_for_Earth-Air_Heat_Exchangers [accessed 17 December 2016]

New4old (2013) *'Trombe Wall'* Available from: http://www.new4old.eu/guidelines/D6_Part2_H5.html [Accessed: 21 June 2013]

Netzsch (2017) *'Definition of Thermal Diffusivity.'* Available From: https://www.netzsch-thermal-analysis.com/en/landing-pages/definition-thermal-diffusivity/ [Accessed 18 January 2017]

Oughton. D.R, Hodkinson, S.L. (2008) *Faber & Kells Heating and Air Conditioning in Buildings*, Tenth Edn. Elsevier Publishing.

Oyeleke, J (2011) *'Controlled tests and monitoring of a Semi-Active PCM Cooling System'*. Brunnel University. Conference Paper, Arup, London.

Phillip, O. J (2011) *'Passive Downdraught Evaporative Cooling: An investigation of its applicability for residential space cooling in Riyadh, Saudi Arabia'*. University of Nottingham, UK. Conference Paper, Arup, London. Conference Paper, Arup, London.

Passivhaus (2012) *'bre passivhaus standard'*. Watford, England. Available From: http://www.passivhaus.org.uk/standard.jsp?id=19 [accessed 27 April 2012]

Pilkington (2015) *'Double Glazing Units - g-value* guide.' Available From: https://www.pilkington.com/en-gb/uk/architects/types-of-glass/solar-control-glass/double-glazing-units-g-value-guide [accessed 8 February 2015]

Rockpanel (2013) *'Facades & Cladding'*. Available From: http://www.rockpanel.co.uk/applications/facade+cladding [Accessed 23 September 2013]

RIBA (2014) *'Royal Institute of British Architects.'* Available From: http://www.architecture.com/TheRIBA/AboutUs/Professionalsupport/RIBAOutlinePlanofWork2013.aspx [Accessed 13 April 2014]

Refractive Index (2017) '*Refractive Index Data Base.*' Available From: http://refractiveindex.info [Accessed 18 January 2017]

Short, C. Cook, M. Lomas, K. (2009) '*Delivery and Performance of a Low-Energy Ventilation and Cooling Strategy*'. University of Cambridge & Loughborough University, UK. Building Research and Information 37(1), 1-30. Rouledge, Taylor & Francis Group

Sanusi, N.Z. Shao, L & Ibrahim, N (2012) '*Passive ground cooling system for low energy buildings Malaysia (hot and humid climates)*'. Renewable Energy Journal. Xxx (2012)1-4. Elsevier. United Kingdom.

Solar Shading louvres (2012) '*Solar Shading Overview.*' Available From: http://www.solarshadinglouvre.co.uk/solar-shading-overview.htm [Accessed: 6 July 2012]

Sustainable Building Construction (2013) '*KEC Earth Duct*'. Available From: http://sustainablebuildingconstruction.blogspot.co.uk/2011/10/kec-earth-duct.html [accessed 15 September 2013]

Sustainable Buildings (2013) '*Torrent Research Centre*.' Available From: http://www.sustainable-buildings.org/index.php?option=com_cstudy&task=details&sid=32 [accessed: 23 September 2013]

Solinear (2013a) '*Bespoke™ Case Study, Morrisons, Sittingbourne.*' Available From: http://www.solinear.co.uk/case-studies-bespoke/article/21/1/ [accessed 16 September 2013]

Solinear (2013b) '*Solex™ Case Study Runnymede Civic Offices.*' Available From: http://www.solinear.co.uk/case-studies-solex/article/13/1/ [accessed 16 September 2013]

Svensson, C. (2011) '*Passive Stack Office, Varberg*'. England, UK. Available From: projects.bre.co.uk/natvent/reports/monitoring/summary/se2summ.pdf [Accessed: 26 April 2013]

Summerfield (2014) '*Offices- Bristol- Vantage Point.*' England, UK. Available From: http://www.summerfield.co.uk/p/4-27/offices/bristol-vantage-park.php [Accessed: 20 November 2014]

Sadineni, S.B, Madala, S & Boehm R.F (2011) '*Passive building energy savings: A review of building envelope components.*' Renewable and Sustainable Energy Reviews, Elsevier. Available From: http://www.sciencedirect.com/science/article/pii/S1364032111002504 [Accessed: 17 December 2017]

Shaviv, E, Yezioro, A & Capeluto, I.G (2001)' *Thermal mass and night ventilation as passive cooling design strategy.*' Renewable Energy, Elsevier. Available From: http://www.sciencedirect.com/science/article/pii/S0960148101000271 [Accessed: 17 December 2017]

Sustainable by Design (2016) '*Sustainable by Design.*' Available From: http://www.susdesign.com/overhang/index.php [accessed 17 December 2016]

Technical University Berlin and Pontificia Universidad Católica de Chile (2012) '*Nocturnal natural ventilation for low and zero energy office buildings in Central Chile*'. Available From: http://www.energyandbuilding.uc.cl/papers.html [Accessed: 6 July 2012]

Tantasavasdi, C. Jareemit, J. Suwanchaiskul, A & Naklada, T (2007) '*Evaluation and design of Natural Ventilation for Houses in Thailand*'. Volume 5 Issue 1, Thammasat University, Thailand.

Torcellini, P & Pless, S (2004) '*Trombe Walls in Low Energy Buildings*'. Conferences Paper. NREL/CP-550-362-77. NREL, Colorado, USA.

Use Hughes (2013) '*Rain-Screen Façade System*'. Available From: http://usehughes.com/rain-screen_facade_systems [Accessed 23 September 2013]

University of California Berkeley (2013) '*Mixed Mode Case Studies and Project Database.*' Available From: http://www.cbe.berkeley.edu/mixedmode/aboutmm.html [Accessed 30 September 2013]

United Nations (2014) Kyoto Protacol: Status of the Doha Amendment. Available From: http://unfccc.int/kyoto_protocol/doha_amendment/items/7362.php [Accessed: 19 November 2014]

United Nations (2016) *'The Paris Agreement.'* Available From: http://unfccc.int/paris_agreement/items/9485.php [accessed 18 December 2016]

Thornton, B.A, Wang, W, Cho. H, Liu. B, Rosenberg. MI, Xie. Y, Mendon. VV, Richman. EE, Zhang. J, Athalye. RA (2011) *'Achieving the 30% Goal: Energy and Cost Saving Analysis of ASHRAE Standard 90.1-2010.'* PNNL-20405. Department of Energy, USA.

The Shard (2015) 'The Shard.' Available From: http://www.the-shard.com/ [Accessed: 2 July 2015]

Vangtook, P & Chirarattananon, S (2007) *'Application of radiant cooling as a passive cooling option in hot humid climates'*. Elsevier. Asian Institute of Technology, Pathumthani, Thailand.

Windows & Daylighting (2013) *'Shading Strategy Section 5.'* Available From: http://windows.lbl.gov/daylighting/designguide/section5.pdf [accessed: 14 January 2013]

Watermark Architecture (2012) *'Black Mores Campus'*. Sydney, Australia. Available from: http://www.watermarkarchitecture.com.au/practice/sustainability/blackmores-campus-sustainability/ [Accessed: 6 July 2012]

Walliman, N & Resalati, S (2011) *'Developing a new model as a fixed shading device and comparing the energy results with external shading devices'*. Oxford Brooks University. Conference Paper, Arup, London. Conference Paper, Arup, London.

World Meteorological Organisation (2014a) *Nairobi, Kenya, Africa Weather Statistics.* Available From:http://worldweather.wmo.int/071/c00251.htm [accessed: 3 November 2013]

World Meteorological Organisation (2014b) *Lisbon, Portugal Weather Statistics.* Available From: http://worldweather.wmo.int/003/c00002.htm [accessed: 3 November 2013]

Warwick, D (2010) '*Integrating Active Thermal Mass Strategies in Responsive Buildings.*' Available From: http://bura.brunel.ac.uk/bitstream/2438/7384/1/FulltextThesis.pdf [accessed: 12 December 2016]

WBDG (2016) 'Whole Building Design Guide.' Available From: https://www.wbdg.org/resources/natural-ventilation [accessed 17 December 2016]

Exeter (2016) *'Weather files for Current and Future Climates.'* Available From: http://www.exeter.ac.uk/media/universityofexeter/research/newsandevents/newsandeventsarchive/Weather_Files.pdf [accessed 18 December 2016]

Yilmaz, Z (2006) *'Evaluation of energy efficient design strategies for different climatic zones: Comparison of thermal performance of temperate-humid and hot-dry climate'*. Energy and Buildings 39, 306-316. Elsevier Publishing. Taksim, Turkey.

Zeospot (2014) *'Modern Small Office Buildings Verkerk Group in Netherland.'* Available From:http://zeospot.com/modern-small-office-buildings-verkerk-group-in-netherland/modern-small-office-buildings-night-photo/ [accessed: 26 March 2014]

Zhou, J. Zhang, G. Lin, Y. & Li, Y (2007) '*Coupling of thermal mass and natural ventilation in buildings.'* Energy and Buildings, Elsevier. Available From: http://www.sciencedirect.com/science/article/pii/S0378778807002083 [Accessed: 17 December 2017]

Zebra 2020 (2016) *'Zebra Monitoring Euro Data.'* Available From: http://www.zebra-monitoring.enerdata.eu/overall-building-activities/windows-u-values-building-codes.html#windows-u-values-building-codes.html [Accessed: 17 December 2017]

Appendix A- Case Studies of Existing Buildings Incorporating Passive Ventilation and Cooling Systems (Reference)

A.1 General

This appendix has been created to identify existing buildings that adopt passive ventilation and cooling strategies. These buildings have been selected in terms of providing an example how passive systems are used globally however not specific for hot climates, as detailed in chapter 1.

A.2 Natural Ventilation Case Study 1- Mode Gakuen Spiral Towers

The Mode Gakuen Spiral Towers in Nagoya, Japan (Figure A.1) are towers spread over 36 storeys (170 metres). This was designed by architectural group Nikken Sekkei and incorporates a double-glazed airflow window system and a natural air ventilation system (Flahiff, 2009). Flahiff (2009) states that the double-glazed airflow system *'…significantly reduces heating and cooling loads by passing indoor/outdoor air (exhaust air/return air) between two panes of glass. The cavity between the panes typically includes blinds which can be shut according to heating/cooling requirements.'*

Figure A.1- Mode Gakuen Spiral Towers in Nagoya, Japan (My Modern Met, 2014) and Internal View of Upper Level (My Modern Met, 2014)

A.3 Natural Ventilation Case Study 2- Harlequin 1

BskyB's new headquarters in London is the Harlequin 1 building (Figure A.2), which has an advanced building envelope with the aim of being the world's first production studio to be cooled by natural ventilation (Michler, 2010). The building is shown in figure 4.5 with large vents running up the 100 x 50 metre complex. Natural daylight is incorporated in the offices with actuated perimeter windows and its capacity is 1,300 people. The building core consists of studios at the ground floor, computer server rooms in the middle of the building and transmission platforms at the roof level (Michler, 2010).

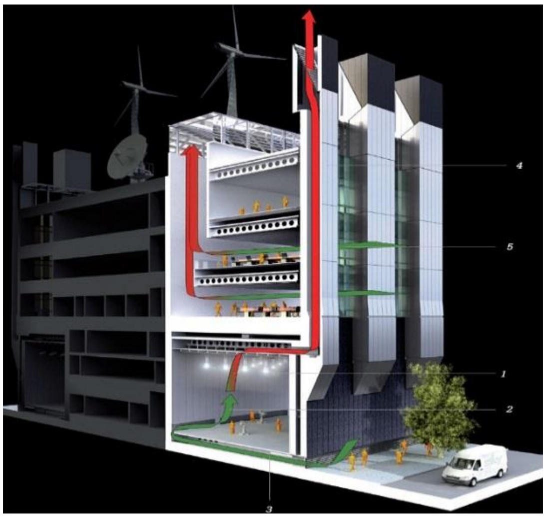



Figure A.2- Harlequin 1 building, London, UK (Michler, A, 2010) and Natural Ventilation Method for Studios (Building, 2014)

A.4 Natural Ventilation Case Study 3- Vaarberg Building, Sweden

As detailed by Svensson (2010), *'This building was originally built, at the turn of the century, as a school with two stories and a basement. The front facade of the building faces east. The floor area is approximately 2000m^2 and room heights are between 3.8m and 5.8m. All the walls of the building are of masonry construction. … The ventilation system is a traditional user controlled, passive stack system, with no fan. This kind of system used to be very common in Scandinavia.'* Svensson (2010) continued to state that rooms are connected directly or indirectly to a passive stack and the majority of windows are equipped with an automatic supply vent which is temperature-controlled. There is no necessity for increased night ventilation for night cooling. The building layout and ventilation concept is detailed below in Figure A.3.

Figure A.3 (Svensson, 2010)- The Vaarberg Building; Plan View; Ventilation Concept (Section)

Analyses taken from this building are summarised below:

- <u>Summertime Monitoring</u>- Ventilation: Average ventilation rates, measured between 27th August and 16th September 1997, were 4.7l/s.person; Thermal Comfort: During August 1997, the average air temperature in the monitoring rooms was above 26^{o}C for 80 per cent of the time; Indoor Air Quality: During the summer monitoring period the CO_2 concentration varied between the background level of approximately 350ppm and a maximum of 800ppm (Svensson, 2010).
- <u>Wintertime Monitoring</u>- Ventilation: Average ventilation rates, measured between 4th December and 12th December 1997, were 6.5l/s.person; Thermal Comfort: During December 1997, the average air temperature in the monitoring rooms was slightly below 20^{o}C; Indoor Air Quality: During the summer monitoring period the CO_2 concentration varied between 800ppm and a maximum of 1100ppm depending on the room (Svensson, 2010).
- The energy usage was 75kWh/(m^2/year) and electricity 50kWh/(m^2/Annum).

A.5 Natural Ventilation Case Study 4- Energon Passive Office Building, Germany

The Energon building has five storeys with a main usable floor area of 5,412m^2 and gross volume of 32,223m^3. For building ventilation, conditioned supply air is channelled into the central atrium where it flows through noise-insulated overflow openings in the atrium facades and through air ducts in the concrete ceilings to the exterior offices. The atrium can also be ventilated naturally via smoke and heat vents and all offices/lounges have openable windows. For exhaust air, this occurs via suction in the offices and is ventilated through the roof air exhaust (ENoB, 2011). The building is a reinforced concrete skeleton with facades made of prefabricated wooden elements of largely equal dimensions. The foundation slab insulation material is 0.2m; 0.35m for the external facade; 0.5m insulation in the roof; and triple-glazed thermally insulated frames. '*As glass accounts for 44 per cent of the building envelope, solar loads are kept low, and nevertheless, good use of daylight is guaranteed* (ENoB, 2011)*.'* An overview of the building is shown below in Figure A.4.

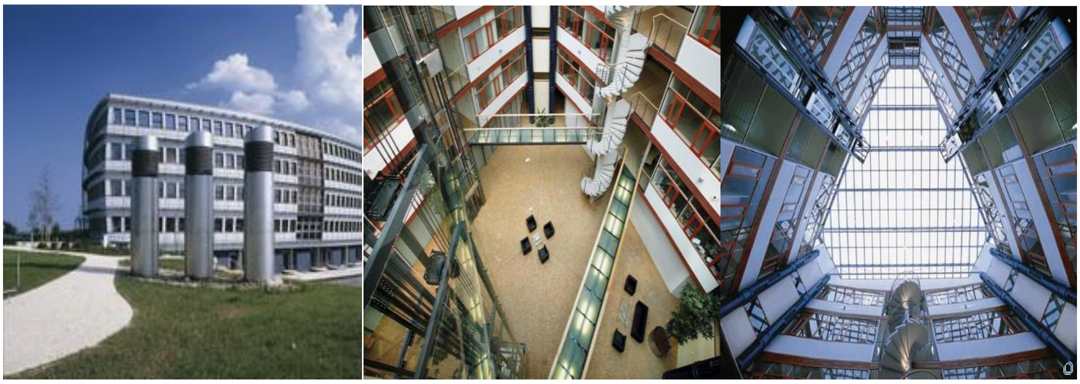


Figure A.4- (ENoB, 2011) - Site Elevation View Figure; Energon Building Internal; Internal Atrium

For building performance, ENoB (2011) states: *'In 2005, the final energy consumption for heating, ventilation, cooling and lighting, including building cooling and the cafeteria (without refrigeration devices) was very low at 47.2 kWh/m² p.a., and is well beneath the support initiative's required level. However, the heating consumption of 34.6 kWh/m² p.a. is still above the calculated requirement of 12 kWh/m² p.a. In 2005, the primary energy consumption was 81 kWh/m² p.a.; if the energy fed from the building's own PV system is taken into account, this is reduced by another 5 kWh/m² p.a.'*

A.6 Natural Ventilation Case Study 5- Commercial Office, Blackmore Campus, Sydney

As detailed below in Figure A.5, Blackmores Campus in Sydney, Australia has commercial offices that employ a range of passive design strategies using assisted natural ventilation, ground labyrinth cooling and thermal stacks. The building was designed to maximise daylight with smart low-energy lighting and associated control systems, 100% fresh air via automated windows and ventilated raised floor cavity, and fresh air has been maximised with temperature-sensitive windows (Watermark Architecture, 2012).

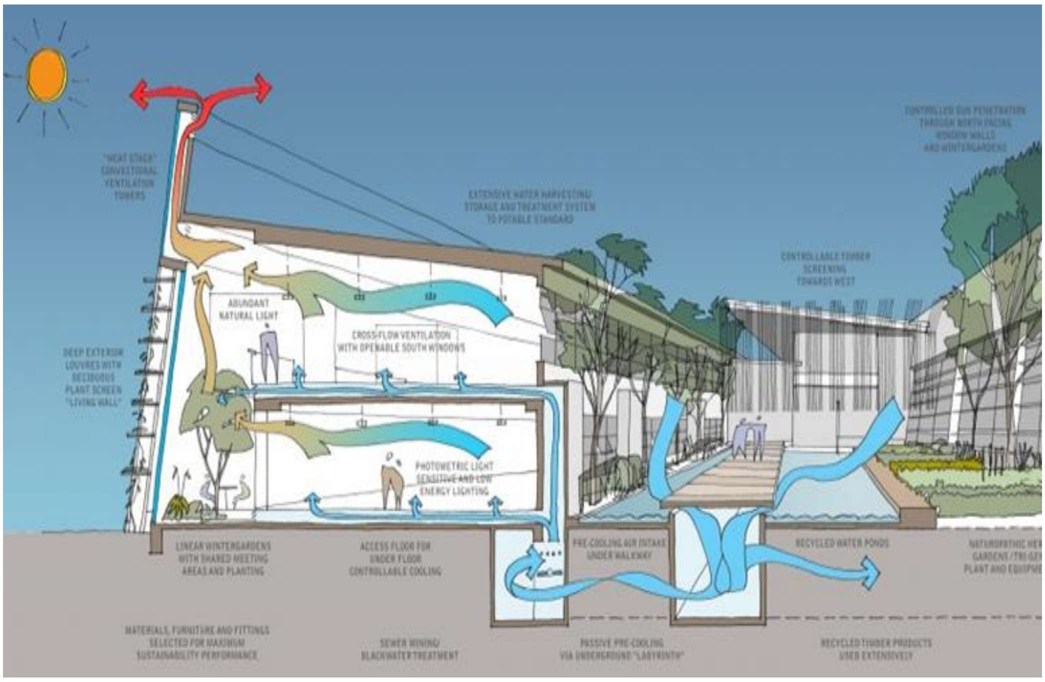


Figure A.5- Natural Ventilation Strategy at Blackmores Campus, Sydney (Watermark Architecture, 2012)

In Figure A.5, the sketch shows a section through the building indicating anticipated airflows from the subterranean level to the high-level outlet of the ventilation stack, which can be classed as a solar chimney (one side transparent).

A.7 Solar Chimney Case Studies

Solar chimneys are used globally and are shown in Figures A.6, one of these is a new French school in Damascus, Syria (Carboun, 2013) known as Lycée Charles de Gaulle. The school was designed by the French architects Ateliers Lion and Transsolar, a German environmental engineering firm (Carboun, 2013) and can accommodate 900 students ranging from kindergarten to high school. As shown in Figure 2.13 (Carboun, 2013) below, the night view of the school's central courtyard, there are solar chimneys for each room.

Figures A.6- Lycée Charles de Gaulle (Carboun, 2013) and Statistic Centre, Lancaster University (Levolux, 2013a)

Lancaster University's southern elevation of the Statistics Centre has five chimneys installed (Figure A.6). The front of the chimneys is glass with ducts at the rear which connect into the building (Levolux, 2013a). The solar chimneys heat the air by drawing warmer air out of the classroom spaces thus maintaining optimum temperature for studying.

Solar chimneys are often referred to as thermal chimneys as a way to increase air buoyancy and airflow through a building via convection. A solar chimney is a vertical shaft utilising solar energy to enhance the natural stack ventilation through a building through increased air buoyancy. Chatzipoulka (2011) states: *'It differs from a conventional chimneys in at least one of its walls is made transparent.'* The main feature of this method is to make one side of the chimney south-facing to make it susceptible to higher solar thermal gains. This is either achieved via glass (transparent) or high emissivity material (opaque). The internal surface will heat up incoming air flowing between the internal room and chimney, thus increasing air velocity. This creates a negative air pressure at extract outlets within the internal room. Figure A.7 below shows the process of airflow from the subterranean level through the building and into the solar chimney stack increasing stack air temperature and air velocity.

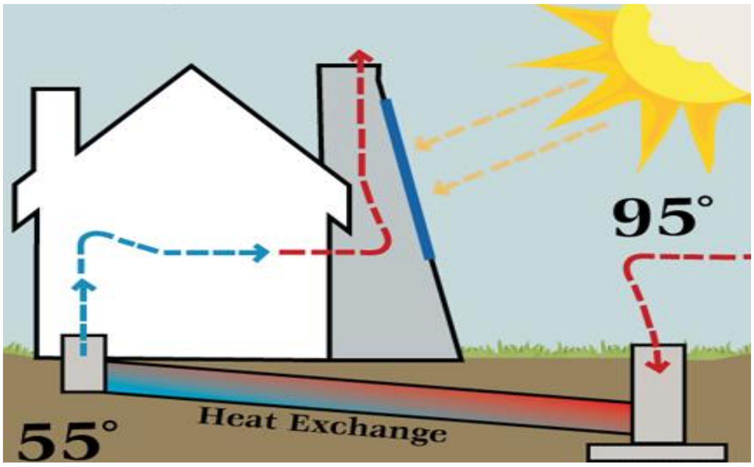


Figure A.7- Diagrammatic Air/Temperature Flow Representation of Solar Chimney Using Transparent Surface (Solar Innovations, 2013)

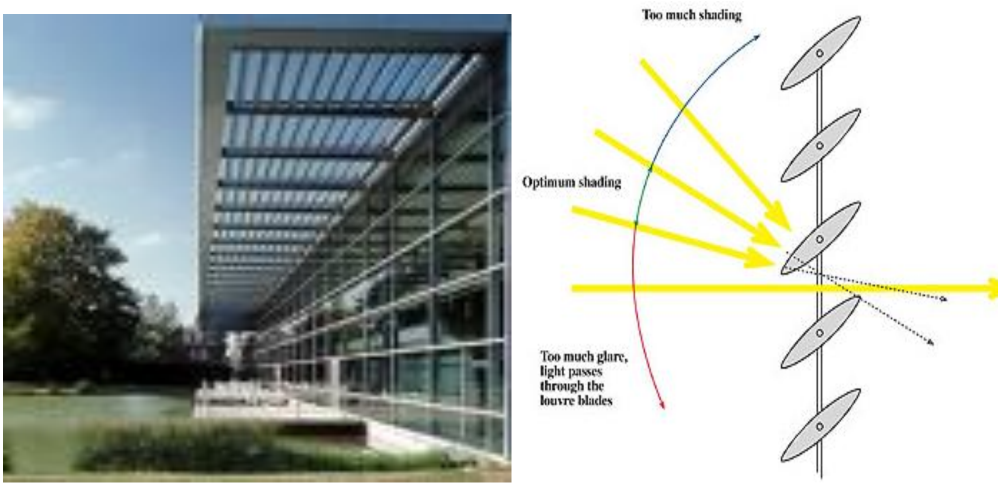
A.8 External Solar Shading Case Studies

These systems can be applied in any shape or form provided base design criteria are satisfied with regards reducing direct solar radiation. A project completed by Levolux (2013b) shows TTPCom's two-storey headquarters, a software development company located at Melbourne Science Park, Royston, Hertfordshire, UK. The shading system was provided to control light, glare and solar heat gain. The shade comprised of aerofoil fins which reduced loads on air-conditioning. For the external solar shade, 0.3m aerofoil fins are fabricated as one piece in extruded aluminium sections. To assist this external solar shading, motorised and manual roller blinds were provided for all remaining windows. It was deemed important that occupants had control of shading locally.

Figure A.8 shows an external fixed shading device installed at Morrisons, Sittingbourne, UK which has a Solex Halo 200 with extruded aluminium using cold bending techniques to shape the shade around the building's curve. Curved brackets were designed to be connected to glulam columns. The shade was arranged as a vertical array comprising of seven 200mm long elliptical blade profiles (Solinear, 2013a). The second image in Figure 2.25 shows a Solex Halo 400-65 with one elliptical profile external solar shade with trapezoidal shading fins and natural anodised energy shields at the Runnymede Civic Offices, UK.

Figures A.8- Examples of Applied External Solar Shading Devices-
Solinear (2013a) and Solinear (2013b)

Solar shading devices reduce direct solar heat gains to external glazing by absorbing a percentage of the short-wave solar radiation. These have to be designed and positioned correctly to maximise day lighting and minimise solar gain. Figure A.9 below shows a typical solar shading arrangement and also indicates how the optimum angle is important when for maximum heat reduction and maximum day light contribution.



Figures A.9- Typical Solar Shading and Optimum Angle for Solar Shading
(Levolux, 2012 and Solar Shading Louvres, 2012)

When discussing optimum angles for heat deflection and daylight maximisation, Lieb (2001) states that: *'The sun shading provides either a complete screening of an area behind it or, in the cases of louvres, it may be in a so called "cut off" position. This is the angle of the louvres at which the blind allows no direct radiation to penetrate it. Applying the above mentioned DIN standard, all values are calculated on the basis of a perpendicular incidence of light, so that the cut off angle position for the louvres will usually be 45^o. When louvres are set at a steeper angle, there will be a greater degree of shading, but reduced rate of light transmission* *as well.'* The cut-off angle stated shows the optimum shading possible without dramatically effecting daylighting contribution.

A.9 Ventilated Double Facades Case Study

The Richard J Klarchek information commons and digital library at Loyola University Chicago, USA, located at Lake Shore Campus, incorporates ventilated double façade technology (Designbuild-network, 2013). The building implements a number of natural and mechanical strategies in the building form and materials to reduce energy consumption by approximately 50 per cent. '*Upon its completion towards the end of 2007, the building will achieve silver LEED certification* (Designbuild-network, 2013)*.'* The main energy-saving feature is the double skin façade, which allows passive management of heat flow and natural ventilation annually. Figures A.10 show the front of the building and the large double ventilated façade.

Figures A.10- Richard J Klarchek Information Commons Elevations (Designbuild-network, 2013) and Loyola University Chicago (2013)

The façade has internal operable blinds (mechanical) that adjust according to daylight levels and solar heat gains from the westerly sun. These systems are controlled by an array of sensors monitoring temperature, humidity and CO_2 levels. Additional sensors take account of the outside conditions. All windows, dampers, shades and blinds are fully automated and controlled via BEMS.

A.10 Rain Screen Facades Case Study

Rainscreen facades are available in many different styles to suit architects' vision. As shown in the Figure A.11 below, this system can be applied to any type of building.

Figures A.11- Typical Rainscreen Facade (Just Facades (2013), Rockpanel (2013) and Use Hughes (2013))

A.11 PDEC Case Studies

The Torrent Research Centre is a pharmaceutical complex of research laboratories (19,700 sq.m) located on the outskirts of Ahmedabad, India. Sustainable Buildings (2013) states that the completed design maximises local natural materials and minimises artificial light. One of the main features is its minimal use of conventional air-conditioning due to the introduction of a PDEC system. Figure A.12 below shows the laboratory building with PDEC towers on both elevations.

Figure A.12- Torrent Research Centre, Ahmedabad, 1997 (Architecture Today, 2013)

The building designer has to be careful not to add too much moisture to avoid internal rain conditions. As with all low-carbon systems, Phillip (2011) identifies the main limitations with a PDEC system:

- Wind and Sand Storms: Ventilation louvre outlet baffling can be implemented to prevent air backflow caused by high external air pressure.
- Water Sourcing (Misting Towers): Water sourcing and harvesting is energy intensive in Riyadh and can be addressed by using alternative tower types/systems (e.g. cooling towers).

For maintenance, adequate training is required for occupants regarding operation of the system and dangers such as legionella bacteria treatment and control. Annual maintenance is required for this type of system. As previously discussed in chapter 1, a study completed for a stock exchange in Malta by WSP Environmental (Ford, 2002) suggested that passive building strategies achieve a 48 per cent reduction of energy when using a PDEC system. This was realised by removing peak loads from mechanical systems. The approximate results from the study are as follows:

- Mechanical Mode Only (Fan Coil Units): Approx. 103,924kWh/Annum.
- Passive System Used with Mechanical System (PDEC and Cooling Coils): Approx. 54,139kWh/Annum.
- Total Reduction of CO_2 Emissions: Approx. 28,152 kgCO_2/Annum.

A.12 Earth Ducts Case Study

Construction of earth duct networks can be considered a major task during the landscape phase of the construction. When installing earth ducts in landscape areas, it is important that sufficient depth is achieved to ensure ducts are not diurnally influenced by ambient air temperature otherwise there will be little to no heat transfer. The standard method is to excavate a large trench and place the earth duct in accordance with the engineers' design and plan. As shown in Figures A.13 (Homes in the Earth, 2013), BSRIA (2013) and (Sustainable Building Construction, 2013) below, earth ducts are buried in parallel with each other connecting to a large header, which connects into the building.

Figures A.13- Typical Examples of Earth Duct Installation/On-Site Construction

A small office village in Butterfields Business Park, Luton, UK (Figure A.14) has two-storey 400–800m^2 office blocks with 13-metre deep zones and unpainted exposed soffits. The earth duct systems are concrete earth ducts buried 1 metre underground, providing design air volume between 1.5 air changes per hour in the winter and approximately 4 air changes per hour in peak summer conditions (Building, 2013).

Figures A.14- Butterfield Business Park, Bedfordshire, UK (Building, 2013)

When air reaches the office block, if heating is needed, recirculation and low-pressure hot water heater batteries are used. Supply air is provided in the floor void and then in the office space via swirl diffusers.

Appendix B- Analytical Parameters for Building & Passive System Performance assessment (Reference)

B.1 General

This appendix has been created to provide reference equations used as a basis for this research as fundamental background for passive system analysis described in chapter 3 and completed in chapters 4 and 5.

B.2 Building Thermal Performance

Basic principles for steady state conduction heat loss are calculated as (Cengel et al., 2008):

$$Q_{cond} = k\,A\,\frac{(T_1 - T_2)}{\Delta x} = -\,k\,A\,\frac{\Delta T}{\Delta x} \qquad \text{Eq. B.1}$$

Where: Q_{cond} is the heat transfer rate of the material; k is the thermal conductivity of material; A is the surface area; Δx is the thickness of material; T_1 is the outer surface temperature; T_2 is the inner surface temperature; and ΔT is the difference in temperature. For radiative heat transfer (Q_{R}), the following equation applies from (Cengel et al., 2008)):

$$Q_R = \varepsilon\,\sigma\,A\,(T_1^4 - T_2^4)\,F_{1\text{-}2} \qquad \text{Eq. B.2}$$

Where: ε is surface emissivity; σ is stefan boltzmann constant (5.67×10^{-8}); A is area of surface; T_1^4 is surface air temperature; T_2^4 secondary surface/body temperature and $F_{1\text{-}2}$ is view factor.

When considering fluid heat transfer analysis for convective fluid flow and heat transfer from a surface, Cengel et al. (2008) state: *'The governing equation of natural convection and the boundary conditions can be non-dimensional by dividing all dependent and independent* *variables by suitable constant quantities'*. They continue to define the dimensionless parameter that represents natural convection effects:

$$Gr_L = \frac{g\ \beta v\ (Ts - T_\infty)Lc3}{v^2} \qquad \text{Eq.B.3}$$

In order to calculate GrL, where $\beta v = \frac{1}{T}$ and convective heat transfer coefficient h_c can be obtained by re-arranging Nusselt's correlation (Cengel et al., 2008):

$$Nu = \frac{hLc}{k} = C\ (Grl.Pr)^\wedge = CRa_L^n \qquad \text{Eq. B.4}$$

Where the Prandtl number is denoted as $\frac{\mu Cp}{k}$, relative thickness of velocity and thermal boundary layer, the convective heat transfer equation can be used (Cengel et al., 2008):

$$Q_c = h_c\ A_s\ (Ts - T_\infty) \qquad \text{Eq. B.5}$$

For weather data usage in building simulations, location is critical to determine overall building performance. As a minimum, data should include dry bulb air temperature (^oC), relative humidity (%RH), solar radiation (I) and wind speed (Ψ). For solar admittance into the fabric (CIBSE, 1999a):

$$q_{(\theta + \varnothing)} = U\ (Teo_{(m)} - T_i) + fU\ (Teo_{(\varnothing)} - Teo_{(m)}) \qquad \text{Eq. B.6}$$

Where $q_{(\theta + \varnothing)}$ is the instantaneous heat flow rate per unit area at time; θ is the time at which outdoor temperatures are known; $\varnothing$ is the time lag between indoor and outdoor temperatures; U is the thermal conductivity; $Teo_{(m)}$ is the combined environmental temperature (air temperature and radiant temperature) known as sol-air temperature; T_i is the mean internal temperature (^oC); f is the decrement factor, which is the ratio of indoor to outdoor temperature amplitudes; and $Teo_{(\varnothing)}$ is sol-air temperature at time. For consideration of heat storage assuming no temperature gradient (lumped parameter method), Q_{Store} is equal to Q_{Input} then the lumped parameter is calculated as (Cengel et al., 2008):

$$\ln \frac{T(t) - T_{\infty}}{T_i - T_{\infty}} = -\frac{h A_s}{\rho \upsilon C_p} t \qquad \text{Eq. B.7}$$

Where $T(t)$ is the temperature at time; t is the time; T_{∞} is the body placed in a medium temperature; T_i is the internal uniform temperature; h is the heat transfer coefficient; A_s is the surface area; ρ is the density; υ is the volume; and C_p is the specific heat capacity.

For calculation of heat transfer using nodes using finite differencing (Firth, 2009):

$$\theta_{m+1,n} = \theta_{m,n} (1\text{-}2K) + \left[\theta_{m,n+1} + \theta_{m,n-1}\right] K_f \qquad \text{Eq. B.8}$$

Where $^{\theta}m+1,n$ is the temperature at the same position (next timestep); $^{\theta}m,n$ is the temperature at the same position (same timestep); $^{\theta}m,n+1$ is the temperature at the next position along (same timestep); and $^{\theta}m,n-1$ is the temperature at the previous position back (same timestep).

Simple methods used are steady state (transient) equations to determine building loads and annual energy consumption via the use of degree day data. For heat loss through a building fabric (Chadderton, 2004):

$$Q_{Total} = F_{1CU} \sum U A + F_{2CU} \, 0.33 \, N \, V \, (^{\theta}T) \qquad \text{Eq. B.9}$$

Where Q_{Total} is the rate of heat transfer through fabric; U is the thermal conductivity of fabric; N is the number of air changes; V is the volume; A is the area of fabric; $^{\theta}T$ is the difference in temperature between the inside and outside air temperature (T_o - T_i); and F_{1CU} and F_{2CU} are factors related to the characteristics of the heat source with respect to operating temperatures. To determine annual energy consumption, Q_A (joules/Annum) is based on building fabric and ventilation heat losses (Chadderton, 2004):

$$Q_A = (\sum UA + 0.33NV) \times 24 \times 3600 \times D_A \qquad \text{Eq. B.10}$$

Where D_A is annual degree days.

The above equations are used with worst case external temperatures and base line degree days (below 15.5°C) for a given location. Steady state models provide a semi-accurate load assessment based on simplified calculation criteria.

British standards provide accurate design guidance with more specific criteria in order to enable building simulation compliance. Simulation calculations are based upon parameters and formulas, for example, heat transfer of homogeneous materials, stated in International Standard (2007b):

$$R = d/ \lambda \qquad \text{Eq. B.11}$$

Where R is the thermal resistance; d is the distance; and λ is the thermal transmittance.

For calculation of all fabric to determine thermal conductivity (U) (Chadderton, 2004):

$$U = 1/ \sum R\text{'s} \qquad \text{Eq. B.12}$$

To calculate values through a building element, for example through a wall, the total sum of thermal resistance must be calculated (International Standard, 2007a):

$$U = \frac{1}{(R_{so} + R_{brick} + R_{insulation} + R_{block} + R_{plaster} + R_{si})} \qquad \text{Eq. B.13}$$

Where R_{so} is the resistance of external air on the outer surface and R_{si} is the resistance of external air on the outer surface.

When reviewing the Standard that accounts for moisture content within construction materials, International Standard (2007a) gives specific guidance on design moisture levels and takes into account material (concrete, glass, metals) density, specific heat capacity and water vapour resistance.

B.3 Base Passive System Performance

Base input parameters of the simulations influence the computer's algorithm and predicted output for the base case model (primary output) including effects on performance using a low-carbon building design (Figure A.2).

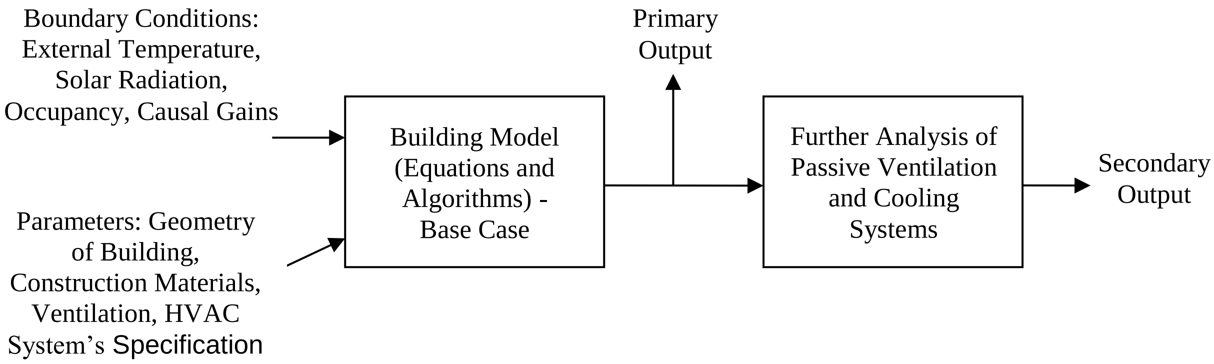


Figure A.1- A Building Model Incorporating Passive Ventilation and Cooling (Building Simulation)

As passive systems are based on natural laws of physics, in particular air convection and pressure, the following base rule applies (Douglas and Matthews, 1996):

$$P = \rho \text{ g h} \qquad \text{Eq. B.14}$$

To calculate effects of wind on natural ventilation air flow rates (British Standard, 1991):

$$Q_w = C_d A_w u_r (\Delta C_p)^{1/2} \qquad \text{Eq. B.15}$$

Where Q_W is the wind airflow rate; C_d is the coefficient of discharge; A_w is the effective opening area; u_r is the reference wind speed; and ΔC_p is the specific heat capacity of air.

Where cross-ventilation applies, the effective opening area (Aw) is expressed as (British Standard, 1991):

$$\frac{1}{A_w^2} = \frac{1}{(A_1 + A_2)^2} + \frac{1}{(A_3 + A_4)^2} \qquad \text{Eq. B.16}$$

To calculate effects of temperature on natural ventilation airflow rates (Q_b), (British Standard, 1991):

$$Q_b = C_d\, A_b \left(\frac{2\, \Delta\theta_g\, H_1}{\overline{\theta}} \right)^{½} \qquad \text{Eq. B.17}$$

Where C_d is the coefficient of discharge; A_b is the effective opening area; θ is the difference in temperature (T_i-T_o); is the higher ambient air temperature; and H_1 is the difference in height in effective opening areas.

To calculate the effective opening area of a single sided ventilated surface with low and high level openning, A_b is expressed as (British Standard, 1991):

$$\frac{1}{A_b^2} = \frac{1}{(A_1 + A_3)^2} + \frac{1}{(A_2 + A_4)^2} \qquad \text{Eq. B.18}$$

For wind effects on surface, the surface pressure coefficient is expressed as (British Standard, 1991):

$$Cp = (P - P_o)/\tfrac{1}{2}\ \rho u_r^2 \qquad \text{Eq. B.19}$$

Where Cp is the surface pressure coefficient; P is instantaneous pressure generated at a particular point on the external surface; P_o is static pressure of wind; ρ is air density; and u_r is the reference wind speed.

The base equations above form a platform for passive system design. For each of the following sections, expressions are more specific to the nature of the system and form the fundamental principle of the design.

B.4 Natural Ventilation Analytical Parameters

For airflow through an aperture (British Standard, 1991):

$$Q = C_d\, A \left(\frac{2\Delta P}{\rho} \right)^{1/2} \qquad \text{Eq. B.20}$$

Where Q is the airflow rate; C_d is the coefficient of discharge; P is the air pressure; ρ is the external air density; and A is the area of outlet.

B.5 Further PDEC Analytical Parameters

For humidity ratio (Engineering Toolbox, 2013):

$$\Delta x = \frac{Mw}{Ma} \qquad \text{Eq. B.21}$$

Where M_w is the mass flow rate of water; and M_a is the mass flow rate of air.

B.6 Further Earth Duct Analytical Parameters

As denoted by Homes in the Earth (2013) to calculate frictional pressure losses in earth ducts more accurately, the D'Arcy-Weisbach equation applies as it takes into account viscous interactions between the air and the pipe walls:

$$\Delta P_f = \frac{\lambda f \, L \, v^2}{2 \, g \, D_m} \qquad \text{Eq. B.22}$$

Where ΔPf is the frictional pressure drop; λf is the friction factor (based on material, Re and Dm); L is the length of duct; v is the mean duct velocity; g is the gravitational constant; and Dm is the hydraulic mean diameter (cross-sectional area/perimeter). To calculate the Reynolds number for predicted transition to turbulent flow (Re > 2300 for round ducts), the following equation applies (Homes in the Earth, 2013):

$$Re_d = \frac{\rho V d}{\mu} \qquad \text{Eq. B.23}$$

Where ρ is the fluid density; V is the mean flow velocity; d is the hydraulic diameter (inside tube diameter, which may be different from the 'nominal diameter'); and μ is the dynamic viscosity of the fluid. To calculate the mean turbulent velocity profile, which accommodates small fluctuations in velocity and direction, the following equation is applied (Homes in the Earth, 2013):

$$\frac{Le}{d} = 4.4\ \mathrm{Re}^{1/6} \qquad \text{Eq. B.24}$$

'Since this average is relatively constant, the resulting wall shear is constant and the pressure drop becomes linear with X. The distance to a stable flow profile is between 18 and 20 times the diameter up to Re = 10000' (Homes in the Earth, 2013).

Appendix C- Basis of Design for Theoretical Commercial Building Models

C.1. Overview

In order to develop theoretical building models, existing buildings have been researched to aid with their development in terms of envelope geometry, internal layout and space. For each theoretical building model, a specific commercial (office) type building space has been identified as a basis of design for these research works. These have been selected to ensure the ease of application of passive ventilation and cooling systems identified for this research.

C.2. Building Examples for Model A

Model A is based upon generic office building types as identified below in Figures C.1 and C.2. The buildings identified are Vantage Point located in Bristol, England (Summerfield, 2014) and Office building in Rozenburg by Sputnik, Netherlands (Archinect Firms, 2014).

Figures C.1 & C.2- Vantage Point Façade View (Summerfield, 2014) and Office building in Rozenburg Façade View (Archinect Firms, 2014)

a) Vantage point, Bristol, UK

These are self-contained office suites separated over three floors. Unit B2 has a total floor area of 4,447 sq.ft (413 sq.m). The building appears to be conventional modern type build with standard construction materials.

b) Office building in Rozenburg, Netherlands

Archinect Firms (2014) describe the building as; *The building fits in this robust context with a modestly designed façade. Behind the aluminium panelling an inventive, sustainable VRF air conditioning system is hidden. All piping and equipment are incorporated in the parapet, leaving no need for suspended ceilings in the offices.'*

C.3. Building Examples for Model B

Model B is based upon a generic building design identified in Figures C.3 and C.4. These buildings identified are 1 North Bank, Sheffield, Yorkshire (e-architect, 2014) and Modern Small Office Buildings Verkerk Group in Netherland (Zeospot, 2014).

Figures C.3 & C.4- 1 North Building Façade View (e-architect, 2014) and Modern Small Office Building Façade View (Zeospot, 2014)

a) 1 North Bank, Sheffield, Yorkshire, UK

As described by (e-architect, 2014): *'The 61,000sq-ft office scheme in the historic Wicker area of the city is the first phase of a masterplan, also carried out by BDP, for a former industrial site, bounded on one side by a neglected stretch of the river Don.' The first phase speculative office building called 1 North Bank is a striking five storey office building with a flexible plan and two reception areas and two circulation cores to allow a variety of sublets. The accommodation comprises clear floor plates arranged in a shallow 'U' with the long side parallel to the street and a short return along the river.'*

b) <u>Modern Small Office Buildings Verkerk Group, Netherlands</u>

Karmatrendz (2014) describes the building as: '*To stand out from the surrounding area has a special new shape. The rounded corners and different colors and materials give the building and therefore the organization has its own identity. The property has a modern and functional appearance, durability, maintenance, expandability and features numerous technical innovations. The new accommodation for the Group Verkerk gives a positive impulse to the future development of industrial Hogebrink and contributes to the revitalization of old industrial site.'*

Appendix D- Energy Performance Benchmarks for Model Verification

D.1. Overview

For this research, models are verified against energy performance bench marks set out in CIBSE, BSRIA and ASHRAE publications. The values obtained from the theoretical building models are inter-compared with typical practice values for cooling load (W/m^2) and annual energy consumption (kWh/m^2). These are further described in sections D.2, D.3 and D.4 of this appendice. For BSRIA and CIBSE, it is important to note that these values are based upon UK climate and average bench mark values. These do not reflect higher envelope heat gains via building fabric in different countries hence bench marks may be exceeded in some cases.

D.2. Energy Performance Benchmarks (BSRIA)

Cooling load benchmark values for UK climates are detailed below in Table D1 below (table 16, BSRIA, 2011):

Table D.1- BSRIA BG9, 2011 Benchmark Cooling Loads for Office

Description	Rule of thumb	Comments	Ref
	Cooling load (W/m^2)	Please refer to the glossary for a definition of gross internal area	61, 12
Offices	87	The project design reports analysed during the production of this document had an average total cooling load of 87 W/m^2 GIA*	

Table D.2- BSRIA, 2011 Benchmark Electricity Consumption per Annum for Air Conditioned Offices

Table 28: Annual energy consumption and CO_2 emissions benchmarks for different building types (continued)

Building type	Annual energy consumption benchmarks		Annual CO_2 emissions benchmarks			Comments
	Electricity (kWh/m^2)	Fossil thermal (kWh/m^2)	Electricity (kg CO_2/m^2)	Fossil thermal (kg CO_2/m^2)	Total (kg CO_2/m^2)	
Offices	95	120	49.1	23.8	72.9	This is a general office benchmark for all offices, whether air conditioned or not

D.3. Energy Performance Benchmarks (CIBSE)

CIBSE (2012) & CIBSE (2008) guidelines for offices are detailed in this section. Table D.3, D.4, D.5 and D.6 below, building energy bench marks (Extracts from CIBSE, 2012):

Table D.3- CIBSE (2012) Fossil and Electric Building Bench Marks (Extract)

Table 20.1 Fossil and electric building benchmarks — *continued*

Building type	Energy consumption benchmarks for existing buildings / (kW·h·m^{-2}) per year (unless stated otherwise)				Basis of benchmark
	Good practice		Typical practice		
	Fossil fuels	Electricity	Fossil fuels	Electricity	
Offices[10][e]:					
— air conditioned, standard	97	128	178	226	Treated floor area
— air conditioned, prestige	114	234	210	358	Treated floor area
— naturally ventilated, cellular	79	33	151	54	Treated floor area
— naturally ventilated, open plan	79	54	151	85	Treated floor area

Table D.4- CIBSE (2012) Fossil and Electric Building Bench Marks for Some Public Sector Buildings in Northern Ireland (Extract)

Table 20.4 Fossil and electric building benchmarks for some public sector buildings in Northern Ireland[18]

Building type	Mixed fuel buildings					All-electric buildings			
	Electricity / kW·h·m^{-2} p.a.		Fossil fuel / kW·h·m^{-2} p.a.		Sample size	Electricity / kW·h·m^{-2} p.a.		Sample size	Floor area type
	Good	Typical	Good	Typical		Good	Typical		
Offices:									
— naturally ventilated, cellular	47	83	92	138	32	65	104	65	Net lettable
— naturally ventilated, open plan	65	81	143	166	38	118	149	12	Net lettable

Table D.5- CIBSE (2012) Offices: Component Benchmarks

Table 20.10 Offices: component benchmarks

System	Delivered energy for stated office type / (kW·h·m^{-2}) per year							
	Type 1		Type 2		Type 3		Type 4	
	Good practice	Typical	Good practice	Typical	Good practice	Typical	Good practice	Typical
Lighting:								
— installed loading (W·m^{-2} floor area)	12	15	12	18	12	20	12	20
— full load hours/year (h)	1125	1500	1800	2100	2240	2720	2450	2975
— system hours/year (h)	2500	2500	3000	3000	3200	3200	3500	3500
— utilisation (%)	45	60	60	70	70	85	70	85
Fans (only):								
— consumption (kW·h per year)	0	0	0	0	22	42	24	44
— full load (W·m^{-2} floor area)	0	0	0	0	8	12	8	12
— full load hours/year (h)	0	0	0	0	2750	3500	3000	3700
Desk equipment:								
— load (W·m^{-2} floor area (local))	10	12	12	14	14	16	15	18
— percentage floor area (%)	60	60	65	65	60	60	50	50
— load (W·m^{-2} floor area (building))	6.0	7.2	7.8	9.1	8.4	9.6	7.5	9.0
— operating hours/year (h)	2000	2500	2500	3000	2750	3250	3000	3500

Note: Type 1: cellular naturally ventilated; Type 2: open plan naturally ventilated; Type 3: 'standard' air conditioned; Type 4: 'prestige' air conditioned

Table D.6- CIBSE (2012) Mixed use Buildings: System and Energy Benchmarks

Table 20.19(a) Mixed use buildings: system and building energy benchmarks — building types 1 to 4

System	Delivered energy for stated building type / (kW·h·m^{-2}) per year							
	Type 1		Type 2		Type 3		Type 4	
	Good practice	Typical	Good practice	Typical	Good practice	Typical	Good practice	Typical
Lighting:								
— installed loading (W·m^{-2} floor area)	11.4	14.3	11.4	17.1	10.8	18.0	10.2	17.0
— illuminance (lux)	380	428	380	428	360	450	340	425
— installed power density ((W·m^{-2})/100 lux)	3	3	3	4	3	4	3	4
— full load hours/year (h)	1125	1500	1800	2100	2240	2720	2450	2975
— system hours/year (h)	2500	2500	3000	3000	3200	3200	3500	3500
— utilisation	45%	60%	60%	70%	70%	85%	70%	85%
Fans (only):								
— consumption (kW·h per year)	0	0	0	0	20	38	20	37
— full load (W·m^{-2} floor area)	0.0	0.0	0.0	0.0	7.2	10.8	6.8	10.2
— full load hours/year (h)	0	0	0	0	2750	3500	3000	3700
Desk equipment:								
— consumption (W·m^{-2} floor area (local))	10	12	12	14	14	16	15	18
— percentage floor area (%)	57%	57%	62%	62%	54%	54%	43%	43%
Equipment:								
— load (W·m^{-2} floor area (building))	5.7	6.8	7.4	8.6	7.6	8.6	6.4	7.7
— hours/year (h)	2000	2500	2500	3000	2750	3250	3000	3500

Note: Type 1: cellular naturally ventilated office; Type 2: open plan naturally ventilated office; Type 3: standard air conditioned office; Type 4: prestige air conditioned office

D.4. Energy Performance Benchmarks (ASHRAE)

Thornton, B.A,. et al (2011) Achieving the 30% Goal: Energy and Cost Saving Analysis of ASHRAE Standard 90.1-2010.

Table D.7- Thornton, B.A; et al (2011) Energy and Energy Cost Savings with Plug and Process Loads

Table ES.2. Energy and Energy Cost Savings with Plug and Process Loads

Building Type	Building Prototype	Site Energy (kBtu/ft²/yr)		Energy Cost ($/ft²)		Site Energy Savings	Energy Cost Savings
		90.1-2004	90.1-2010	90.1-2004	90.1-2010		
Office	Small office	41.3	32.8	$1.17	$0.93	20.6%	20.3%
	Medium office	51.6	37.3	$1.42	$1.01	27.7%	29.1%
	Large office	46.0	33.4	$1.21	$0.92	27.5%	24.3%

Using information detailed in Table D6, British Thermal Units are converting to kWh/m^2/Annum in order to make a like for like comparison with CIBSE/BSRIA values:

Table D.8- BTU/ft^2/Annum Energy Conversion to kWh/m^2/Annum

Building Prototype	BTU/ft^2/Annum (2010 Values)	BTU/ft^2/Annum to BTU/m^2/Annum Conversion	Converted BTU/m^2/Annum to kWh/m^2/Annum
Small Office	32800	352928	103.36
Medium Office	37300	401348	117.54
Large Office	33400	359384	105.25

Appendix E- Mechanical Modelling Inter-comparison

E.1. Mechanical Cooling System Selection

Using building model B.1 as a benchmark for mechanical cooling system comparison and Lisbon, Portugal weather data, DTS of various mechanical systems had to be completed to determine ideal mechanical cooling system for the base case. This is to ensure the most efficient cooling system was used as part of this analysis. As detailed in Table E.1 below, ideal mechanical ventilation and cooling system for this simulation is split cooling (Direct expanding) with separate extract ventilation.

Table E.1- HVAC Cooling System Analysis to Determine Accurate Base Case

System Description	Month	ZONE/SYS SENSIBLE COOLING ENERGY [kWh]	ZONE/SYS SENSIBLE COOLING RATE {Maximum}[W]	ZONE TOTAL INTERNAL LATENT GAIN [kWh]	ZONE TOTAL INTERNAL LATENT GAIN {Maximum} [W]
Split Cooling + Separate Extract Ventilation	July	2,323.53	9,683.64	239.56	1,434.65
VAV + Heat Recovery + Outside Air Reset	July	2,342.08	9,694.11	240.39	1,439.85
VAV with Outside Air Reset	July	2,342.08	9,694.11	240.39	1,439.85
CAV	July	2,342.08	9,694.11	240.39	1,439.85

Appendix F- Effectiveness of Internal Blind at Peak Periods

F.1. Calculations

Manual calculation are completed to determine how effective internal blinds are reducing solar heat gains into the internal space at peak periods. The maximum solar radiation is 1095.2w/m^2 (Øs) and external air temperature 44.2^{o}C for July taken from IES VE software for Egypts climate. Using equations 3.2 (chapter 3), B.1 and B.2 (Appendix A), Table F.1 details the calculation methods used to determine heat exchange from internal blind. This method is used for increments of 10% of blind closed up to 100% over the window by adjusting area of the blind (A_b). Furthermore, identical calculations are completed for alternative effective g-values (0.7, 0.55 and 0.3). The results are detailed in Figure 4.13, chapter 4.

Table F.1- Calculation Method for Internal Blind Effectiveness Using Microsoft Excel

					Percentage of Blind Open	1								
Window 1														
Calculation 1														
Qs	4,818.88	=	Aw	8	Eff. g value (Window)	0.55	Øs	1095.2						
Solar Heat Gain to Space (Base Case)														
Calculation 2														
QR-r Solar heat Gain Reflected	5.834256	=	ε	0.71	σ	5.67E-08	A_b	8	T_3^4	1E+10	T_2^4	1E+10	F_{1-2}	1
							Area of Blind				External Air Temeratu re			
Calculation 3														
					Percentage of Heat Gain	1								
T_3	44.77	=	T_1	24	q	4818.88			dx	0.001				
Surface Temperature of Blind			Internal Room Temperature		k	0.029	A_b	8						
							Area of Blind							
Calculation 4														
QR-o	25.67073	=	Ab	8	Eff. g value (Window)	0.55	QR-r	5.8343						
Blind to External Space Via Glazing														
Calculation 5														
Heat Gain Reduction Using Blind	4,793.21	=	Qs	4,818.88	-	QR-o	25.6707266							

Appendix G- Effectiveness of External Light Shelf

G.1. Calculations

Manual calculation are completed to determine how effective external light shelf is at reducing solar heat gains into the internal space at peak periods. The maximum solar radiation is 1095.2W/m^2 (øs) and external air temperature 44.2^{o}C for July taken from IES VE software. Using equations 3.2, B.1 and B.2, Table G.1 details the calculation methods used to determine solar heat gains via glazing to internal space and irradiated heat exchange from the light shelf horizontal surfaces (Top and Bottom). The results are detailed in Figure 4.17, Chapter 4.

Table G.1- Calculation Method for Light Shelf Reduction

Calculation A- 0.5% Height of Window														
Calculation 1- Base Case Window without Light Shelf														
Qs_{BC}	4,818.88	=	Aw_1	8	Eff. g value (Window)	0.55	Øs	1095.2						
Calculation 2- Area Above Light Shelf														
Qs_1	2,409.44	=	Aw_2	4	Eff. g value (Window)	0.55	Øs	1095.2						
Calculation 3- Area Below the Light Shelf Excluding Light Shelf shading zone														
Qs_2	1,445.66	=	Aw_3	2.4	Eff. g value (Window)	0.55	Øs	1095.2						
Absorbed and Re-transmitted via Light Shelf														
QR-r Solar heat Gain Irradiated via Light Shelf	284.21	=	ε	0.91	σ	6E-08	A_{LS}	0.96	T_3^4	1.4E+10	T_2^4	7.8E+09	F_{1-2}	1
							Area of Light Shelf				External Air Temerature			
					Percentage of Heat Gain	1								
T_3	68.22	=	T_1	44.2	q	1095.2			dx	0.004				
Surface Temperature of Light Shelf			External Air Temperature		k (Poly Carbonate)	0.19	A_b	0.96						
							Area of Light Shelf							
Calculation 6														
Qs_3	375.1636	=	Aw_3	2.4	Eff. g value (Window)	0.55	Øs	284.21						
Solar Gain irradiated Through Glazing into Internal space from Light Shelf Upper Level														
Calculation 7														
Qs_4	62.527266	=	Aw_4	0.4	Eff. g value (Window)	0.55	Øs	284.21						
Solar Gain irradiated Through Glazing into Internal space from Light Shelf Lower Level														
Calculation 8														
Qs_5	526.09	=	Q_{SBC}	4,818.88	-	Qs_1	2,409.44	Qs_2	1446	Qs_3	375.163599	Qs_4	62.5	
Solar Heat Gain Reduction of Light Shelf														
Calculation 9														
% Reduction Compared Against Base Case	10.92	=	Qs_5	526.09	/	Q_{SBC}	4,818.88							

Appendix H- Mechanical Ventilation Operation Times at Varying Set Point temperatures

H.1. Description

This performance analysis is completed to determine daily operational period of mechanical ventilation and cooling system. This is required to determine natural ventilation period before the external air temperature exceeds thermal comfort BEMS set point, i.e. full mechanical ventilation and cooling operation is required.

For base case data identified in Model B.2 (Chapter 3), temperature set point is identified on the graph and time periods are manually measured to identify approximate time for mechanical ventilation and natural ventilation operation. Where the temperature is below the set point line, natural ventilation is active. Above the set point line, full mechanical ventilation operation will occur. The approximate times are detailed in a table for each system detailing time periods available.

From the times derived, approximate energy consumption of mechanical ventilation can be calculated. The effects of the natural ventilation will show as a percentage reduction of mechanical ventilation operation when compared with building model B.2 base case energy performance values.

H.2. Mechanical Ventilation Operation Period with a set point of 24^{o}C

Figure H.1 shows that the external air temperature does not exceed 24^{o}C for January and therefore no HVAC operation is required.

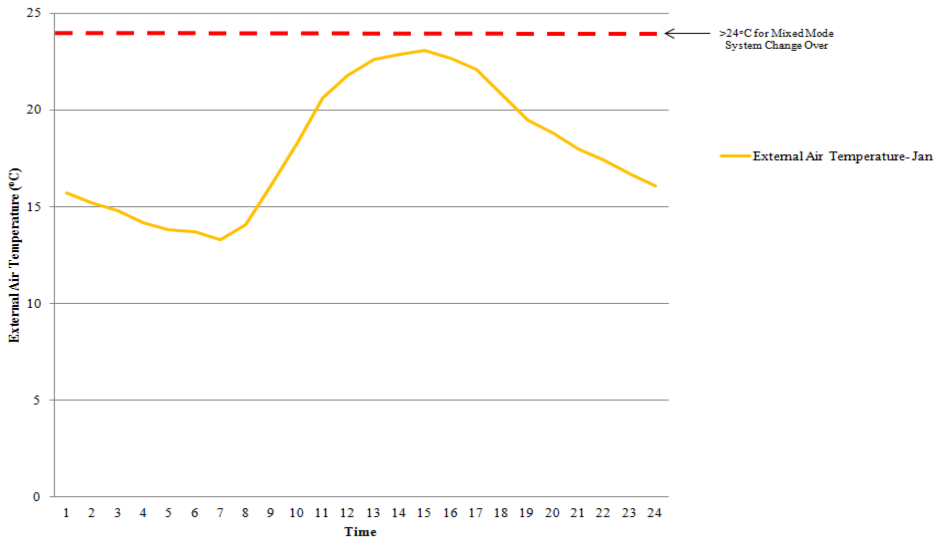


Figure H.1- Average Daily Dry Bulb Temperatures <26^{o}C

Figure H.1 details the months that external dry bulb air temperature clearly exceeds 24^{o}C and full HVAC operation is required in this extreme climate. Also a base line shows diurnal temperature relationship to time when set point is 28^{o}C.

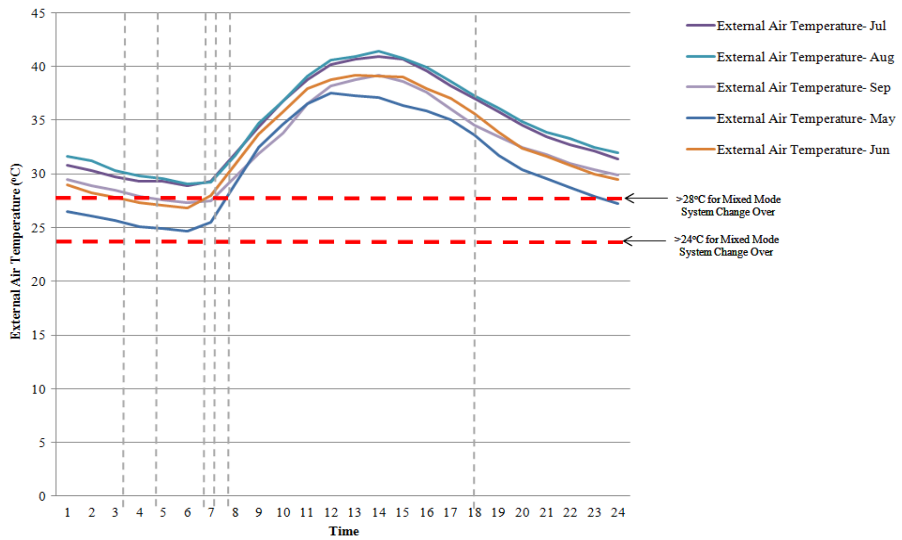


Figure H.2- Average Daily Dry Bulb Temperatures >26^{o}C & >28^{o}C

When analysing the above graph in Figure H.2, raising HVAC set point towards 28^{o}C, natural ventilation can be used as detailed in Table H.1 below showing time periods before HVAC operation is required.

Month	NV (t) Start (Time)	NV (t) Stop (Time)	Natural Ventilation Cooling Period (Time)	Excessive Time Required for HVAC
May	01:00	07:45	07:45	00:45
June	03:15	06:50	03:40	00:00
September	04:45	07:05	02:20	00:05

Table H.1- Effects on Time Period when Increasing Internal Comfort Temperature

Because these excessive times are during pre-cooling period, it is deemed not to be included as this does not affect the occupied period for HVAC operation i.e. instantaneous from 0800. Using the same methodology, times were derived for temperatures 25°C, 26°C, 27°C and 28°C.

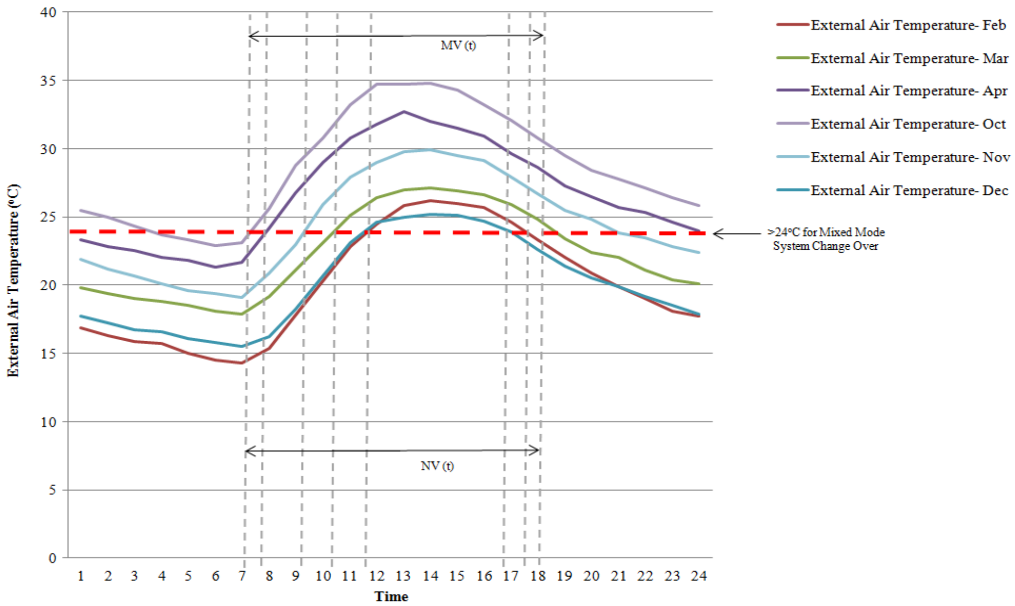


Figure H.3- Average Daily Dry Bulb Temperatures >24°C During Occupied Hours

The occupied office time period for natural ventilation operation (NV $_{(t)}$) and mechanical HVAC operation (MV $_{(t)}$) is taken from the graph (Figure H.3), is detailed in Table H.2 below and then calculated into kilowatt hours per month.

Table H.2- Time Period for External Air Temperature Exceeding 24ºC

Month	MV (t) Start	MV (t) Stop	Time Difference (Hours)	Occupied Hours (Converted)		Available Working Days For Month (Mon - Fri)
				MV (t)- Time	NV (t)- Time	
February	11:30:00	17:00:00	05:30:00	5.5	5.5	20
March	10:15:00	18:00:00	07:45:00	7.75	3.25	20
April	07:45:00	18:00:00	10:15:00	10.25	0.75	22
October	07:00:00	18:00:00	11:00:00	11	0	23
November	09:10:00	18:00:00	08:50:00	8.87	2.13	20
December	11:30:00	17:00:00	05:30:00	5.5	5.5	17

H.3. Mechanical Ventilation Operation Period with a set point of 25ºC

For a set point temperature of 25ºC, six months are identified where the external temperature is equivalent or greater than the set point temperature and time operations are determined from Figure H.4 below.

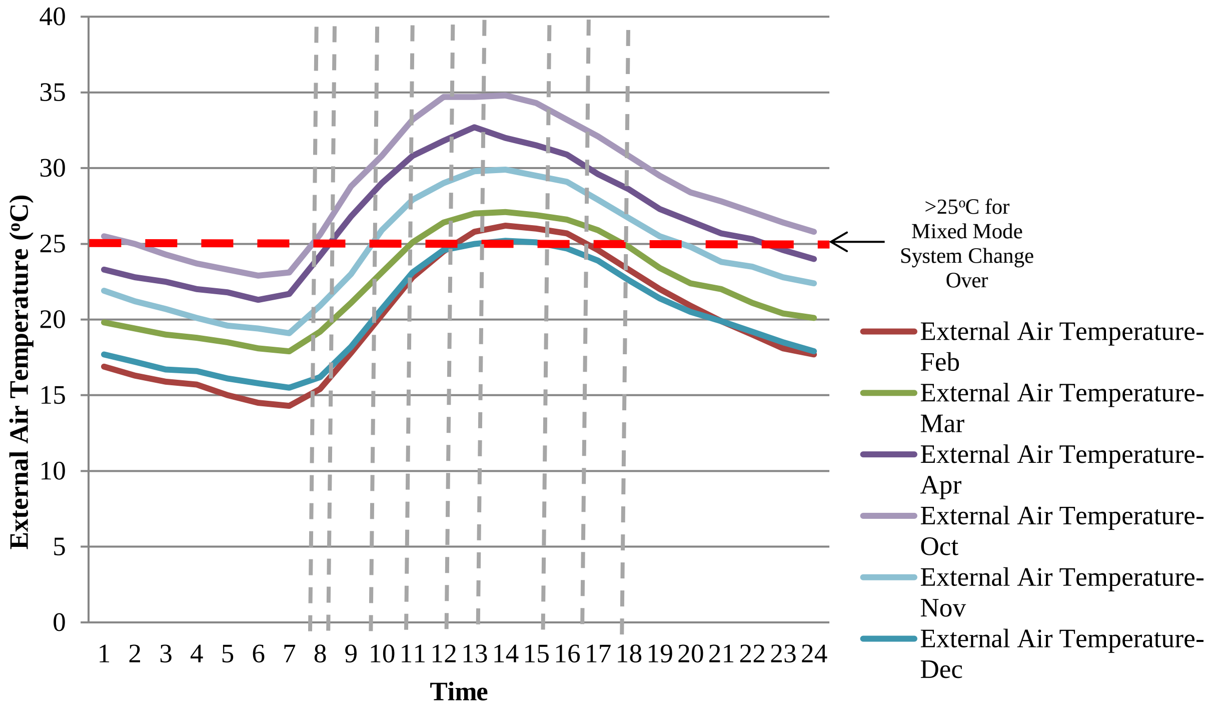


Figure H.4- External Air Temperature/Occupancy Periods (db>25ºC)

Table H.3 shows month this is applicable, mechanical ventilation start and stop time approximated from Figure H.4, time difference in hours when compared to Model B.2 (Chapter 3) base case values. The occupied hours are divided into mechanical ventilation operational time (MV $_{(t)}$) and natural ventilation activation time (NV $_{(t)}$).

Table H.3- Time Period for External Air Temperature Exceeding 25°C

Month	MV (t) Start	MV (t) Stop	Time Difference (Hours)	Occupied Hours (Converted) MV $_{(t)}$- Time	Occupied Hours (Converted) NV $_{(t)}$- Time	Available Working Days For Month (Mon - Fri)
February	12:00:00	16:00:00	04:00:00	4	7	20
March	11:50:00	17:50:00	06:00:00	6	5	20
April	08:10:00	18:00:00	09:50:00	9.8	1.2	22
October	07:30:00	18:00:00	10:30:00	10.5	0.5	23
November	09:45:00	18:00:00	09:15:00	9.25	1.75	20
December	13:00:00	15:10:00	02:10:00	2.167	8.833	17

H.4. Mechanical Ventilation Operation Period with a set point of 26°C

For a set point temperature of 26°C, six months are identified where the external temperature is equivalent or greater than the set point temperature and time operations are determined from Figure H.5 below.

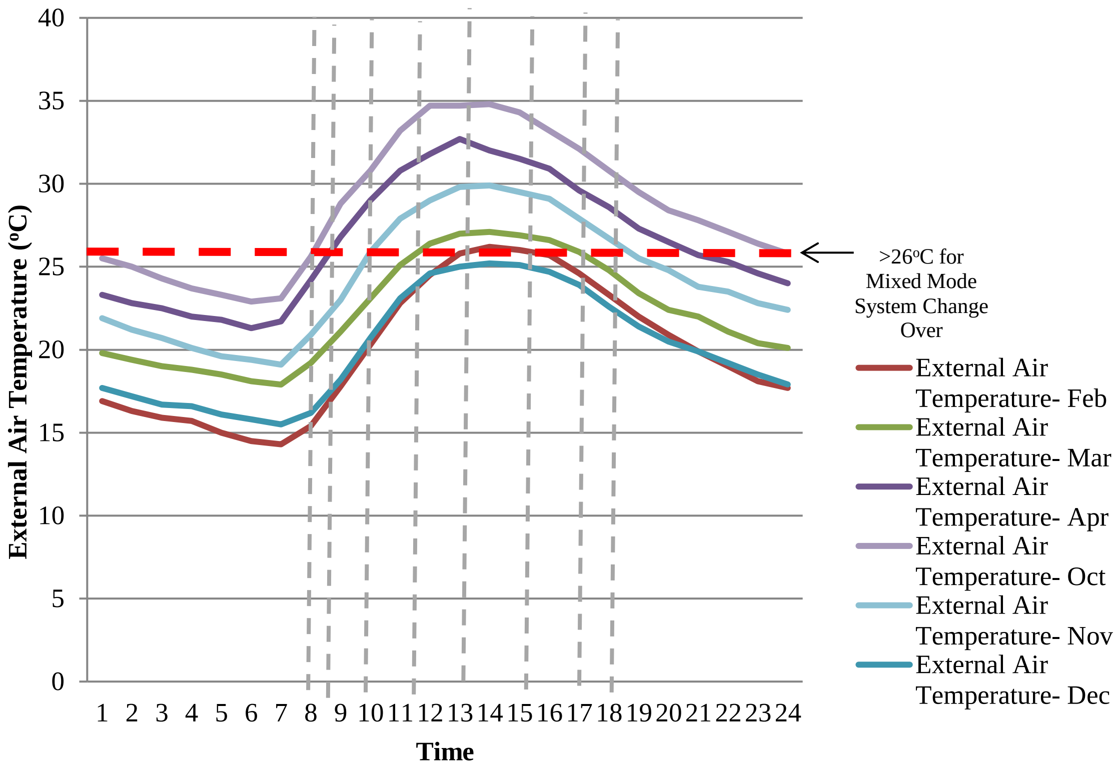


Figure H.5- External Air Temperature/Occupancy Periods (db>26°C)

Table H.4 shows month this is applicable, mechanical ventilation start and stop time approximated from Figure H.5, time difference in hours when compared to building model B.2 (Chapter 3) base case values. The occupied hours are divided into mechanical ventilation operational time (MV $_{(t)}$) and natural ventilation activation time (NV $_{(t)}$).

Table H.4- Time Period for External Air Temperature Exceeding 26°C

Month	MV (t) Start	MV (t) Stop	Time Difference (Hours)	Occupied Hours (Converted)		Available Working Days For Month (Mon - Fri)
				MV (t)-Time	NV (t)-Time	
February	13:00:00	15:05:00	02:05:00	2.083	8.917	20
March	11:30:00	17:00:00	05:30:00	5.5	5.5	20
April	08:30:00	18:00:00	09:30:00	9.5	1.5	22
October	07:50:00	18:00:00	10:10:00	10.167	0.833	23
November	09:55:00	18:00:00	08:05:00	8.083	2.917	20
December	N/A	N/A	N/A	0	0	17

H.5. Mechanical Ventilation Operation Period with a set point of 27°C

For a set point temperature of 27°C, six months are identified where the external temperature is equivalent or greater than the set point temperature and time operations are determined from Figure H.6 below.

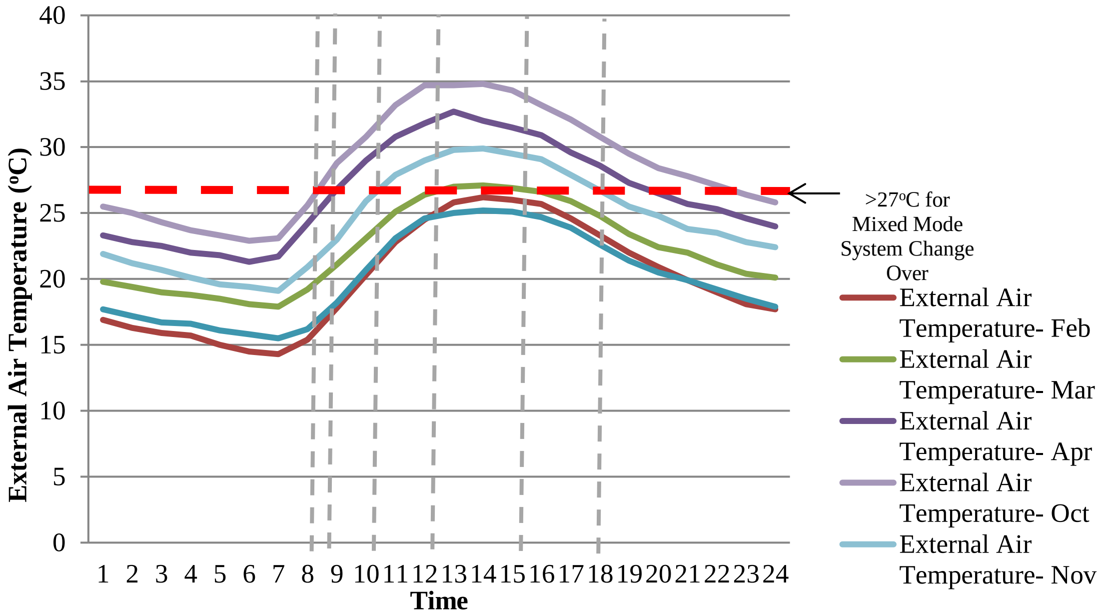


Figure H.6- External Air Temperature/Occupancy Periods (db>27°C)

Table H.5 shows month this is applicable, mechanical ventilation start and stop time approximated from Figure H.6, time difference in hours when compared to building model B.2 (Chapter 3) base case values. The occupied hours are divided into mechanical ventilation operational time (MV $_{(t)}$) and natural ventilation activation time (NV $_{(t)}$).

Table H.5- Time Period for External Air Temperature Exceeding 27ºC

Month	MV (t) Start	MV (t) Stop	Time Difference (Hours)	Occupied Hours (Converted)		Available Working Days For Month (Mon - Fri)
				MV (t)-Time	NV (t)-Time	
February	N/A	N/A	N/A	0	0	20
March	12:10:00	15:05:00	02:55:00	2.91	8.09	20
April	08:50:00	18:00:00	09:10:00	9.167	1.833	22
October	08:10:00	18:00:00	09:50:00	9.8	1.2	23
November	10:05:00	18:00:00	06:55:00	6.91	4.09	20
December	N/A	N/A	N/A	0	0	17

H.6. Mechanical Ventilation Operation Period with a set point of 28ºC

For a set point temperature of 28ºC, six months are identified where the external temperature is equivalent or greater than the set point temperature and time operations are determined from Figure H.7 below.

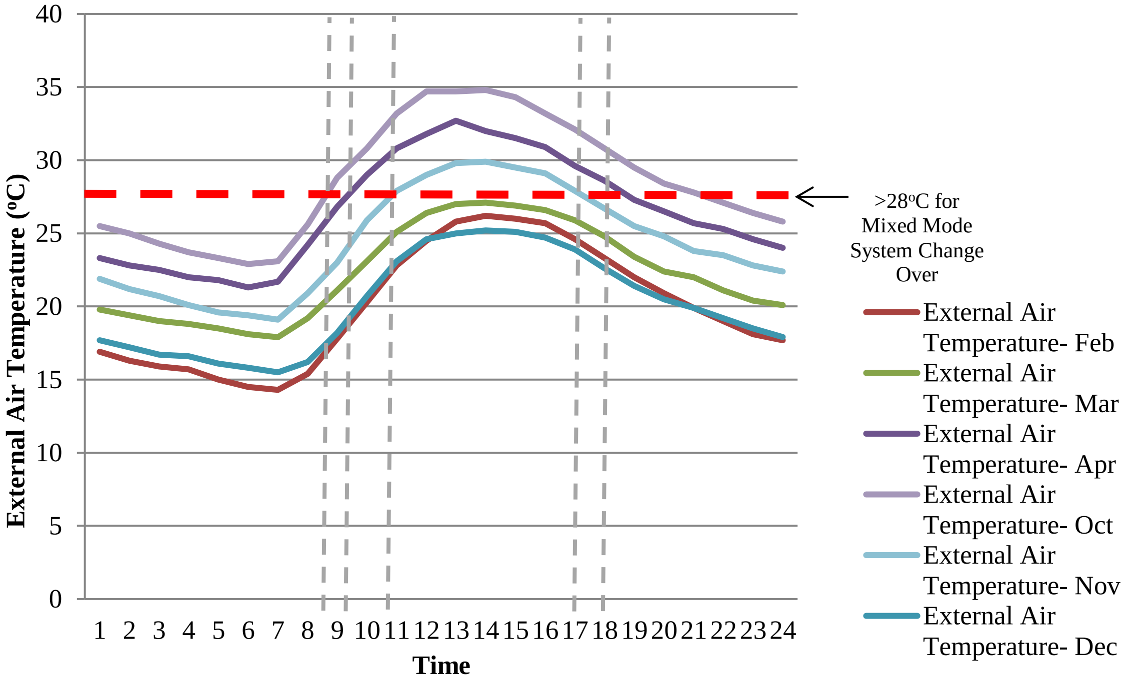


Figure H.7- External Air Temperature/Occupancy Periods (db>28ºC)

Table H.6 shows month this is applicable, mechanical ventilation start and stop time approximated from Figure H.7, time difference in hours when compared to building model B.2 (chapter 3) base case values. The occupied hours are divided into mechanical ventilation operational time ($MV_{(t)}$) and natural ventilation activation time ($NV_{(t)}$).

Table H.6- Time Period for External Air Temperature Exceeding 28°C

Month	MV (t) Start	MV (t) Stop	Time Difference (Hours)	Occupied Hours (Converted)		Available Working Days For Month (Mon - Fri)
				MV (t)- Time	NV (t)- Time	
February	N/A	N/A	N/A	0	11	20
March	N/A	N/A	N/A	0	11	20
April	09:15:00	18:00:00	08:45:00	8.75	2.25	22
October	08:30:00	18:00:00	09:30:00	9.5	1.5	23
November	10:45:00	17:00:00	06:15:00	6.25	4.75	20
December	N/A	N/A	N/A	0	11	17

Appendix I- Solar Chimney Performance Analysis

I.1. Performance Data For Solar Chimney Analysis

Heat gains to chimney stack are calculated using parameter identified in section 3.6.2, Chapter 3; are detailed in Table I.1, I.2 and I.3 below. These are used as a calculation basis for section 5.3.2, chapter 5.

Table I.1- Calculation Parameters for Solar Chimney Analysis (Single Glazed)

$1/A_p$	Ag (M^2)	ØS	g-eff (glazing)	Ma (kg/s)	Cp	T_i	T_o	ΔT_1
0.20	5	Existing Weather Data	0.7	Calculated	1.2	26	29	3

Table I.2- Calculation Parameters for Solar Chimney Analysis (Double Glazed)

$1/A_p$	Ag (M^2)	ØS	g-eff (glazing)	Ma (kg/s)	Cp	T_i	T_o	ΔT_1
0.20	5	Existing Weather Data	0.55	Calculated	1.2	26	29	3

Table I.3- Calculation Parameters for Solar Chimney Analysis (Double Glazed with Solar Treatment)

$1/A_p$	Ag (M^2)	ØS	g-eff (glazing)	Ma (kg/s)	Cp	T_i	T_o	ΔT_1
0.20	5	Existing Weather Data	0.3	Calculated	1.2	26	29	3

The effective g-values based upon manufactures detailed Pilkington (2015) information, where lower values are obtained from glazing that incorporates silver power coating or blue film treatment which deflects majority of external solar heat transmittance.

Appendix J- Ventilated Double Facades Performance Analysis

J.1. Performance Data For Ventilated Double Façade Analysis

Ventilated Double Façade is designed as 0.3m deep with low and high level external grills 18.92m (L) x 0.1m (W) for the complete length and height of the South façade. The parameters used to calculate heat gains and reduction are detailed in Table J.1 below. For external air temperatures and direct solar radiation, data was extracted from Designbuilder software.

Table J.1- Ventilated Double Façade Core Parameters

P	h_c	A_1 (m^2)	A_2 (m^2)	Ma (kg/s)	(Cd)	eff_{gg}
100	25	1.89	1.89	0.0183	0.61	0.8

Appendix K- Rain Screen Facades Performance Analysis

K.1. Performance Data For Rain Screen Façade Analysis

The rain screen façade consists of 13mm weatherboard and 200mm Air Gap (combined U value- 2.258W/m^2 K). The façade weather board are 1.995m (L) x 0.995m (w) panels allowing a 0.01m air gap between each panel. The parameters used to calculate heat gains and reduction are detailed in Table K.1 below. For external air temperatures and direct solar radiation, similar to method used in VDF.

Table K.1- Rain Screen Façade Core Parameters

Heat Transfer Co-efficient of Air	Air Flow Rate (l/s)	Ma (kg/s)	Equivalent Effective g value of Fibre Insulated weather board	U value of wall
25	100	0.12	0.6	0.25

For calculation of equivalent effective g-value of fibre board, using equation A.1 from Appendix A, rearranging for cavity temperature allows a comparative value against external air temperature in which this is derived. Table K.2 details the calculation for cavity air temperature and Table K.3 shows the calculated equivalent effective g-value which is used in the chapter 5 calculations.

Table K.2- Rain Screen Façade Cavity Temperature Calculation

T_{CA}	14.44	=	T_O	24	q	670			Δx	0.013
					k	0.048	A	18.98		

Table K.3- Equivalent Effective g-value for Weatherboard

T_{CA}	14.44	=	0.60
T_O	24		

Where; T_{CA} is temperature of air in cavity (°C); T_O is external air temperature (°C), q is solar irradiance (W/m^2); k is thermal conductivity (w/m k); A is surface area of weather board and Δ_x is weatherboard thickness (m). The thermal conductivity value (k) is taken from Engineering Toolbox (2014).

Appendix L- PDEC Performance Analysis

L.1. Description

This section provides background information on how PDEC parameters work and provides a basis for calculating cooling load reductions and effects to mechanical cooling energy when adopting this system. This appendix includes:

- PDEC System Parameters
- Effects of External Air Flow/Moisture Contents
- Available Cooling Capacities from PDEC system
- Daily Cooling Performance of PDEC System

L.2. PDEC System Parameters

Typical parameters for PDEC system operation are detailed in Table L.1 (below) and details maximum environmental ranges to be expected from this system.

Table L.1- Typical PDEC System Parameters

External Temperature (°C) Range	Air Flow Rate (m/s)	Microniser Flow Rate (kg/s) Range	Relative Humidity (%) Range	Internal Heat Gains (kW) Range
26-45	0.5-1	0.001-0.01	30-40	1-20

The PDEC system parameters are detailed in Table L.2 below. Dry bulb temperature maximum mean average is also used.

Table L.2- Typical PDEC System Parameters

Mass Flow Rate of Water kg/s	Air Flow Rate (kg/s)	Max. External Relative Humidity (%)
0.0092	0.5	50

L.3. Effects of External Air Flow/Moisture Contents

In order to determine cooling potentials of micronised vapour, analysis is completed to determine optimum micronised water to air based on external air temperature. Analysis detailed in Figure L.1 shows amount of water vapour that can be introduced (kg/hr) at variable flow rates without exceeding 50% relative humidity.

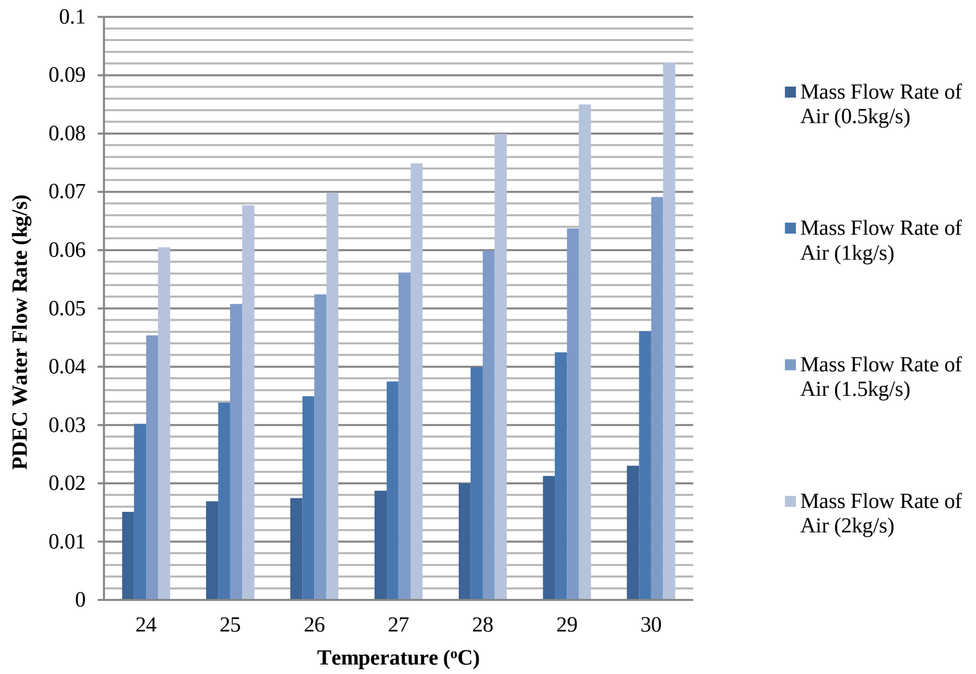


Figure L.1- Maximum Air Moisture Content of Air at Differing Air Flow Rates

As shown above, higher air flow rates allow for more water to be introduced into the supply air stream. Maximum water flow rates are depended on external relative humidity where lower external air moisture contents limit ability to absorb moisture (latent heat of water vapourisation). Table L.3 below shows total amount of water that can be absorbed into dry air for each temperature as detailed on CIBSE psychrometric chart providing base data for performance analysis.

Table L.3- Maximum Rate of Moisture Absorption <50%RH

Ability of Moisture absorption at Temperature (^{0}C)	Maximum Water Absorption Rate (<50%RH)	Total Amount of Moisture Absorption At Temperature (kg/s)
24	0.0094	0.0084
25	0.0104	0.0094
26	0.0107	0.0097
27	0.0114	0.0104
28	0.0121	0.0111
29	0.0128	0.0118
30	0.0138	0.0128

Total change in enthalpy and moisture content can also be determined from CIBSE psychrometric chart. Values for specific enthalpy (dry air) and moisture content for relative humidity’s 30%, 40% and 50% are taken from CIBSE psychrometric chart. Interpolation of these values leave an approximate error of +/-5%. The differing values of specific enthalpy and moisture content are shown in Figure L.2 and L.3 below.

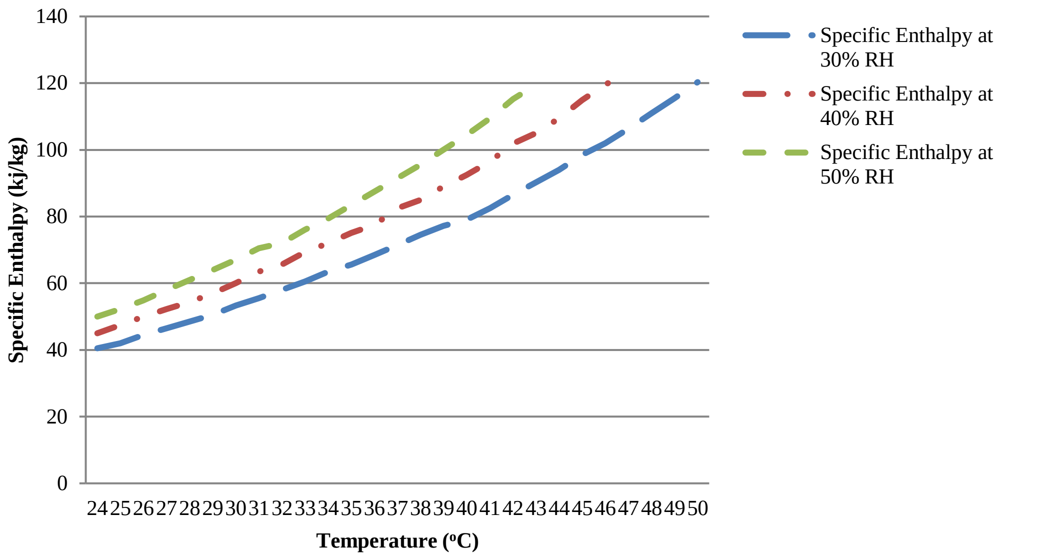


Figure L.2- Specific Enthalpy at Varying Humidity's

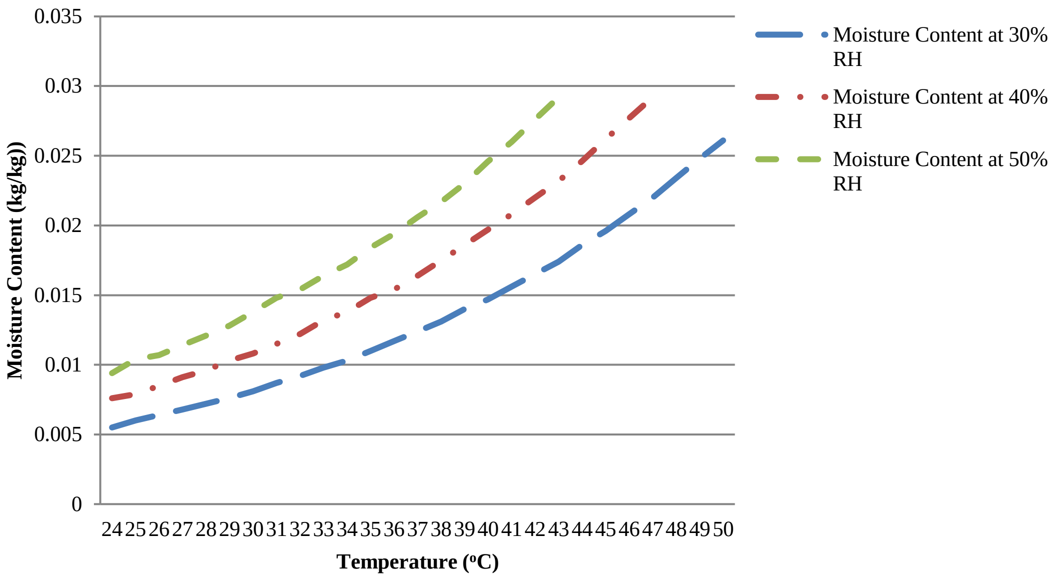


Figure L.3- Moisture Content at Varying Humidity's

PDEC cooling capacity can be calculated using a combination CIBSE psychrometric charts and equations detailed in section 3.6.5 in chapter 3 to determine cooling potential for each maximum dry bulb air temperature and external air humidity enabling cooling load to be deducted from simulated base case (Q_{Sim}).

L.4. Available Cooling Capacities from PDEC system

It is important to ensure thermal comfort parameters are achieved and target comfort zone is defined by research completed on bioclimatic charts (Lomas et al, .2004). Total cooling load associated with a PDEC system is a function of external air temperature, air mass flow rate and rate of water micronisation (Q_{PDEC}) based upon specific enthalpy. Using this method of calculation, PDEC cooling potential is determined for temperatures between 24°C to 50°C and PDEC system water flow rate of 0.0092kg/s. Calculating cooling load potential (Q_{PDEC}) at different relative humidity's is detailed below in Figure L.4.

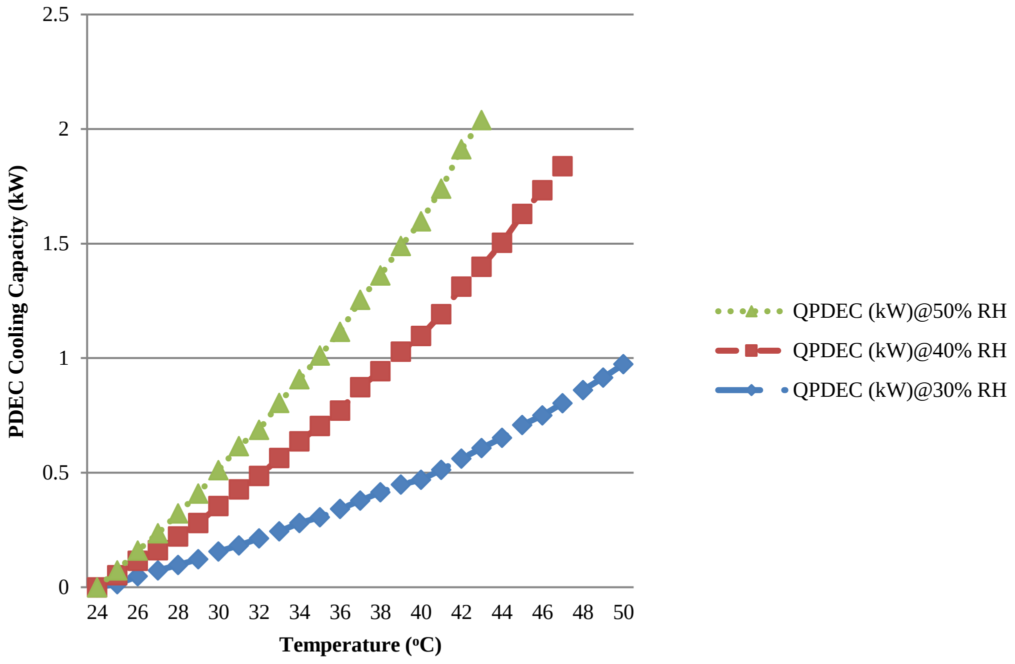


Figure L.4- PDEC Cooling capacities

Increasing PDEC water flow rates can improve the rate of cooling capacity available as shown in Table L.4 below at a limiting humidity of 50%RH.

Table L.4- Cooling Capacities at Varying PDEC Water Flow Rates

Minimum External Air Temperature (^{0}C)	Total Amount of Moisture Absorption At Temperature (kg/s)	% Increase in Cooling Capacity
26	0.0095	3.15
27	0.0105	12.38
28	0.0115	16.36
29	0.0122	24.59
30	0.0132	30.30

The limiting factor identified is additional cooling capacity's can only be achieved at given external air temperature i.e. higher PDEC water flow rates at lower temperatures will increase relative humidity beyond 50%.

L.5. Daily Cooling Performance of PDEC System

Using cooling capacities shown in Figure L.4, diurnal analysis of temperature reduction for varying relative humidity (hourly) is shown below in Figure L.5 where the mass flow rate of air is 0.5kg/s. The greater temperature reductions are observed at 14:30.

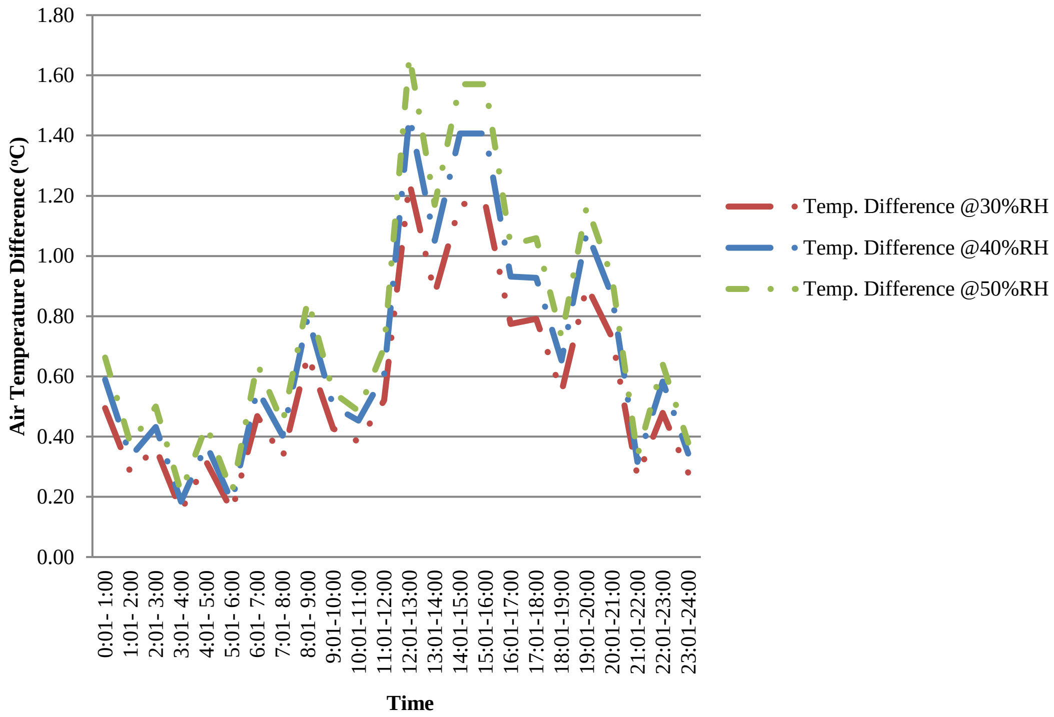


Figure L.5-Daily Temperature Reduction Comparison Using PDEC System

For maximum daily temperature reductions using PDEC system, calculated values show maximum temperature differences of 1.24ºC (30% RH), 1.46ºC (40% RH) and 1.67ºC (50% RH).

Appendix M- Earth Ducts Performance Analysis

M.1. Description

This section provides background information on earth duct parameters and provides a basis for calculating cooling load reductions including effects on mechanical cooling energy when adopting this system. This appendix includes:

- Earth duct parameters
- Minimum air velocity to achieve turbulent air flow

M.2. Earth Duct Parameters

Earth duct parameters for an earth duct system are detailed in Table M.1 below:

Table M.1- Earth Duct Parameters & Unit

Parameter	SI Unit	Notation	Value
Thermal Conductivity of Material	W	K	0.1 to 0.6
Length	M	L	10
Surface Area of a Cylinder	M^2	As	-
Volume	M^3	V	0.64
Wall Resistance of Earth Duct	W/M^2 K	Rwall	-
Outside Diameter of Earth Duct	mm	Do	-
Inside Diameter of Earth Duct	mm	Di	-
Thermal Heat Loss	W	Q	-
Volumetric Flow Rate of Air	M^3/S	V	-
Air Flow Rate	l/s	q	-

For common types of materials used for this type of system, calculation parameters for heat loss from external air to ground are shown below in Table M.2 below. The thermal conductivity values (k) are taken from Engineering Toolbox (2014).

Table M.2- Earth Duct Calculation Parameters

Earth Duct Materials	Cross Sectional Area-M^2	Volume (V)-M^3	Surface Area (As)-M^2	Thermal Conductivity (k)	Diameter (D)	Wall Thickness (mm)	Length (m)
Clay (Dry to Moist)	0.64	6.36	1.30	0.15	900	10	10
Clay (Saturated)	0.64	6.36	1.30	0.6	900	10	10
Concrete (Lightweight)	0.64	6.36	1.30	0.1	900	10	10
Concrete (Medium weight)	0.64	6.36	1.30	0.4	900	10	10

M.3. Minimum Air Velocity to Achieve Turbulent Air Flow

Using equation B.23 in appendix A, the minimum air velocity (V) required to achieve turbulent air flow to increase air to surface contact with earth duct walls is detailed below in Table M.3.

Table M.3- Minimum Air Velocity Required for Turbulent Air Flow

Parameter	Value	Metric
Re_d	2300	Non Dimensional
ρ	1.2	kj/kg
V	**0.034053**	**m/s**
d	0.9	m
μ	1.599×10^{-5}	Kg/m s

Appendix N- External Solar Shading Analysis (Building Model B.1)

N.1. Description

This section shows calculations completed for external solar shading to all windows for building model B.1. This incorporates optimum solar shading solution discovered on chapter 4 (multi-angled). This section analyses maximum heat gains (sensible and latent) and energy performance analysis and comparing against building model B.1 base case.

N.2. Performance Analysis

Figures N.1 (Portugal) and N.2 (Kenya) below show impacts on maximum space cooling load for each month when compared against the base case model.

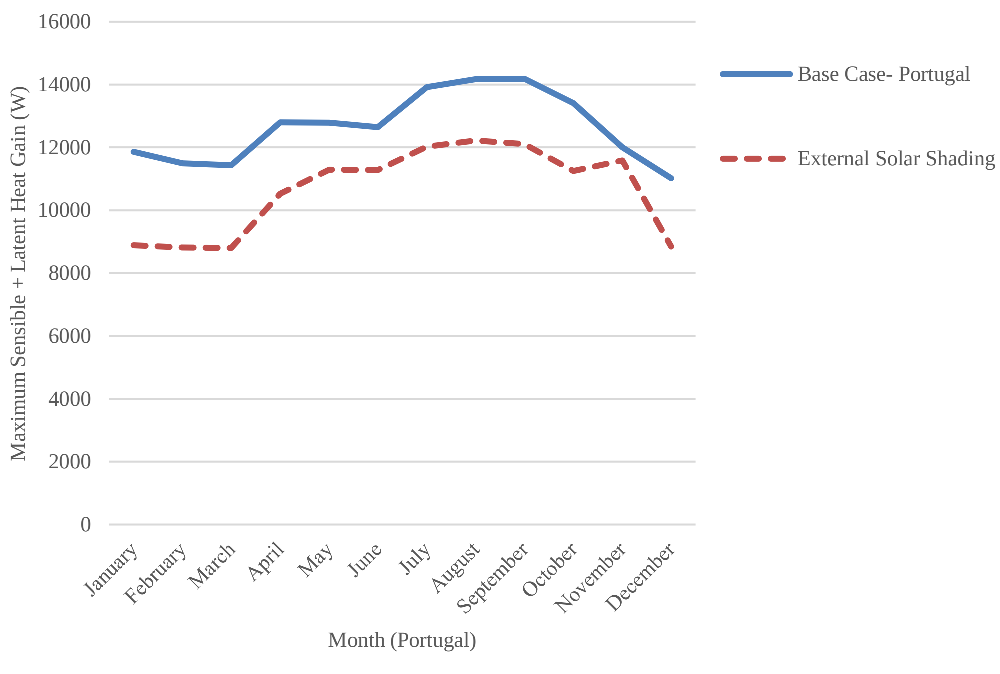


Figure N.1- Maximum Heat Gain Performance Analysis of External Solar Shading for Portugal

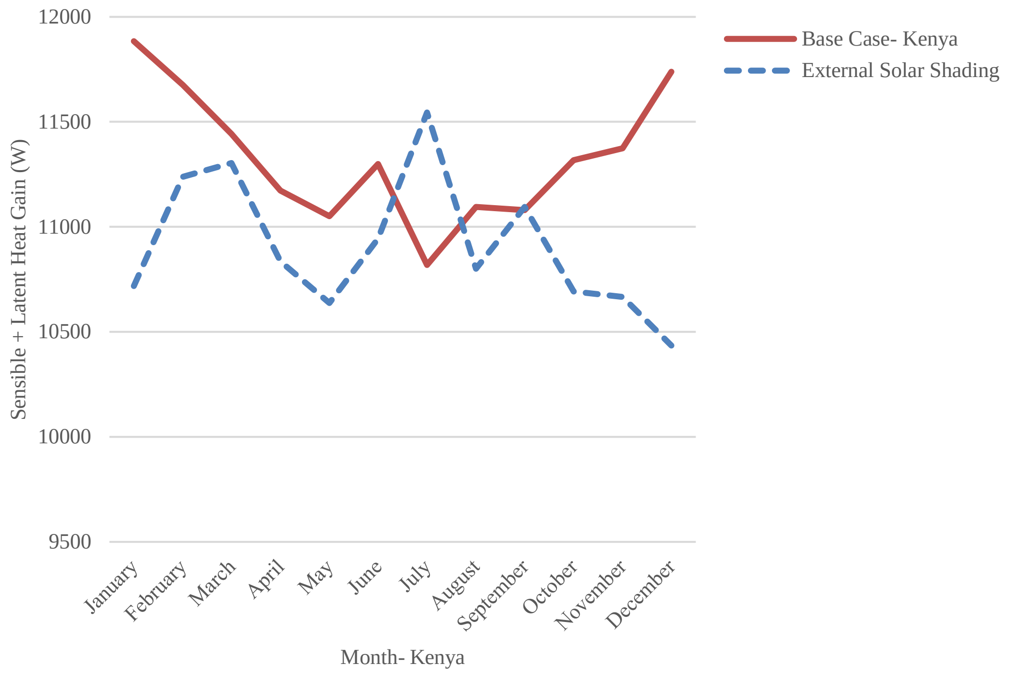


Figure N.2- Maximum Heat Gain Performance Analysis of External Solar Shading for Kenya

Figure N.2 above shows that in July, there is no reduction due to low solar azimuth. Figures N.3 and N.4 below show annual energy performance when adopting external solar shading

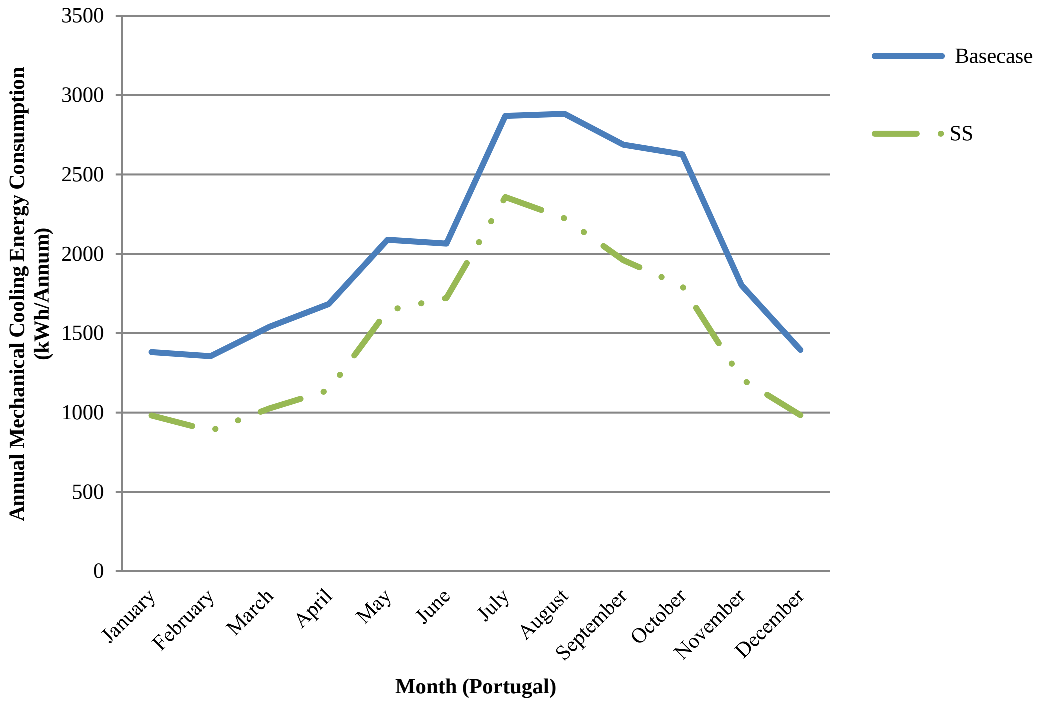


Figure N.3- Annual Mechanical Cooling Energy Performance Adopting External Solar Shading for Portugal

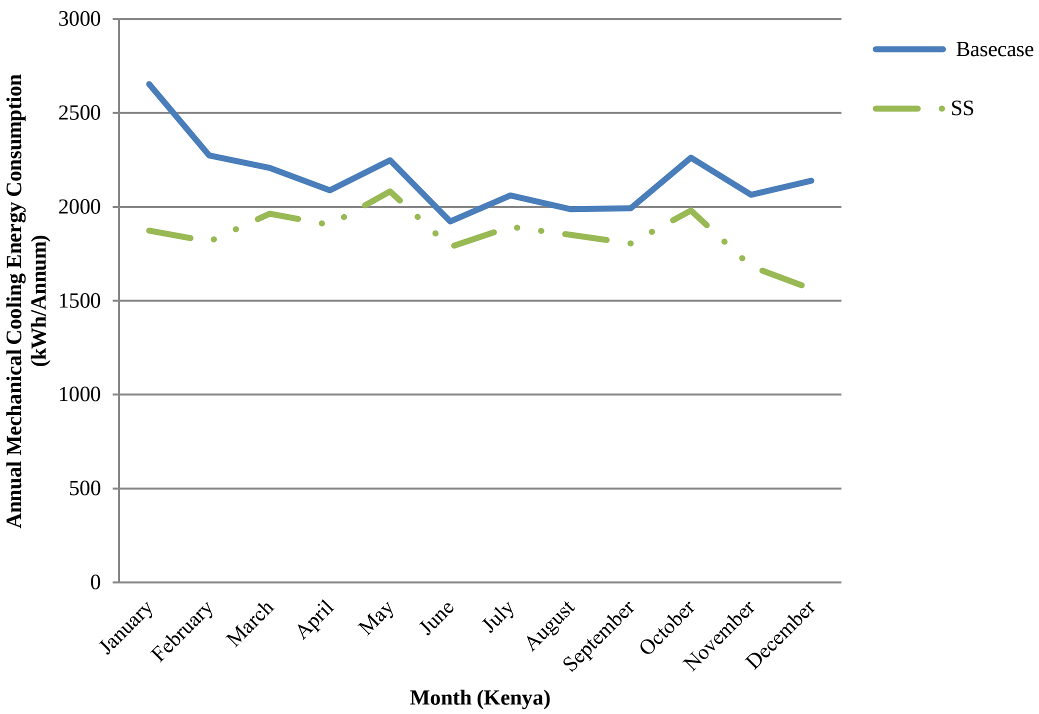


Figure N.4- Annual Mechanical Cooling Energy Performance Adopting External Solar Shading for Kenya

Table N.1 (Portugal) and N.2 (Kenya) below show actual DTS simulated values and percentage reductions for each month.

Table N.1- DTS Values for Model B.1 Located in Portugal

Month	Base case Energy Values for Portugal	SS Energy Reduction	Revised Basecase Energy Demand Incorporating SS	Reduction against Base Case
	Zone/Sys Cooling Energy [kWh]	[kWh]	Zone/Sys Cooling Energy [kWh]	%
January	1379.78	399.64	980.14	29
February	1354.73	470.16	884.57	35
March	1539.08	514.41	1024.67	33
April	1682.68	541.88	1140.8	32
May	2089.06	445.63	1643.43	21
June	2064.58	343.39	1721.19	17
July	2868.81	511.33	2357.48	18
August	2881.99	659.36	2222.63	23
September	2687.97	729.23	1958.74	27
October	2626.52	830.2	1796.32	32
November	1801.03	590.38	1210.65	33
December	1395.41	412.05	983.36	30
Total	24,372		17,924	26

Table N.2- DTS Values for Model B.1 Located in Kenya

Month	Base case Energy Values for Kenya	SS Energy Reduction	Revised Basecase Energy Demand Incorporating SS	Reduction against Base Case
	Zone/Sys Cooling Energy [kWh]	[kWh]	Zone/Sys Cooling Energy [kWh]	%
January	2653.79	780.59	1873.2	29
February	2273.94	458.03	1815.91	20
March	2207.93	244.94	1962.99	11
April	2088.48	184	1904.48	9
May	2247.77	165.51	2082.26	7
June	1922.29	136.73	1785.56	7
July	2061.28	167.1	1894.18	8
August	1987.68	136.88	1850.8	7
September	1992.78	187.75	1805.03	9
October	2261.3	280.45	1980.85	12
November	2064.2	382.3	1681.9	19
December	2139.84	576.66	1563.18	27
Total	25,901		22,200	14

N.3. Verification of Mechanical Cooling Energy Reductions

Direct verification of energy reduction values is difficult to determine as similar analysis only review effects of an individual shading device types. As climates vary, levels of cooling load reduction can only be determined by simulation of identical external solar shading in identical climate using similar building parameters. As detailed in section 2.8.3 (Chapter 2), cooling reduction identified as 32 percent for a building in Shiraz, southern Iran (Walliman and Resalati, 2011) but it is difficult to verify against various unknown building parameters (published).

Appendix O- Passive System Energy Assessment Tool (PSEAT)

O.1. Overview

This section provides a hard copy overview of the passive system energy assessment tool. Section provided include:

- Instructions
- PSEAT User Interface/Outputs
- Data A- Alternative Climate Base case Mechanical Cooling Energy Data
- Date B- Natural Ventilation Set Point Percentage Reduction Data
- Data C- External Solar Shading Percentage Reduction Data
- Data D – PDEC Percentage Reduction Data
- Data E – Earth Duct Percentage Reduction Data
- Data F- Mechanical Cooling Outputs- Natural Ventilation Impacts for Various Climates
- Data G- BREEAM Credit Data for Energy 4 Credits (Ene 4)

INSTRUCTIONS

Passive System Energy Assessment Tool (PSEAT)

General

1 This performance assessment tool has been created to enable simultanious assessment of passive ventilation and cooling systems when reducing HVAC energy per annum.
2 This performance assessment tool is intended to be used at RIBA Stage 2 (Concept Design).
3 Approximate values are calculated and will have a margin of error of +/-0-5% when applying percentages to different hot climates. Where greater acuracy is required, calculation methods identified in Chapter 3 should be adopted.
4 The percentages used for annual energy reductions are calculated for each passive system in Chapters 4 & 5.
5 Base Case Building Model B.1 Is used as a basis these results.
6 Individual Instructions are given in RED at specific points on the Performance Assessment Tool Sheet.
7 Use the control panels drop down menu's (Embedded in cell) to select specific parameters highlighted in Chapter 4 & 5.
8 For External Solar Shading, All mean East, South and West Elevations
9 BREEAM Credit are on the basis that a feasibility study has been completed (Excluding Life Cycle Assessment). Furthermore, exemplary level is ignored in this calculation (Reductions>30%)
10 For details on Theoretical Building Model B.1 refer to section 3.3.10, Chapter 3.
11 Natural ventilation reductions are based upon combined ventilation and cooling energy values.
12 Conversion for kgCO2/kWh can be changed in cell to enable user to update per country.

Limitations

a) BEMS Set points are calculated from Chapter 5 using Abu Dhabi Climate data. There will be a margin of error of +/-0-5% in reductions and user should refer to Chapter 6 for further details.
b) Ventilated double facades must be connected to all internal spaces in order to for approximate reduction.
c) Rain screen façade reductions apply when all building fabric (excluding windows, roof and doors) is provided.
d) Further worksheets are supporting data taken from Chapters 4 and 5. Data A is Basecase Mechanical cooling data from Model B simulations; Data B is Natural Ventilation Data; Data C is External Solar Shading Data; Data C is PDEC Data; Data E is Earth Duct Data.
e) For data B, C, D & E; averages are taken from calculated annual cooling energy reduction results detailed in Chapter 5.
f) This tool does not allow for fabric anaylsis, heat gain or heat loss analysis.

Location/Climate	Base Case Mechanical Cooling Electrical Energy (kWh/Annum)	Percentage Reduction Incorporating Passive Systems with HVAC (%)	Revised Mechanical Cooling Electrical Energy (kWhr/Annum)	Energy Cost/Annum (£)	Energy Cost Saving (£)	Carbon Dioxide Production/Annum ($kgCO_2$)	Mechanical Cooling Energy Reduction (kWh/m^2/Annum)
Select Location/User Defined From In Cell Drop Down Menu Below (A6)							
Defined By User	**25,000.00**	-	-	**£2,750.00**	-	**14,250.00**	-
Passive System Type	***System Active (Yes/No)*** ***Select from Drop Down Menu in Cell***						
Natural Ventilation for Cooling (NV)	Yes	20.31	19,922.50	£2,191.48	£558.53	11,355.83	99.61
External Solar Shading (SS)	Yes	3.1	24,225.00	£2,664.75	£85.25	13,808.25	121.13
Ventilated Double Façade (VDF)	Yes	2	24,500.00	£2,695.00	£55.00	13,965.00	122.50
Rain Screen Façade (RSF)	Yes	6	23,500.00	£2,585.00	£165.00	13,395.00	117.50
Passive Downdraught Evaporative Cooling (PDEC)	Yes	12.595	21,851.25	£2,403.64	£346.36	12,455.21	109.26
Earth Duct (ED)	Yes	12.535	21,866.25	£2,405.29	£344.71	12,463.76	109.33

Summary of Reduction	*BaseCase*	*Totals for All Passive Systems (Reductions)*
Total Annual Energy Reduction (kWh/Annum)	25,000.00	10,865.00
Total Carbon Dioxide Production ($kgCO_2$/Annum)	14,250.00	6,193.05
Total Mechanical Cooling Energy Cost Per Annum	£2,750.00	£1,195.15

Calculated Value for Mechanical Cooling Energy Reduction (kWh/m^2/Annum)	**54.33**
Benchmark Value for Mechanical Cooling Energy (kWh/m^2/Annum) (Table 3.2, Chapter 3)	**156.60**
Total Percentage Reduction Per Annum (%)	**56.54**
Mechanical Cooling Electricity Cost (m^2/Annum)	**5.98**
BREEAM Credits Available (Based Upon CO_2 Reductions)	**4.00**

User Control Panel (Select Values from In Cell Drop Down)	
User Defined Basecase Annual Cooling Energy (kWh/Annum) (Manual Input); If Required	25,000.00
Natural Ventilation & Cooling BEMS Internal Air Temperature Set Point (^oC)	26
Window Orientation for External Solar Shading	East
Type of External Solar Shading	Angled
Average Relative Humidity (%RH)	50%RH
Earth Duct Material	Dry Clay
Electricity Unit Cost (£) Per kWh (Manual Input)	0.11
Conversion for $kgCO_2$/kWh (Manual Input)	0.57

Data A- Alternative Climate Base case Mechanical Cooling Energy Data

Location	Base Case Cooling (kWh/Annum)- Model B.1
Abu Dhabi	43,776.78
Adelaide City, Australia	24,425.15
Aswan, Egypt	46,913.50
Cape Town, South Africa	21,911.92
Defined By User	25,000.00
Doha, Qatar	43,584.80
Hyderabad, India	42,441.51
Istanbul, Turkey	20,692.95
Lisbon, Portugal	24,371.64
Nairobi, Kenya	25,901.28
San Fransisco, Calafornia, USA	20,844.22

Date B- Natural Ventilation Set Point Percentage Reduction Data

Natural Ventilation

BEMS Set Point Temperature for HVAC	Percentage Reduction Based upon Set Point (%)	List
24	11.34	Yes
25	16.03	No
26	20.31	
27	24.93	
28	27.99	

Data C- External Solar Shading Percentage Reduction Data

List	List	Orientation	Type of External Solar Shading	Annual Energy Reduction (%)	All (East, South & West)	Combined (%)
All	Horizontal	East	Horizontal	1.23	Horizontal	4.55
East	Vertical	East	Vertical	2.04	Vertical	7.24
South	Angled	East	Angled	3.1	Angled	9.91
West	Multi-Angled	East	Multi-Angled	11.27	Multi-Angled	33.92
		South	Horizontal	2.33		
		South	Vertical	3.31		
		South	Angled	4.11		
		South	Multi-Angled	12.31		
		West	Horizontal	0.99		
		West	Vertical	1.89		
		West	Angled	2.7		
		West	Multi-Angled	10.34		

Result	East Angled	
	All Angled	9.91
	All Horizontal	4.55
	All Multi-Angled	33.92
	All Vertical	7.24
	East Horizontal	1.23
	East Vertical	2.04
	East Angled	3.1
	East Multi-Angled	11.27
	South Horizontal	2.33
	South Vertical	3.31
	South Angled	4.11
	South Multi-Angled	12.31
	West Horizontal	0.99
	West Vertical	1.89
	West Angled	2.7
	West Multi-Angled	10.34

Data D – PDEC Percentage Reduction Data

Average Relative Humidity (%RH)
30
40
50

	% Annual Cooling Energy Reduction		
	30%RH	40%RH	50%RH
Portugal	6.87	14.4	15.96
Lisbon	12.11	8.37	9.23
	30%RH	40%RH	50%RH
Average	**9.49**	**11.385**	**12.595**

	%RH	
Average	30	9.49
	40	11.385
	50	12.595

Data E – Earth Duct Percentage Reduction Data

Earth Duct Material	Lightweight Concrete	Medium Concrete	Dry Clay	Dry Clay (Saturated)
Lisbin, Portugal	7.81	25.6	11.33	33.78
Nairobi, Kenya	9.48	31.07	13.74	40.34
Average	8.645	28.335	12.535	37.06

Dry Clay	12.535
Dry Clay (Saturated)	37.06
Lightweight Concrete	8.645
Medium Concrete	28.335

Data F- Mechanical Cooling Outputs- Natural Ventilation Impacts for Various Climates

	Base Case Cooling (kWh/Annum)- Model B.1	Revised Annual Energy Consumption (kWh/Annum) at BEMS Set Point 24 Degrees Celcius	Revised Annual Energy Consumption (kWh/Annum) at BEMS Set Point 25 Degrees Celcius	Revised Annual Energy Consumption (kWh/Annum) at BEMS Set Point 26 Degrees Celcius	Revised Annual Energy Consumption (kWh/Annum) at BEMS Set Point 27 Degrees Celcius	Revised Annual Energy Consumption (kWh/Annum) at BEMS Set Point 28 Degrees Celcius
Lisbon, Portugal	24371.64	18,209.23	16,708.09	14,637.05	14,511.00	13,324.62
Nairobi, Kenya	25901.28	19,352.10	17,756.74	15,555.72	15,421.75	14,160.91
Abu Dhabi	43776.78	32,707.75	30,011.37	26,291.34	26,064.92	23,933.92
Aswan, Egypt	46913.5	35,051.35	32,161.76	28,175.18	27,932.53	25,648.84
Istanbul, Turkey	20692.95	15,460.71	14,186.15	12,427.72	12,320.69	11,313.38
San Fransisco, Calafornia, USA	20844.22	15,573.73	14,289.85	12,518.56	12,410.75	11,396.08
Adelaide City, Australia	24425.15	18,249.21	16,744.77	14,669.19	14,542.86	13,353.87
Hyderabad, India	42441.51	31,710.11	29,095.97	25,489.41	25,269.89	23,203.89
Doha, Qatar	43584.8	32,564.32	29,879.76	26,176.04	25,950.61	23,828.95
Cape Town, South Africa	21911.92	16,371.46	15,021.82	13,159.80	13,046.47	11,979.82

Data G- BREEAM Credit Data for Energy 4 Credits (Ene 4)

BREEAM Credits for Ene 4

Percentage Reduction in energy Made	Credits Available
0	0
10	3
20	4

Credits Available	
Free Cooling	1
% reduction in regulated CO_2 emissions	
10%	2
20%	3

Appendix P- Passive System Energy Assessment Tool (CD ROM)

P.1 Overview

Enclosed with this thesis document is PSEAT in Microsoft Excel Format on CD ROM.