METHODOLOGY TO INVESTIGATE THE ENERGY AND INDOOR ENVIRONMENTAL PERFORMANCE OF TYPICAL EGYPTIAN OFFICES

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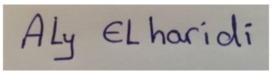
I would like to dedicate this thesis to my loving parents, wife & son …

Declaration

I hereby declare that this thesis and all material contained herein is a record of work carried out in the Department of Mechanical & Aerospace Engineering, Energy Systems Research Unit [ESRU], Engineering Faculty, University of Strathclyde during the period from January 2012 to December 2016. This thesis is the result of the author's original research except where otherwise indicated. It has been composed by the author and has not been previously submitted for examination, which has led to the award of a degree.

Signed: 

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Publications

In addition to this thesis, the research has been captured in a number of publications. These publications represent the research of the lead author and the supervisory inputs of the co-authors.

- **Aly M. Elharidi**, C. Joumaa, M.A. Elazm, M. A., and Ahmed F. Elsafty. (2013). Case study analysis for building envelop and its effect on environment. Energy Procedia, 36, 958-966.
- **Aly M**. **Elharidi**, P.G. Tuohy, and M.A. Teamah. “Facing the growing problem of the electric power consumption in Egyptian residential building using building performance simulation program”. Building Simulation Cairo 2013 Conference, IBPSA Egypt. 2013.
- **Aly M**. **Elharidi**, P.G. Tuohy, M.A. Teamah., and A.A. Hanafy "Calibration of numerical simulations modelling of non-residential building in hot humid climate region." BS2015, 14th International Conference of the IBPSA. 2015.
- **Aly M. Elharidi** and Paul G. Tuohy "Capturing uncertainty in operation, behaviour and weather in building performance assessment: An Egyptian case study." NCEUB, 9th Windsor Conference. 2016.
- **Aly M**. **Elharidi**, P.G. Tuohy, M.A. Teamah., and A.A. Hanafy "Energy and indoor environmental performance of typical Egyptian offices: Survey, baseline model and uncertainties." Energy and Buildings 135 (2017): 367-384.
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Abstract

Buildings are a contributor to increasing electricity demand in Egypt, straining the existing supply network causing economic and social impacts. Current initiatives that aim to improve building performance include the adoption of international standards. Existing Egyptian buildings performance is not understood making the impact of current initiatives uncertain.

The main aim of this thesis is to better understand current energy performance and Indoor Environmental Quality (IEQ) for Egyptian office buildings and capture this knowledge in methods to inform new Egyptian policy.

Performance of current Egyptian office buildings was assessed through a 59 office energy survey and a more detailed energy and indoor environmental investigation for a case study office. The case study office was representative of the most common type found in the survey which has natural ventilation and locally controlled cooling systems. Naturally ventilated offices with local cooling were found to use less than 50% of the energy of fully centrally serviced offices.

A two-step process to capture the observed performance in a representative model and input parameter set is elaborated based on first creating a calibrated model for the case study office; then adjusting this model to be more representative of the broader survey data. The representative model uses the appropriate thermal comfort standard selected by comparing observations against various pre-existing comfort standards. Uncertainties are captured in the formulation of the model input parameter sets.

The representative model is then used to investigate the impacts of parameters including location, weather, building envelope, occupancy, behaviour, and installed systems including Heating, Ventilation, & Air Conditioning (HVAC) strategy. HVAC strategy installed system efficiencies and occupant behaviour was identified as the three most influential parameters.

Possible policy measures to promote system energy efficiencies and encourage adoption of energy conscious behaviour are proposed. Together these can reduce the energy used in the naturally ventilated and locally cooled offices by 50%. Trade-offs between energy use and IEQ are discussed.

In summary, this research gives new insight into energy, indoor environmental conditions and behaviour in Egyptian office buildings. A new method for defining a representative model capturing uncertainties in input data sets is elaborated. The representative model's use to identify the impacts of various parameters for the Egyptian context is illustrated through a combinatorial parametric study. Insights useful to inform future Egyptian policy were proposed. The methodology developed in this work has applicability to other contexts and building categories.

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Nomenclature

Symbol	Description	Units
Δ	Delta	-
h	Enthalpy	kJ/kg
LL_{person}	Latent heat generated by one person	W/person
m^{-}	Mean measured data	-
m_{air}	Mass flow rate of the air moving from outside the room to inside	kg/s
m_i	Simulated data at instance time	-
n	The count of the number of values used in the calculation	-
N_{person}	Number of persons	Person
R^2	coefficient of determination	-
RLL	Room latent load	kW
s_i	Measured data at instance time	-
$T_{(Comf\ (ASHRAE\ 55))}$	Indoor operative comfort temperature based on the ASHRAE 55 Standard	̊C
$T_{(Comf(EN15251))}$	Indoor operative comfort temperature based on the EN15251 Standard	̊C
T_{Comf}	Indoor operative comfort temperature	̊C
$T_{e(d)}$	Daily mean outdoor temperature	̊C
$T_{e(d-1)}$	Daily mean outdoor temperature for day before	̊C
$T_{e(m)}$	Mean Monthly out door dry bulb temperature	̊C
T_{rm}	Running mean daily outdoor temperature	̊C
α_{rm}	The speed at which the running mean responds to outdoor temperature	-

Abbreviations

ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BC	Base Case
BEEC	Building Energy Efficiency Code
BEPS	Building Energy Performance Simulation
BES	Building Energy Simulation
BESt	Building Energy Standards
CAD	Computer-Aided Design
CCS	Central Cooling System
CIBSE	Chartered Institution of Building Services Engineers
CRT	Cathode Ray Tube
CS	Calibrated Simulation
CUEER	Cooling Use Electrical Efficiency Ratio
CV(RMSE)	Coefficient of Variation of Root Mean Square Error
CWEC	Canadian Weather Year for Energy Calculation
D.F.	Diversity Factor
DHW	Domestic Hot Water
DOE	US Department of Energy
DRY	Design Reference Year
DSY	Design Summer Year
ECG19	Energy Consumption Guide 19
ECP	Egyptian Commercial Buildings Energy Code
EIA	Energy Information Administration
EPBD	Energy Performance of Buildings Directive
ETMY	Egyptian Typical Methodology Year
EU	European Union
HR	Human Resources
HVAC	Heating, Ventilation, & Air Conditioning
IC	Influence Coefficient
IEQ	Indoor Environmental Quality
IES-VE	Integrated Environmental Solution – Virtual Environment

IP	Input Variables
IWEC	International Weather for Energy Calculations
LCS	Local Cooling Systems
LEED	Leadership in Energy & Environmental Design
LPD	Lighting Power Density
M.F.	Modulating Factor
MBE	Mean Bias Error
MEES	Middle East Economic Survey
MENA	Middle East and North Africa
MV	Mechanical Ventilation
NCS	No Cooling System
NV	Natural Ventilation
OP	Output Variables
p.a	Per Annual
p.m	Per Month
PMV	Predicted Mean Vote
PPD	Percentage of People Dissatisfied
RMSE	Root Mean Square Error
SEER	Seasonal Energy Efficiency Ratio
TMY	Typical Meteorological Year
TMY2	Typical Meteorological Year 2
TRY	Test Reference Year
UK	United Kingdom
USA	United States of America
WYEC	Weather Year for energy Calculations
WYEC2	Weather Year for energy Calculations 2

Chapter 1 RESEARCH OVERVIEW

1.1 Introduction

The demand for energy has been a concern for governments since the world energy crisis of the 1970s and the more recently observed phenomenon of global warming, which is a threat to the future of humanity. In all countries governments are upgrading their codes and developing policies with the aim of reducing the demand for energy derived from fuel combustion, such as electricity generated in traditional fossil fuel burning power stations, or of replacing it with renewable energies.

The building sector is one of the biggest consumers of energy in many countries. Energy use in office buildings has risen in recent years because of the growth in information technology, air-conditioning (sometimes specified when not required), and intensity of use. Recent international surveys have shown that office buildings are one of the most common building types and the greatest energy consumers in the developed countries [1, 2] though in some developing countries the energy consumed by residential buildings exceeds the commercial buildings' portion [3, 4].

In common with many other nations, Egyptian peak and base load electricity demands have increased substantially since the 1990s, contributing to the increasing occurrence of power cuts and blackouts with significant economic, political and social impacts. One key driver for demand growth has been increased urban development concentrated in the Nile Delta [5]. This development was not required to meet any energy performance standards until 2005 with the introduction of a new code, the Egyptian Commercial Buildings Energy Code (ECP) 306-2005 [3]. The urban development resulted in particular problems with cooling demands in summer months, also associated with a shift away from traditional vernacular designs [6]. Clients and the majority of designers are inclined to adopt air-conditioned commercial building designs that maintain a high level of occupant satisfaction at the expense of relatively high energy consumption and carbon emissions.

Energy performance analysis plays a major role in developing an optimum design and operation of new buildings and in determining the most effective modifications to existing buildings. In new buildings, it is important that the energy analysis process is implemented for individual design decisions early in the design process. In existing buildings, a comprehensive energy analysis is a basis for making rational decisions on cost-efficient building and systems modifications. As the need for making accurate energy utilization decisions has become more and more important, many standards and codes have been adopted which require energy analysis procedures to demonstrate compliance. Research studying energy performance and Indoor Environmental Quality (IEQ) has focused mostly on European buildings, for example Energy Consumption Guide 19 (ECG19) [7].

The challenge is to find a methodology to study the energy performance and the IEQ in the Egyptian building sector, especially the existing office buildings, with the aim of developing a well-founded policy for this area given the scarcity of comprehensive research in this field.

Since the late 1960s various methods have been used to represent the energy and environmental performance of buildings, encompassing methods from simple degree day procedures to comprehensive and computerized procedures which simulate building heat transfer and systems / internal loads performance on a minute by minute basis. Dynamic simulation models are increasingly frequently used nowadays; these models represent physical behaviour at various levels of detail [8, 9]. At the same time, dynamic simulation is used to underpin performance standards such as the European Union (EU) Energy Performance of Buildings Directive (EPBD) [10] and the United Kingdom (UK) building regulations [11].

The improvement of energy efficiency in Egypt is currently a high priority due to the continuous increase in loads in all sections, with problems arising from the shortage and cost of the fuel required to produce energy. The energy consumption in Egyptian buildings is considered one of the paramount factors that affect the energy sector in Egypt and is estimated to be responsible for half of the generated national electricity [12]. Office buildings in Egypt face problems of high energy consumption by low-efficiency systems, besides perceived poor thermal comfort in the traditional constructions without central Heating, Ventilation, & Air Conditioning (HVAC) systems.

The building envelope, climate variation, installed loads, and occupancy operation and behaviour all have a significant effect on building energy performance and at the same time affect the indoor environmental air quality and thermal comfort in any building [13, 14]. The variation in the power demand of HVAC systems, lighting systems, and equipment is one of the main factors affecting the energy performance of office buildings. However, power demand of installed system is only one factor affecting the total energy consumption in offices. Arguably, the variation of the behaviour of occupants in using these systems is a more significant factor for determining the total energy consumption.

1.2 Problem Definition

The Egyptian Government initially responded through the implementation of an integrated energy strategy aiming to reduce energy demand and to provide the secure, reliable and affordable energy services required to support economic stability and development [15]. Political instability has resulted in limited progress, but there has recently been a renewed focus on the introduction of new building design codes largely based on existing national energy standards such as American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) in USA, and ECP in Egypt [4, 16]. The Egyptian Government has also supported the adoption of voluntary international sustainability rating systems such as Leadership in Energy & Environmental Design (LEED) [17], and the introduction of Egyptian sustainability rating systems such as Green Pyramid [18].

Potential concerns with the adoption of these new standards are: (i) that the current energy performance of Egyptian buildings is not well known, so the change in performance from adoption of these new design standards is therefore uncertain; (ii) that the appropriateness of these new build design standards to the Egyptian context (weather, customs) has not been fully explored; and (iii) that the new standards do not apply to existing buildings, even though improvement measures for these buildings must be an essential part of reducing overall demand.

To be able to address these concerns, and appropriately inform future strategy, it would appear to be essential to (i) characterize the energy and indoor environmental performance of the existing building stock, then (ii) encapsulate this performance in an appropriate modelling framework to be used to underpin future strategy decisions. The second step is especially problematic particularly as the performance of the existing building stock is subject to high variation in operations, user behaviour and weather, and these variations and their effects are difficult to comprehend.

1.3 The Value Of Solving The Problem

The main benefit from studying the energy performance and IEQ for office buildings is to understand the energy used in this type of building, which can have a direct impact on economic, environmental and social life in any country. Among the benefits likely to arise from understanding the energy performance in buildings are: reduced energy use for space heating and/or cooling and water heating; reduced electricity use for lighting, office machinery, and domestic type appliances; lower maintenance requirements; improved comfort; enhanced property value. In developing countries where electricity is intermittent, and power rationing is frequent, there is a significant demand for fossil fuel for power generation from end-users. Reducing power and energy requirements in buildings reduces the capital outlay required and the running costs of these systems.

Studying their energy performance and the IEQ will raise the awareness of the potential to improve the energy and environmental performance of offices in Egypt and will encourage positive management action leading to the following:

- Decision makers: develop a well-founded policy for the office sector in Egypt.
- Building owners: lower life cycle cost is expected.
- Occupants/users: maintaining occupants' satisfaction (thermal comfort and indoor air quality) and enhanced productivity.
- Researchers: give a guide for the current gaps in knowledge, make some contribution to address the gaps and identify areas for future study.

1.4 Research Scope

This research focuses on Egyptian office buildings that are considered the common commercial building type with high energy consumption [2]. This study is concerned to investigate a method to analyze the energy performance and the IEQ in existing Egyptian office buildings that can be used to inform future policy.

Many building types make up this stock. In this work, the main focus is on 'typical' Egyptian offices which are naturally ventilated, cooled using local cooling systems, and built prior to the introduction of energy standards in regulations. This category was identified as the most common through the 59 building survey carried out in this thesis, but other categories of office are also covered, and the applicability of the methods developed to other contexts is also discussed.

1.5 Research Questions, Aims And Objectives

Studying the energy performance and the IEQ has been widely adopted for office buildings in developed countries. It is time to extend this study to Egyptian office buildings. The main questions that this research seeks to address are:

I. What are the current energy and IEQ performance characteristics of existing Egyptian offices?
II. How can these performance characteristics be captured within a valid modelling framework?
III. How can this framework be used in scenario analysis to inform future strategy?
IV. Can a methodology be generalized for use in other building stocks and contexts?

Currently, there are gaps in each of these areas with a lack of understanding of current performance, with the absence of a well-established modelling framework that captures existing performance, no parameter sets available to be used to investigate future scenarios, and no general methodology addressing these gaps.

Based on these research questions, the study aims to:

I. Provide insights into energy use and IEQ associated with current Egyptian office buildings.
II. Develop a method for producing a model to represent current Egyptian office performance to be used in future to inform upgrades and policy directions.

III. Use this modelling framework to investigate the relative and combinatorial impact of apposite parameters, and to present this information to inform decision makers usefully.
IV. Propose possible future scenarios for Egyptian office buildings that will minimize energy use.
V. Illustrate how this process can be usefully extended to other building sectors and contexts.

1.6 Overall Research Methodology

To achieve the thesis aims, the research work has been subdivided into six main phases. A description of these six phases with relevant chapters of this thesis is outlined in Table 1-1.

The first phase introduces the research and highlights the most significant findings in related fields through a comprehensive literature review where the state of the art is summarized and remaining gaps to be addressed in this thesis are identified.

The second phase provides insights into energy use and IEQ associated with current Egyptian office buildings. Survey methods to achieve the outputs required for performance characterization and representative model creation were deployed to gather relevant information on Egyptian offices through a 59 building energy survey and a more detailed energy and IEQ survey of a case study office.

The third phase includes the creation of a representative model. This involved application of current stae-of-the-art calibration methods in the Egyptian context, and the development of new methods to generalize the model, capture thermal comfort and variation in behaviours, in particular with regard to the individual use of local cooling systems, in a representative modelling framework.

The fourth phase includes developing a methodology to study the effect of different categories of input parameters on energy performance and IEQ across realistic parameter ranges. The methodology allows individual and combinatorial effects to be quantified and visualized.

The fifth phase uses the modelling framework developed to analyze and propose possible future scenarios for Egyptian office buildings that will minimize future energy use.

The last phase presents conclusions, discusses the generalization of the methods developed, and makes recommendations for further research.

1.7 Summary

This chapter described the research project regarding the research problem definition, scope, research question and specific aims, and the applied research methodology. Studying the energy performance and the IEQ for Egyptian office buildings is necessary for the adoption of new Egyptian standards, and to help in reducing the energy consumption in this sector.

Energy performance and IEQ study are of concern to several groups including decision makers, building owners, architects, occupants/users and researchers. The research work has been subdivided into literature review, energy survey, creating a representative modelling framework, a detailed parametric study of influences on energy performance and IEQ, identification of future scenarios for the Egyptian office sector, and the concluding discussion and recommendations for future work.

The next chapter presents a literature review of this subject area.

Table 1-1. Thesis outline summary

Phase	Chapter	Methodology	Objective
One	1	Outlining the overall research	Describing the research structure
	2	Conducting comprehensive literature review	Establish the latest finding in the area of study
Two	3	An energy survey is carried out to establish energy use across range Egyptian offices and a more detailed energy, environmental and behavioural survey for a case study office building.	Provide insights into energy use and IEQ associated with current Egyptian office buildings
Three	4	The collected data is used to create a valid modelling framework using a dynamic simulation model tool.	Create a calibrated Egyptian office buildings representative model
	5	Studying the thermal comfort model and the gathered data was used to create a valid modelling framework, i.e. typical model, and case parameter sets describing possible variations in input parameters.	Reach the most representative thermal comfort model and generalization of the calibrated model to be typical model
Four	6	The modelling framework is used to demonstrate the relative and combinatorial effects of various model input parameters formed into appropriate categories and modulated to represent realistic ranges.	Investigate the relative and combinatorial impact of apposite parameters, and present this information in a useful form
Five	7	The modelling framework is used to analyze scenarios with potential to mitigate the growth of energy demand in the office sector	Propose possible future measures for Egyptian office buildings that will minimize energy use
Six	8	Highlighting the research findings including generalisation of the methodology while stating possible future elaborations.	Concluding and suggesting further research

Chapter 2 LITERATURE REVIEW

Building energy performance faces a major challenge if it is to meet the growing demand for energy in addition to raising the level of comfort in buildings. This chapter outlines the research problems associated with building energy performance and highlights its current situation in Egypt. The main purpose of this chapter is to identify and discuss the most significant published findings concerning: energy performance of office buildings, the use of dynamic simulation tools, climate data and classifications, thermal comfort, building energy standards and codes for commercial buildings, and energy saving innovations in buildings. Finally, a conclusion is drawn which highlights the main gaps found in each topic discussed.

2.1 Energy Use In Egypt

In the last few years, Egypt has witnessed a trend in sustained economic growth. Keeping up with the growth in total consumption and peak demand for electricity, both the total generation and the greatest generating capacity also grew steadily till 2010. In 2010, according to British Petroleum Statistical Review published in 2013, the Egyptian consumption of oil overtook production and this has had a direct effect on power generation. In addition, the recent repetition of power cut-off and blackouts that started in the summer of 2012 has had great economic, political and social impacts. For instance, frequent power outages resulted in significant losses for enterprises and manufacturing in forgone sales and damaged equipment [5].

The Egyptian revolution in 2011 led to instability in all fields and is one of the main factors in the deterioration in the energy sector. Other key factors have been: the low nominal generation capacity for peak summer demand, the increase in the peak electricity demand of more than 300% between 1992 and 2010 [19], and the high customer base electricity usage which has increased five-fold during the last five years. Subsequently, these factors led to the implementation of an integrated strategy aiming to reduce energy demand in the various socioeconomic sectors in order to provide secure, reliable and affordable energy services for economic stability and development [15]. Correspondingly, this can help to avoid the repetition of electricity blackouts that occurred regularly in 2012.

Ongoing political and social disturbance in Egypt has impeded the government's plan to expand power generation capacity. However, private sector and international organizations have provided funds for brownfield and greenfield projects which have led to significant improvements during the last two years. According to the latest statistics of the Middle East Economic Survey (MEES), Egypt's generating capacity during May 2015 was 31.45GW, which is slightly higher than the peak demand in 2015 of 30GW [20].

Along with the perceived improvement in the production of electricity, increasing the energy efficiency in all Egyptian sectors became an important issue. According to the Electricity Holding Company reports 2012/2013 and 2014/2015 [19, 21] shown in Figure 2-1 the main sector responsible for high electricity consumption is the residential sector accounting for around 42% of the total consumption in 2013 and increasing to 52% by 2015. This is followed by the industrial sector that accounted for about 28% of the total energy consumption in 2013 and decreased to 15% in 2015. In contrast, the commercial sector accounted for 10% of the total energy consumption in 2013, increasing to 14% by 2015. According to the Ministry of Electricity and Energy, the steadily high increase in electricity consumption by the residential sector during recent years is due to two main factors: the expansion of residential compounds and new communities, and the high usage of domestic appliances especially air conditioners during hot weather [21].

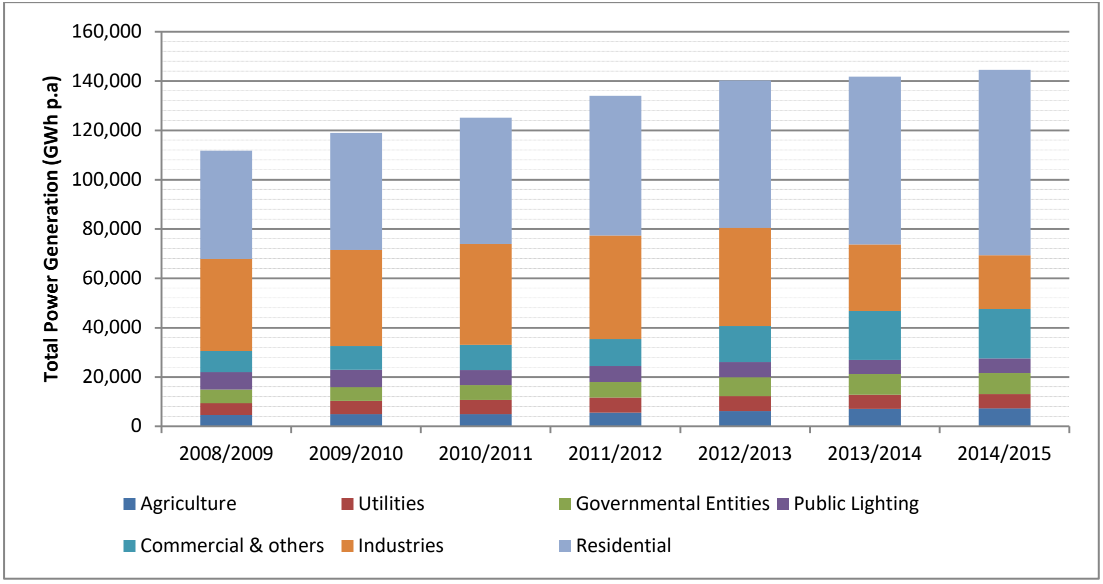


Figure 2-1. Electricity consumption by sectors (GWh p.a.) 2008-2015 [19, 21].

From the mid-90s, the buildings sector in Egypt showed high development due to the urban and economic growth concentrated in the Nile Delta. Due to the lack of control in the energy field, many new buildings were constructed without paying attention to environmental considerations at the early stages of design. As a result, high usage of electricity is needed for cooling to provide acceptable thermal comfort and for electric lighting. Also, most of these new buildings have been designed as glass boxes devoid of local architectural character or vernacular style [22].

2.2 Energy In Buildings

In recent years, the rapid growth in world energy use has raised many concerns over supply difficulties, the exhaustion of energy resources and heavy environmental impacts such as ozone layer depletion, global warming, and climate change. The Energy Information Administration (EIA) stated that during the last two decades primary energy use has grown by 49% and CO_2 emissions by 43%, with an average annual increase of 2% and 1.8%, respectively [2]. This rapid inflation in the energy sector and its negative impact on the environment requires an investigation of the primary consumers of this energy. This section discusses the building sector which is responsible for a large proportion of the energy consumption in any country.

In most countries, the energy consumption is usually classified by sectors, which are: industry, transport, agriculture, public services, and the building sector. The building sector is considered one of the biggest sectors in energy consumption, and it is broken down into domestic (residential) and non-domestic (non-residential) buildings. Energy consumption in this sector accounts for 20.1% of the total worldwide delivered energy consumed. In developed countries, energy consumption in buildings accounts for 40% of the total energy consumption. In the Middle East and North Africa (MENA) regions, this sector is one of the fastest growing sectors compared with others.

Figure 2-2 shows the energy consumption in the building sector as a percentage of total energy consumption in six MENA region countries, which are; Morocco, Algeria, Tunisia, Egypt, Jordan, and Lebanon [23]. Of the MENA region countries, Egypt has one of the largest energy consumptions in buildings.

The building sector can be classified into residential, commercial, and industrial buildings. The commercial buildings such as offices, educational facilities, stores, restaurants, malls, and hotels use a wide variety of energy services, such as; HVAC systems, lighting, equipment and domestic hot water. Offices are common in a large number of commercial facilities, and shared buildings with residential parts, are also commonly found in Egypt. This overlap makes it difficult to gather information on energy performance in office buildings, especially in developing countries. Over time many studies word-wide have aimed to identify the energy consumption and patterns of use in office buildings.

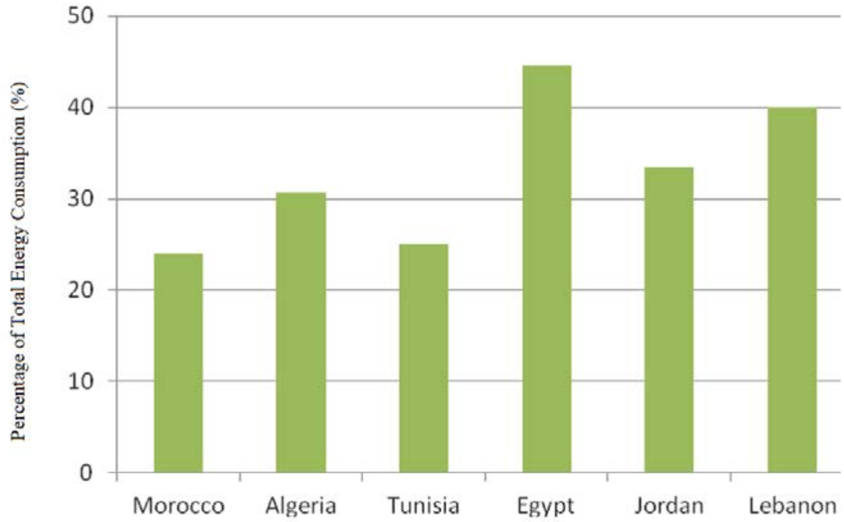


Figure 2-2. The energy consumption in the building sectors as percentage of total energy consumption of six MENA region countries [23]

Figure 2-3 highlights the primary fields of the present study. Other services such as Domestic Hot Water (DHW), food preparation, refrigeration, escalators, elevators, and fire systems are not included in the review. In most developed countries, such as United States of America (USA), UK and EU, these data are available for designers and researchers based on previous publications and case studies. In contrast, in developing countries, these data are not available with the same detail or there might be no data at all. This is one of the main factors that limit research in this area.

2.2.1 Energy Use In Office Buildings

According to the EIA [2], office buildings consume about 14% of the total energy used in the commercial sector, and they are in second place after the mercantile and service sector (malls and stores, car dealerships, dry cleaners, etc.) Energy use in office buildings is classified into: HVAC systems, lighting systems, equipment (plug loads), Direct Hot Water (DHW), food preparation, refrigeration, and other services.

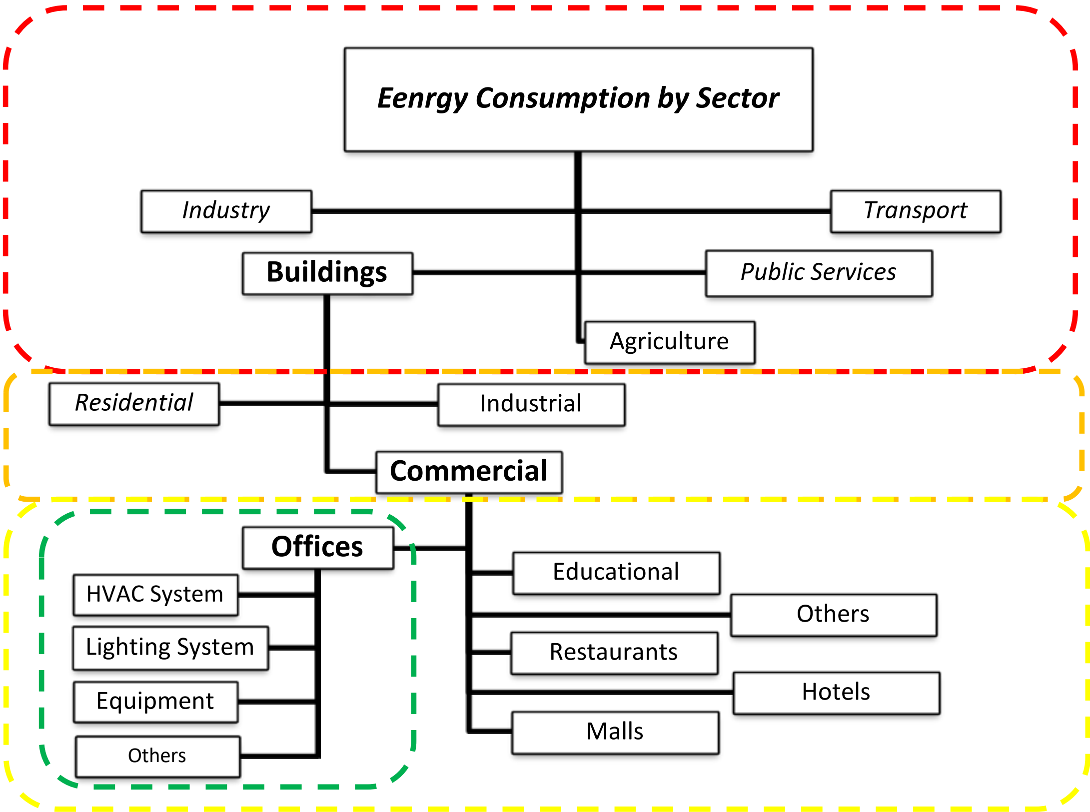


Figure 2-3. . Schematic of the main fields of the study

A survey conducted across USA commercial buildings in 2013 showed that the office building is the most significant consumer of energy with about 19.1% of total non-domestic consumption [2]. In Spain, one of the EU countries, office buildings account for about 30% of energy consumption in commercial buildings, and in the UK about 17% [24]. In some countries, the energy use for office buildings is reported to be in the range of 70-300kWh/m^2 p.a. [25]. In developing countries, the range of energy consumption by the office buildings is unknown due to the lack of the research in this area and to the weakness of the codes and standards.

In the literature, many studies have been conducted to understand the key drivers for energy use in office buildings, such as U.S. EIA in the United States [2], and the UK ECG19 in the UK [7]. They focus on the breakdown of energy use by office type and category of energy use within the building, such as power consumed by IT equipment, lighingt, HVAC systems and services. The main aim of this review is to investigate and highlight the key loads of the energy consumption in office buildings including; HVAC system loads, lighting system loads, and office equipment loads.

Currently, there is little data available related to the electricity consumption of small power equipment in the context of office buildings. Existing data published in Chartered Institution of Building Services Engineers CIBSE Guide F (ECG19) is over a decade old, and the use of office equipment and its associated technologies has changed significantly over this period [26]. Significant improvements in the energy efficiencies of the loads have been observed in the last few decades, resulting in reduced energy requirements per device. However, the extent to which this has been offset by the proliferation of electronic devices is unclear. This lack of up-to-date benchmarks makes it increasingly difficult for designers to include small power consumption accurately in their energy models [26]. Hence, it is important that this uncertainty is included in analysing future scenarios.

2.2.1.1 HVAC Systems

The energy consumption by HVAC systems is considered important as obtaining acceptable thermal comfort depends on them. It is the largest energy end use in both the residential and non-residential sectors [24].

Nowadays, HVAC systems have been widely adopted in office buildings because of the need to control the indoor environment with good thermal comfort as people spend more time in buildings. Additionally, internal temperatures have risen due to heat gains from equipment, etc., and to increasing outdoor ambient temperatures potentially caused by global warming as well as the urban heat island effect [8]. HVAC and lighting system energy use accounts for around 70% of total office building energy consumption in the US and 72% in the UK [24]. Overall, HVAC systems are responsible for about half of the energy used in buildings. For instance, in the USA HVAC systems consume about 51% of the energy used in commercial buildings. [23]. This is lower than the 57% encountered at the European level [24], 52% in Spain, and 58% in the United Kingdom. However, in the Asia region, for Hong Kong "space conditioning" was the largest end use, consuming 26% of the total energy by the commercial sector [27].

Many sources showed that significant increases in the use of air conditioning create serious supply difficulties during peak load periods especially in developing countries [28]. For instance, in the MENA region, the HVAC consumption reaches more than 58% of the total energy use in commercial buildings, 70% in Saudi Arabia and 71 % in Bahrain [23]. In Egypt 35% of electricity use is by cooling systems [29]. Two case studies by Abdelhafez in Egypt [29] found that the annual energy consumption by the HVAC system for an existing building was around 117kWh/m^2 p.a., but for a new building it was around 47kWh/m^2 p.a. A case study by Ezzeldin [30] on a building in Cairo concluded that the cooling system was the major energy demand. The cooling system used 57% of the total annual energy consumption of 96.5kWh/m^2 p.a. in the base case and between 32kWh/m^2 p.a. to 8kWh/m^2 p.a. in investigated alternative scenarios.

Cooling and heating demands are affected by several factors, including some external factors such as climatic conditions (cold or hot, dry or humid). A detailed review of the climate classification is discussed later in section 2.4. Other factors include building envelope, and internal factors such as internal heat gains due to occupants, lights and equipment, and the efficiency of the equipment. These internal heat gains mainly depend on the efficiencies of the lighting and plug loads and on occupant behaviour. The UK ECG19 [7] provides typical and good practice benchmarks for office and catering equipment electricity consumption.

Four different types of office buildings are discussed based on the HVAC system, which are: Type 1 - naturally ventilated cellular office, Type 2 - naturally ventilated open plan office, Type 3 - air-conditioned standard office, and Type 4 - air-conditioned prestige office (typically including a large catering kitchen and/or central server rooms). Thus the energy consumption by the HVAC system is the key load in the office building. The lighting and equipment systems have a direct effect on total power consumption, and, as heat sources, these systems also have an indirect effect on the HVAC system consumption.

2.2.1.2 Lighting System

In commercial buildings, lighting consumption varies significantly from one building to another with a range between 20 and 45% of the electricity consumption [31]. In a typical large office building in the Arab region lighting energy makes up about 15% of the total energy consumption. According to UK ECG19, the energy consumption for lighting systems varies between 14 and 60kWh/m^2 p.a. for the four types of office buildings [7]. In Sweden, lighting normally accounts for 25 to 30% of electricity use in non-residential premises which have an average energy consumption intensity of 21kWh/m^2 p.a. for office lighting and an average installed Lighting Power Density (LPD) of 10.5W/m^2 [4].

The ASHRAE 90.1-2010 recommended that lighting power density for offices be around 9.68W/m^2 [32]. This value is reduced to 8.82W/m^2 in ASHRAE 90.1-2013 [16]. The ECP recommended that the lighting power density for offices should be 14W/m^2 and 300lux [4].

Based on studies done on office buildings in Egypt, Ezzeldin [30] estimated that the lighting density is 15W/m^2. However, through two different case studies Abdelhafez [29] concluded that lighting energy consumption accounts for around 36% of the electricity used in the non-residential sector, with this ranging from 16kWh/m^2 p.a. to 13.1kWh/m^2 p.a. Hanna [33] estimated that the lighting density in Egyptian offices is about 15W/$m^{2,}$ increasing to 30W/m^2 in large buildings with heavy operating conditions. The Egyptian Electricity Holding Company has stated that among measures taken to improve efficiency and achieve energy conservation in government buildings some pilot projects have been implemented to replace existing lighting systems by efficient ones, and real savings have been achieved reaching an average of 30% of the lighting consumption [21].

2.2.1.3 Plug Loads

The plug loads are one of key drivers of building energy use. On average, 18% of energy is used for office equipment in a typical large office building in the Arab region [23]. Various works have provided data on these loads for use in design and regulatory calculations. UK ECG19 highlights the variation in energy consumption for small power equipment varying between 14 and 47kWh/m^2 p.a. for the four types of office buildings. It also provides benchmarks for power load density, ranging from 10 to 18W/m^2. These values can be used to appraise the electricity consumption when coupled with the number of run hours (daily, monthly, annually) [7].

CIBSE Guide F [34] suggested that a benchmark figure for building loads during working hours of 25W/m^2 is adequate for most office buildings. However, adjustments should be made based on office use and diversity of occupancy and activity, e.g. 15W/m^2 may be used when general office activity is taken into account but may be too low for a high occupancy / high IT office, etc. The updated Guide F also suggests that using a loading of approximately 140–150W/desk might be a more appropriate approach when occupancy details are known [35]. The new CIBSE TM54 [34] proposed a simpler calculation based on the expected power demand and operating hours of individual desks/workstations, accounting for common appliances separately. This approach allows for variations in equipment specification and intensity of use to be accounted for, yet usage patterns are not dealt with in detail.

There is enormous variation in the energy required by different office equipment, especially for computers and monitors. The computers are commonly the single biggest source of energy use, directly affecting the internal heat gains [36]. A large number of studies observed the energy consumption by desktop computers and laptops [37-43]. Based on these studies, it was concluded that the average desktop computer requires between 30W and 169W when it is active and between 1W and 49W when it is in low power mode. Computers, like many other electrical devices, can draw power even when they are apparently turned off. The average computer drew between 0.5W and 3W when turned off but plugged into a mains socket. On the other hand, laptop computers require 12W to 75W when they are active, 1.5W to 6W in low power mode and 0.3 W to 2W when they are turned off but plugged into the mains socket. Monitors, like computers, vary in the amount of energy they require. The average Cathode Ray Tube (CRT) monitor requires between 66W and 135W when active, between 0W and 19W when it is in low power mode, and between 0W and 5W when switched off.

For copiers and laser printers, rollers are heated intermittently even during idling to keep the fuser at a minimum temperature for prompt printing. It is impossible to distinguish copiers and printers by the power demand patterns. Kawamoto et al. [44] estimated the power consumption for copiers and printers based on pages printed per hour. The study revealed that the average copier's monochrome setting requires 185W when active, 76W when in low power mode and 8.7W when turned off. The average laser printer needs 77W when it is active, 2W in low power mode and 1W when turned off [44]. According to recent studies in Egypt, the office equipment loads are in the range of 5 - 23W/m^2 [1, 29, 33].

2.2.1.4 Conclusion on Available Data for Energy Use in Egyptian Office Buildings

The studies found no available reference data for the power required by the HVAC system, lighting system, and office equipment plug loads. None of the studies addressed the variation in energy performance of office buildings in Egypt. This information is critical and its absence therefore forms a gap in understanding the energy performance in the Egyptian buildings and in the resources needed for planning future reductions in energy consumption. Hence more detailed research is needed to address this gap.

2.2.2 Modelling Methods Used To Estimate The Energy Used In Buildings

Various methods are used to estimate the energy used in buildings. Attia [45] explored the methods used to estimate energy consumption in buildings. Zhao and Magoules [46] published a review paper categorising the methods of predicting building energy consumption into engineering methods (deterministic modelling), statistical methods, and artificial intelligence methods.

The engineering methods are based on calculating the energy performance using detailed physical functions for all the components of the building in addition to the environmental information available. Building simulation tools are used to predict the energy performance of the building using engineering methods. These building simulation tools are effective and accurate, but they require details of building and environmental parameters.

The statistical models use a historical record of the energy performance data to predict the energy used, while artificial intelligence methods (neural networks) are used to predict the energy use for more highly complex buildings. More details and some of the main studies done with each method can be found in the review paper by Zhao and Magoules [46].

The main focus of the work in this thesis is the engineering method; this approach was selected as it is the most common method being adopted internationally, e.g. by EU and USA ASHRAE building performance standards [16, 47]. Some statistical methods are also used in this work to represent uncertainty in parameters required as inputs for the engineering methods in order to correctly represent the energy performance in Egyptian offices.

A detailed review of building simulation modelling tools is discussed in the following section. The current status of these simulation tools in Egypt is also reviewed, as is recent building simulation work in Egypt.

2.3 Simulation Models

Simulation is the representation of a real-world process or system over time. This simulation requires a model to be developed that represents the key characteristics or behaviours of a physical system or process. In summary, models describe how things work, and a simulation project describes how that system will perform.

Saltelli et al. [48] give general scientific definitions for a deeper understanding of the building simulation models. These could be either diagnostic or predictive models. Diagnostic models are used to understand the laws which govern a given system and thus identify the reason for some related phenomenon. Predictive models are used to define a set of laws governing the system in order to predict the behaviour of the system. Simulation models can also be classified as law driven model or data driven models. The law driven models apply a set of laws which governs a given system to identify the nature or cause of some phenomenon and to predict the behaviour of a system [9]. However, the data driven models work on the opposite approach, using system behaviour as a predictor of system properties which then describe a system with a minimal set of adjustable inputs [49].

2.3.1 Building Performance Simulation Models

Building simulation models originated with the scaled two-dimensional models for buildings hand drawn by architects and engineers. These drawings defined what the builder had to interpret to construct the building. However, this type of building model need not be limited to a paper description of the building but can be used to create a scaled physical model indicating shading and daylight.

Subsequently, architects and engineers have turned to the computerized two-dimensional drafting of Computer-Aided Design (CAD) that enabled three-dimensional models to start to develop. Engineers started to use rules of thumb or simple equations to estimate heating and cooling loads for equipment sizing. Over time the complexity of the models increased by including the building systems such as heating, cooling, lighting, and plug loads. Nowadays designers are likely to use sophisticated rendering and lighting modelling tools to generate realistic looking images for building design and additionally to understand how energy is used.

For designers to understand how energy is used in space, they need to model all building details. These include: the building envelope construction (wall, windows, floor and ceiling), the outer environment which changes with weather (temperature, humidity, wind speed and other climatic factors), the transfer of heat/light in and out of the building, sun and cloud movement, and finally the active systems (lighting, heating, cooling, ventilation, etc.). Any building is designed with certain assumptions about how it will be operated, but in practice the building inevitably operates in a way different from what was planned from the first day [8].

Simple simulation models are no longer helpful due to all these complexities in design. Designers now need to use building performance simulation software to address the complexity of today's buildings. Building simulation software is the key to evaluating critical building performance issues such as energy efficiency, human comfort, and code compliance. It is also the only means of predicting energy performance at the design stage before the building is constructed and operated.

Building Energy Simulation (BES) models used at the design stage can be classified into pyrogenetic law-driven models that are used to predict the behaviour of a system for a given set of well-defined laws (e.g., energy balance, mass balance, conductivity, heat transfer, etc.) or data-driven models that use monitored data from an existing building [9].

Reddy and Anderson [50] classified the methods for energy use estimation in buildings into two main extremes which are empirical black-box and physical grey-box. There are different degrees of greyness which depend on the amount of physical knowledge used in the model building process and the type of assumptions or simplifications made.

2.3.2 Building Energy Performance Simulation (BEPS) Tools

Early modelling attempts can be referred to as "steady-state" models whereby a building could be broken down into an array of points or "nodes" with energy flows between different nodes, as shown in Figure 2-4. Such a system of nodes can be thought of as an electrical network where each node is at a different temperature (analogous to voltage). There are heat flows between nodes (analogous to current) with the rate of transfer being dependent on the thermal resistance (analogous to electrical resistance) [51].

For the last 40 years, dynamic building energy simulation programs have been available with different capabilities used throughout the building energy community [52]. During the past decade, building performance simulation programs have progressed from a strictly text-based language to multiple programs for different uses and users, like DOE-2 developed by the U.S Department of Energy (DOE) [53], EnergyPlus developed based on the work carried out on DOE-2 with many advanced features [54], TRANSYS transient system simulation program with a modular structure which implements simple and complex systems [55], and ESP-r. These four simulation programs represent the most common research tools [9]. Commercial tools have been developed with increased user friendliness. Over time all programs are developing continuously [8].

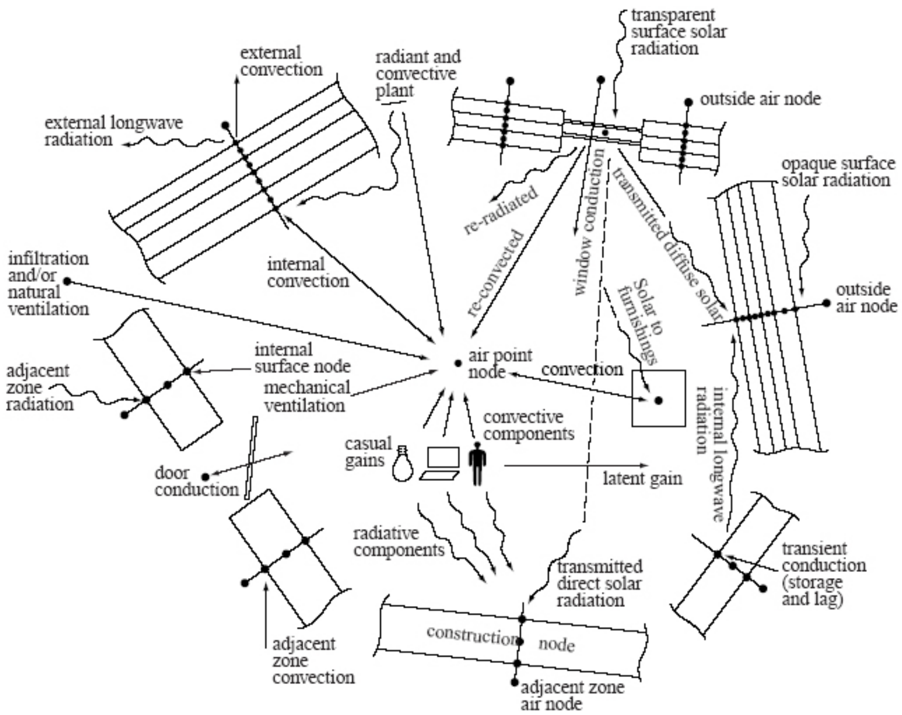


Figure 2-4. Energy flows in buildings [31].

Crawley et al. [56] provided a comparison of the features and capabilities of twenty major building energy simulation programs (BLAST, BSim, DeST, DOE-2.1E, ECOTECT, Ener-Win, Energy Express, Energy-10, EnergyPlus, eQUEST, ESP-r, IDA ICE, IES-VE, HAP, HEED, PowerDomus, SUNREL, Tas, TRACE and TRNSYS). The four simulation programs DOE-2, EnergyPlus, TRANSYS, and ESP-r, have represented the most powerful tools [9]. There are many recent national and international standards for the application of these tools, often aimed at ensuring consistent results in underpinning compliance to regulations and non-regulatory standards.

Several studies have highlighted great disagreements between simulated building energy performance and measured performance, as buildings do not perform as well as predicted [57]. This performance gap is due to the uncertainty for a range of factors [58]. One of these is the failure of the model and model input parameters used in prediction to correctly represent the actual building. To make BEPS a more reliable tool for the design process, and a better match with monitored building energy performance, a process of fine-tuning, “calibrating”, the simulation inputs is needed so that the observed energy consumptions closely match those predicted by the simulation program. This particular application of building simulation is called Calibrated Simulation (CS) which is discussed in the following section [59]. It has also been stated that some of the performance gaps may be due to faults in systems or controls. Such faults are not explicitly addressed in the work of this thesis, but others have done work on the use of engineering models in fault detection, etc. [60, 61].

2.3.3 Building Simulation Model Calibration

Several studies based on calibration have been carried out, but as yet no clear universal methodology has been presented [52]. This means the calibration process depends on the user’s skill and judgement. While studies use different methods for calibration, there is general agreement on the ASHRAE standard criteria to be met for ‘good’ calibration [57].

According to ASHRAE Guideline 14-2002 [62], there are two main dimensionless indicators of errors in calibrating the building model, which are the Mean Bias Error (MBE) (%), and the Coefficient of Variation of Root Mean Square Error (CV(RMSE)) (%).

Currently, the building model is considered calibrated if these indicators meet the criteria set out by ASHRAE Guideline 14 [62]. However, it is essential to define the level of calibration required before verifying that the data collected are sufficient to carry out the calibration. Fabrizio and Monetti [57] discussed the requirement for each level of the calibration. Utility bills data are always necessary as they represent the minimum requirement for calibration, in terms of measurements and historical data about the building [57, 63].

Clarke et al. [52] classified the calibration models into four classes that were used by Reddy et al. [25]. This classification can be summarized as follow;

- Calibration based on manual, iterative and pragmatic intervention.
- Calibration based on a suite of informative graphical comparative displays.
- Calibration based on special tests and analytical procedures.
- Analytical/mathematical methods of calibration.

After the contributions of Coakely et al. [9] and Fabrizio and Monetti [57] the calibration model classification was simplified to two main approaches which are:

- Manual – including any methods which don't use any form of automated calibration.
- Automated –having some form of automated process to assist model calibration.

Based on Coakely et al. [9] calibration techniques can be further classified as follows:

- Analytical techniques: generally manual user-driven techniques, but could be used as a part of the automated calibration process [25, 59, 61, 64-69].
- Mathematical/statistical techniques: generally used in automated approaches [70-75].

To holistically address calibration of building simulation modelling, it is important also to consider the issue of model uncertainty which is often neglected in the BEPS calibration process. Models with complex systems are difficult to calibrate, and in order to simulate this complex model, it has to be subjected to some simplification and constraints. This is the case when the purpose of the model is to provide some insight into the non-observable parts of the system [76]. De wit et al. [76] and Coakley et al. [9] classified the various sources of uncertainty in building performance simulation as follows:

- Specification uncertainty: arising from the incomplete or inaccurate specification of the building or systems modelled. These may include any model parameters such as geometry, material properties, HVAC specifications, plant and system schedules, etc.
- Modelling uncertainty: simplifications and assumptions of complex physical processes. These assumptions may be explicit to the modeller (zoning and stochastic process scheduling) or hidden by the tool (calculation algorithms).
- Numerical uncertainty: errors introduced in the discretization and simulation of the model.
- Scenario uncertainty: external conditions imposed on the building, including outdoor climate conditions and occupant behaviour.

Many studies in the literature have aimed at looking for the uncertainties in model parameters, such as uncertainty in the thermal properties of the materials. Macdonald [77] quantified the uncertainties for construction materials, for example, thermal transmittance, solar absorptance, and emissivity. Also included was an aggregate parameter called effective heat capacity, which approximates the dynamic heat storage (thermal mass) of the building envelope plus building contents which interact with the indoor air. Other studies looked for the uncertainty in parameters describing ventilation and infiltration rate, in energy models, these variables are quantified by estimating the volumetric flow rate of outside air into the building or the number of air changes per hour, but there is a weather dependence and user dependence which make it difficult to quantify the building envelope infiltration [78, 79]. Standards and field studies provide normal infiltration rates, but still, there is uncertainty in these values as they change from one building to another and from one time to another. Heo et al. [80] studied the uncertainty in the ventilation rate for the natural ventilation models.

The uncertainties in the HVAC systems include the efficiency of the system equipment and the losses in the distribution system. The efficiency of the HVAC system equipment depends on thermal efficiency and the operation conditions as well as maintenance factors. The internal loads are produced by occupants, lighting, plug loads, and any other heat generating equipment within the building and these are all considered as uncertainties as they have a stochastic nature. Occupant heat gains depend on their activity level, while the lighting and plug loads and other equipment depend mainly on the efficiency of these devices in addition to occupant use and behaviour. In the literature, various studies have been done on the uncertainties for these systems (HVAC, equipment, and lighting) [31, 37, 39, 40, 77, 81, 82].

Arguably, the uncertainty in estimating occupant behaviour in using these systems is a more significant factor in determining total energy use than the uncertainty in system efficiencies. According to Hoes et al. [83], user behaviour can have a large influence on the energy performance of a building, more than the thermal processes within the building façade. It is important to understand and model the behaviour of occupants in buildings and the way this behaviour impacts energy use and comfort. It is likewise important to understand how a building's design affects occupant comfort, occupant behaviour and eventually the energy used in the operation of the building [84].

To obtain accurate energy demand simulations, user patterns are needed that capture the wide variations in behaviour without making simulations overly complicated.

Aerts et al. [85] developed a probabilistic model which generates realistic occupancy sequences that include three possible states. The method used to construct this occupancy model is based on the 2005 Belgian time-use survey. The modelling of individual occupancy sequences based on this method enables the inclusion of highly differentiated yet realistic behaviour that is relevant to building simulations and can be used for individualised feedback based on peer comparison [85].

Sami Karjalainen [86] quantified the effect of occupant behaviour on energy consumption and showed how it is affected by design strategies. Numerical simulations of an office were performed with the dynamic thermal simulation software TRNSYS. Three types of behaviour (‘careless’, ‘normal’, and ‘conscious’) and two types of design (‘ordinary’ and ‘robust’) were considered. The results showed that the effect of occupant behaviour on energy consumption is significantly diminished with robust design solutions, which make buildings less sensitive to occupant behaviour.

Most studies focus on energy used during occupied hours. However, Webber et al. [87] developed the results of 11 after-hours walk-throughs of offices in the San Francisco CA and Washington D.C. areas. The main purpose of these walk-throughs was to collect data on turn-off rates for various types of office equipment (computers, monitors, printers, fax machines, copiers, and multifunction products). They found that only 44% of computers, 32% of monitors, and 25% of printers were turned off at night. O.T. Masoso and L.J. Grobler [88] showed that energy used during non-working hours was a significant percentage of the total energy consumption in five case study buildings. This arises primarily from occupants’ behaviour in leaving lights and equipment on at the end of the day, and also partly from poor zoning and controls.

Zhang et al. [89] developed an agent-based model which integrates four essential elements, i.e. organisational energy management policies/regulations, energy management techno-logies, electric appliances and equipment, and human behaviour, to simulate the electricity consumption in office buildings. Through a field study in the UK, the results found that 60% of occupants never switch off their computers while leaving the office.

Finally, external conditions imposed on the building, including outdoor climate conditions and the building envelope, are key to the uncertainties which affect building modelling. Climate conditions are discussed in detail in the following section.

It is important that these sources of uncertainty are identified and quantified when assessing model-predicted performance. However, as found in the earlier review, there is no specific method or guide to address all of these uncertainties in one model. Thus, this is one of the gaps that will be covered in the proposed methodology to study the energy performance in Egyptian buildings.

2.3.4 Building Energy Performance Simulation (BEPS) Tools In Egypt

In the recent survey by Attia et al. [90], it was concluded that the usage of BEPS tools in Egypt is extremely low except for mechanical engineers using HVAC sizing tools in design firms (e.g., Hap and Trace 700…etc.). This is because the use of BEPS tools is not required for code compliance or regulatory conformance. Until 2013, the energy and fuel prices for consumers in Egypt were very low and did not reflect the real value of energy [91]. The shortage of information on Egyptian building performance also led to difficulty in calibrating simulation models. Additionally, no comprehensive dynamic BEPS are available in Arabic, and the lack of academic and professional educational facilities are factors that negatively affect the interest in energy efficiency and indoor environmental quality. This is in addition to the lack of understanding of simulation outputs [22].

Attia et al. [90] conducted a literature review and two online surveys and outlined the major criteria for building performance simulation tool selection and evaluation based on analysing the needs of architects and engineers.

Some studies have been done using building simulation tools for investigating residential buildings in Egypt. For instance, Attia et al. [92] developed representative simulation building energy data sets and benchmark models for the Egyptian residential sector. A field survey for residential apartments was conducted for three different locations in Egypt (Alexandria, Cairo and Asyut) and two building performance simulation models were created using the EnergyPlus simulation tool. One of these models was used later by Elharidi et al. [93] to develop a model for the Egyptian residential building sector using IES-VE 2013 software and to conduct a sensitivity analysis for some variables affecting electric power consumption to help manage the growing problem in Egypt. ElDabosy and AbdElrahman [94] used CFD software and Ecotect to study a naturally ventilated office in Egypt in order to enhance thermal comfort in the building. Dabaieh et al. [95] performed an experimental simulation study using Design Builder software with EnergyPlus. The same room in a typical residential apartment was used for an EnergyPlus evaluation carried out by Attia et al. [92] and used later for a study using IESVE by Elharidi et al. [93]. In order to apply 37 proposed cool roof solutions, Mahdy and Nikolopoulou [96] used the Design Builder software to study the effect of external window specifications and their associated shading devices on the optimization of energy consumption and investigated three climatic zones in Egypt under different climate change scenarios.

The interest in using BEPS tools in the commercial sector in Egypt is less than for residential buildings due to the significant number of barriers facing the researchers to collect data about these types of building, especially office buildings. Mohaimen et al. [97] applied detailed simulation analysis using DOE-2.1E, which is a whole building simulation tool, on the impact of daylighting on electrical lighting energy as well as total electricity use for commercial buildings in Egypt. Ezzeldin [30] examined the performance of different mixed-mode cooling strategies for office buildings in arid climates, and a comprehensive methodology has been developed and tested on an existing modern office building located in Cairo, Egypt using EnergyPlus software. Saleem et al. [98] conducted a field study in a school building located in Egypt that is designed based on natural ventilation, and electrical utility bills have been collected in the study. Then a dynamic building energy simulation model was carried out by using, Design Builder software for examining indoor comfort conditions as well as the energy consumption of a typical school building in Egypt. In the literature, there are other studies reported using simulation tools focusing on examining the effect of building envelope parameters [33, 99].

2.4 Climate Classification

As discussed earlier, the climate has a significant effect on building energy performance, and at the same time it affects the indoor environmental air quality in any building. It is important to identify the classification and the sources of the climatic data before performing any detailed study on office buildings. This section gives details on climate classification and on the sources of this data, followed by a detailed description of climate conditions in Egypt.

Climate classification enhances the technical understanding of climate by providing a system capable of identifying, illuminating, and simplifying climatic similarities and differences between geographic areas. This system is mainly based on one of two main factors which are the station measurements of climate characteristics, such as air temperature and cloud cover, and the post-processed form of those measurements, such as gridded datasets. Climate classifications provide an appropriate and simple tool for the validation of climate models and the analysis of simulated future climate changes [100].

In 1884, Vladimir Köppan published the first widely used quantifiable empirical climate classification system that aimed to define climatic boundaries corresponding to those of the vegetation zones. The first full version of the map published in 1918 was revised until an updated version of the map was published in 1936. The major climate classes included in Köppen's map are tropical humid climates, hot dry climates, mild mid-latitude climates, cold mid-latitude climates, polar climates, and highland climates. These six major climate types are further subdivided into hot/cold and dry/wet, creating 20 regions that represent the worldwide range of climatic conditions [101]. In 2007, Peel et al. [102] made a new global climate map using the Köppen-Geiger system which is based on an extensive global dataset of long-term monthly precipitation and temperature station time series.

Figure 2-5 shows the Köppan-Geiger climate classification world map with a description of symbols given in Table 2-1.

According to the system applied by ASHRAE standards 90.2-2007 [103], the climate zones are classified into eight main groups. Each group contains cities that have similarities in their datasets between different climate indices, such as heating and cooling degree-days, incident solar radiation, or average relative humidity, with marine, humid or dry subdivisions [45].

It is important to discuss the arid climatic zone as it covers quite a large percentage of Africa where Egypt is located. The arid climatic zone characterises about 30.2% of the land area of the world [102], and the hot desert arid zone (Bwh) covers about 14.2% of this arid climatic zone. Arid zones cover 57.2% of Africa, 23.9% of Asia, 15.3% of North America, 15% of South America, 78% of Australia, and 36.3% of Europe–considering the Arabian Peninsula and the middle-eastern countries as part of Europe [45]. The arid zone is considered the dominant zone in Africa and is the largest portion of Australia. In the last 50 years, the polar and cold zones have decreased due to global warming and climate change which has also expanded the arid zone in Africa with a 5% increase in area [45, 104].

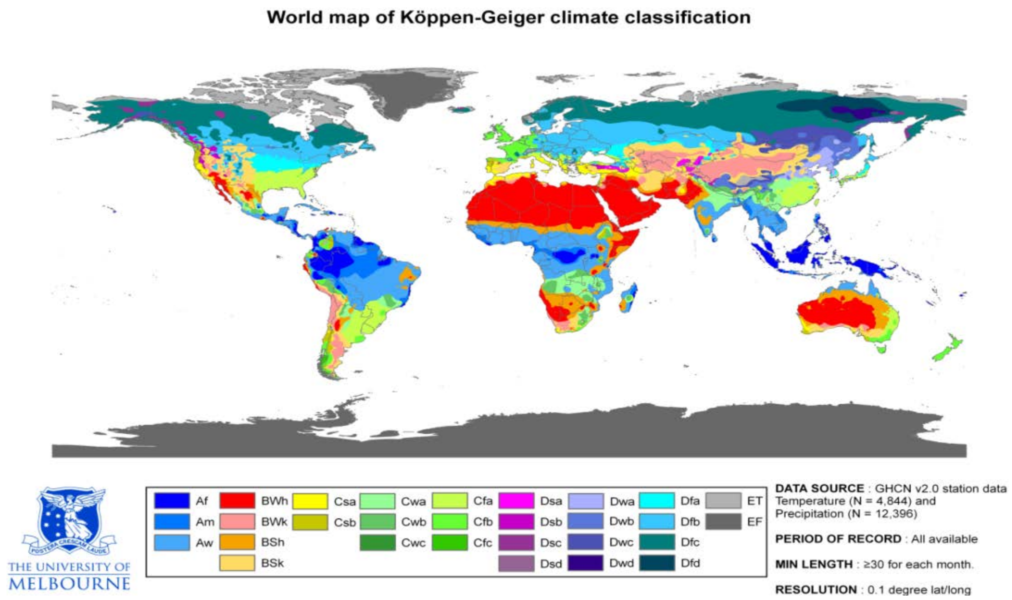


Figure 2-5. World map of Köppan-Geiger climate classification [45, 102].

Table 2-1. Köppen climate classification symbols description [45]

Main Climate	Precipitation	Temperature
A: Equatorial	w: Desert	h: Hot Arid
B: Arid	s: Steppe	k: Cold Arid
C: Warm Temperature	f: Fully Humid	a: Hot Summer
D: Snow	s: Summer Dry	b: Warm Summer
E: Polar	w: Winter Dry	c: Cool Summer
	m : Monsoonal	d: Extremely Continental
		F , T : Polar

According to the ECP 306-2005 [4], Egypt is classified into eight main zones based on the weather condition. These zones are North coast, Cairo & Delta, Desert, North upper Egypt, South opper Egypt, South Egypt (Lower Egypt), Eastern coast, and Highland [105], as shown in Figure 2-6. Ezzeldin [30] classified Egypt based on the Köppan-Geiger climate classification as having a hot arid climate. Attia et al. [92] summarized these eight zones into three main zones throughout his study, as shown in Figure 2-7. The author also selected a city representative of each zone, namely, zone 1-Alexandria, zone 2-Cairo, and zone 3-Asyut. Fahmy et al. [105] used the same three main regions and classified them as hot humid, hot mild, and hot dry regions.

For ambient temperatures, the northern winds are a welcome respite from the heat and keep the temperatures slightly moderated. Egypt's weather is also characterized by especially good wind regimes with excellent locations along the Red Sea and Mediterranean coasts. Regions with an annual average of 6.0–6.5m/s have been recognized along the Mediterranean coast and approximately 8–10m/s along the Red Sea coast. Average annual temperatures also vary from a minimum of 14°C to a maximum of 37°C in the coastal locations, and the most humid area is along the Mediterranean coast [106].

The temperature values vary widely in the desert locations, particularly in the summer season ranging from 7°C at night to 43°C during the day. In winter, temperatures fluctuate less dramatically with a range from 0°C at night to 18°C during the day. In general, the average annual temperature increases moving southward from the Delta in the north to the south of Egypt, where temperature values are similar to those of the open deserts to the east and west. Also, throughout the Delta and the northern Nile Valley, there are occasional winter cold spells that may be accompanied by light frost and even snow. There are some sandstorms that occur as a result of hot spring winds, which are known in Egypt as Khamsin winds and they are equivalent to the Sirocco winds in Europe. These sandstorms may continue for days during the spring and can lead to a temperature rise of 20°C in two hours [106].

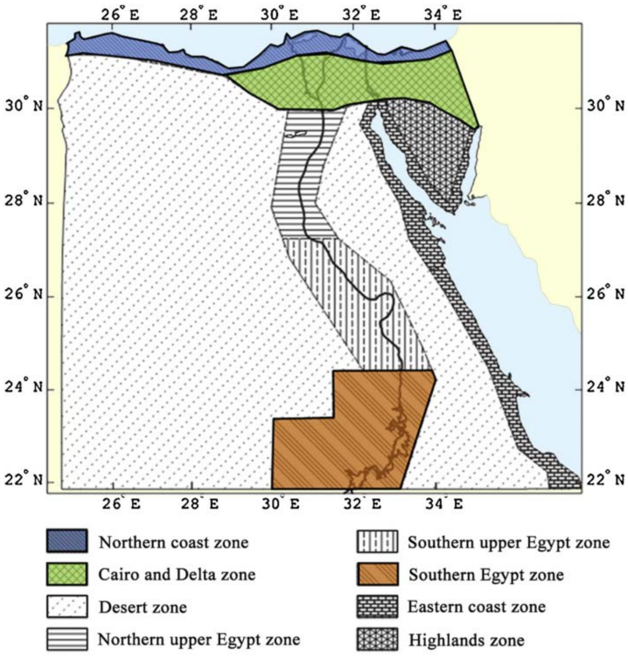


Figure 2-6. Egypt's climatic zones classification map [105].

Figure 2-7. The three major Egyptian climatic regions [45].

2.4.1 Types Of Climate Data

Weather data are available with different representations depending on their intended use. Near-extreme datasets are available that represent hot or cold weather for testing indoor thermal comfort and system performance during peak conditions, typical year datasets with average conditions are available for predicting the overall building energy consumption and carbon emissions [107].

This weather data can be used in building simulation at early design stages to reduce processing time. Nevertheless, the results may not be as accurate as using annual datasets, especially when simulating heavyweight buildings with high thermal inertia [108, 109]. For the UK only, there are Design Summer Year (DSY) datasets which represent near-extreme conditions by selecting the year with the third hottest summer within 20 years (90th percentile) using summer daily mean dry-bulb temperatures [107].

The production of these datasets has been developed over the past three decades. Typical year weather datasets are ideal for building energy simulation, but they need to be regularly updated [107]. Commonly used datasets include the following:

- The North American Typical Meteorological Year 2 (TMY2) developed from the original TMY by NREL in 1995 based on the period 1961-1990 and its European equivalent Test Reference Year (TRY).
- The Weather Year for Energy Calculations 2 (WYEC2) developed by NREL in coordination with ASHRAE from the original Weather Year for Energy Calculations (WYEC) in 1998 and its European equivalent Design Reference Year (DRY).
- The Canadian Weather Year for Energy Calculation (CWEC).
- The International Weather for Energy Calculations (IWEC).

The Typical Meteorological Year (TMY) and the TRY datasets are generated by selecting the most average months from a period of 20-30 years in order to derive a typical year with average conditions. However, the typical year is produced with the WYEC, CWEC, IWEC, and the DRY files by substituting days and hours of the same month over the 30 year period [110]. The DRY dataset is generated with more accurate monthly mean values than TRY data.

2.4.2 Sources Of Weather Data

Weather data can be obtained through publications, national meteorological services, airports, airfields, universities or research organizations. The US Department of Energy (DOE) provides typical year weather datasets for more than 2100 worldwide locations in more than 100 countries. In 2006, Forejt et al. [111] confirmed the absence of worldwide databases offering typical years for most of the non-typical regions in developing countries, including arid zones. Meteonorm is commercial software which can generate weather data from recorded monthly climatological data for the period 1961-1990 from about 7400 worldwide stations. Meteonorm also provides precipitation data that is missing in other datasets [1, 45].

Regarding the hot locations, The US Department of Energy (DOE) weather datasets are considered more accurate than those generated by Meteonorm in representing typical climate conditions for a specific location. The DOE data uses hourly measurements extracted from the months closest to mean conditions within a 30 year period to form a typical year dataset while Meteonorm interpolates monthly mean measurements for the same period from the nearest weather stations and generates hourly measurements based on these monthly means. Meteonorm has the advantage that it can provide weather datasets for any arid worldwide location not included in the DOE weather datasets. As a result, Meteonorm is used in the present research to generate typical weather data for locations that are not provided by the DOE.

2.5 Thermal Comfort

Since the 1990s, many studies have indicated that the productivity of employees is directly affected by environmental factors, including indoor air quality and thermal comfort [112]. Additionally, the achievement of the recommended level of thermal comfort and indoor air quality is inversely related to the pursuit of energy saving plans. Employees spend approximately half their life at work, so it is imperative to provide a satisfactory environment which has a positive impact on productivity level. Therefore, attempts to reduce the energy consumption in buildings, especially offices, should be accompanied with thermal comfort and indoor air quality studies to ensure the minimum acceptable comfort level is reached.

Thermal comfort is defined as 'that condition of mind which expresses satisfaction with the thermal environment'[113]. Based on the work of Fanger 1970 [114], the thermal sensation is affected by environmental and personal parameters. The parameters include air temperature, mean radiant temperature, air velocity, humidity, metabolic rate and clothing level. Other contributing parameters include climate change over time, the building and its services, and occupants' perceptions [115].

2.5.1 Temperature Definitions Relevant To Thermal Comfort

Temperature can be a major significant measure in the built environment when considering the thermal comfort of occupants and in the design of building services systems. As a consequence, it is very important to define the different temperature parameters which are used in this work.

A measured (or observed) temperature is the temperature reported by a device based on the signal from the particular sensor that is being used to carry out the measurement.

Dry-bulb temperature is a measure of air temperature. It is referred to as dry-bulb temperature since the thermometer bulb is dry and so the temperature recorded does not vary with the moisture content of the air. This is as opposed to wet-bulb temperature which is the temperature recorded by a thermometer that has its bulb wrapped in cloth and moistened with distilled water. Wet-bulb temperatures are the same as dry-bulb temperatures at a relative humidity of 100%, but otherwise, wet-bulb temperatures will be lower than dry-bulb temperatures due to the cooling effect of evaporation (described as wet-bulb depression). Dry-bulb temperature can be measured by a thermometer exposed to the air but shielded from radiation and moisture [116].

All bodies exchange thermal radiation with their surroundings, depending on the difference in their surface temperatures and their emissivity, e.g. short wave from the sun, long wave from other objects. This radiant exchange is an important component of the thermal comfort that will be experienced by a person. The mean radiant temperature is defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure [117].

The human experience of temperature, i.e. how warm or cold they perceive the temperature to be in a given environment within a specific location in a building, will be influenced by air temperature, radiant temperature and some other factors. Operative temperature is the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment. Operative temperature is also known as resultant temperature or dry resultant temperature, but the trend is for thermal comfort studies based on ASHRAE and ISO standards [116] to use the term ‘operative’, while in building energy modelling it is common to use the term ‘resultant’, which is the convention used in this thesis.

The temperature measured by a globe thermometer is generally considered to give a response closely related to that of humans and combines the effect of air and radiant temperature (dry resultant temperature) [151]. Common indoor environmental temperature sensors of the type used in this work nominally measure primarily air temperature only when they are ideally situated in freely circulating air. However it is commonly recognised that in most unobtrusive monitoring exercises such a situation is rarely possible and the temperature reported will be close to the resultant temperature due to the influence of the local environment (surfaces, still air, etc.) [118].

Because the sensors in the monitoring study of this thesis were situated on busy desks among paperwork and close to wall and desk surfaces the assumption is made that they are recording something close to the resultant temperature. This assumption is a recognised limitation in this work and is underlined in the recommendation that in future more extensive and detailed studies should be undertaken. These should be based on standardised indoor environmental monitoring protocols and instrumentation specifications; a good summary of these is given by Parkinson et al.[119]. These authors highlighted that even with high precision instrumentation the inherent spatial and time-based variations and heterogeneity mean that there are uncertainties which cannot realistically be measured but must be otherwise assessed. The work in this thesis is to provide a pathway for future work to follow. The uncertainties are captured later in this work by considering ranges for key parameters within which variation is likely to occur, and evaluating the probable impact of these likely variations on overall performance.

2.5.2 Thermal Comfort Models

Prediction of the range of temperatures for desired comfort is complicated and subject to cultural influences that depend on environmental and personal factors. A chronological review of current work on thermal comfort shows that there are two different approaches for thermal comfort prediction, climate chamber tests and field studies. The former, which are based on heat exchange processes of the body, have led to steady-state laboratory thermo-physiological models and standards such as ASHRAE 55-1992, and ISO7730. The latter have produced adaptive thermal comfort models and standards such as; the American ASHRAE 55-2010 standard, the European EN15251 standard, and the Dutch ATG guideline. Today, these standards are increasingly used in research and practice within the field of thermal comfort [120].

Occupants' thermal sensations can be recorded based on the seven-point psychophysical scale that ranges from -3 (cold) to +3 (hot) (ASHRAE 2004)[114]. Based on the outcomes of recent field studies, several thermal models have been introduced, for example, Predicted Mean Vote (PMV) / Predicted Percentage of Dissatisfaction (PPD) (PMV/PPD) model and adaptive models which are discussed in the following section.

2.5.3 Fanger's Rational Comfort Model

Based on climate chamber experiments, Fanger [113] introduced the so-called thermal sensation to the PMV/PPD model of thermal comfort prediction. The thermal comfort model combined a relationship between six primary factors, metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity. The model was based on a thermal balance equation developed under steady-state conditions [113] [121]. As indicated in Figure 2-8, the PPD is correlated to the PMV value using equation 2-1 whose mathematical structure shows that a small percentage of dissatisfied people (5%) can be expected under thermal neutrality conditions (i.e. PMV = 0).

$$PPD = 100 - 95\,.\,exp\,(-0.3353\,PMV^4 - 0.2179\,PMV^2) \tag{2-1}$$

The PMV/PPD model, should only be used for buildings in which the occupants have no control over the artificial indoor environment or opening of windows, in other words sealed air-conditioned buildings. Recent derived field measurements highlighted some inaccuracies in hot regions when the model is applied to either air-conditioned or non-air-conditioned buildings [122, 123]. Givoni [124] indicated that there is a gap in the heat balance equation used by Fanger [113] as air velocity is only considered when computing the convective heat exchange coefficient and not for the calculation of sweat evaporation and therefore it appears inaccurate. Nevertheless, the PMV/PPD model is commonly applied in the design of air-conditioned office buildings in hot climate zones.

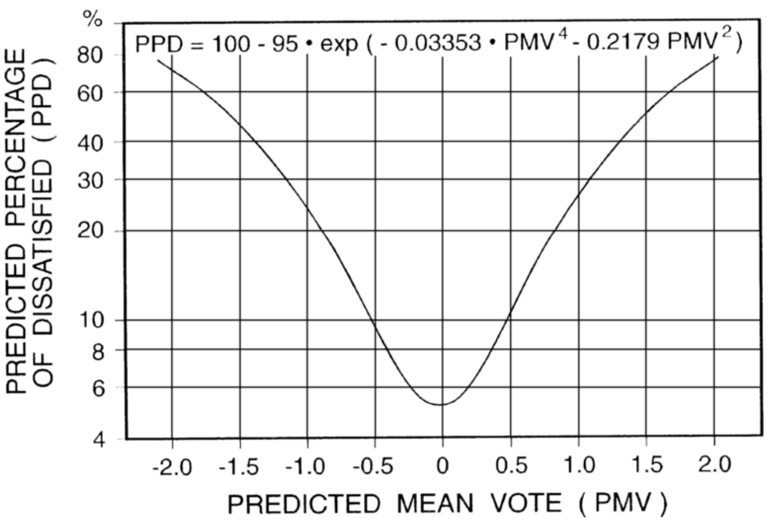


Figure 2-8. Predicted percentage dissatisfied (PPD) as a nonlinear function of predicted mean vote (PMV) [114].

2.5.4 Adaptive Thermal Comfort Models

In 1995, ASHRAE sponsored a field survey project focused on statistical analysis of high-quality data from existing buildings rather than the heat balance approach. Based on this survey, occupants in naturally ventilated buildings accept wider temperature variation and higher indoor temperatures compared to those in air-conditioned buildings [114] [125]. Occupants adapt the surrounding environment and their personal situation within it to suit their expectations using windows, blinds, (ceiling) fans and doors, change their metabolic rate, (for example, through activity level or cold drinks), or change their rate of heat loss (through changes in clothing or posture) [114, 120].

Some studies revealed that occupants of office buildings showed a low sensitivity to indoor temperature changes [125-127]. Some adaptive models observed that thermal comfort is a function of external temperatures and the internal temperature. The adaptive comfort models are derived from a black box approach and relate indoor operative (resultant) temperature (T_{Comf}) to a computed mean outdoor air temperature ($T_{e(m)}$) by a linear regression equation. The mean monthly outdoor temperature is the arithmetic average of the mean daily minimum and mean daily maximum outdoor dry-bulb temperature for a month [114], The optimal indoor resultant temperature is as follow:

$$T_{Comf} = a \,.T_{e(m)} + b \qquad 2\text{-}2$$

Several adaptive comfort models have been developed with different approaches to quantification of the outdoor air temperature which affects behaviour $T_{e(m)}$, and for different values of the coefficients ‘a’ and ‘b’. This indicates the lack of universal values for these parameters. A good summary of the values based on some recent studies for an Egyptian context is given by Attia and Carlucci [122].

2.5.4.1 American Adaptive Comfort Model (ASHRAE 55)

The ASHRAE adaptive comfort model, presented in the American standards ASHRAE 55:2004 [120], is applicable for monthly mean outdoor air temperatures in the range 10 - 33.5°C and is delivered together with an indication of comfort boundaries. Figure 2-9 shows two proposed ranges for an acceptability, of 80% and 90% (considered as complementary to the predicted percentage of dissatisfaction), which correspond to a deviation of ±3.5°C and ±2.5°C, respectively from the optimal comfort temperature[114],[125]. The optimal comfort temperature is given by:

$$T_{Comf\ (ASHRAE\ 55)} = 0.31.T_{e(m)} + 17.8 \quad 2\text{-}3$$

Where $T_{Comf\ (ASHRAE\ 55)\ i}$ is the indoor comfort temperature based on the ASHRAE 55 Standard, and $T_{e(m)}$ is the mean monthly outdoor air temperature.

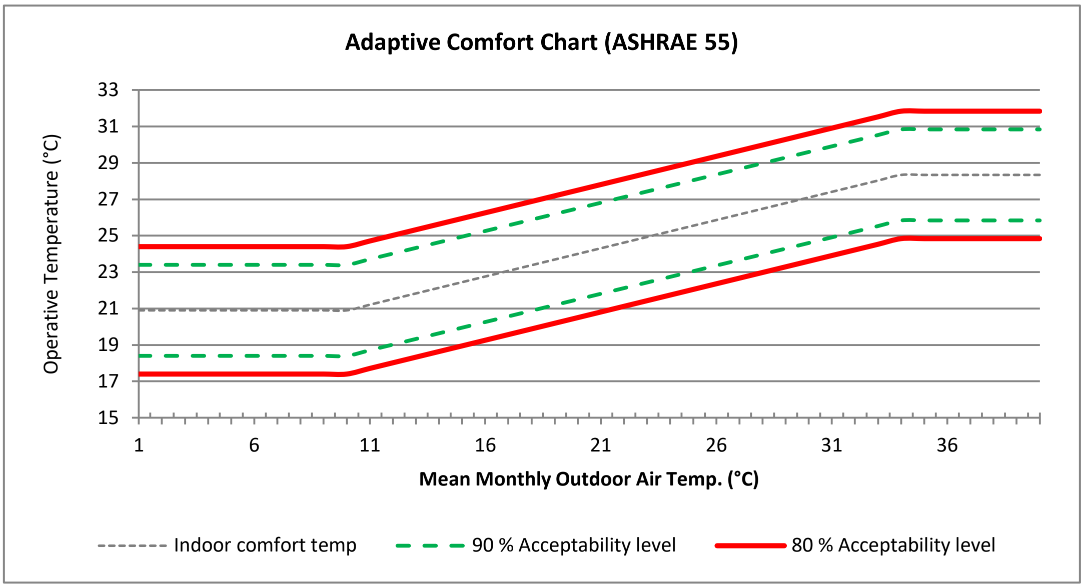


Figure 2-9. Indoor comfort resultant temperature as a function of the monthly mean outdoor dry-bulb air temperature according to ANSI/ASHRAE 55[114].

2.5.4.2 European Adaptive Comfort Model (EN 15251)

According to the European standard EN 15251[128], acceptable comfort temperatures depend on the type of system used to provide summer comfort. If cooling is provided by an active system, then indoor temperatures must reflect those defined by the Fanger model [129] plus certain assumptions of acceptability for different categories of building. But if summer comfort is provided by passive cooling strategies then the upper temperature limit is set by an adaptive model plus particular assumptions of acceptability for different categories of building.

Generally, Figure 2-10 shows the implementation of the adaptive model which indicates that indoor thermal comfort is accomplished with a wider range of temperatures than with the ISO 7730 model [115, 128, 130]. Both models use statistical analysis of survey data to back up their predictions in their respective areas of applicability. In some situations, it proves possible to maintain a building's interior conditions within the EN 15251 adaptive comfort limits totally by natural means. In these cases, there is no energy use associated with achieving indoor summer comfort. The optimal operative (resultant) comfort temperature can be calculated based on the daily mean outdoor dry-bulb air temperature of previous days as follows [128];

$$T_{rm} = (1 - \propto_{rm}) \left[T_{e(d-1)} + \propto_{rm} \; T_{e(d-2)} + \propto_{rm}^{2} \; T_{e(d-3)} \ldots \ldots \right] \quad 2\text{-}4$$

Where T_{rm} is the running mean outdoor air temperature (°C), α_{rm} is a constant between 0 and 1 which describes the rate at which the running mean responds to the outdoor temperature, $T_{e(d)}$ isthe daily mean outdoor temperature (°C) for the previous day, and $T_{e(d-1)}$ is the daily mean outdoor temperature (°C) for the day before that, etc. A recommended value for α_{rm} of 0.8 suggests that the characteristic time taken to adjust fully to a change in the outdoor temperature is about a week. To simplify calculations, the EN 15251 standard suggest a simplified equation (equation 2-5) to calculate inside comfort temperature based on the exponentially weighted running mean of the daily outdoor dry-bulb air temperature, the assumptions of acceptability are given for different categories of occupants inside a building and are expressed as symmetrical ranges around the optimal comfort temperature. Figure 2-10 reports the optimal comfort temperature and the upper and lower limits of the comfort levels [128].

$$T_{Comf(EN15251)} = 0.33\,.\,T_{rm} + 18.8 \tag{2-5}$$

Bands within which comfortable conditions have been found to lie are shown in relation to the running mean outdoor temperature, and are given by:

Upper margin:

$$T_{Comf(EN15251)} = 0.33\,.\,T_{rm} + 20.8$$

2-6

Lower margin:

$$T_{Comf(EN15251)} = 0.33\,.\,T_{rm} + 16.8$$

As shown in Figure 2-10, the upper comfort boundary is defined for a running mean indoor air temperature from 10°C to 30°C, while the lower comfort boundary is defined from 15°C to 30°C. Applying this interpretation to the EN 15251 graph, the running mean of the outdoor air temperature of 15°C might be considered the “switching temperature” between summer and the rest of the year.

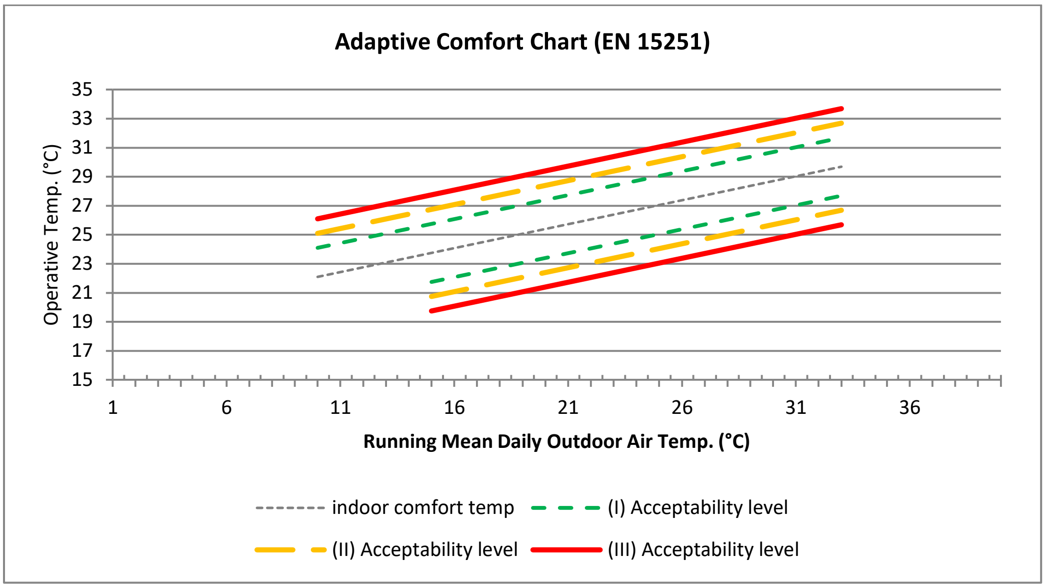


Figure 2-10. Indoor comfort resultant temperature as a function of the exponentially weighted running mean of outdoor dry-bulb air temperature according to EN 15251[128].

2.5.4.3 Dutch Adaptive model

In 2004, a third model was introduced in the Dutch ISSO-74 Adaptive Temperature Limits Guideline based on an external temperature expressed in an exponential weighted Running Mean Outdoor Temperature) [127]. Three comfort classes are suggested where 90% (A), 80% (B) and 65% (C) of occupants are satisfied.

Ezzeldin [30] conducted a detailed review of the bioclimatic analysis methods to evaluate mixed mode strategies in arid climates. These methods are Olgyay's bioclimatic chart, Givoni's Building Bioclimatic Chart, Szokolay, the CPZ method and the climate suitability analysis method.

Finally, the adaptive models deal with outdoor temperatures and neglect the other five factors in equation 2-1 which lead Fanger and Toftum [129] to disagree with adaptive models. They propose some modifications for the PMV/PPD model by extending the original model ranging between 0.5 for natural ventilation and 1 for air conditioned buildings, and by allowing changes in the metabolic rate to reflect changes in activity level.

From the above review of thermal comfort models, mainly focused on office buildings, it can be concluded that there is significant variation between the models and there is no thermal comfort model specifically useful for Egyptian office buildings. Thus in any study of office buildings in Egypt a large effort is required to select the model most representative for buildings with natural ventilation and using air conditioning.

2.6 Building Energy Standards (BESt)

Building performance has a significant effect on energy efficiency and thermal comfort. However, to understand high building performance a deeper understanding of the minimum energy efficiency standards for common buildings is required. This section discusses the importance of Building Energy Standards (BESt), and their classification. It also gives a brief review for the ASHRAE Standard 90, and the Egyptian Energy Codes for buildings.

The main idea of the Building Energy Codes and Standards is developing standards for building construction, systems specification, and designs in order to ensure the safety of the people using the building and to offer minimum/maximum accepted values to help the designers achieve optimal energy use and carbon emission. All energy concerns are to be considered in the design phase which assists both new buildings to achieve their potential, and existing buildings to be evaluated. Setting the energy efficiency requirement may, depending on the country, be contained in a single document, form part of a larger document, or be spread over several documents.

The BESt uses prescriptive language for building requirements including construction and design. Local energy codes may replace international ones in some countries. The adoption and enforcement of these energy codes are done by state or local government. To ensure the high quality of BESt, the building requirements standards are written by professionals, and published by national organizations including the American ASHRAE [16].

2.6.1 Building Energy Standards Classifications

Most countries aim to develop, improve, and expand their BESt. There are around 40 countries with some form of standards for energy use in buildings [131]. Energy regulation in buildings can be classified based on the method of the BESt implementation either as voluntary energy standards with less government involvement, or mandatory energy standards with the force of law. There are three approaches to building energy standards which are the prescriptive approach, the trade-off approach, and the performance approach. Firstly, the traditional BESt is often prescriptive in nature. It specifies the minimum requirement for each component used in building design, and hence it is easy to define. Also, it provides lists of minimum/maximum acceptable limits of different building components. The trade-off approach is more flexible than the performance one and shows more consideration of the whole building energy efficiency rather than particular components. This approach allows some limits to be exceeded by some components against better performance of others. Finally, the performance approach sets maximum allowable calculated overall energy consumption levels without specification of the particular inputs (except maybe back-stop values).

Most of the countries in America and Europe have set up mandatory performance based energy standards for new dwellings and new service sector buildings. Other non-Organization for Economic Co-operation and Development countries outside

Europe have recently established mandatory or voluntary standards for service sector buildings.

Figure 2-11 shows a range of countries classified according to the status of Building Energy Standards implementation into no standard, mandatory, mixed, and proposed standards.

As indicated in Figure 2-11, Egypt uses mixed standard types. In most countries, standards are applied to both dwellings and service sector buildings, except in Africa and Asia where most standards are only applied to non-residential buildings [132]. The recent energy codes/standards applied in hot climate countries are: NCC 2015 in Australia, ASHRAE Standard 90.1-2013 in America and other countries, ICC 2009 International Energy Conservation Code IECC, BEE 2006 in India, ECP 306-2005 in Egypt, and ENERCON 1990 in Pakistan.

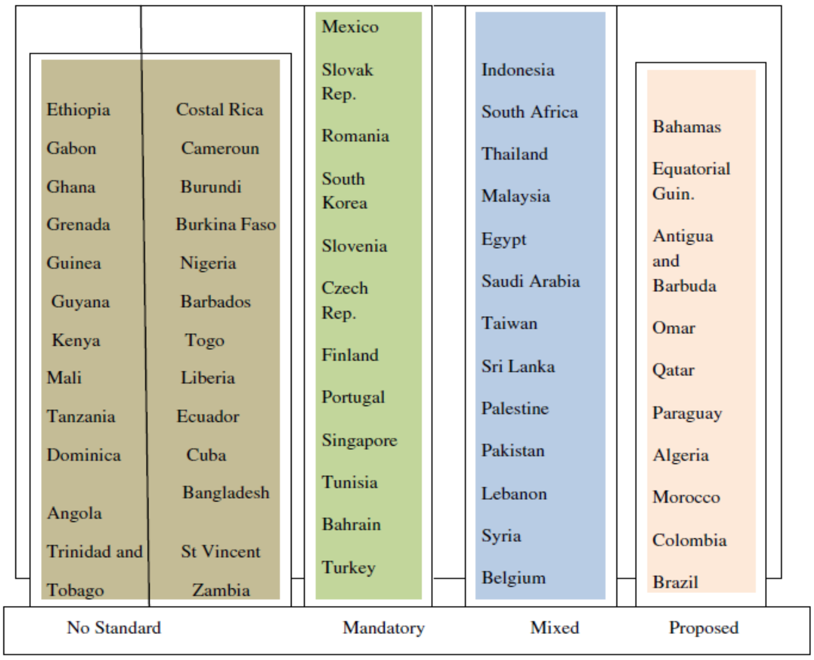


Figure 2-11. Status of building energy standards implementations in 60 countries [28, 133].

2.6.2 The American Society Of Heating, Refrigerating, And Air-Conditioning Engineers (ASHRAE Standard 90)

The ASHRAE Standards 90 series is the most widely adopted standard model in the world. After the first oil crisis in 1975, there was a development period with the first edition of ASHRAE standards published in 1980, and further versions in1989, and 1999. In line with the maintenance procedures used by American National Standards Institute (ANSI) and ASHRAE, the standard was publicly reviewed and published in its entirety each time. In 1999, the mature period of the standard started when the ASHRAE board of directors voted to place the standard on continuous maintenance, allowing it to be updated several times each year through the publication of approved addenda. The standard has been published every three years since 2001 till now [16].

The latest edition of ASHRAE 90 is ASHRAE Standard 90.1-2013 which is used extensively as the baseline for minimum energy efficiency in commercial buildings, covering the following: the building envelope, heating, ventilating and air conditioning services water heating, power, lighting, and other equipment.

2.6.3 Egyptian Building Energy Efficiency Codes

In Egypt, three Building Energy Efficiency Codes (BEEC) are used, which are categorized according to sector into residential, commercial, and public buildings. The Ministry of Housing, Utilities, and Urban Development holds the responsibility for upgrading national BEECs. The BEECs for the residential sector, the commercial sector, and public buildings were published by a ministerial declaration in 2005 (ECP 306/1-2005), 2009 (ECP 306/2-2005) and 2010, respectively under the instructions of the United Nations Development Program and the Global Environment Facility [3, 4]. These codes, like the ASHRAE Standard 90.1-2001, are classified as prescriptive voluntary energy standards as they give minimum performance standards for building windows and openings, natural ventilation, ventilating and air conditioning equipment, natural and artificial lighting, and electric power [105].

Developing an updated version of the Egyptian code for energy consumption in buildings requires field study, more detailed research, and typical case studies to take account of the current situation in Egypt and to keep up-to-date with the rapid development of the fields of construction and energy. Thus, the methodology followed in the present study, based on field study and monitored data, aims to help in future in upgrading the current Egyptian codes.

2.6.4 The Role Of Thermal Comfort And Occupant Behaviour In Energy Use In Buildings

A lot of effort is made to reduce energy consumption in buildings. Such energy reduction efforts come in widely diverse forms, including more energy efficient lighting and equipment, more insulation, passive cooling strategies, smart controls, and the use of renewable energy. All of these techniques and technology are operated by humans, and failure of the human component can undermine the whole strategy. This makes the occupancy behaviour one of the weakest links in the energy efficiency and conservation equation. There are many techniques that can reduce the use of air conditioning in summer based on occupant behaviour with the resulting thermal comfort in the acceptable range. The acceptance of higher indoor temperatures in summer conditions would lead to less use of cooling systems, and hence less electricity consumption by the air conditioning systems [134]. There have been some studies investigating the energy use implications in the built environment of adopting different thermal comfort regimes.

Most of the publications for hot climate regions focused on either simply setting a higher summer setpoint temperature or implementing a wider/varying range of indoor design temperature for different times of day and different outdoor conditions

[135-140]. Others study different types of cooling systems and use supplementary systems (economizer, heat exchanger, modified control system) to reduce the energy required by the cooling systems. Ezzeldin [1] examined mixed-mode cooling strategies for an existing typical modern office in Cairo, Egypt.

Givoni [124] expanded the boundaries of the comfort zone based on the expected indoor temperatures achievable with different passive design strategies, applying a “common sense” notion that people living in unconditioned buildings become accustomed to, and grow to accept, higher temperature or humidity. In another approach, a proposed addendum in September 2008 suggested the use of the PMV model with air speeds below 0.20 m/s. Air speeds greater than this value may be used to increase the upper resultant temperature limits of the comfort zone in certain circumstances. They could be achieved by using ceiling fans to elevate air speed to offset increased air and radiant temperatures.

As shown in Figure 2-12, elevated air speed is effective at increasing heat loss when the mean radiant temperature is high, and the air temperature is low. However, if the mean radiant temperature is low or humidity is high, elevated air speed is less effective. The required air speed for primarily sedentary activities may not be higher than 0.8 m/s depending on clothing and activity. However, the ceiling fan effect cannot control humidity. Figure 2-13 shows the acceptable range of resultant temperature and air speed for a given clothing level.

Figure 2-13 provides additional limits not based on setpoint temperature. The chart is divided into two areas, with and without local control. When occupants have control of local air speed the full equal heat-loss envelope for a given clothing level applies. For effective control over their local air speed, directly accessible control must be provided for every six occupants (or fewer) or for every 84m^2 (or less). The range of control fully encompasses air speeds suitable to preserve comfort for sedentary occupants. The air speed should be adjustable continuously or in maximum steps of 0.25m/s as measured at the occupant's location. Within the equal heat-loss envelope, if occupants do not have control over the local air speed in their space, limits apply as shown by the light grey area. They apply for light, primarily sedentary office activities. There is little quantitative information obtainable for other types of occupancies. For resultant temperatures above 25.5°C, the upper limit to air speed is 0.8m/s. Below 22.5°C, the limit is 0.15m/s to avoid cold discomfort due to the draft. 0.15m/s is the upper limit of the still-air zone and is fortunately equal to the air speed self-generated by an office worker at 1.2 met. Between 22.5°C and 25.5°C, the allowable speed follows an equal SET curve dividing the light and dark grey areas. This local-control boundary between 22.5°C and 25.5°C is not related to any PMV comfort zone but is based on temperatures that have been observed in office field studies to cause virtually no objection to the draft [142, 143].

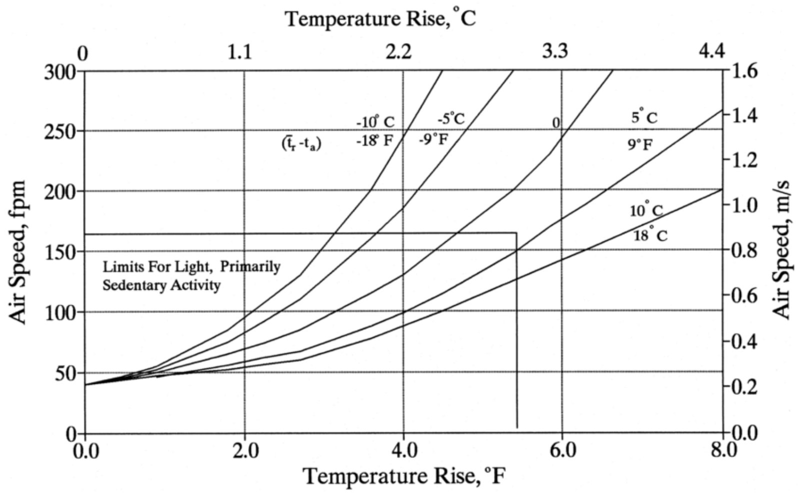


Figure 2-12. Air speed required offsetting increased temperature [141].

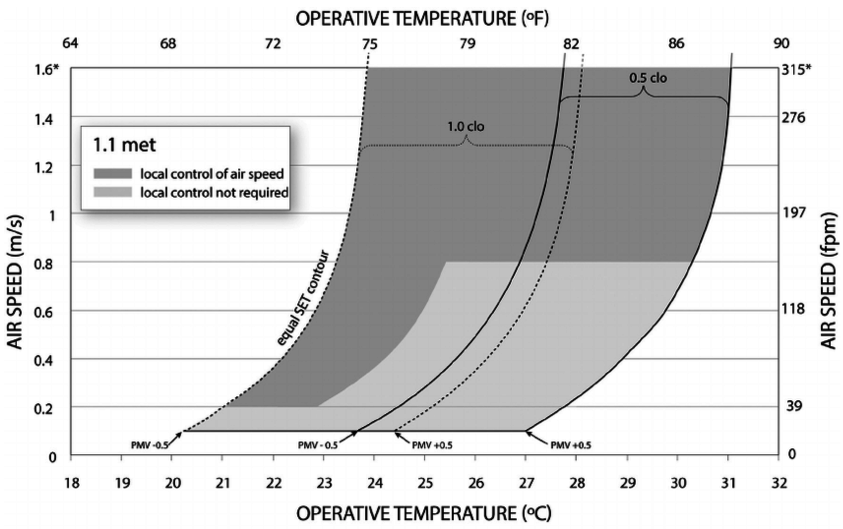


Figure 2-13. Acceptable ranges of operative (resultant) temperature and airspeeds [142].

The proposal is made in this thesis of using ceiling fans in an air conditioned space to raise the setpoint temperature, and increase the readiness of the occupants to change their behaviour to prevent the waste of energy especially during unoccupied hours in an office building.

Large numbers of governments are launching initiatives and adopting awareness campaigns to improve the energy performance of buildings to realise benefit economically, socially or scientifically. These initiatives are more important as preventative actions than when tackling problems after they have occurred.

In the UK and EU [144] there is a great number of initiatives in the residential and commercial sectors, such as:

- Community Energy Saving Programme (CESP): CESP targets households across Great Britain, in areas of low income, to improve energy efficiency standards and reduce fuel bills
- Energy Assistance Package: Government funded scheme available in Scotland, giving up to £3,500 to households on certain benefits to improve their heating and energy efficiency.

- Feed-in Tariff (FITs): Feed-in tariff schemes encourage home-owners and businesses in the UK to install renewable technology by guaranteeing a long-term premium payment for electricity generated from small-scale renewable installations and fed into the grid.
- Warm Front; UK Government funded scheme operated in Scotland, Wales and Northern Ireland, giving up to £3,500 to households on certain benefits to improve their heating and energy efficiency.
- Green Deal: UK governments funded the company which made energy saving improvements to residential systems, e.g insulation, heating, renewable energy generation.

In Japan in 2005, a successful campaign called the Cool Biz campaign was launched to reduce the energy used for air-conditioning during summer by wearing comfortable clothes. Cool Biz was initiated by the Japanese Ministry of the Environment (MOE). This was enabled by changing the standard office air conditioner temperature to 28°C and adopting a liberal summer dress code in the bureaucracy of the Japanese government so staff could work at the warmer temperature. The campaign then spread to the private sector [145]. Later, Korea adopted Cool Biz in 2006.

In Egypt, the Egyptian initiative launched in 2014 aimed to raise the awareness of users to rationalize energy used in buildings. The campaign aimed to save 20% of the energy used in Egyptian buildings. It focused on the energy used by lighting systems, urging citizens to use natural light during the day, turn off lighting in unoccupied spaces, and replace regular bulbs with energy-saving bulbs. It also focused on buying the most efficient air conditioners, while adjusting the temperature to not less than 25°C, attending to the regular maintenance of air-conditioners, and unplugging all loads when not in use.

This initiative focused on the residential sector as it is the biggest sector in Egypt. Similar public initiatives have not yet been launched in the non-residential sector.

2.7 Summary

The review developed in this chapter covers selected major fundamental topics of the research area: energy used in office buildings, dynamic simulation tools, climate classification, thermal comfort in hot climates, building energy standards, and energy saving innovations in some countries.

The main finding of this chapter can be summarized as follows:

1. The rapid increase in the use of energy and its negative impact on the surrounding environment requires investigation of the main consumers of this energy.
2. Energy consumption by the building sector accounts for 20.1% of the total delivered energy consumed worldwide.
3. In developing countries, the range of energy consumption by office buildings is unknown due to the lack of the research in this area, and to the weakness of codes and standards.
4. The key loads of the energy consumption in office buildings are HVAC system loads, lighting system loads, and office equipment loads. According to recent studies in Egypt, there is no available reference data for these loads. None of the studies addressed the variation in energy performance in office buildings in Egypt.
5. Building simulation tools are accredited, and on standard tests are shown to be effective and accurate. Several studies have however highlighted great disagreements between simulated building energy performance and measured performance as buildings often do not perform as well as predicted for a wide range of reasons. One key element in improving predictions based on

modelling is rigorous model calibration; a second key element is the inclusion of uncertainties in realistic input parameter sets.

6. The usage of BEPS tools in Egypt is extremely low as their use is not required for code compliance, or regulatory conformance. The energy and fuel prices do not reflect the real value of energy. The shortage of information on Egyptian building performance has also led to difficulty in calibrating simulation models. Additionally, no comprehensive dynamic building simulation tools are available in Arabic, and the lack of academic and professional educational facilities are factors that negatively affect the interest in energy efficiency and indoor environmental quality. This is in addition to the lack of understanding of simulation outputs.
7. Several studies based on calibration have been carried out, but as yet no clear universal methodology has been presented. Subsequently, the calibration process depends on the user’s skill. To holistically address calibration of building simulation modelling, it is important to consider the issue of model uncertainty including climate condition, building envelope, power demand by systems, and occupant behaviour in using these systems.
8. According to the world map climate classification of Köppan-Geiger Egypt is located in the hot arid region. According to the Egyptian Code for Energy (ECP 306-2005), Egypt is classified into eight main zones based on weather conditions, North Coast, Cairo & Delta, Desert, North Upper Egypt, South Upper Egypt, South Egypt (Lower Egypt), Eastern Coast, and Highland. Based on the review study, these eight zones summarize into three main zones, the hot humid, hot mild, and hot dry regions.
9. To reduce the energy consumption in buildings especially in offices, thermal comfort and indoor air quality studies are essential to ensure minimum comfort levels. Through the review of thermal comfort models, which are mainly focused on office buildings, it could be concluded that the variation

between the models is very high and there is no typical thermal comfort model for the Egyptian office building.

10. Finally, publishing a new version of the Egyptian code requires field study, more research, and typical case studies reflecting the current situation in Egypt and in line with the rapid development of the fields of construction and energy. In addition, more energy saving procedures should be established by the government to protect the access of future generations to energy and a suitable environment.

In the next chapter the first main gap, which is the lack of data for existing Egyptian offices, will be addressed through an energy survey to study energy use across a wide range of these buildings. It is structured according to the building environmental services and includes detailed data monitoring to identify a case study office representing the most common type found in the survey, in order to investigate energy use, IEQ, comfort and occupant behaviour for this type of building.

Chapter 3 OFFICE BUILDINGS IN EGYPT: TYPOLOGY, MULTI-BUILDING ENERGY USE SURVEY, AND DETAILED ENERGY AND IEQ STUDY FOR A TYPICAL CASE STUDY

3.1 Introduction

Understanding the current performance and nature of the energy use in Egyptian buildings, and the subsequent development of methods to reduce the energy consumption is of great importance. The main objective of this chapter is to present insights into the nature of the energy use in Egyptian buildings and their current classification.

A 59 building energy survey was done to study the energy use across a wide range of Egyptian offices which are categorized according to the building environmental services type into Natural Ventilation (NV) with No Cooling System (NCS); Natural Ventilation (NV) with Local Cooling Systems (LCS); Mechanical Ventilation (MV) with Local Cooling System (LCS); and Mechanical Ventilation with Central Cooling System (CCS).

A more detailed investigation into energy, IEQ and occupant behaviour was then carried out for a case study office with the most commonly observed service strategy (natural ventilation with local cooling systems). Based on this detailed survey, a basic simulation model will be developed in Chapter 4 and then calibrated.

3.2 Building Classification

Based on the literature review there are three main types of building namely commercial buildings, residential buildings for living purpose, and the industrial buildings for manufacturing and production. Commercial buildings cover everything from schools to hospitals, office buildings to grocery stores. They can be single use such as an office building, or complex combinations of offices, cooking and dining facilities, and even living space as with hospitals. Essentially, they are buildings that are designed, built, and operated for any use other than residences. As the uses for buildings and demands on them have multiplied, they have evolved into increasingly complex aggregations of diverse technologies (ranging across construction materials and practices, building equipment, and maintenance and operation).The type of activities involved in the commercial building has a significant effect on the energy required [24]. In general commercial buildings can be classified based on the activities or functions performed in the building as mentioned in the literature review [1].

Egyptian commercial buildings can be classified according to the Egyptian code to improve the efficiency of energy use in commercial buildings (ECP 306/2-2005) into three main categories which ar: new commercial buildings, commercial parts of new multi-purpose buildings, and whole or part of existing buildings [4]. Figure 3-1 to Figure 3-3 show examples of these main categories of Egyptian commercial buildings.

These Egyptian commercial building classifications have some similarities with classifications from literature such as in the UK ECG19 [7] but also some differences. The UK classifications are by building form and service type as illustrated in Table 3-1. To provide direct comparisons with available UK data (Table 3-2) a categorization based on building form and service type was adopted for Egyptian offices.

Figure 3-1. Examples of the first category of Egyptian commercial buildings - new commercial buildings.

Figure 3-2. Examples of the second category of Egyptian commercial buildings - commercial parts of new multi-purpose buildings.

Figure 3-3. Examples of the third category of Egyptian commercial buildings - whole or part of existing buildings.

Table 3-1. UK energy consumption guide 19 (ECG19) office buildings classification. [7]

Type of office building	Typical size range	Building details
Naturally Ventilated cellular (Type 1)	100 m^2 - 3000 m^2	Domestic approach with individual windows, minor illuminance levels, local light switches, heating controls. Cookery; odd sink, refrigerator, and kettle.
Naturally Ventilated open Plan (Type 2)	500 m^2 - 4000 m^2	Purpose built. More office equipment, and vending machines.
Air Conditioned, Standard (Type 3)	2000 m^2 - 8000 m^2	Analogous in occupancy and planning with build Type 2. Deep floor plan. Tinted or shaded windows buildings. Variable air volume (VAV) air conditioning with air cooled water chillers.
Air conditioned Prestige (Type 4)	4000 m^2 - 20000 m^2	Purpose-built. Longer Plant running hours. Catering kitchens. Air-conditioned rooms. Extensive storage, parking and leisure facilities.

Table 3-2. UK energy conservation guide 19 - energy use in offices (kWh/m^2 p.a.) [7].

Category of Office by Services Type	Naturally Ventilated Cellular		Naturally Ventilated Open-plan		Air-Conditioned Standard		Air-Conditioned Prestige	
	Good Practice	Typical	Good Practice	Typical	Good Practice	Typical	Good Practice	Typical
Cooling	0	0	0	0	14	31	21	41
Lighting	14	23	22	38	27	54	29	60
Equipment	12	18	20	27	23	31	23	32
Total electricity	33	54	54	85	128	226	234	358
Total heating	79	151	79	151	97	178	114	210

3.2.1 Survey Of Energy Use In 59 Egyptian Offices

In the area of energy modelling, different methods have been applied to estimate the energy use in many countries. Based on the literature review the three most common methods to estimate energy use in buildings are (1) linear regression models, (2) neural networks and (3) surveys [22]. Many studies have aimed to identify the energy consumption use and patterns in buildings by conducting field visit surveys. The main purpose of these surveys is to estimate the energy consumption per building and the annual consumption nationally.

The next section will show the methodology used in this thesis for the energy survey applied to 59 Egyptian office buildings.

3.2.1.1 Methodology

This survey aims to assess the energy consumption characteristics of office buildings in Egypt. Building characteristics and energy use data were gathered through field surveys. The surveys gathered data on the office activity, servicing strategy and floor area. The offices were then categorized by servicing strategy and a statistical analysis done to represent monthly energy use.

To gain a snapshot of energy use a simple field survey was conducted for 59 offices all of them located in Alexandria. The field survey was done by a group of students based on specific questions to be answered.

The students were asked to use their network of personal connections to gain access to offices. In this regard, the survey could be viewed as being somewhat random. Based on introductions through their personal networks, visits were undertaken by pairs of students.

The main questions they asked through the survey are:

- The type of business activity of the office.
- The approximate total floor area.
- The category of the building as part of a commercial or residential building or a separate building.
- The type of the ventilation and cooling system in the building.
- The monthly energy consumption for the building for the last 12 months.

Gathered data is summarised in Table 3-3 which includes: office total internal floor area, office business activity, building type, building services type, and electricity bill data for 12 continuous months during 2013-2014.

Many barriers faced the team conducting this survey due to the social and economic troubles in Egypt after the revolution. There are some limitations in the record data:

- In many cases, the office administrator was reluctant to have the specific activity of the office recorded for fear of identification, and so a ‘no response’ was recorded (N/A in Table 3-3)
- The floor area was obtained from the occupants based on their knowledge of the property (in Egypt property costs of sales and rentals are all based on the

internal floor area, i.e. cost per m^2, there is no official standard for this value, but it normally includes the clear space within the property).

- The surveyed offices included lawyers, accountants, travel agents, sales, health administration, insurance, consultants, bank administration, human resources, and government. Surveyed offices were within both mixed office / residential buildings and in single function multi-floor offices.
- In general, there is no obligation to follow any construction standard or code in Egypt. Questions on construction, materials properties and building age were considered but it was decided that the answers would be too difficult to determine accurately, so these questions were not asked.
- The energy recorded is based on monthly energy bills, but sometimes bills were missed, so a monthly profile had to be estimated from a two month period, etc.

Various ways to categorize the offices were possible here, but the most influential factor on the energy consumption was found to be service strategy. Offices were categorized into:

- Natural Ventilation (NV) with No Cooling System (NCS);
- Natural Ventilation (NV) with Local Cooling Systems (LCS);
- Mechanical Ventilation (MV) with Local Cooling Systems (LCS);
- Mechanical Ventilation with Central Cooling System (CCS).

Here 'Local Cooling Systems (LCS)' is used as an abbreviation of 'local cooling under personal control through individual unitary or split systems colloquially referred to as 'A/C' '.

Data for the surveyed offices categorized into these four types is shown in Table 3-4 and Figure 3-4.

Table 3-3. Data recorded based on the field survey for the Egyptian office buildings

Office NO.	Office Business Activity	Floor Area	Building Type: Part of Multi-Purpose Building	Building Type: Separate Building	Building Services Type: Ventilation System: Natural	Building Services Type: Ventilation System: Mechanical	Building Services Type: Cooling System: None	Building Services Type: Cooling System: Local	Building Services Type: Cooling System: Central	Monthly Electricity Consumption Through 2013-2014: January	February	March	April	May	June	July	August	September	October	November	December	Annual	kWh/m^2 p.a.
1	N/A	195	x		x		x			577	536	596	589	479	585	610	689	510	543	501	490	6705	34.4
2	Law	130	x		x			x		355	310	339	340	344	385	404	511	481	533	453	308	4763	36.6
3	N/A	250	x		x			x		738	645	678	638	680	1170	1280	1305	1156	1043	733	753	10819	43.3
4	N/A	200	x		x			x		590	577	564	479	553	936	1091	1118	1119	1024	709	549	9309	46.5
5	Consultant	140	x		x			x		510	530	505	534	551	620	850	865	870	805	525	533	7698	55.0
6	N/A	140	x		x			x		520	535	584	576	597	722	896	952	894	774	510	405	7965	56.9
7	N/A	220	x		x			x		476	479	487	486	537	747	894	987	952	765	555	464	7829	35.6
8	medical service	120	x		x			x		236	224	218	227	230	290	336	381	314	339	326	261	3382	28.2
9	Lawyer	150	x		x			x		275	278	246	293	260	300	521	560	544	363	278	355	4273	28.5
10	Company	6000		x		x			x	64000	60000	65000	75000	83000	93000	115000	113000	116000	100000	85000	71000	1040000	173.3
11	Company	4000		x		x		x		12800	12000	13000	15000	16600	18600	23000	22600	23200	20000	17000	12200	206000	51.5
12	company	500		x		x		x		1265	1336	1463	1446	1735	2619	2733	2920	3061	2780	2216	1706	25280	50.6

Office NO.	Office Business Activity	Floor Area	Building Type		Building Services Type					Monthly Electricity Consumption Through 2013-2014													
					Ventilation System		Cooling System																
			Part of Multi-Purpose Building	Separate Building	Natural	Mechanical	None	Local	Central	January	February	March	April	May	June	July	August	September	October	November	December	Annual	kWh/m^2 p.a.
13	Design	160	x		x			x		193	187	220	210	187	331	290	681	707	647	386	192	4231	26.4
14	N/A	180	x		x			x		587	612	649	685	604	638	812	987	1076	1189	564	594	8997	50.0
15	Consulting	200	x		x			x		562	579	780	706	580	642	860	1064	1174	984	568	610	9109	45.5
16	Civil Company	320	x			x		x		2124	1867	1775	1648	1613	1374	1943	2412	1807	1589	1417	1717	21286	66.5
17	N/A	90	x		x			x		191	151	171	176	161	210	330	301	255	199	175	194	2514	27.9
18	Insurance Company	1400		x		x		x		10110	10080	10973	10591	12127	13972	14712	15273	14787	13865	12340	13796	152626	109.0
19	N/A	150	x		x			x		501	524	500	524	553	654	720	1025	611	696	643	439	7390	49.3
20	Real Estate Investment	580		x		x		x		1839	1830	2012	1897	2362	2350	5393	3466	3970	3971	2362	1926	33378	57.5
21	Commercial Work	240	x		x		x			673	737	563	355	337	306	701	399	506	673	666	324	6240	26.0
22	Information	90	x		x			x		154	128	129	154	257	270	318	260	308	325	273	208	2784	30.9
23	N/A	120	x		x			x		233	286	220	240	386	331	290	681	707	648	386	378	4786	39.9
24	Consulting	140	x		x			x		430	470	520	477	422	458	563	969	662	692	374	446	6483	46.3

Office NO.	Office Business Activity	Floor Area	Building Type		Building Services Type					Monthly Electricity Consumption Through 2013-2014													
					Ventilation System		Cooling System																
			Part of Multi-Purpose Building	Separate Building	Natural	Mechanical	None	Local	Central	January	February	March	April	May	June	July	August	September	October	November	December	Annual	kWh/m^2 p.a.
25	Commercial work	90	x		x		X			325	334	255	214	176	172	241	205	172	234	180	192	2700	30.0
26	N/A	180	x		x			x		418	1107	502	1064	951	993	1135	711	691	883	512	823	9790	54.4
27	N/A	120	x		x			x		227	234	286	382	453	485	533	466	300	470	337	368	4541	37.8
28	Tourism Company	150	x		x			x		478	515	791	1037	1022	1027	1211	1011	640	683	537	608	9560	63.7
29	N/A	120	x		x			x		258	330	354	385	477	653	685	597	466	373	217	312	5107	42.6
30	N/A	110	x		x			x		386	416	241	320	401	442	582	399	265	285	330	301	4368	39.7
31	N/A	180	x		x		X			354	332	588	683	609	387	372	406	612	564	497	387	5791	32.2
32	N/A	140	x		x			x		167	178	184	214	217	220	223	328	288	318	323	297	2957	21.1
33	Tourism Company	140	x		x			x		478	481	532	860	1262	1169	1126	955	793	725	505	412	9298	66.4
34	N/A	100	x		x			x		204	270	254	279	191	214	246	263	215	164	214	188	2702	27.0
35	N/A	120	x		x			x		367	334	312	383	409	466	533	555	622	492	454	411	5338	44.5
36	N/A	90	x		x			x		122	104	80	68	68	96	118	146	122	132	66	64	1186	13.2
37	Financial	1200		x	x			x		2960	3640	5000	5640	5865	6460	7000	7100	7140	7560	5000	4300	67665	56.4
38	Bank	4000		x		x			x	32960	34000	34480	36080	42240	44640	48640	50240	50800	50960	45200	42080	512320	128.1

Office NO.	Office Business Activity	Floor Area	Building Type: Part of Multi-Purpose Building	Building Type: Separate Building	Building Services Type – Ventilation System: Natural	Building Services Type – Ventilation System: Mechanical	Building Services Type – Cooling System: None	Building Services Type – Cooling System: Local	Building Services Type – Cooling System: Central	Monthly Electricity Consumption Through 2013-2014: January	February	March	April	May	June	July	August	September	October	November	December	Annual	kWh/m^2 p.a.
39	Account	160	x		x			x		491	516	641	842	542	491	440	429	315	401	441	411	5960	37.3
40	N/A	1000		x	x			x		2688	3024	3352	3376	4400	4592	4688	5040	4072	4472	4104	3456	47264	47.3
41	N/A	1400		x	x			x		4951	5184	6247	6402	3266	2919	2776	2836	3892	3936	3023	2084	47516	33.9
42	N/A	800	x		x			x		3826	2837	2907	2895	3682	3917	3996	5715	5526	3395	4516	3748	46960	58.7
43	Sales	120	x		x			x		120	127	124	118	120	200	205	220	180	150	130	110	1804	15.0
44	N/A	2000		x	x			x		4653	4650	9990	9074	4944	5927	5078	7161	6087	7101	15404	5181	85250	42.6
45	N/A	110		x	x			x		257	229	258	253	261	246	255	201	133	223	262	233	2811	25.6
46	N/A	130	x		x			x		250	192	501	460	425	607	789	800	787	484	275	190	5760	44.3
47	Consultant	120	x		x			x		248	320	360	390	487	650	695	609	468	373	216	322	5138	42.8
48	Consultant	350	x			x		x		1000	1000	1060	1200	1286	1500	1800	1900	1756	1655	1420	312	15889	45.4
49	N/A	340	x		x			x		891	740	744	762	701	1180	1331	1053	1292	1279	665	312	10950	32.2
50	Law	110	x		x			x		113	124	197	159	186	224	110	365	245	268	193	312	2496	22.7
51	Consultant	280	x		x			x		311	291	210	379	299	359	412	398	659	389	255	312	4274	15.3

Office NO.	Office Business Activity	Floor Area	Building Type		Building Services Type					Monthly Electricity Consumption Through 2013-2014													
					Ventilation System		Cooling System																
			Part of Multi-Purpose Building	Separate Building	Natural	Mechanical	None	Local	Central	January	February	March	April	May	June	July	August	September	October	November	December	Annual	kWh/m^2 p.a.
52	traveling	209	x		x			x		648	598	497	689	789	869	968	769	710	619	578	312	8046	38.5
53	Sales	110	x		x		X			76	80	43	27	83	199	203	330	110	14	43	312	1520	13.8
54	N/A	90	x		x		X			115	102	77	65	70	100	115	145	120	130	73	312	1424	15.8
55	medical service	680	x			x		x		3535	4031	4641	5174	4813	5380	5210	4640	4590	4550	4128	312	51004	75.0
56	N/A	350	x			x		x		1052	1065	1130	1760	1780	2784	2139	2649	2798	2088	2630	312	22187	63.4
57	Sales	475	x			x		x		2327	2449	3198	3566	3933	3897	4155	2531	2355	2745	3528	312	34996	73.7
58	N/A	150	x		x			x		391	327	300	460	580	674	748	735	758	644	433	312	6362	42.4
59	N/A	80	x		x		X			67	60	86	41	75	70	80	85	71	68	66	312	1081	13.5

Table 3-4. Egyptian office survey overview.

Office Type	No. of survey offices	Ventilation System	Cooling System	Description
Type 1	7	Natural	No Cooling	Offices in residential buildings
Type 2	41	Natural	LCS	Offices in residential or multiple floor offices
Type 3	9	Mechanical	LCS	Multi floor office buildings
Type 4	2	Central HVAC		Multi floor office buildings

Annual energy use is summarised by service strategy in Table 3-5 which also gives a comparison with the UK ECG19 data for electricity (the ECG19 energy for space heating has been excluded, as not relevant to the Egypt context).

The survey data only included two buildings with central HVAC. To supplement the survey data the published monthly electrical energy data of Abdelhafez [29] and Ezzeldin [1] for this type of Egyptian office is also presented in Table 3-5. Abdelhafez gives 202kWh/m^2 p.a. of total energy use, and162 kWh/m^2 p.a. for HVAC, lights and equipment over two years of monitoring, the difference is possibly infrastructure such as lifts or external security lights. Ezzeldin [1] reported total energy use within the range of 118 to 237 with an average of 170kWh/m^2 p.a. depending on the specific pattern of use. These values are not inconsistent with those measured in the survey.

Table 3-5. Average annual electricity consumption for the Egyptian office surveys plus supplementary data from *Abdelhafez [29] and ** Ezzeldin [1]; and comparable ECG19 [36] data with space heating excluded.

Category by Services	NV and NCS (Type 1)	NV and LCS (Type 2)	MV and LCS (Type 3)	MV and CCS (Type 4)
Annual average kWh/m^2	23	40	67	150 162*, 118 / 237**
ECG19 best practice / typical	31 / 48	50 / 77	124 / 218	230 / 350

Figure 3-4. Examples of the 4 types of Egyptian office buildings.

A statistical analysis was applied to show the ranges of the energy consumption for each type, as shown in in Figure 3-6 and Figure 3-7. Figure 3-5 shows a diagram explaining the monthly energy consumption survey data in Figure 3-6. Solid bars represent +/- 25 percentiles while the lines show the highest and lowest figure for each month.

The survey data shows that the naturally ventilated offices without cooling have the lowest energy use, those with cooling systems have higher consumption particularly in summer months, offices with mechanical ventilation have higher energy use than those with natural ventilation, and those with centralised cooling or centralised HVAC have the highest consumption. The results show the same trend as in the ECG19 [7] shown in Table 3-5, where more highly serviced buildings consume higher levels of electrical energy. However, it appears that in general the total electrical energy use is lower for the Egyptian offices in the survey than the UK or US benchmarks.

There were many difficulties in gathering the survey data; given the socioeconomic situation, it was difficult to find building occupants willing to share their energy use data. This limited the quantity of data gathered, leaving scope for further work to be done in this area.

While the monthly bill data of the survey provides some useful insights, a more detailed performance survey would be required to provide a deeper understanding and inform the creation of a representative simulation model.

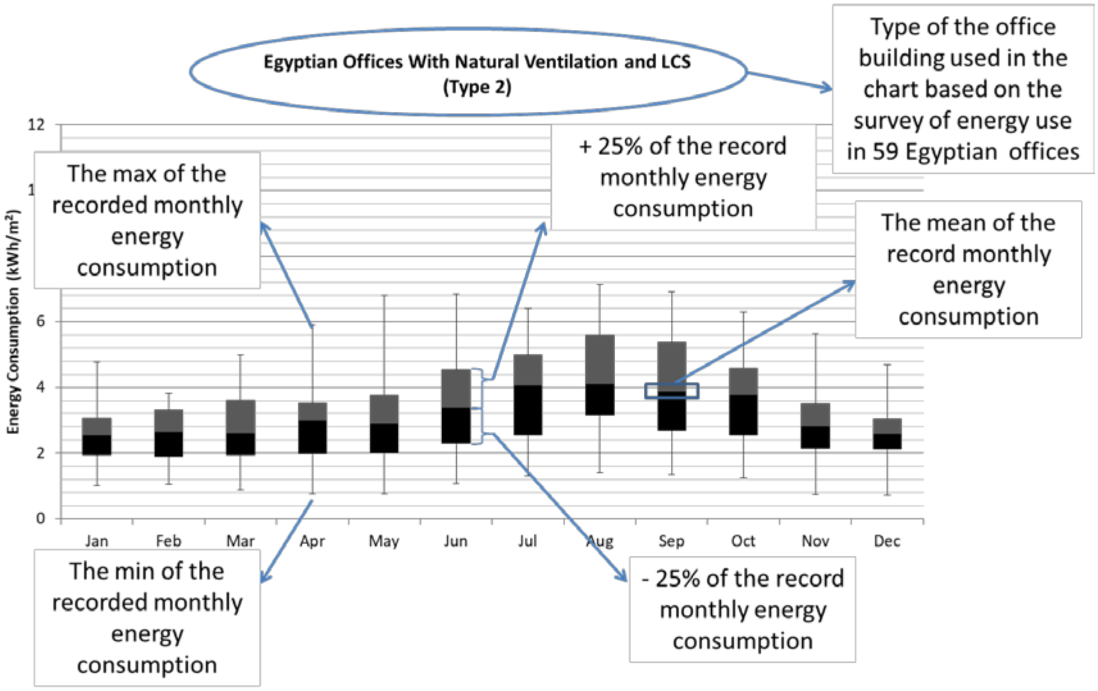


Figure 3-5. Diagram explaining for monthly energy consumption survey data

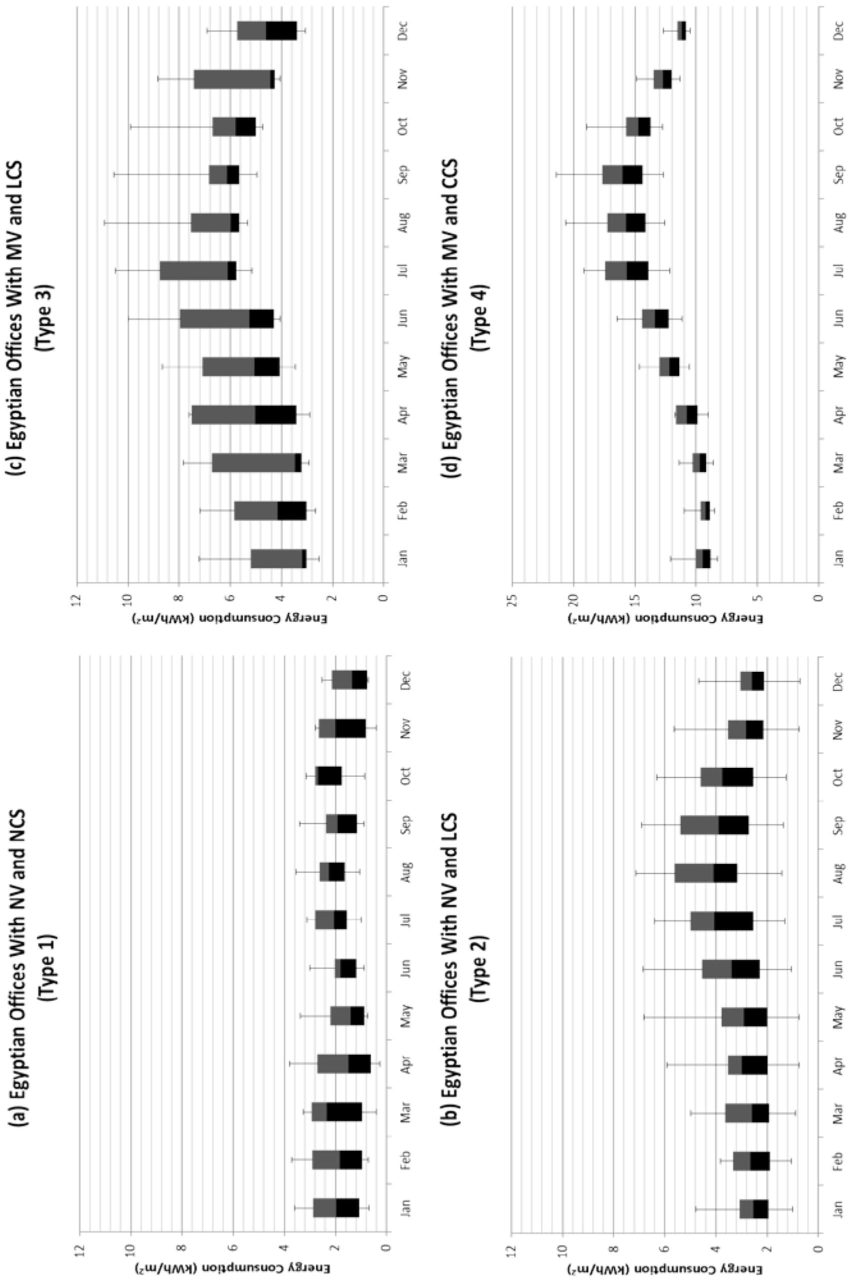


Figure 3-6. Monthly energy consumption (solid bars are +/- 25 percentiles, lines the range) for Egyptian offices: (a) with Natural Ventilation (NV) and No Cooling, (b) with Natural Ventilation (NV) and Local Cooling System (LCS) , (c) with Mechanical Ventilation (MV) and Local Cooling System (LCS), and (d) with Mechanical Ventilation (MV) and Central Cooling System (CCS)

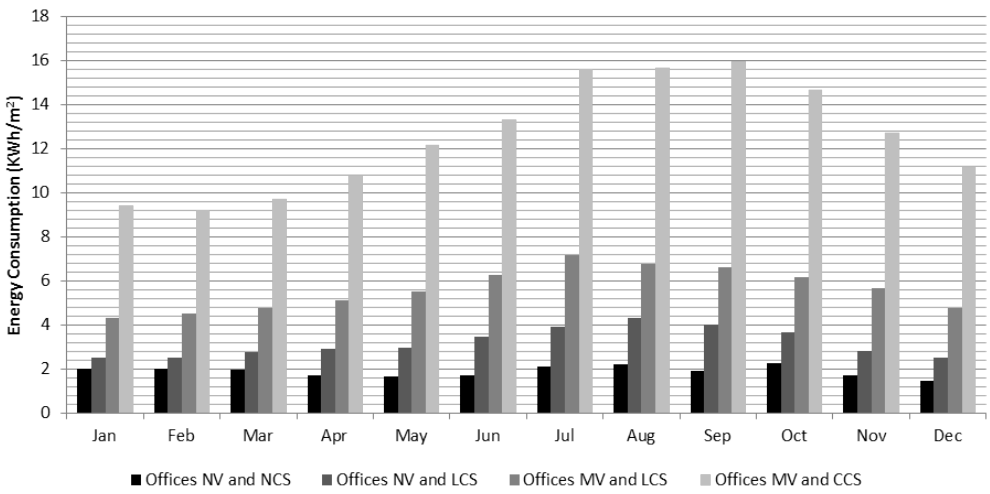


Figure 3-7. Monthly office energy use vs. service strategy.

3.3 Detailed Energy And IEQ Performance Evaluation For A Case Study Office

The most common office type found in the 59 building survey was 'Type 2' with natural ventilation and local 'A/C' cooling units. A case study building of this type was identified, and a detailed energy and indoor environmental evaluation were then carried out.

The case study building was selected based on factors including building type and service strategy, work activities, available access to the building and agreement from occupants, availability of plans, construction and systems information, and access to local weather data.

The study was designed to provide sufficient information to inform the creation and calibration of a dynamic simulation model. The steps in the performance evaluation were first to gather general building data, then to carry out a detailed monitoring exercise, and then to establish an appropriate weather dataset.

3.3.1 Building Description

The office building selected is a University Human Resources (HR) building. The building, constructed in the mid-nineties, serves the “Arab Academy for Science, Technology & Maritime Transport”.

Figure 3-8 and Figure 3-9 show the location of the building, internal and external views. The building is fairly typical in terms of construction, lighting, cooling, IT and other equipment use, and the general nature of the work activities inside the building. Activities in this building follow the academic calendar with increased activities associated with the conclusion and beginning of the academic year (June and August); activities are also affected by Ramadan which fell in July in the year of the monitoring study. This typical activity pattern needs to be considered while building a baseline model in the next chapter.

Figure 3-8. Location and external view of the office building.

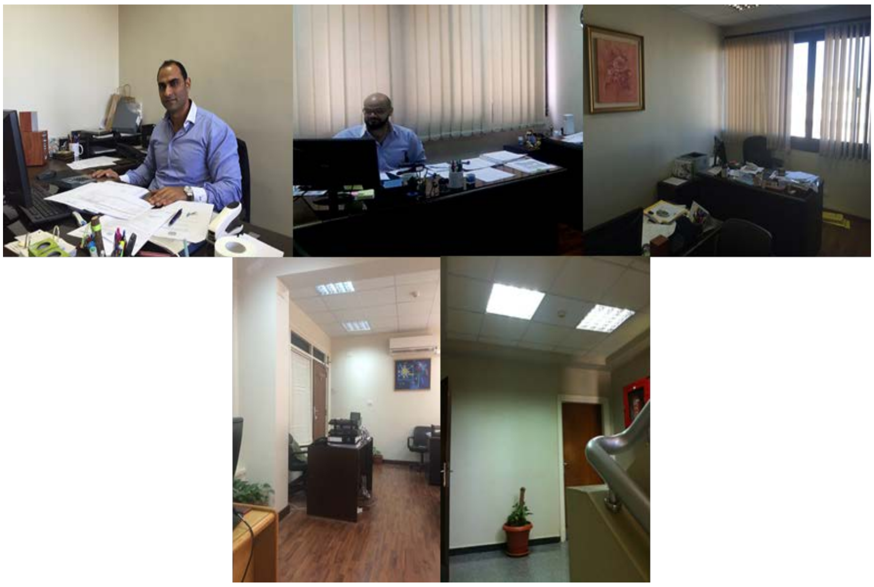


Figure 3-9. Internal views of the office building.

3.3.2 Building Geometry

The building comprises three floors with a corridor on each floor for connection with an extension building. The two buildings are separated by connecting doors which are normally closed. The building floors are nearly rectangular in shape with a total floor area 1090m^2 with 27 office spaces of varying areas.

Figure 3-10 shows the outline of one of the building floors. The floor height is 2.8m. The workspace is arranged as closed office space with an average floor area of 20m^2 with some small open spaces.

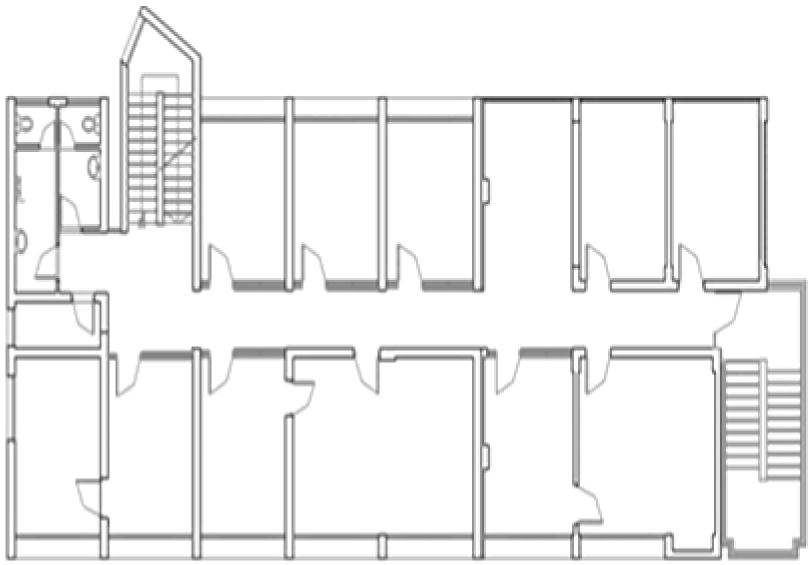


Figure 3-10. Schematic of office building floor plan.

3.3.3 Initial Data Gathering (Construction, Systems, Occupancy And Patterns Of Use, Energy, And IEQ)

Initial data were collected for the building (Table 3-7). This was gathered from available plans (Table 3-6), some initial site surveys, and calculations of U-values based on construction information. No information was available on thermal bridging or infiltration; thermal bridging was assumed to be included within the elemental U-values, and background infiltration was assumed based on the literature review.

3.3.4 Detailed Performance Evaluation

A more detailed investigation is required to capture building energy and IEQ performance, occupant behaviour, building operations and weather for a more comprehensive understanding to allow a calibrated model to be generated.

The parameters to be measured were those identified as critical for building performance and used for model calibration in the literature, including temperature, humidity, energy consumption, and CO_2 level [61, 64, 146]. Portable devices were used for data monitoring, as shown in Figure 3-15, Figure 3-22 and Table 3-8. These devices were purchased for the project and came with their calibration certificates. As a cross check two separate units of each measurement type were compared and gave results within calibration tolerances; a known load was applied to the power monitor as a further confirmation. Due to cost constraints and difficulty of access, not all spaces in the building could be continuously monitored, and devices were moved as required to provide coverage. The electricity supply to the building is through two cables, one for lighting, and the second one for all other loads including cooling systems. The detailed monitoring process started in January 2014 and extended until December 2014 (Table 3-6).

The process followed was:

- First a general survey was done for the external and internal geometry of the building and the neighbouring buildings, more design details were gathered by contact with the building consultant (e.g. building CAD drawings, available data about construction materials used, does the building follow any code or standard, the sources of energy in the building and information about points which can be used to measure this energy consumption)

- Periodic surveys (approximately monthly) were carried out during the monitoring period to assess the occupancy, internal gains from lights and equipment, operation schedule, A/C setpoints, occupant clothing levels, and occupant behaviour in terms of windows, fans, blinds, doors, etc.

- To disaggregate the cooling and equipment use which were on the same power cable, a two-stage process was followed. The energy used for equipment and A/C was initially measured during summer (June) to allow the cooling use to be captured, then measured again in the winter period (December) when cooling was not in use to capture the equipment use only. Transition months were monitored between summer and winter to complete the cooling use profile (September, October and November).

- Lighting energy consumption was assessed using the electricity meter on the lighting circuit for two months; the period of monitoring was July and August. The variation in lighting energy use across the year was then adjusted using observations of lighting use from the physical surveys.

- It was not possible to measure IEQ parameters across all spaces continuously due to the shortage of sensors and access limitations for the offices (only a subset of occupants agreed to take part and allow monitoring in their areas). To get useful data within these constraints single week sample monitoring periods were carried out in individual offices. These were spread over different seasons through the year (i.e. summer, winter and transition months). The sampled offices were in different locations inside the building (e.g. orientation, level, adjacent areas). The temperature and humidity measured during summer (August) allowed the cooling system operation to be captured; then the same office space was measured again in the winter period (December) when cooling was not in use. Transition months were monitored between summer and winter (October and November).

- The CO_2 levels were monitored. Data relating to background infiltration was obtained for periods when the windows were closed; other data when windows were being used gave further insights.

Occupants in this type of building have personal control over their environment through adjustments to the A/C on/off switch and setpoint temperatures, adjustments to windows, doors or blinds. Occupant behaviour affects energy use and indoor environmental conditions through these personal control actions and also through the use of lighting, computers, and other equipment which consume electricity and contribute heat gains. Significant variations in user behaviour were observed through the physical surveys and the monitoring.

Table 3-6. Monitoring process Gantt chart through 2014

	January	February	March	April	May	June	July	August	September	October	November	December
Monitoring Process	Data Gathering for Building Specifications	Data Gathering For Internal Loads, operation Condition and Occupancy Behaviours										
							Lighting Energy Consumption					
						Equipment & A/C Energy Consumption			Equipment & A/C Energy Consumption			
								Temperature & Humidity		Temperature & Humidity		
										CO_2 Level		
	Weather Data (Dry-bulb temperature & Relative Humidity)											

(a) **(b)** **(c)**

Figure 3-11. Monitoring devices used in data gathering (a) Tiny Tag – TGU-4500, (b) Extech CO210 (c) WATTNODE PULSE.

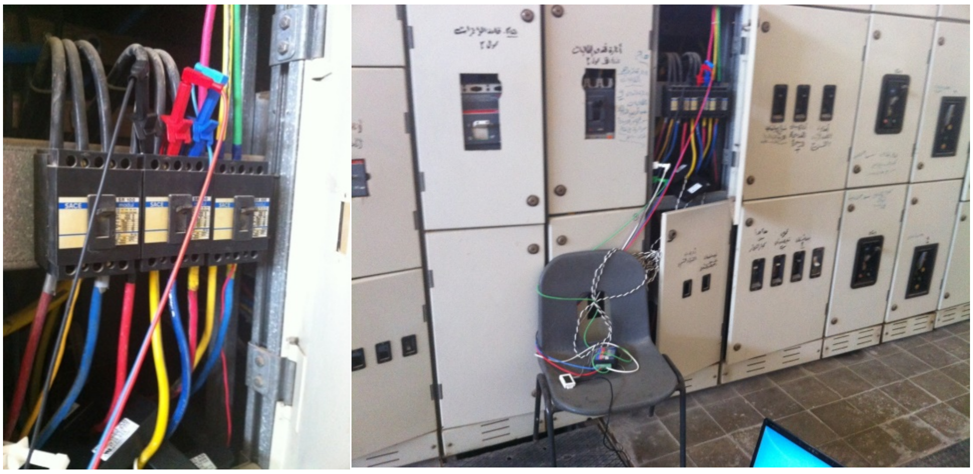


Figure 3-12. Snapshot of the control room for the power supplying lines for the office building.

Table 3-7. Initially estimated occupancy, lighting, equipment, HVAC, and construction parameters.

1. Occupant Density				Source of the data
Density allocated by workstations for offices with up to 3, an average m^2/person for larger office spaces, assumed 9am-5pm occupancy.	1, 2, or 3 persons		Occupant / Office	Site visits
	10		m^2/person	Calculated based on the site visits
2. Lighting				
Installed Lighting Load	9		W/m^2	Estimated based on the site visits
3. Equipment				
Installed Equipment Loads: per workstation for small offices, density for larger office spaces	132.00		W/Workstation	Based on the literature review [34, 35]
	13.2		W/m^2	
4. HVAC				
Cooling setpoint	23.00		°C	Based on measuring data
Background infiltration rate	0.60		$l/s.m^2$	Estimation based on the literature review [14, 147]
5. Type of Air Conditioning				
Air condition type	Model	Capacity	EER W/W	Site visits + manufacturing catalogue
Split	Carrier (42vmc18c)	2.5 H.P	2.96	
6. Construction Material				
External Wall U-Value	2.35		$W/m^2.K$	Estimation based on the literature review for buildings with the same construction materials [33, 99].
Internal Wall U-Value	2.31		$W/m^2.K$	
Roof U-Value	0.40		$W/m^2.K$	
External glazing U-Value	6.40		$W/m^2.K$	
External glass solar transmittance	0.82		---	
Glass visible transmittance	0.76		---	

Figure 3-13 Snapshot of the monitored offices showing the sensor locations.

Table 3-8. Specifications of the monitoring devices used in data gathering.

Monitoring Data	Device	Specification
Space temperature (°C)	Tiny tag – TGU-4500	Measurement ranges (-40°C to 85°C) Accuracy (±0.6 °C)
Space relative Humidity (%)	Tiny tag – TGU-4500	Measurement ranges (0 % to 95 %) Accuracy (±3 %RH)
Space CO_2 levels (ppm)	Extech CO210	Measurement ranges (0 ppm to 9,999 ppm) Accuracy (±1 ppm) Device also records Space Temperature
Electrical energy consumption	WATTNODE Pulse	Measures (1, 2, or 3 phases) Voltage ratings (120 to 600 Vac) Accuracy (±0.5%)

Offices monitored for the indoor environment (temperature, humidity and carbon dioxide) included offices S02, S07 and S08 on the second floor and F10 on the first floor as shown in Figure 3-14. These offices are used here to illustrate the office-to-office and time-to-time variability in behaviours observed. In addition to physical measurements parameters such as cooling system setpoint, occupancy, and clothing level were directly observed during periodic visits.

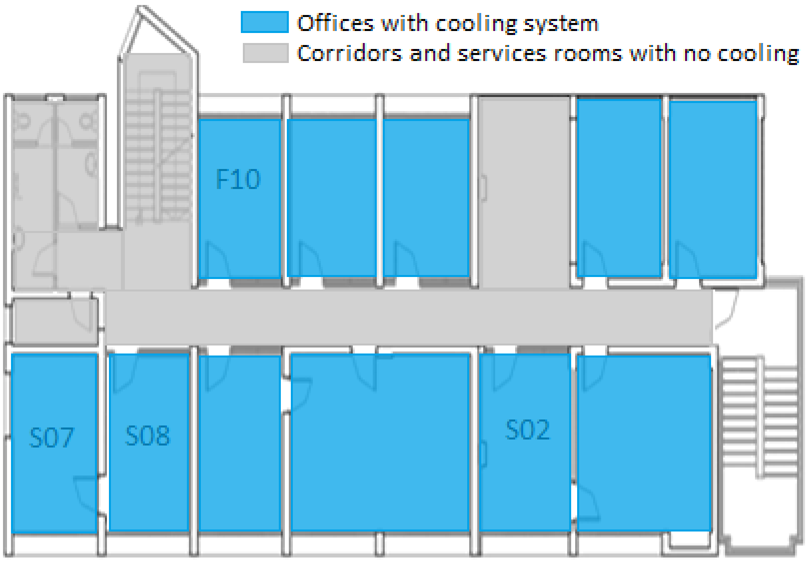


Figure 3-14. Schematic of office building floor plan with office numbering.

Office S08 was judged to be generally representative of the most prevalent ‘typical’ or ‘average’ occupied behaviour observed in the weekly snapshots and the physical survey visits, while the other offices illustrate the wide variations from this more typical behaviour.

Highly variable patterns of air-conditioner use and indoor temperature were observed (Figure 3-15 to Figure 3-21). Figure 3-15 illustrates a range of the different observed behaviours. Figure 3-15 (a) and Figure 3-15 (b) show two different offices in August, both are cooled continuously during the day but with very different achieved temperatures of around 17 and 24°C respectively. Figure 3-15 (c) shows observed behaviour in winter where the cooling was turned on at arrival and then turned off after approximately two hours. Capturing the observed variability in user behaviour for modelling would appear to present a challenge.

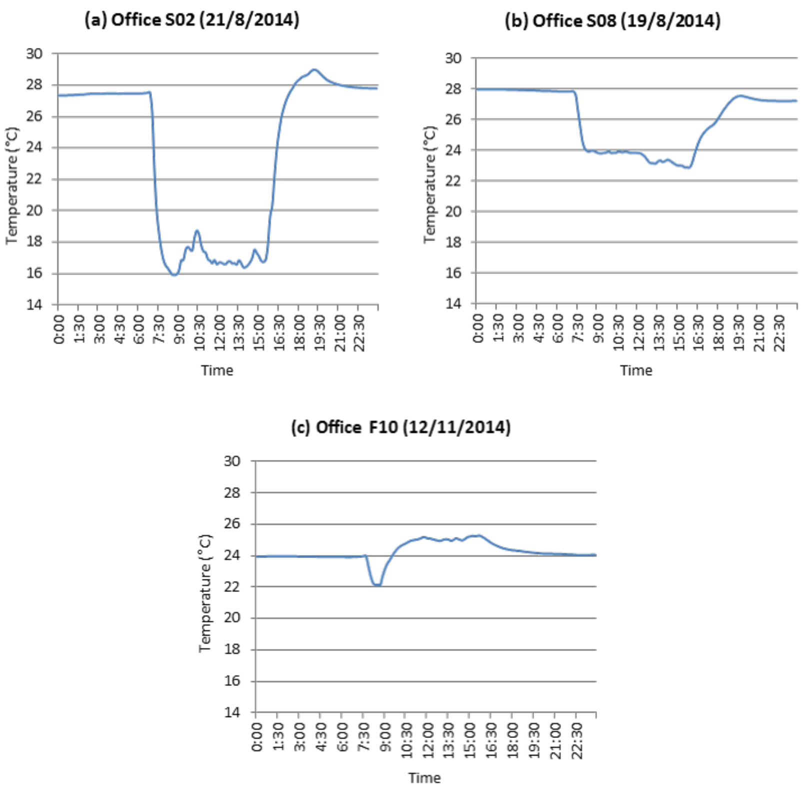


Figure 3-15. Measured temperature during the day for; (a) Office S02 in August, (b) Office S08 in August, and (c) Office F10 in November.

The most commonly observed behaviour (similar to office S08), was to set the A/C setpoint temperature at 21°C during the working day, the actual measured temperature achieved would then depend on the energy balance within the space, the placement of the A/C, and placement of the measurement device within the space.

The relative humidity for different offices was monitored and found to vary between 40% and 80% in summer when the A/C is operating, 65% and 80% in winter when the A/C is not operated (Figure 3-17 and Figure 3-21). Measured CO_2 levels inside the office spaces provide an indirect indicator for both occupant density and occupancy schedule although confounded by air change rate. Figure 3-22 shows CO_2 levels inside the same office that nominally has two occupants for two separate periods, illustrating high variability.

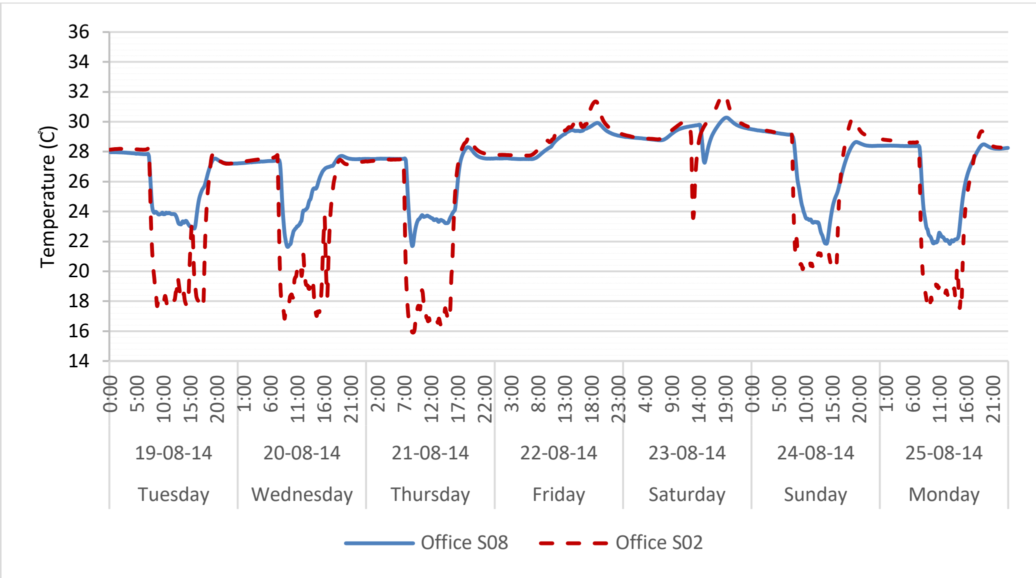


Figure 3-16. Measured temperature during one week in August for Office S08 and S02

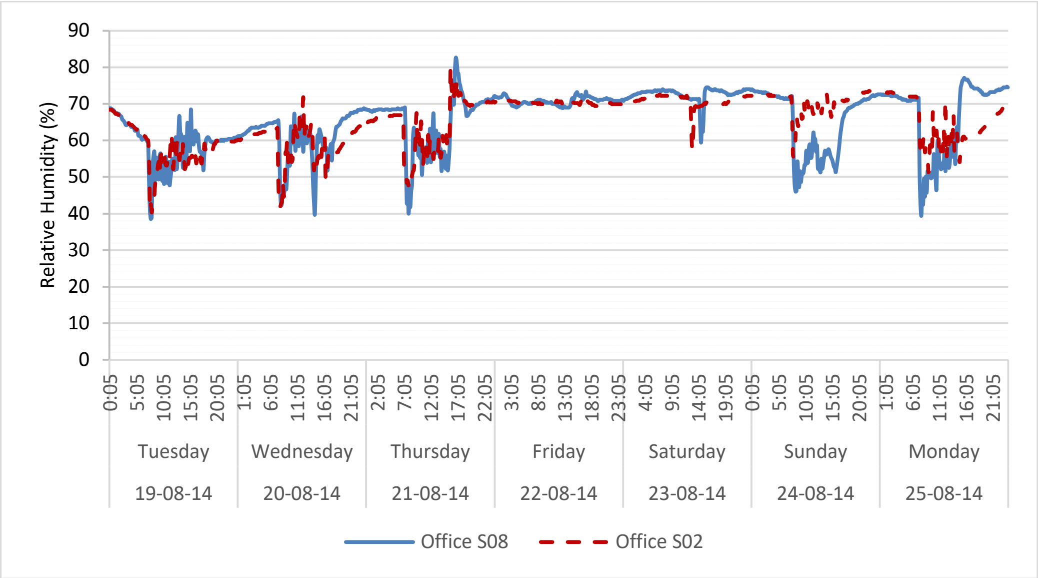


Figure 3-17. Measured relative humidity during a one week in August for Office S08 and S02

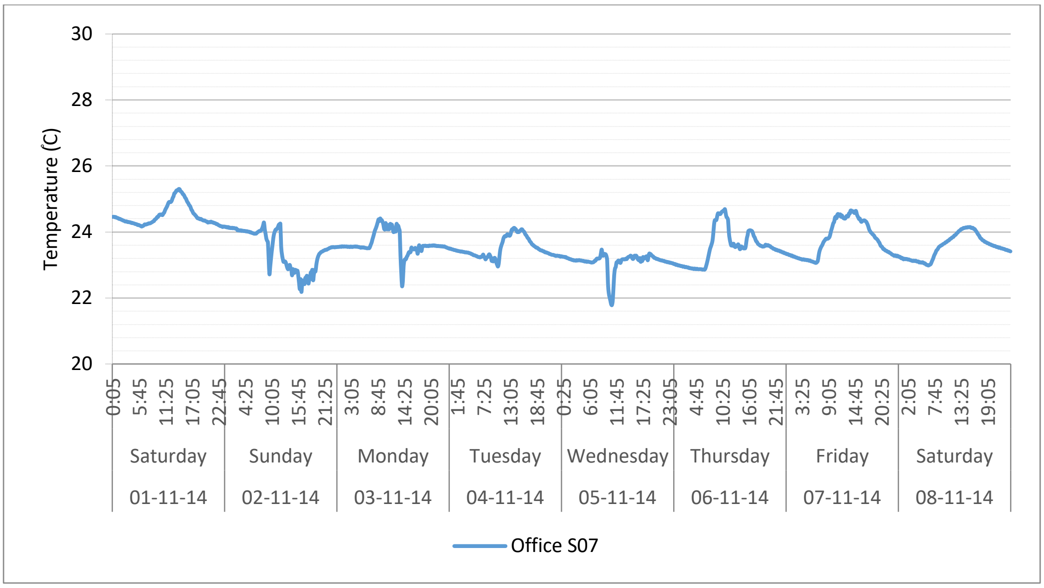


Figure 3-18. Measured temperature during a one week in November for Office S07

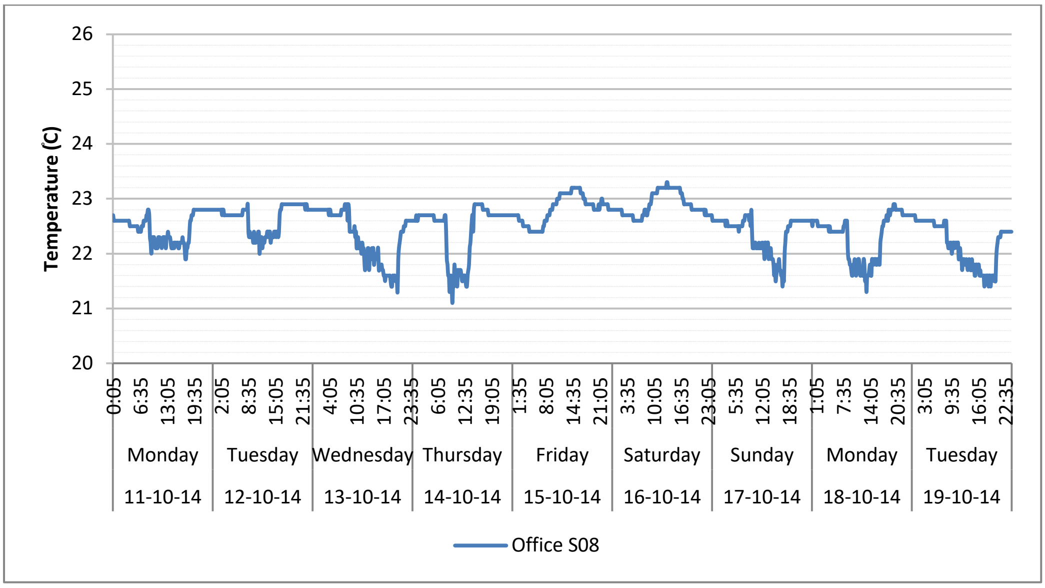


Figure 3-19. Measured temperature during one week in October for Office S08.

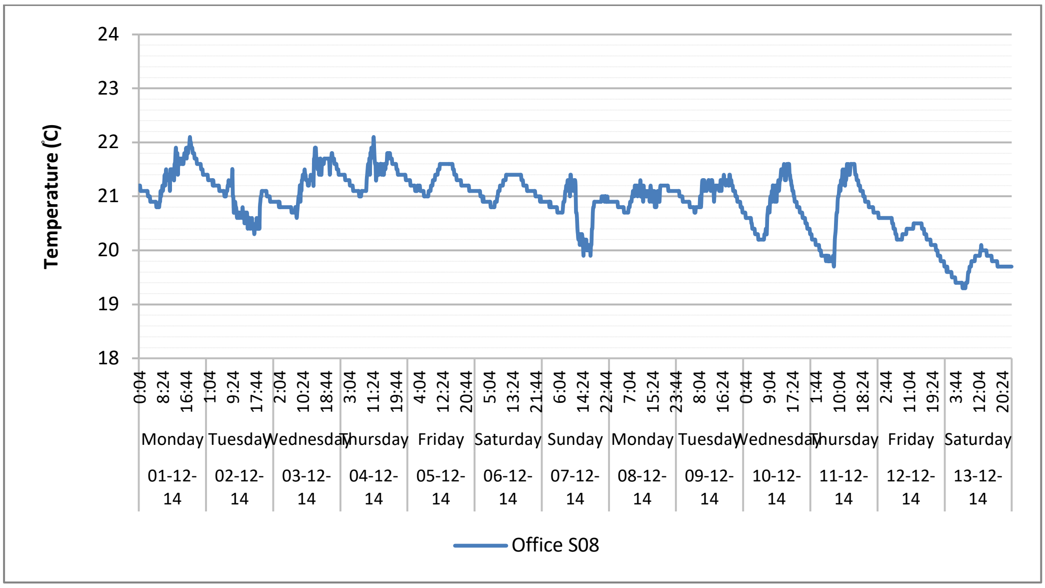


Figure 3-20. Measured temperature during one week in December for Office S08.

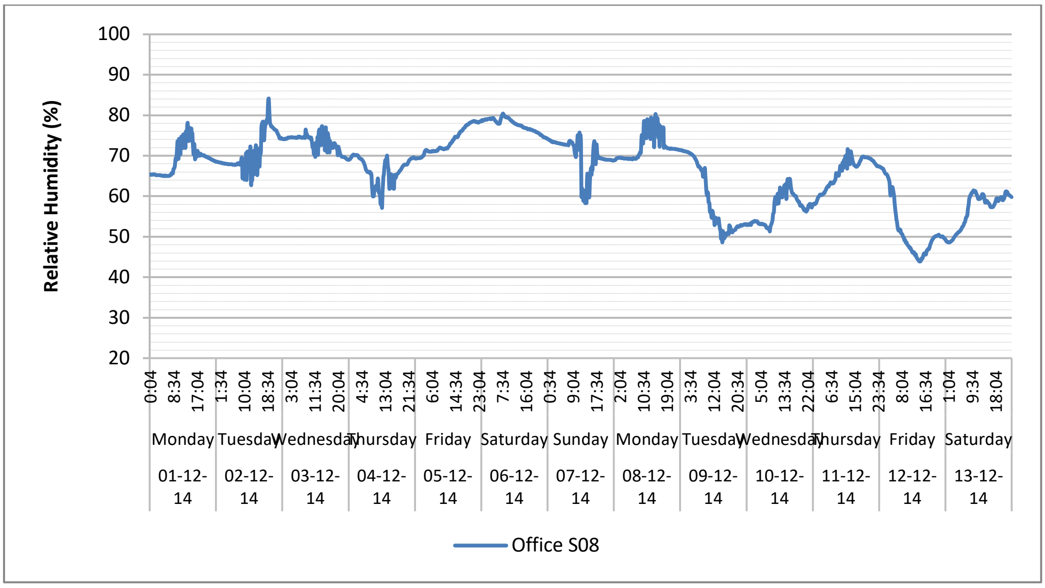


Figure 3-21. Measured relative humidity during one week in December for Office S08.

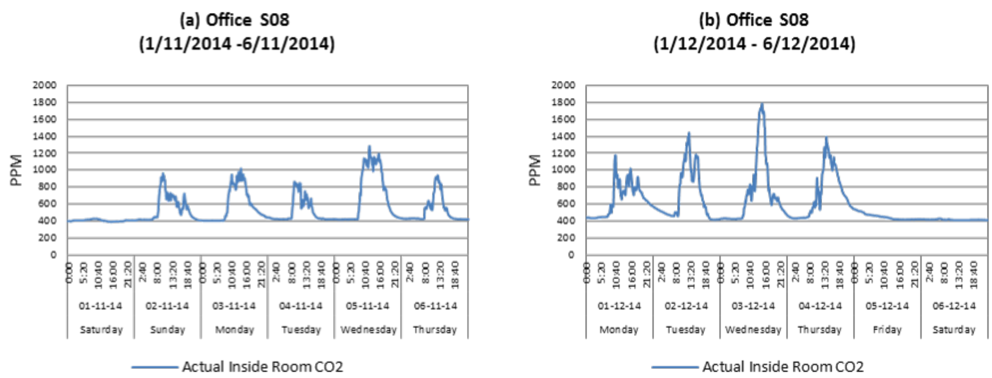


Figure 3-22. Inside room CO_2 level for one of the offices during; (a) First week of November (2014), and (b) First week of December (2014).

External observations were taken to quantify the use of windows and blinds. As in the case of other behaviour-dependent parameters high variability was observed. The office highlighted in Figure 3-23 (a) and Figure 3-23 (b) has different window and blind configurations on different days; Figure 3-23 (c) shows that blinds and windows are in various positions during a winter day. It was observed that in general the windows were predominantly closed in summer when the A/C is turned on. In intermediate and winter seasons, the windows were sometimes opened, less frequently on cooler days.

(a) (b) (c)

Figure 3-23. (a) Front of the building on 07/10/14, (b) Front side of the building on 14/10/14, and (c) Rear of the building on 12/11/14.

The examples discussed above illustrate the variability seen in the monitoring study. Office S08 did appear however to have consistent behaviour with reasonable correspondence to a typical thermal environment found in the literature [114, 125, 148, 149].

3.3.5 Weather

It is important to establish the weather for the case study building as the backdrop for the performance evaluation and inclusion in modelling. Alexandria's climate is characterized by a moderate winter season with average temperature around 18°C and a summer hot season with average temperature around 28°C. Hourly temperatures, and humidityies for the Alexandria location of the case study office for 2014, measured at a nearby weather station, are shown in Figure 3-24 . Normally the temperatures are between 10 and 32°C and humidity between 40 and 90% in this coastal location. However, there are occasional sandstorms that occur due to hot winds, known as Khamsin winds that are equivalent to the Sirocco winds in Europe.

These sandstorms may occur for periods of up to a few days and can lead to a temperature rise of 20°C in 2 hours [106].

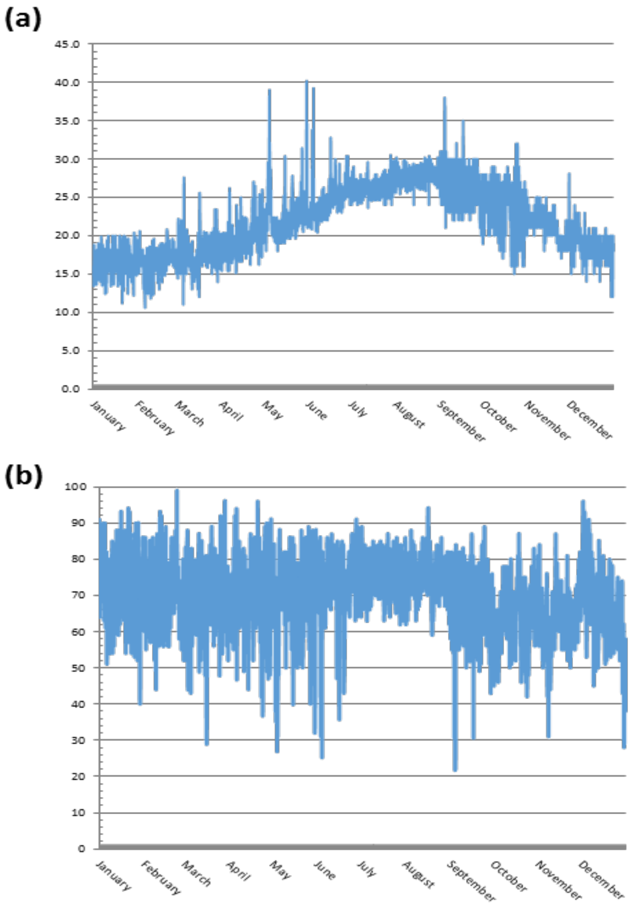


Figure 3-24. Weather data of Alexandria, Egypt measured by local weather station for year 2014; (a) Dry-bulb temperature, and (b) Relative humidity.

An Egyptian Typical Methodology Year (ETMY) weather file based on long term climate analysis is available for use in building design and dynamic simulation studies for the Alexandria region. This includes the full range of weather parameters such as the wind, cloud and solar radiation, in addition to temperature and humidity

[150]. To have a simulation weather file more representative of the actual weather during the monitoring period the measured temperature and humidity from the nearby weather station were superimposed on the ETMY weather file. It would have been ideal to have a full set of measured parameters sufficient to form a detailed (sub-hourly) simulation weather file, but this was not available. Others are investigating methods for synthesising detailed weather files from limited measurement sets [8, 151], but this limitation in the work presented here remains to be addressed in future. Figure 3-25 gives a comparison of the average temperature for the ETMY and the modified simulation weather file used to represent the weather in the model calibration exercise.

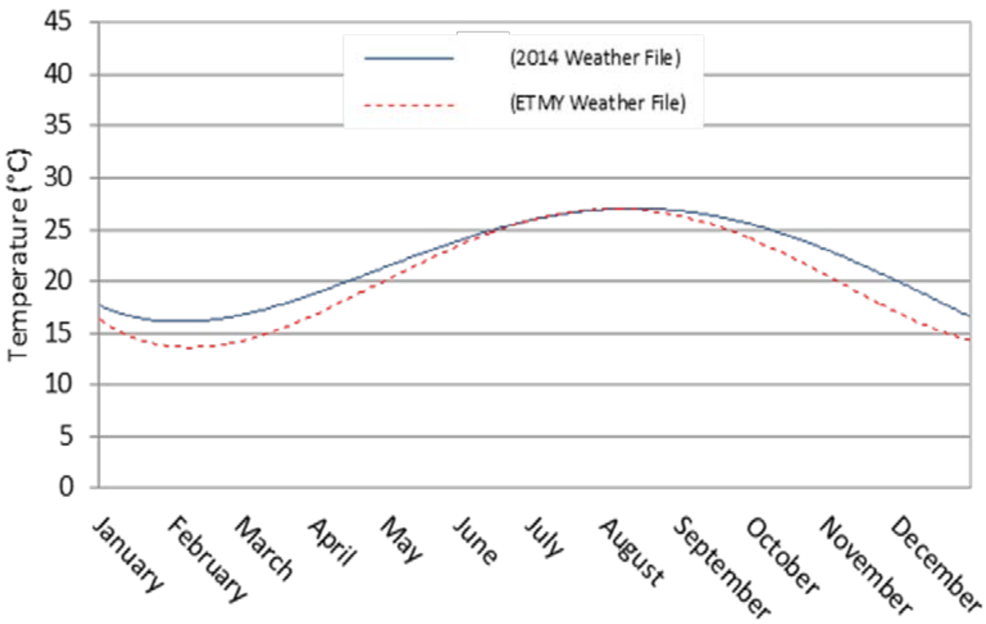


Figure 3-25. Average dry-bulb temperature for Alexandria, Egypt (ETMY and Modified Weather file 2014).

3.4 Summary

The main aim of this chapter is to provide some useful insights on the energy use and indoor environmental quality in existing Egyptian office buildings and to explore a broad survey of an office building in Alexandria, Egypt. It was observed that highly serviced buildings consume more energy, but the reasons and potential justifications for this trend need to be further investigated. Based on the data gathered, it is concluded that the collected information provides only a small body of evidence and further studies of this type should be done.

Aiming to address the gap in the gathered information, a detailed energy audit was done on a selected office building. The monitoring study provided insights into indoor environmental conditions (temperature, humidity, CO_2), the range of user behaviours and operations prevalent in this type of building in Egypt (clothing levels, A/C use, and temperature settings).

Based on the detailed energy audit on the selected office building, a basic simulation model is introduced in the next chapter (Chapter 4) which is further calibrated. Due to the limited measured data and the high variability seen, the approach taken in the modelling required some typical behaviour to be identified from the survey. The behaviour selected as typical was that observed in office S08, i.e. in warm periods of the year to have A/C on in the office space during occupied hours with a setpoint of 21°C.

Chapter 4 A METHOD TO ESTABLISH A CALIBRATED MODEL FOR A CASE STUDY OFFICE BUILDING IN EGYPT

4.1 Introduction

In the field of energy and buildings, simulation is one of the most valuable tools available for saving hundreds of millions of dollars by evaluating alternative designs, technologies, or processes without the need to create the artefact being modelled. It is wiser to create a model for testing alternative configurations than to build a real prototype with the need to change it later based on trial and error [8]. Complete building energy models provide a means of understanding building operation projected into the future as well as optimizing performance [152]. However, to have a representative model, validation is an essential step. Here a new two- stage process is developed, first the creation of a calibrated model for the case study building is presented in this chapter, and then in Chapter 5 the model is generalized to represent the range found within the building stock described in Chapter 3.

The main objective of this chapter is to create a calibrated model for the case study Egyptian office building of Type 2, naturally ventilated with local air conditioning. An introduction to building simulation models and the applicable tool is also discussed.

4.1.1 Overall Calibration Method

The calibration of the model is through two main steps:

- Firstly, an initial ‘best guess’ base model is created using a building simulation tool (Integrated Environmental Solution – Virtual Environment 2014 (IES-VE 2014)), based on the detailed individual office survey discussed in Chapter 3.
- Secondly, a formal calibration method is applied using a stepwise approach, again based on the more detailed measured data, applied at building and individual office level, using the typical performance of office S08 applied across the remaining offices.

In Chapter 5, this calibrated model will then be further modifed to be more typical of the majority of similar buildings in Egypt based on the 59 building survey data. Also, probable variations and uncertainties in input parameters will be captured in realistic worst case input parameter sets which can then be used with the representative model in future scenarios and projections.

4.2 Integrated Environmental Solutions Virtual Environment (IES-VE)

As seen in the literature review, there are numerous simulation tools. “Virtual Environment” by Integrated Environmental Solutions (IES-VE) was selected for use in the thesis due to its technical capabilities and multiple accreditations, plus the availability of comprehensive distance learning training and support. The IES Virtual Environment has been assessed against some global as well as regional standards. IES-VE is fully validated under ASHRAE Standard 140 and has published the results for all versions of ASHRAE Standard 140; 2001, 2004 and 2007 (Heating, Cooling and Envelope). This is in addition to other standards like CIBSE TM33 , and UK National Calculation Methodology [153].

IES-VE is a modern example of dynamic building energy simulation software. IES-VE consists of a suite of integrated analysis tools, as shown in Figure 4-1, which can be used to investigate the performance of a building either retrospectively or during the design stages of a construction project. IES-VE is not an open source tool in computing terms as the underpinning mathematical models, while available in documentation, are not changeable by the user, rather the user is restricted to interaction through a graphical user interface.

To create a dynamic simulation model using IES-VE, there are general steps which must be followed which are common to most of the simulation tools. These steps can be summarized as follows:

1. Adding the construction materials.
2. Adjusting the activity profiles.
3. Specifying the thermal conditions and setpoints.
4. Defining the internal and external loads including equipment, lighting, ventilation, and infiltration.
5. Adjusting the climate and weather data including location, building orientation, weather file, and solar gains.
6. Performing the simulation, analysing the output.
7. Displaying the results.

IES-VE has many features which make it state-of-the-art software in the commercial building simulation field. It is commonly used in the commercial and education sectors though it has limitations in academic research as it is not open source. The tool allows input for HVAC, solar gains, shading, natural ventilation and dimming strategies. Also, the tool allows the simulation of thermal comfort, comparison of results and checking for compliance with LEED and SBEM.

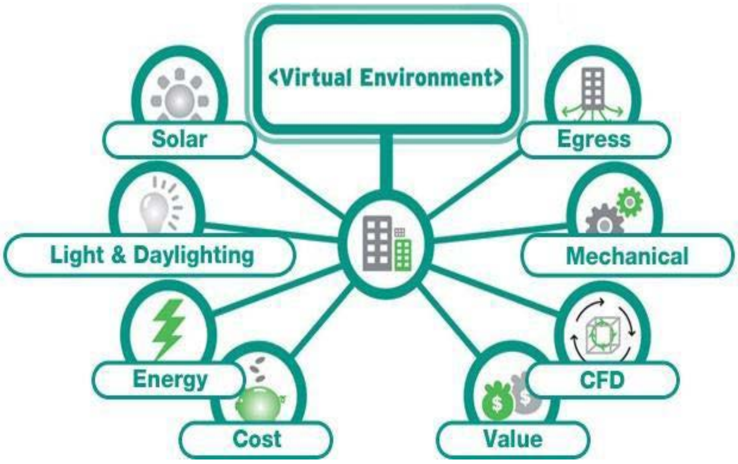


Figure 4-1. Modules and analysis tools available in IES Virtual Environment.[153]

In addition IES-VE tool offers a familiar modelling environment to architects as the building geometry is modelled in Sketch-up or could be imported from other tools like Revit and ArchiCAD in the form of gbXML and DXF files.

The tool is also adapted to different design phases and design users, allowing flexibility in developing the model from early design stages. The IES APACHE thermal analysis system is the core thermal design and energy simulation component, and is classified as an accurate simulation tool having been tested to ASHRAE Standard 140.

4.3 The ‘Best Guess’ Base Model Of The Case Study Building

An initial dynamic simulation model was created from the gathered data presented in Chapter 3. The case study building model contains about 27 individual office and other ancillary spaces, which are different in areas, number of occupants and equipment.

The offices have individually controlled cooling systems while the other spaces are free floating Figure 4-2.

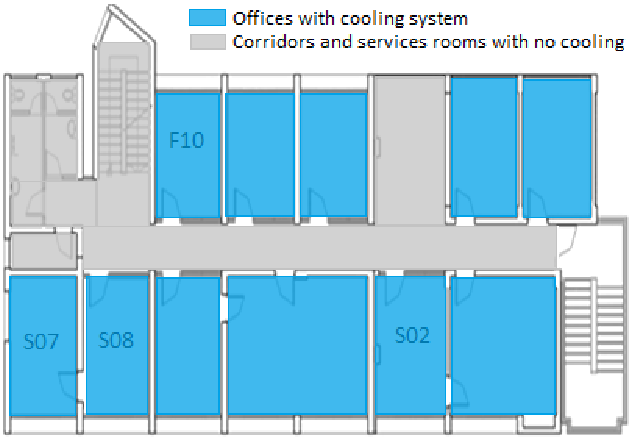


Figure 4-2. Conditioned and unconditioned spaces in the building.

As shown by the monitored data there is considerable variation in office occupancy and behaviour and therefore in environmental conditions and energy use during working hours which creates a challenge for simulation. The available measured energy use data was based on the whole building, while the measured IEQ data was only for specific offices.

The strategy followed then was to create the ‘best guess’ base model with the office spaces and behaviour found to be most typical from the survey (similar to S08). To capture the variations in occupancy in the IES-VE simulation software, occupancy, lighting, and equipment profiles were established. This was done by multipling the maximum installed capacity by a Modulating Factor (M.F.) representing the daily profile. A Diversity Factor (D.F.) was also applied representing the extent to which the modulated capacity is actually in use. For instance, at each time step Equipment Load = Installed Equipment x M.F. x D.F. The product M.F. x D.F. is found from daily 'profiles' captured during the occupied period, with the 'Profile Factor’ (P.F.= M.F. x D.F.) being the extent to which the installed capacity is in use during peak occupancy.

Based on the physical survey observations and monitoring data, 'winter', 'summer' and 'Ramadan' profiles were differentiated, as shown in Figure 4-3. The occupancy profiles were assumed based on monitored temperature, humidity and CO_2 level plus a physical survey. However, the equipment and lighting profile was based on the monitored energy consumption profile for each. The 'summer' profile was applied only to the high activity periods around end May / June and also August / early September, 'Ramadan' was applied to July, and 'winter' to the rest of the year. The variation seen in the monitored data between these periods and indeed on a day-to-day basis is again striking. The extent to which these profiles are unique to the specific activity in this building is discussed later.

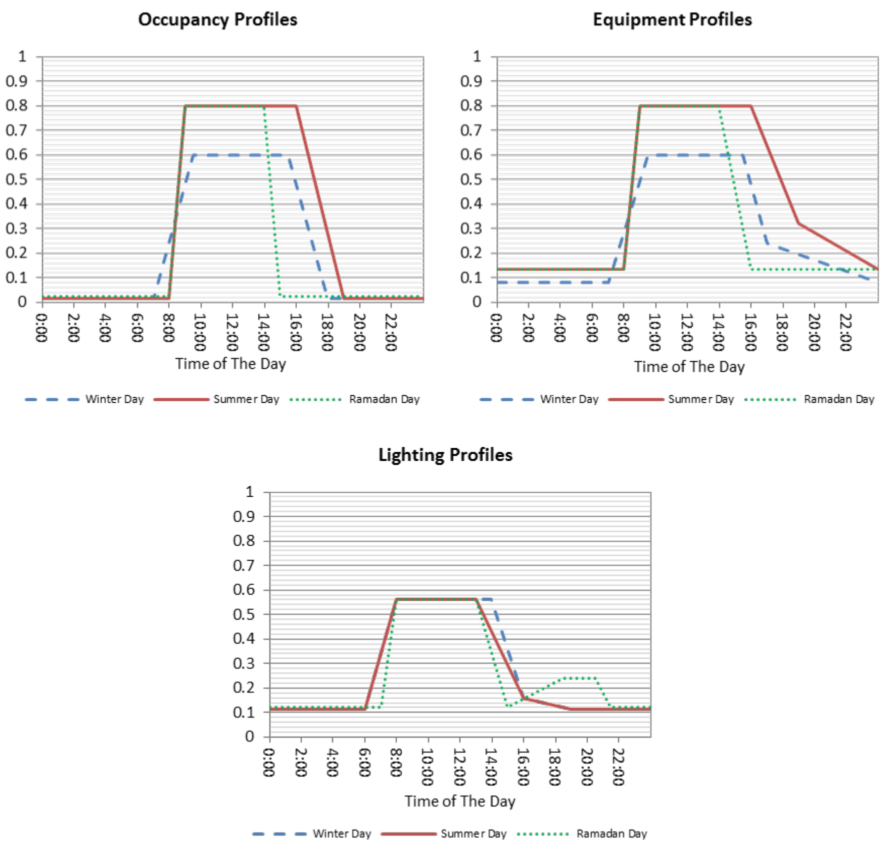


Figure 4-3. Occupancy, equipment and lighting working day profiles.

A novel A/C CUEER (Cooling Use Electrical Efficiency Ratio) parameter was defined to represent the effective SEER (Seasonal Energy Efficiency Ratio) of the cooling systems. This takes into account the pattern of A/C use across the whole building (percentage of the average used devices at the same time, the variation in occupancy behaviour and operation condition).

The CUEER is calculated by dividing the cooling system equipment SEER by the product of the diversity factor and the modulating factor for A/C use within the building (equation 4-1). So, if only 50% of the space is being conditioned at any time, then CUEER is 2 x SEER, if only 25% then 4 x SEER. If for example SEER is 3.5 and only 25% of the space is conditioned then CUEER would be 14, etc. There are other approaches to model the A/C use pattern, but these would require more extensive monitoring than was possible and correspondingly more detailed modelling. Given the variability seen in Chapter 3, the approach of assigning a CUEER based on monitoring of cooling energy use and then refining this value through the calibration process was selected as the best one.

$$CUEER = \frac{SEER}{D.F * M.F} \tag{4-1}$$

Where CUEER is cooling use electrical efficiency ratio (W/W), SEER is seasonal energy ratio (W/W), D.F is the diversity factor, and M.F is the modulating factor. In this case, the M.F. represents the ratio of space with local cooling installed to the total space, and the D.F. is the ratio of space that is currently conditioned to the space with local cooling installed. More discussion of this new parameter is provided later in the thesis.

Based on observations in the physical survey, windows were assumed to be closed during warm periods when the A/C is in use, and during cold winter periods when indoor temperatures are below the normal heating setpoint (there is no heating in the building). In transition seasons the windows were assumed to be opened proportionately to achieve comfort cooling.

Figure 4-4 shows the screen shot from the IES-VE software for the model plan where the building in the blue line shows the case study model, and the light red lines show the adjacent connected building which is not included in the monitoring and analysis process. Figure 4-5 shows the 3D view of the base model, and the adjacent building. Based on the real building all the windows are recessed into the walls by 15mm in addition to the window framing, and shading was included in the base model.

Based on the best guess input parameters the model was run and some graphs are shown here to illustrate the model outputs for single weeks compared with the monitored data. As expected, there was some degree of mismatching between the two.Figure 4-6 and Figure 4-7 show the total energy consumption for equipment plug loads and air conditioning during summer and winter months, respectively. Figure 4-8 shows the energy consumption for the lighting during summer.

Figure 4-9 and Figure 4-10 show the inside room temperature for one of the typical offices (office S08) during summer and winter respectively. The best guess model was then used as the base for the formal calibration process, described in the next section.

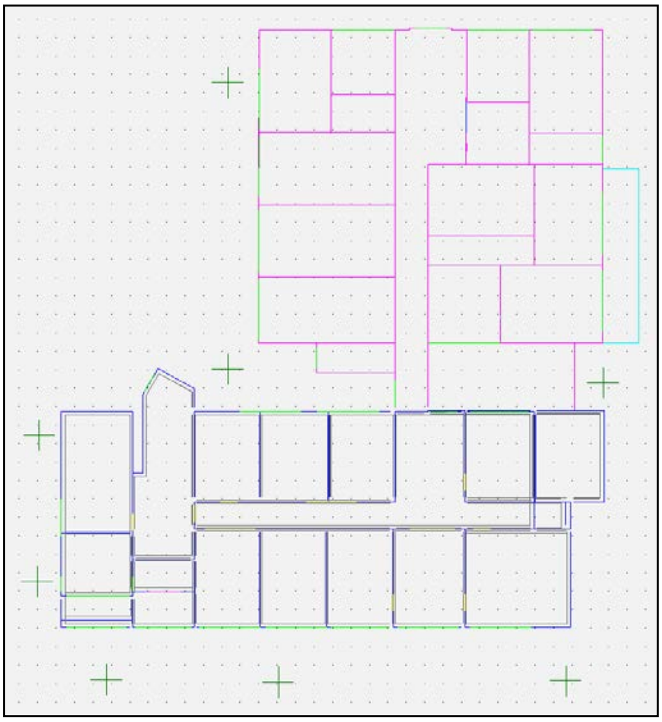


Figure 4-4. Typical floor plan of the base model.

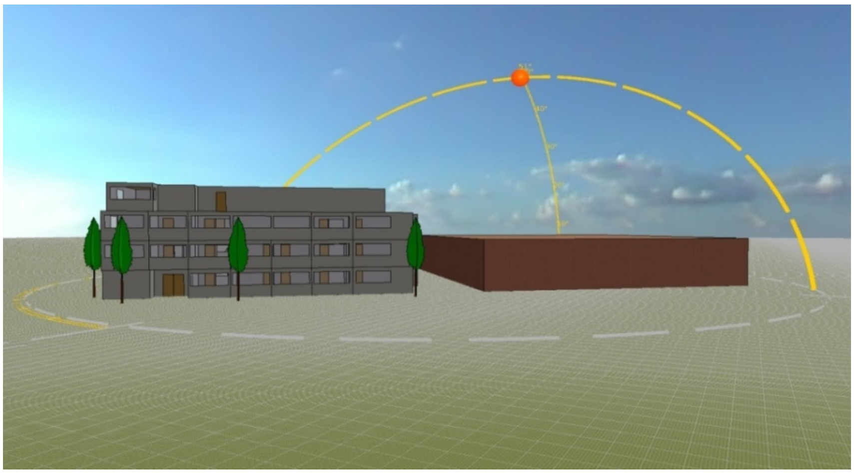


Figure 4-5. Screen shoot from IES-VE software for the simulated base model.

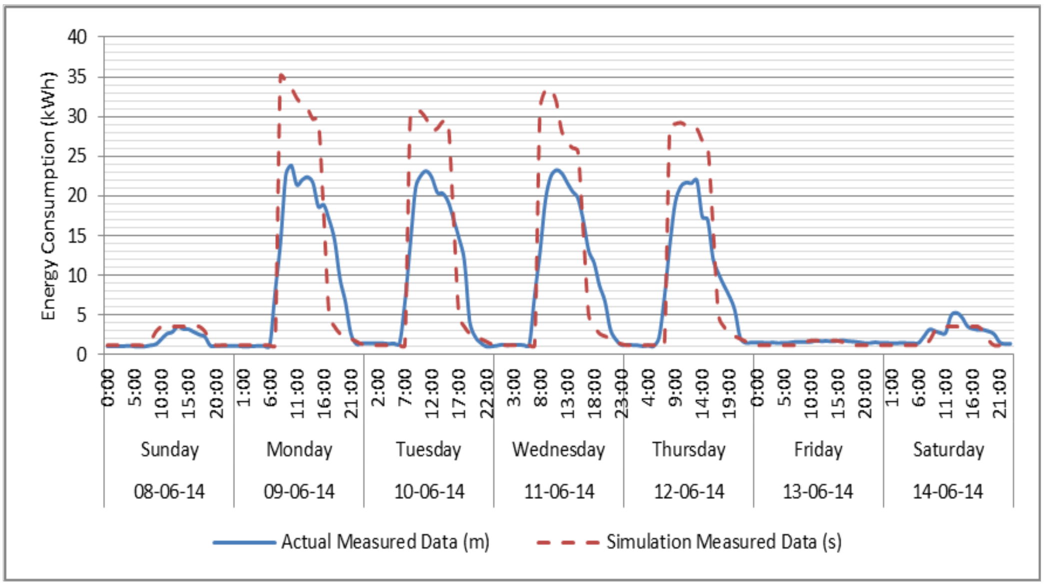


Figure 4-6. Equipment and air conditioning energy consumption during a whole week in summer.

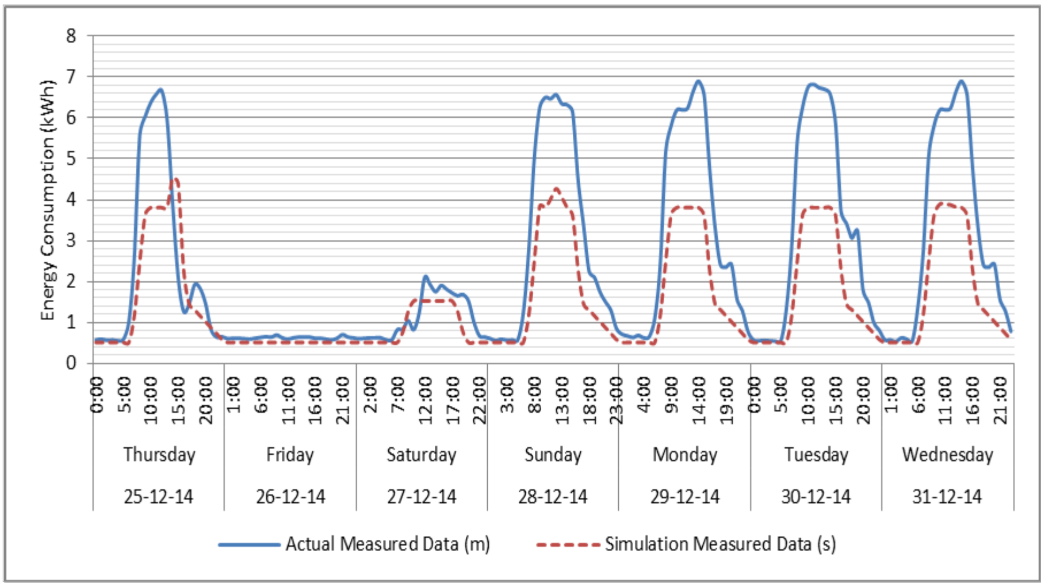


Figure 4-7. Equipment and air conditioning energy consumption during a whole week in winter.

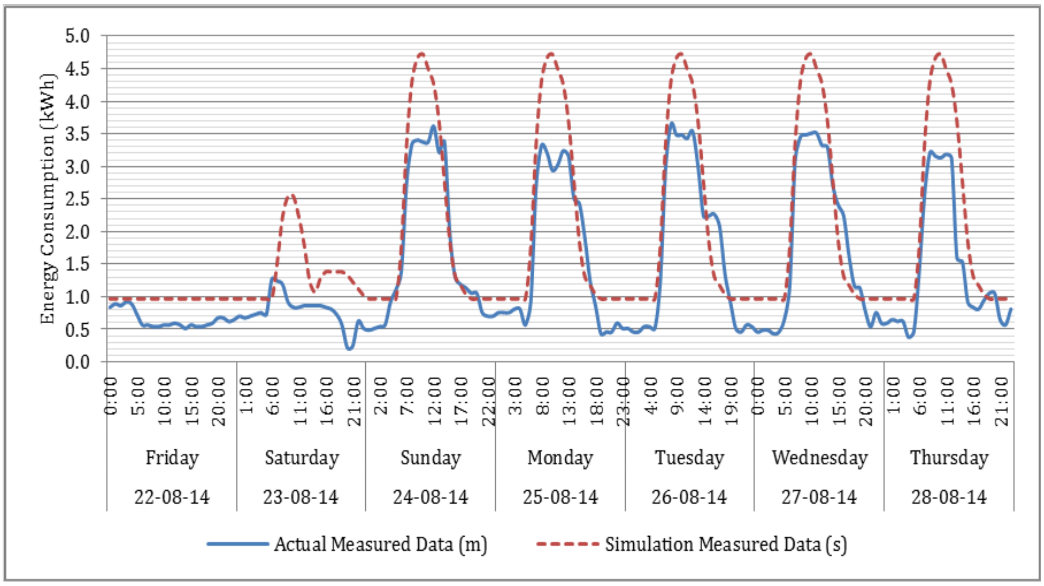


Figure 4-8. Lighting energy consumption during one whole week in summer.

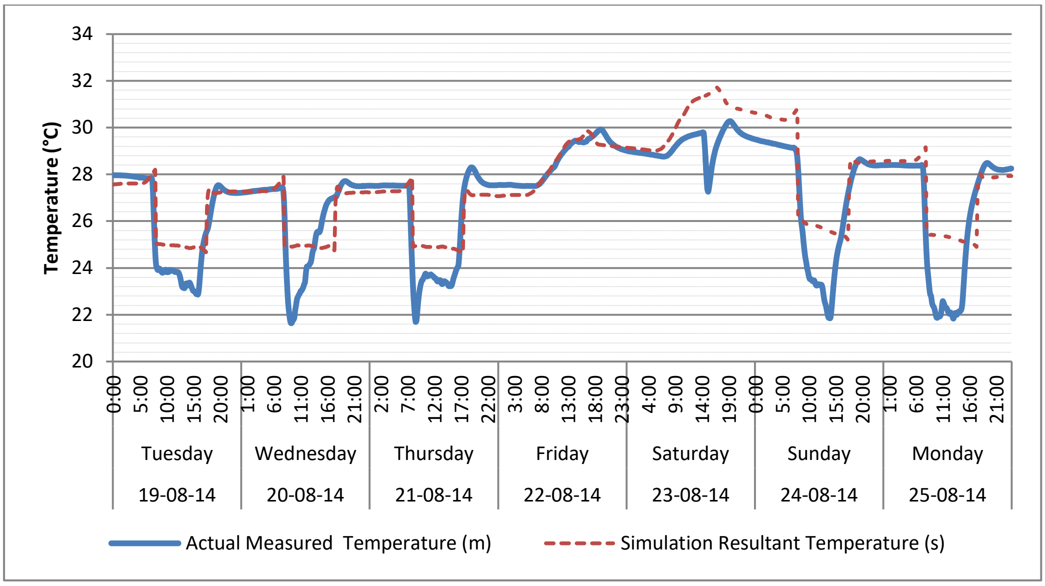


Figure 4-9. Inside room temperature for office S08 during summer

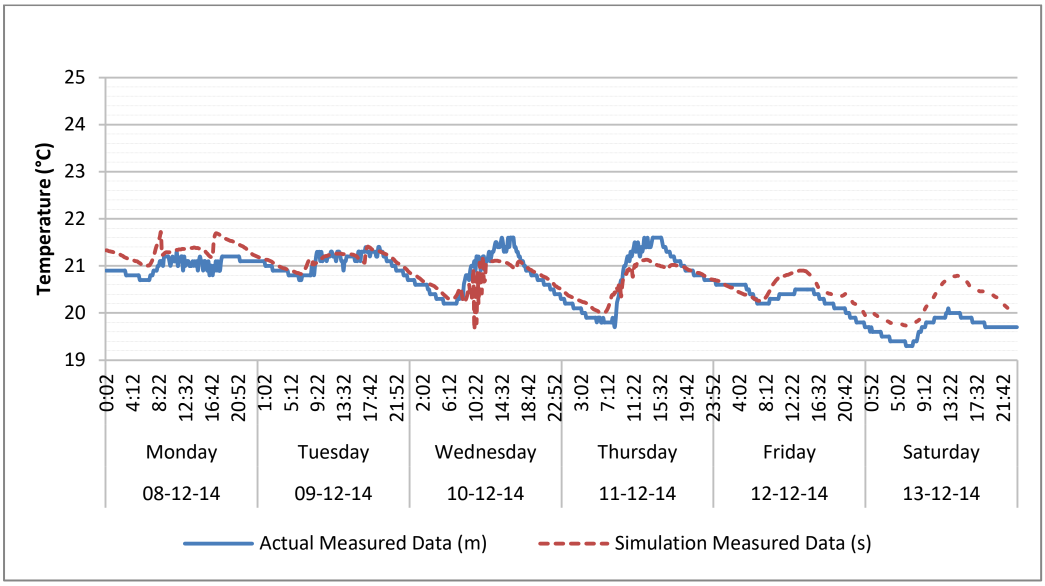


Figure 4-10. Inside room temperature for office S08 during winter.

4.4 Calibration Criteria

According to ASHRAE guideline 14-2002 [62], there are two main dimensionless indicators of errors in calibrating the building model. Firstly, the Mean Bias Error (MBE) (%) which is given by equation 4-2:

$$MBE = \frac{\sum_{i=1}^{n}(m_i - s_i)}{\sum_{i=1}^{n} m_i} \quad \text{4-2}$$

Secondly, the Coefficient of Variation of Root Mean Square Error CV(RMSE) (%) which is given by equation 4-3:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}} \quad \text{4-3}$$

$$CV(RMSD) = \frac{RMSD}{\bar{m}} . 100$$

Where m_i and s_i are respectively the measured and simulated data at instance i, n is the count of the number of values used in the calculation. ASHRAE Guide 14 considered a building model as calibrated if, based on hourly data, MBE values fall within ±10%, and CV(RMSE) values fall below 30%. Additionally, a building model is calibrated based on monthly data if MBE values fall within ±5%, and CV(RMSE) values fall below 10% [61, 62, 152].

On the other hand, Farhang et al. [154] used the "coefficient of determination" (R^2) in equation 4-4 to describe the proportion of the variance in measured data explained by the model. The coefficient of determination varies from 0 to 1. An R^2 of 1.0 indicates that the regression line perfectly fits the data.

$$R^2 = \left(\frac{n \sum m_i s_i - \sum m_i \sum s_i}{\sqrt{\left(n \sum m_i^2 - (\sum m_i)^2\right)\left(n \sum s_i^2 - (\sum s_i)^2\right)}} \right)^2 \qquad 4\text{-}4$$

Table 4-1 shows the data requirement for each level of calibration. Utility bill data are always necessary as they represent the minimum requirement for calibration, in terms of measurements and history for the building [57, 63].

Level 1 is a first calibration based on incomplete and fragmented information due to the availability of nothing but as-built data. It is thus the weakest calibration level as the information about the building definition and operation is not detailed and cannot be cross-checked with on-site visits. In Level 2 site visits or inspections allow the verification of as-built data and the collection of more information. In Level 3, which is based on detailed audit of a case study, on-the-spot measurements of the building operation and energy consumption are collected. Levels 4 and 5, based, respectively on short-term and long-term monitoring, are the most detailed levels of calibration. At this level data loggers are installed in the building to collect all the required information.

In this study the monitoring, although limited as described earlier, is sufficient to support between Level 4 and Level 5 calibration.

Table 4-1. Calibration level based on the data available [57].

Calibration Level	Data Available					
	Utility Bills	As-Built Data	Site Visit	Detailed Audit	Short Term Monitoring	Long Term Monitoring
Level 1	Required	Required	Not Required	Not Required	Not Required	Not Required
Level 2	Required	Required	Required	Not Required	Not Required	Not Required
Level 3	Required	Required	Required	Required	Not Required	Not Required
Level 4	Required	Required	Required	Required	Required	Not Required
Level 5	Required	Required	Required	Required	Required	Required

4.5 Creation Of The Calibrated Model

To capture the performance of the monitored building in a model for use in evaluating potential future changes, a manual calibration method was used.. There were two main steps in the calibration, first a parameter screening sensitivity analysis (parametric analysis) to identify the order of influence of the parameters and then the application of seven calibration stages.

4.5.1. Parametric Analysis

Parametric analysis plays a major role in building energy analysis. It can be used to identify the key variables affecting building energy consumption. The Influence Coefficient (IC) determines the impact of each variable on the model output and can be calculated using equation 4-5 [146]:

$$IC = \frac{\Delta OP \div OP_{BC}}{\Delta IP \div IP_{BC}} \tag{4-5}$$

Where ∆OP and ∆IP are changes in Output Variables (OP) and Input Variables (IP) respectively, and OP_{BC} and IP_{BC} are the output and the input Base Case (BC) values respectively. This sensitivity coefficient is dimensionless and represents the percentage of change in the output due to a percentage of perturbation in the input. The variables with high IC must be calibrated first, before low IC variables, which may not need to be calibrated.

Once the initial best guess model was constructed, a parameter sensitivity analysis was undertaken. The parameters included in the sensitivity analysis were identified based on literature plus initial screening studies; ranges set for these parameters were based on literature and are given in Table 4-2. The model was then used to calculate the influence coefficient (IC) for each main uncertain variable. The influence coefficient was calculated first with respect to the energy consumption, then for the indoor temperature, and then for CO_2 level. Table 4-2 and Figure 4-11 show the variables with greatest IC for the energy use and indoor temperature. They are A/C setpoint temperature, lighting loads, equipment loads and A/C CUEER. For CO_2 levels the variables with greatest IC are the infiltration and occupancy.

Table 4-2. Ranges of main uncertain variables used in the calibration model.

Variable	Units	Base Case Value	Minimum Value	Maximum Value	IC	Source of Data
A/C Control & Setpoint	°C	23	18	26	0.797	Field survey
Installed Lighting Load	W/m^2	9	4	16	0.187	Literature review [4, 16]
Installed Equipment Load	W/ Desk space	148	59	237	0.142	Literature review [37-43]
	(W/m^2)	14.8	5.9	23.7		
A/C CUEER	W/W	3	2	14	0.136	Literature review [16, 32]
Lighting D.F	---	0.8	0.2	1	0.114	Literature review [4, 16]
External glazing G -solar value	---	0.82	0.32	0.9	0.093	Literature review [33, 92, 95, 99, 155]
Equipment D.F	---	0.8	0.2	1	0.084	Literature review [37-43]
External Window U-value	W/m^2.K	6.4	1.54	6.5	0.011	Literature review [33, 92, 95, 99, 105]
Internal Wall U Value	W/m^2.K	2.31	1.2	3	0.009	
Infiltration Rate	L / S. m^2	0.6	0.3	1.3	0.007	Literature review [94],[95]
Roof U value	W/m^2.K	0.4	0.13	0.9	0.004	Literature review [33, 92, 95, 99, 105]
External Wall U-value	W/m^2.K	2.35	0.18	4.3	0.003	
Internal Ceiling U-Value	W/m^2.K	3.5	0.13	4	0.001	

As shown in Table 4-2, of the building envelope parameters it is the Glazing G-solar value that has the highest effect. As the geometry is fixed in this study with specific window recesses, external shading (building extension, neighbouring buildings and trees), and orientation this result may not readily be generalised to other buildings.

In order to make the base model more realistic and able to be used in future, it must go through a systematic calibration process to adjust the IC input parameters against real monitored data.

The key variables affecting building energy consumption which have the highest IC value should be calibrated first. After that, the parameters with lower IC values could be calibrated if there is available data for that.

From the parametric analysis described ,the most influential variables affecting the building energy consumption based on IC values were classified into three main groups (lighting, equipment, and cooling system).These groups have a direct effect on each other so the calibration process should be arranged accordingly (Figure 4-12).

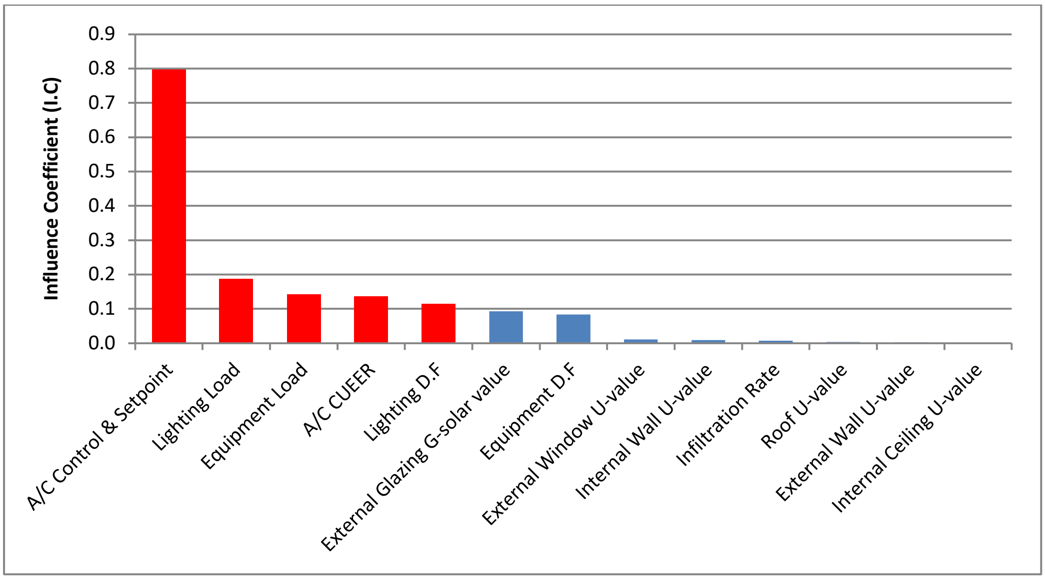


Figure 4-11. Parametric analysis chart based on the influence coefficient for selected parameters.

In order to combine monitoring data for the whole building with that for specific offices in the same calibration process, the offices which represent all the conditioned spaces in the building were assumed to use the same equipment, lighting and cooling loads (intensity of use, setpoint and profile). As the specific monitored data for the offices shows high variations in usage between different offices one office with average or typical operation conditions was selected to represent a typical office. As discussed in Chapter 3, based on the monitored data office S08 was selected to be the representative of typical operations and behaviour and applied to all offices in the building. Office S08 was then used as the base behaviour for calibration of the model (e.g. temperature, humidity and CO_2 level).

Figure 4-12 shows the available monitoring data and how this monitoring data can help to calibrate each group of input.

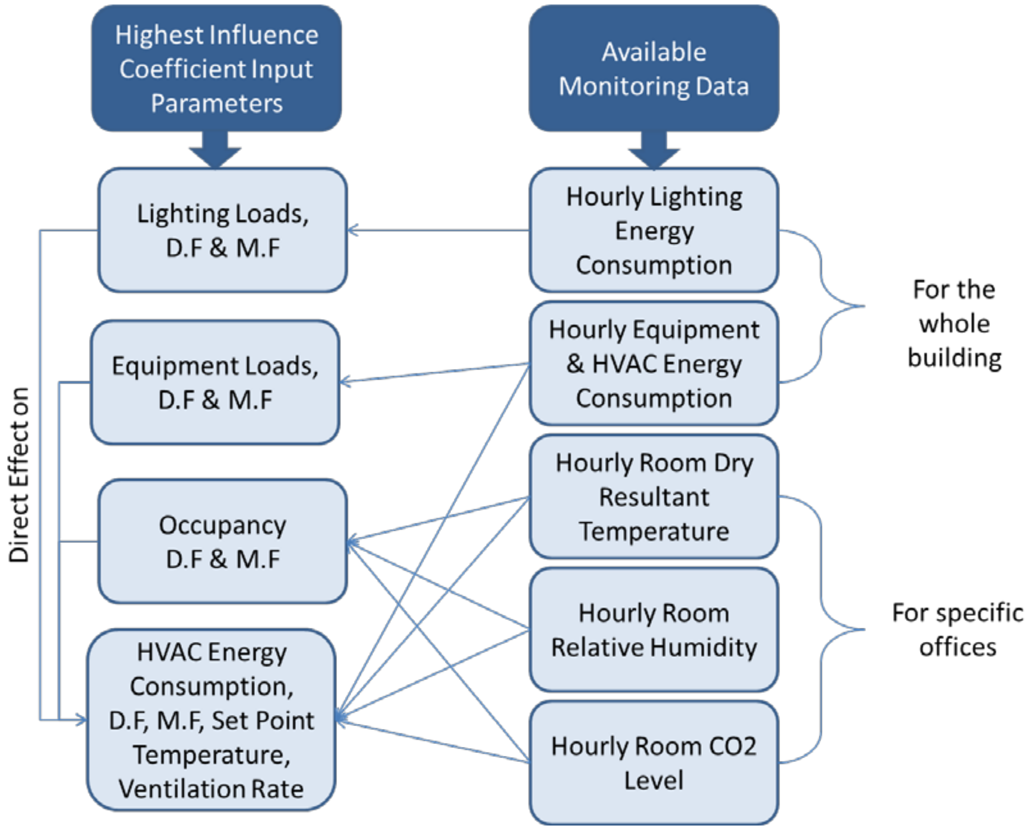


Figure 4-12. Block diagram for the relation between highest IC input parameters and available monitoring data

The calibration was organised into stages (Figure 4-13). The logic applied was that for the first stage, the base model was used, and variable 1 in Table 4-2 (A/C control and setpoint) adjusted, in the next stage, the model with adjusted variable 1 is used as base model, and so on. The stages can be summarized as follows:

1. Stage 1: Building infiltration rate and occupancy profiles were adjusted to minimise error between measured and modelled CO_2 levels during a day when windows were known to be closed, and some occupants were known. This was then checked over two different weeks when windows were expected to be closed.
2. Stage 2: Equipment and A/C have the same common power supply, so to separate their effects equipment load profiles (IT and miscellaneous) were adjusted to minimise error between measured and modelled electricity use for the whole building for a week in winter when A/C was not operating. These equipment loads were used in stage 6 to calibrate the energy used by the cooling system during summer.
3. Stage 3: Lighting loads and profiles were adjusted to minimise the error between measured and modelled lighting electricity use (lighting electricity directly measured) for the whole building during a summer week then an estimate was made for increasing the D.F. by up to 20% towards winter based on observations during the physical survey.
4. Stage 4: A/C unit control profiles (setpoint, on/off times) were adjusted to minimise error in resultant temperature during summer monitoring periods with A/C on for office S08 (representing the average operating conditions), then this operating condition was applied to the rest of the offices.
5. Stage 5: A/C unit controls (setpoint, on/off times) were checked during winter monitoring periods (only very occasional A/C use is seen in winter periods).
6. Stage 6: Stages 1 to 5 have a direct effect on the cooling system energy consumption. Once the calibration achieved a good agreement in these stages

the CUEER was adjusted via the cooling use D.F. to minimise the error between actual electricity use and modelled electricity use during summer periods with A/C on (Figure 4-14).

7. Stage 7: The A/C and equipment loads were not separable in the study after the A/C parameter calibration was completed so a check was applied to the combined A/C and equipment electricity use for the whole building.

Table 4-3 gives a summary of the calibration process stages. Given the high variability seen in the monitoring study driven by unpredictable user behaviours and other uncertainties, the calibration process yielded acceptable results based on the criteria described earlier with high R^2 and acceptable CV(RMSE). The highest CV(RMSE) of 33.8% for the A/C CUEER is a function of the variable and unpredictable nature of the use of these systems in a building of this type which was not possible to capture better in the model.

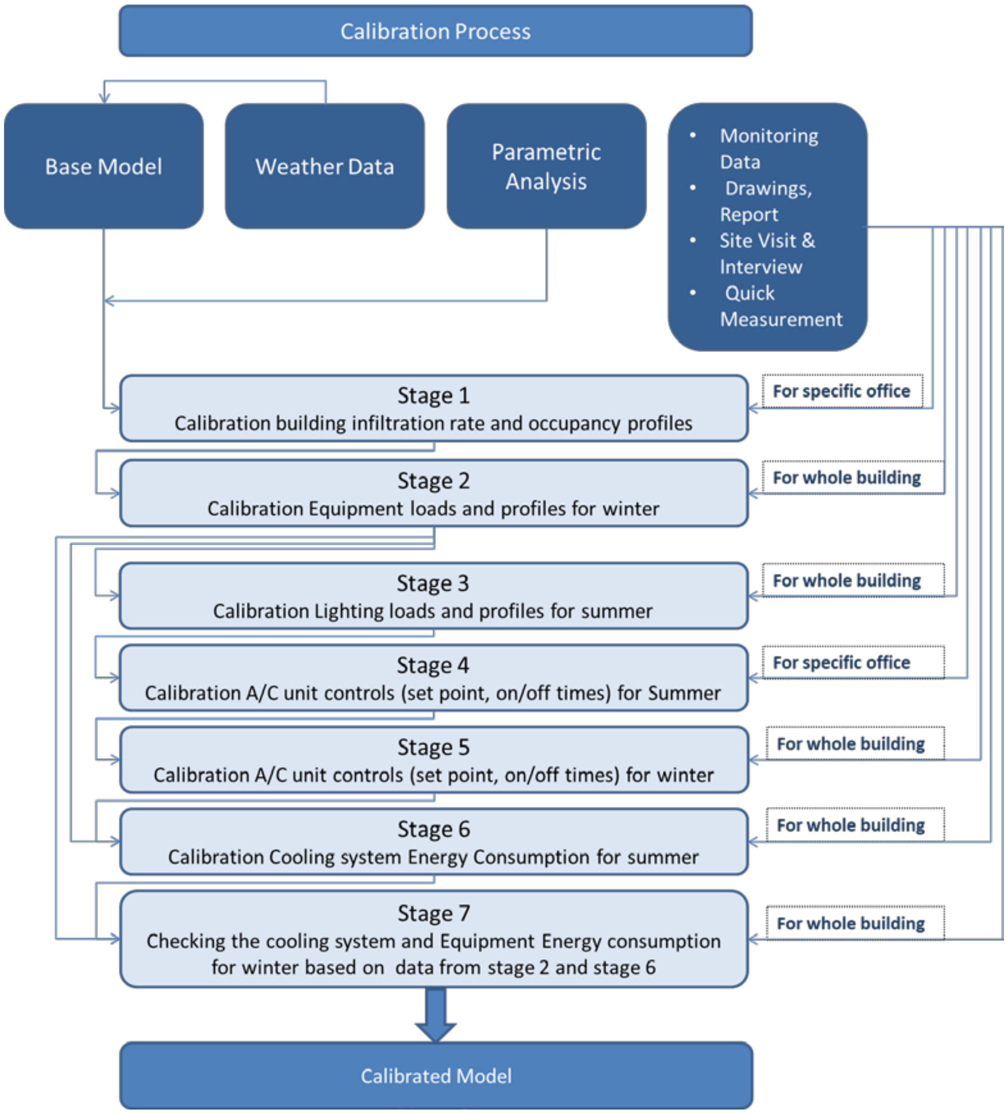


Figure 4-13. Steps for the calibration procedure.

Figure 4-14 shows the total energy consumption for the calibrated model using different CUEER values. The figure shows a calibrated model operating with 100% of the offices using A/C devices during the occupied hours with a cooling system CUEER of 6.5kW/kW, and a calibrated model with 50% of the offices using A/C with a cooling system CUEER of 3.25kW/kW. These results show that the CUEER employed in the modelling was not an indication for the SEER of cooling system only, but it takes into account the occupancy variation and the diversity factor of some offices using the A/C.

Table 4-3. A summary for the calibration process stages.

Calibration Stage and Focus Variable Group		Primary Variable: Unit	Primary Variable: Initial Value	Primary Variable: Calibrated Value	R^2	CV(RMSE)	Method of Calibration
Stage 1	Infiltration rate and profile	l/s.m^2	0.6	1	0.97	7.22%	Based on CO_2 level in one office during typical working day
Stage 2	Equipment load and profile factor	Equipment Load (W/m^2)	14.8	17.6	0.98	14.00%	Based on monitoring energy consumption for whole building for equipment during winter week (when A/C turned off)
		Winter Profile Factor	0.6	0.6			
Stage 3	Lighting load and Profile Factor	Load (W/m^2)	9	12	0.93	21.80%	Based on monitoring energy consumption for lighting for whole building during summer week
		Summer Profile Factor	0.55	0.35			
		Winter Profile Factor	0.55	0.45			
Stage 4	A/C profile, Setpoint and summer control	°C	23	21	0.84	3.47%	Based on monitoring specific office resultant temperature during summer week
		Glass Shading Coefficient (G-solar value)	0.82	0.82			
Stage 5	A/C profile, Setpoint and Winter Control	°C	21	21	0.75	1.64%	Based on monitoring specific office resultant temperature during winter week
Stage 6	A/C CUEER and average number of offices using A/C during summer	CUEER W/W	3	6	0.93	33.80%	Based on monitoring energy consumption for equipment and A/C for whole building during Summer week
		Equipment Load (W/m^2)	17.6	17.6			
Stage 7	Final check for Equipment and A/C power consumption	---	---	---	0.95	24.40%	Based on monitoring energy consumption for equipment and A/C for whole building during winter week

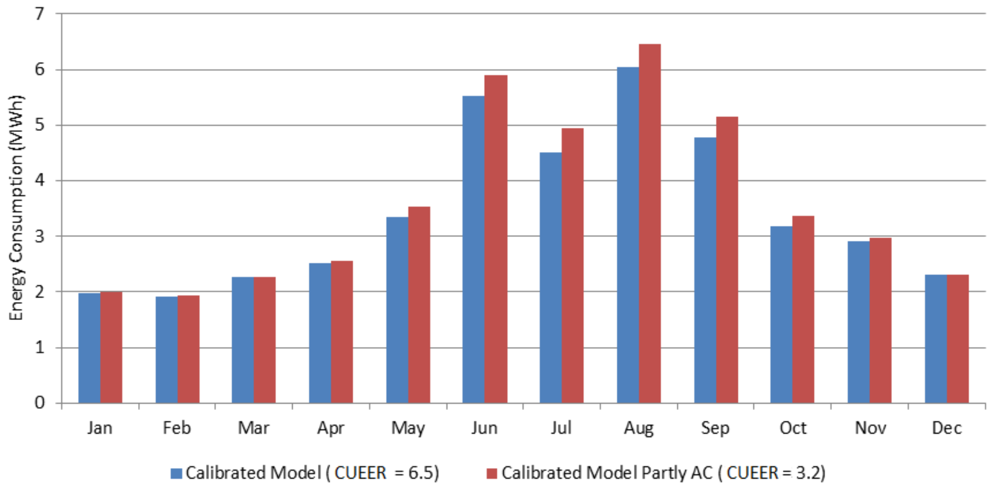


Figure 4-14. Total energy consumption for calibrated model using different CUEER.

To perform dehumidification control validation to ensure the model and actual cooling system performance was matched, random summer days were selected, then some manual calculations performed (equation 4-6), and the results compared with the cooling system latent load output of the simulation. Figure 4-15 reveals that there is proper matching between the simulation and actual calculated latent load during both the night and day periods. On the other hand, there is disagreement at the end of the working hours (16:00 till 19:00). The difference in the two curves is because the air condition control schedule in the model as turned off by 16:00 which results in instant zero latent loads, while in reality, the latent load should be gradually decreasing based on the gradual decline in the latent heat load source.

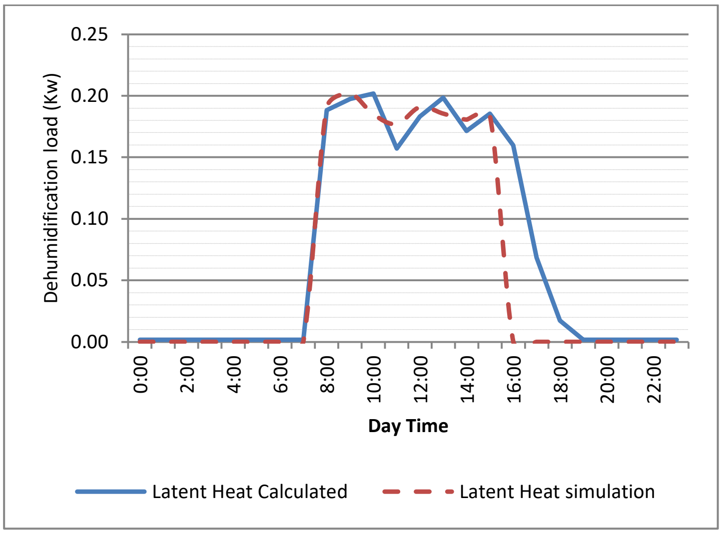


Figure 4-15. Dehumidification load for the simulation and actual calculated latent load during both the night and day periods.

The dehumidification process is based on removing the latent heat from the air. This latent load has two main sources; the external load results from moving air from outside to inside the building and the internal load resuls from occupancy and equipment (if any of the equipment produces latent heat). The room latent load is given by:

$$RLL = m_{air}.(\Delta h) + \left(\left(\frac{N_{person}}{1000}\right).LL_{person}\right) \quad 4\text{-}6$$

Where; RLL, m_{air}, Δh, N_{person}, LL_{person} are the room latent load (kW), the mass flow rate of the air moving from outside the room to inside (kg/s), the difference between the outside and room enthalpy (kJ/kg), the number of the persons in the room and the latent heat generated by one person (W/person), respectively.

4.5.2. Calibrated Model - Results

Following the calibration process, some results are shown in this section to illustrate the degree of matching between the calibrated simulation model and the actual monitoring data.

The first example is for the indoor environmental properties of office S08, selected during the monitoring process as representing the most common behaviour.

Figure 4-16 shows the equipment and A/C energy consumption for the simulation results with the actual measured data. Figure 4-16a shows that during a typical summer day the actual peak consumption for equipment and A/C reaches about 23kWh between 11:00 AM and 2:00 PM due to the increase in the A/C load, and the occupant schedule during the day. The energy consumption during unoccupied hour reduces to 2kWh, which is approximately 9 % of the peak load during the day.

There is generally good agreement between the simulation data and the monitored data. During the transition period between occupied and unoccupied hours there are some differences due to the difficulty in capturing the more gradual effect of the variable timing for switching off the A/C seen in the real case in the simulation model.

Figure 4-16b shows that the consumption for equipment and A/C through the winter day is about 7kWh and during unoccupied periods the load reaches 0.7kWh, in generally good agreement.

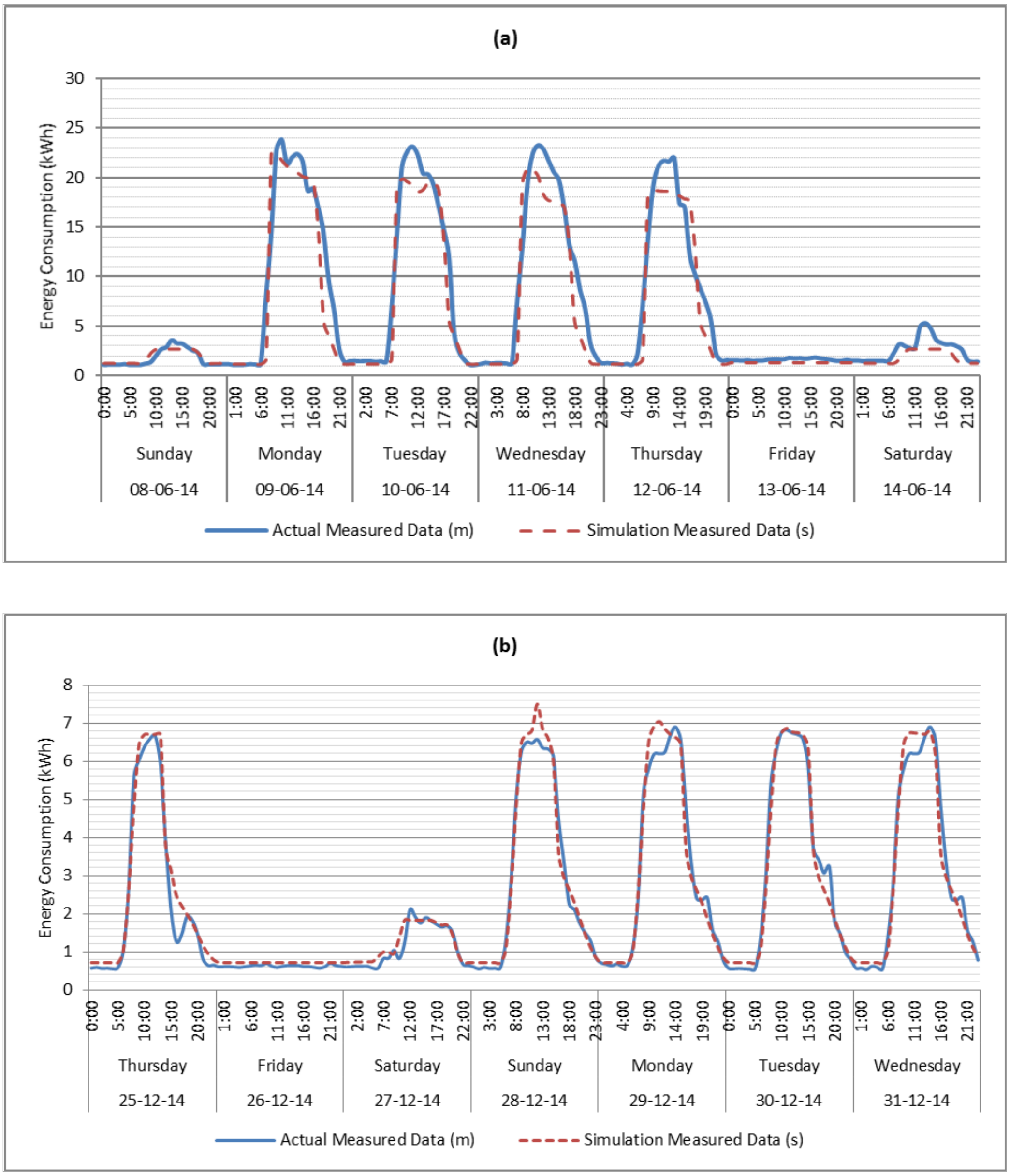


Figure 4-16. Equipment and A/C energy consumption for; (a) a whole week during summer, and (b) a whole week during winter.

Figure 4-18 shows the CO_2 level for simulated offices compared to S08 measured data during the working day during a period when windows were observed to be closed. It shows a generally good agreement between the simulation model and the measured data. During the monitoring the offices all had a high variation in the occupancy profile. This has resulted in some disagreements between the measured and simulated data for this week. It was decided that the variations in behaviour would have to be captured separately from the calibration exercise as will be discussed further later in the thesis.

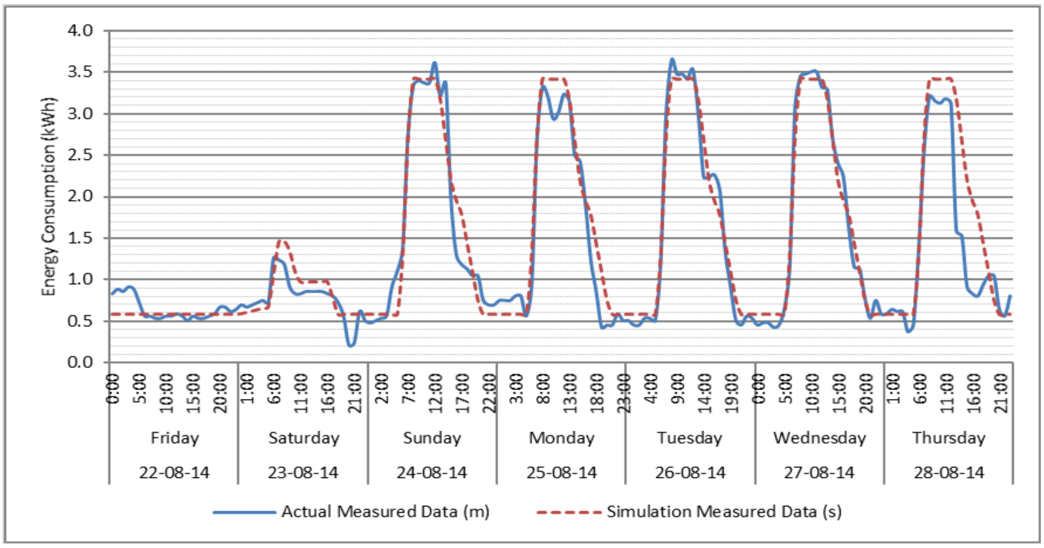


Figure 4-17. Lighting energy consumption

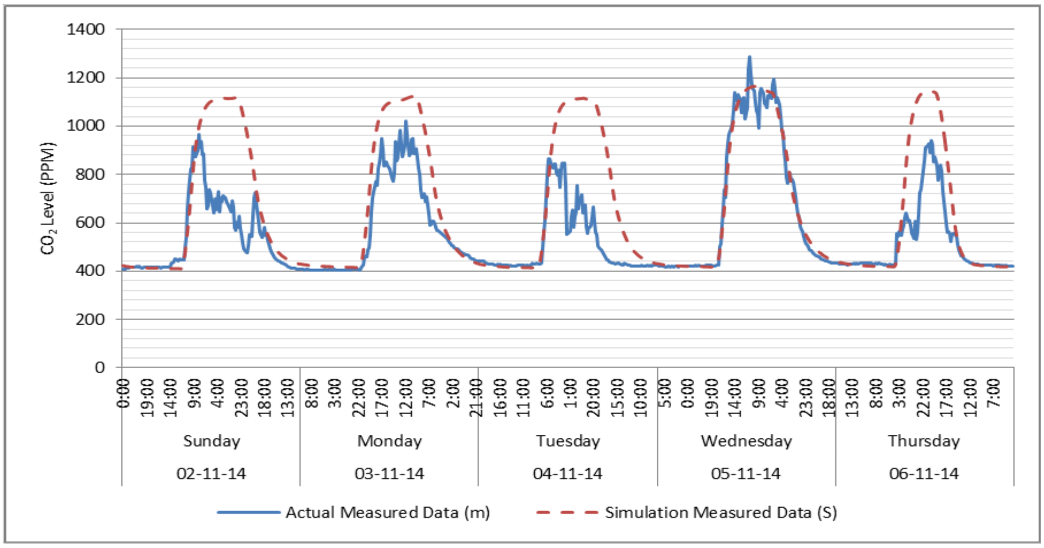


Figure 4-18. Inside room CO_2 level.

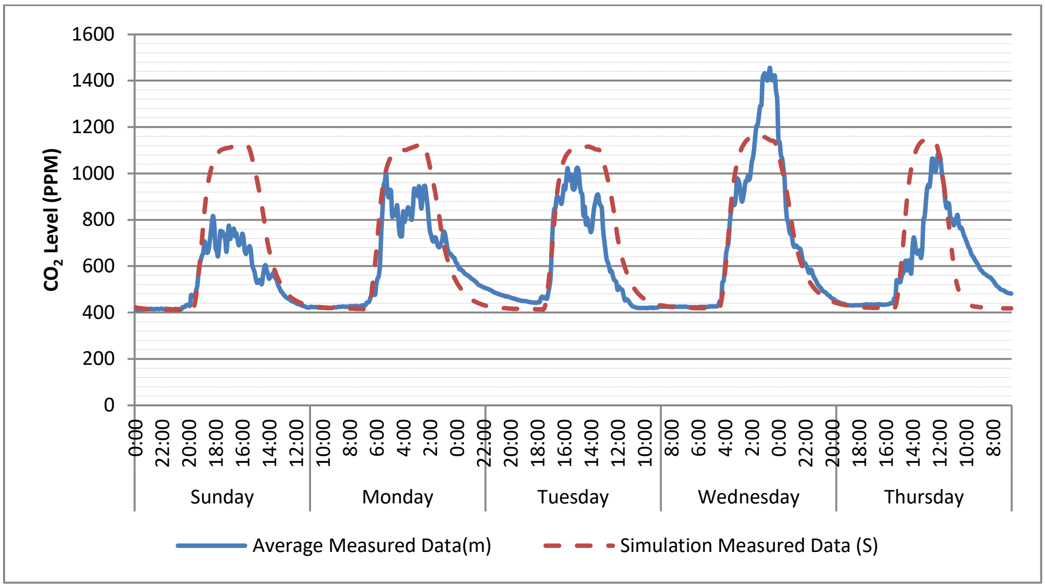


Figure 4-19. Average inside room CO_2 level.

Figure 4-20 shows the degree of matching between the simulation results and the actual measured data for the resultant inside temperature for a whole week during both winter and summer periods. Figure 4-20a shows that the inside resultant temperature matches well during the winter week when the windows are used with some A/C depending on the occupant behaviour, as discussed in a previous section. Figure 4-20b shows good matching in the results for the resultant inside temperature during a summer week when the window is normally closed with some infiltration as a result of the door opening, and through the window and building envelope as it is not completely airtight.

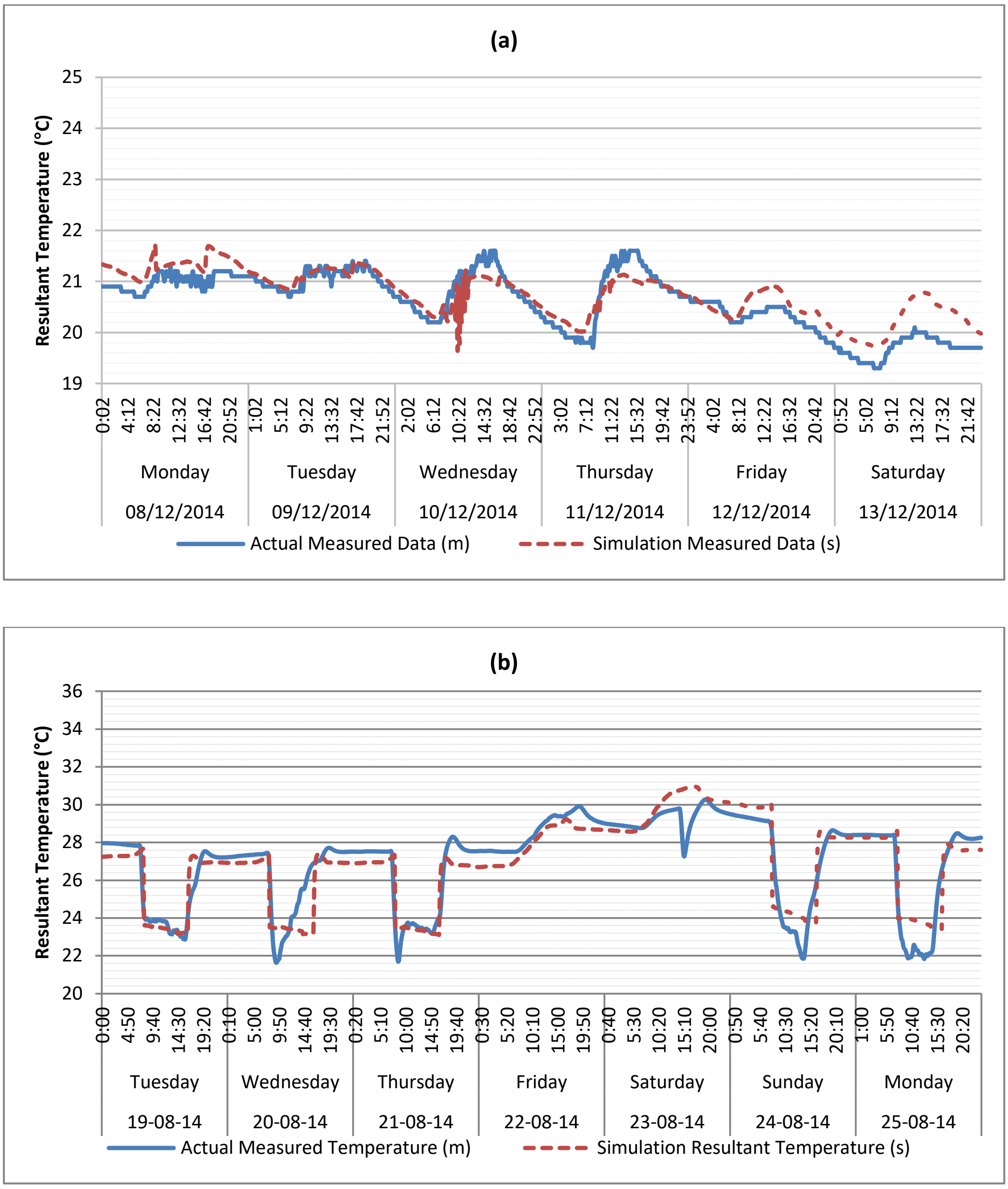


Figure 4-20. Inside room resultant temperature for; (a) a whole week during winter, and (b) a whole week during summer.

To further explore the measured and modelled indoor temperature parameters and their inherent temporal variability as discussed in Chapter 3 calibrated model representations of air (dry-bulb) temperature and resultant temperature were also investigated (Figure 4-21). Modelled air and resultant temperatures appear to have a characteristic which is more digital for on/off periods than the measurements. This draws attention to a number of points such as: (1) the modelled air and resultant temperatures are based on the centre zone/room single point node only, (2) the modelling assumes the zone air to be fully mixed (3) the modelling assumes the A/C system injects heat directly into the air node and instantly achieves setpoint if within the system capacity. In reality there is generally some time lag and some variation in fan power as setpoints are approached due to the real spatial locations and system controls operation which usually has some differential component. These insights serve to indicate that in addition to the measurement uncertainties discussed in Chapter 3 there are modelling assumptions which also have to be made, and uncertainties or inaccuracies associated with the modelling itself. The approach taken in this work has been to make the initial assumption that the measurements are an approximation of the experienced resultant temperatures (while recognising this as an assumption) and to suggest that uncertainties be captured in the parametric investigations which will be elaborated in Chapter 5.

Figure 4-22, Figure 4-23, and Figure 4-24 represent the model and measured total lighting energy consumption during August 2014, and equipment and A/C energy consumption during June (summer), and December (winter) 2014 respectively, and show good agreement.

Figure 4-25 represents in a bar chart the model and measured total lighting energy consumption during July and August 2014, and equipment and A/C energy consumption during July, September, October, November and December 2014. The figures emphasise that generally good agreement is achieved between the simulation results and the actual measured data.

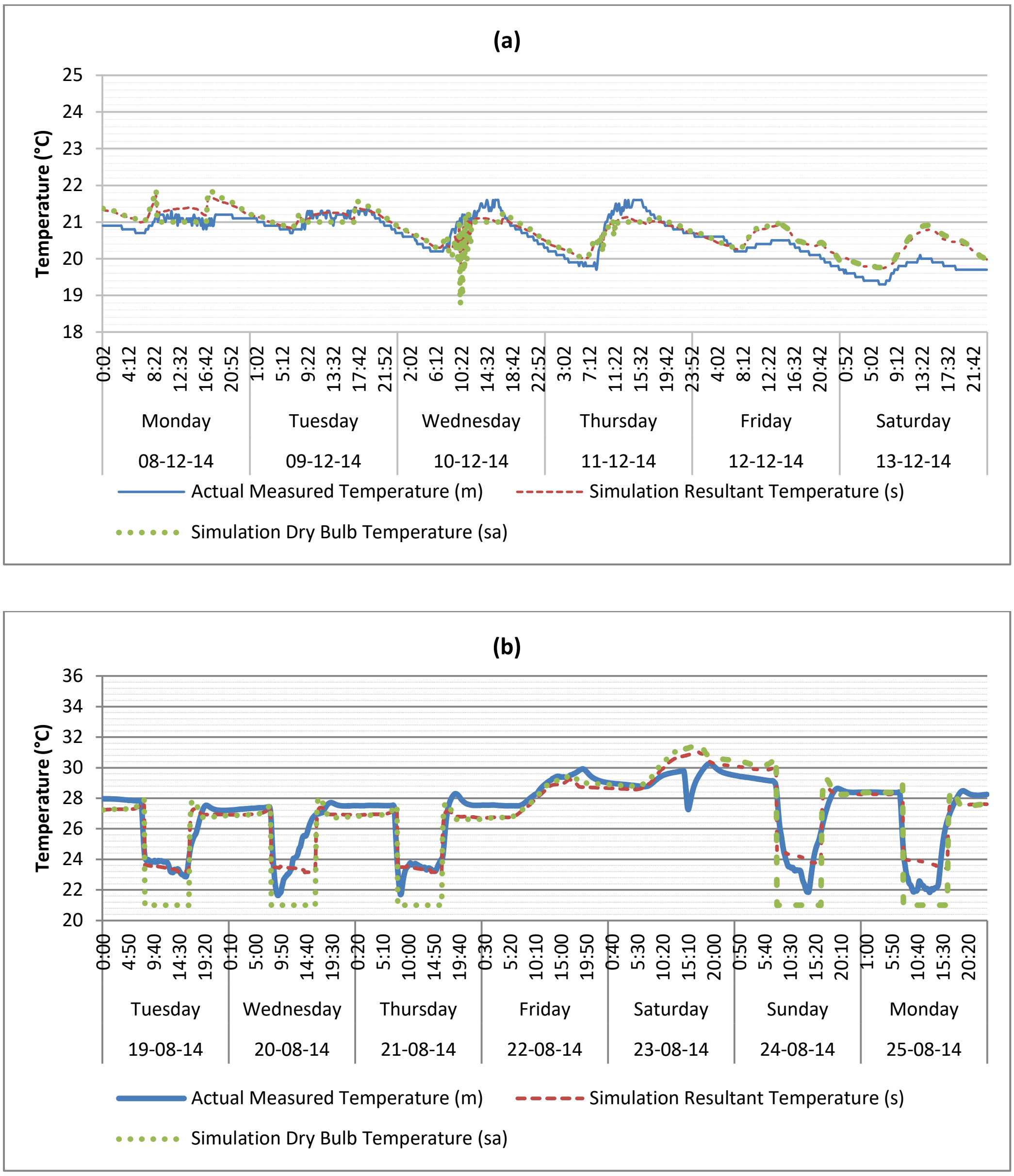


Figure 4-21. Inside room temperature for; (a) a whole week during winter, and (b) a whole week during summer.

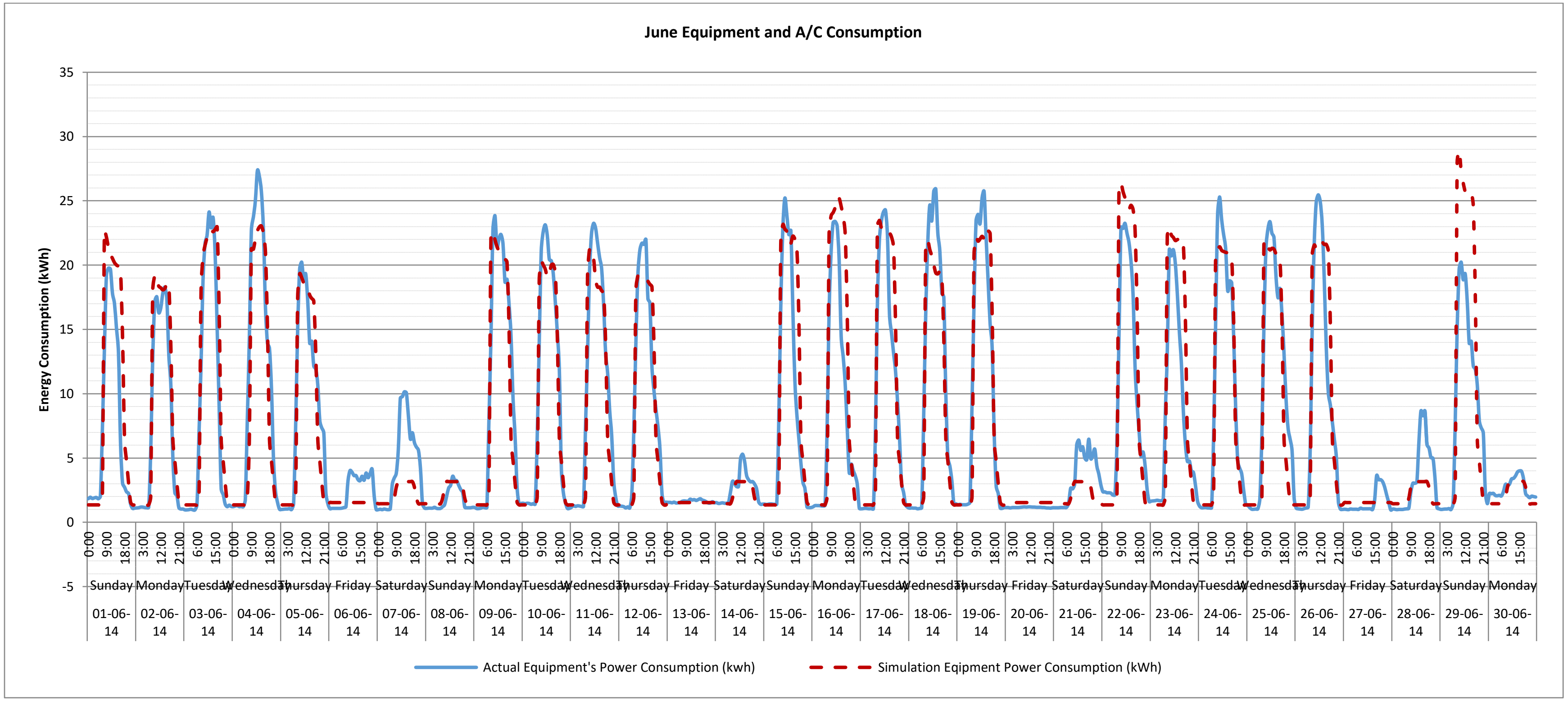


Figure 4-22. Equipment and& A/C energy consumption during June.

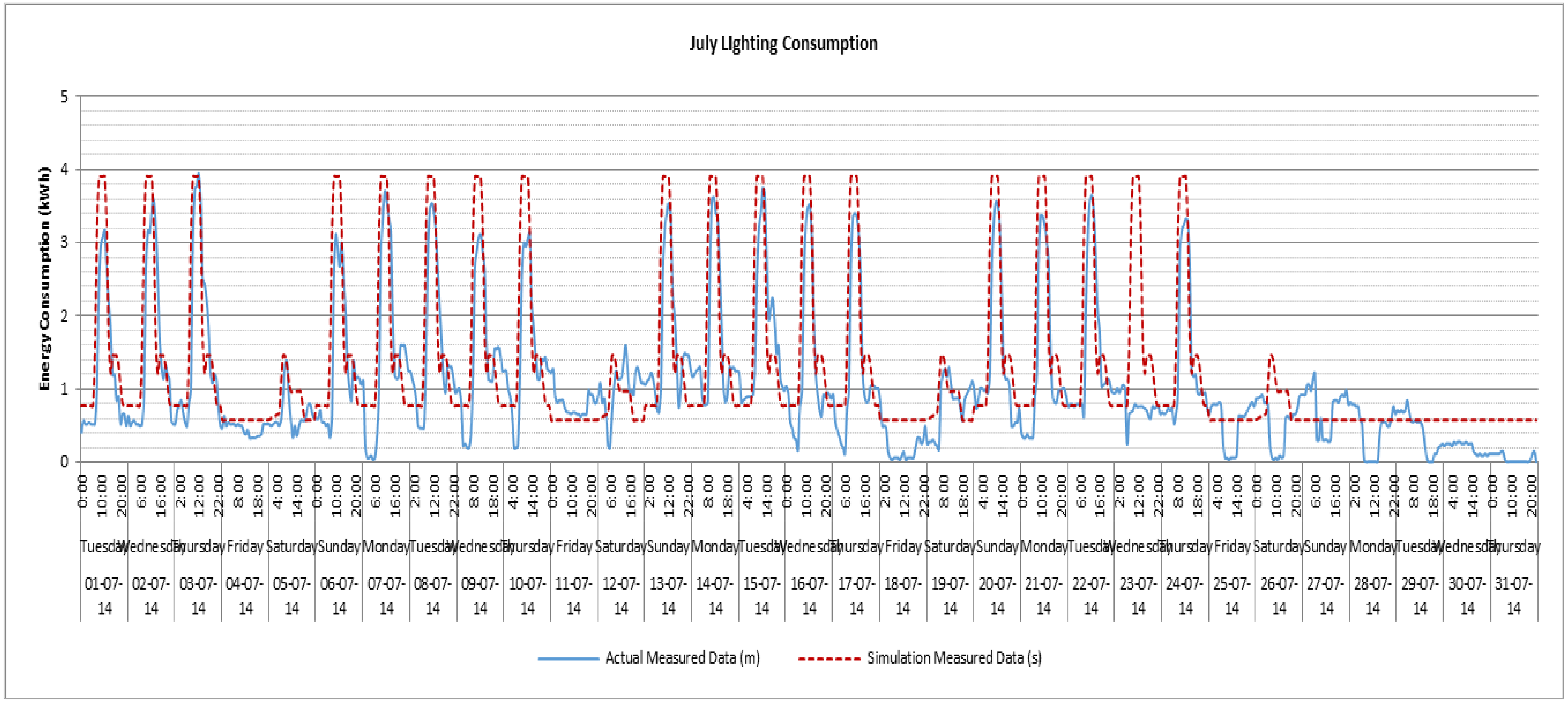


Figure 4-23. Lighting energy consumption during July.

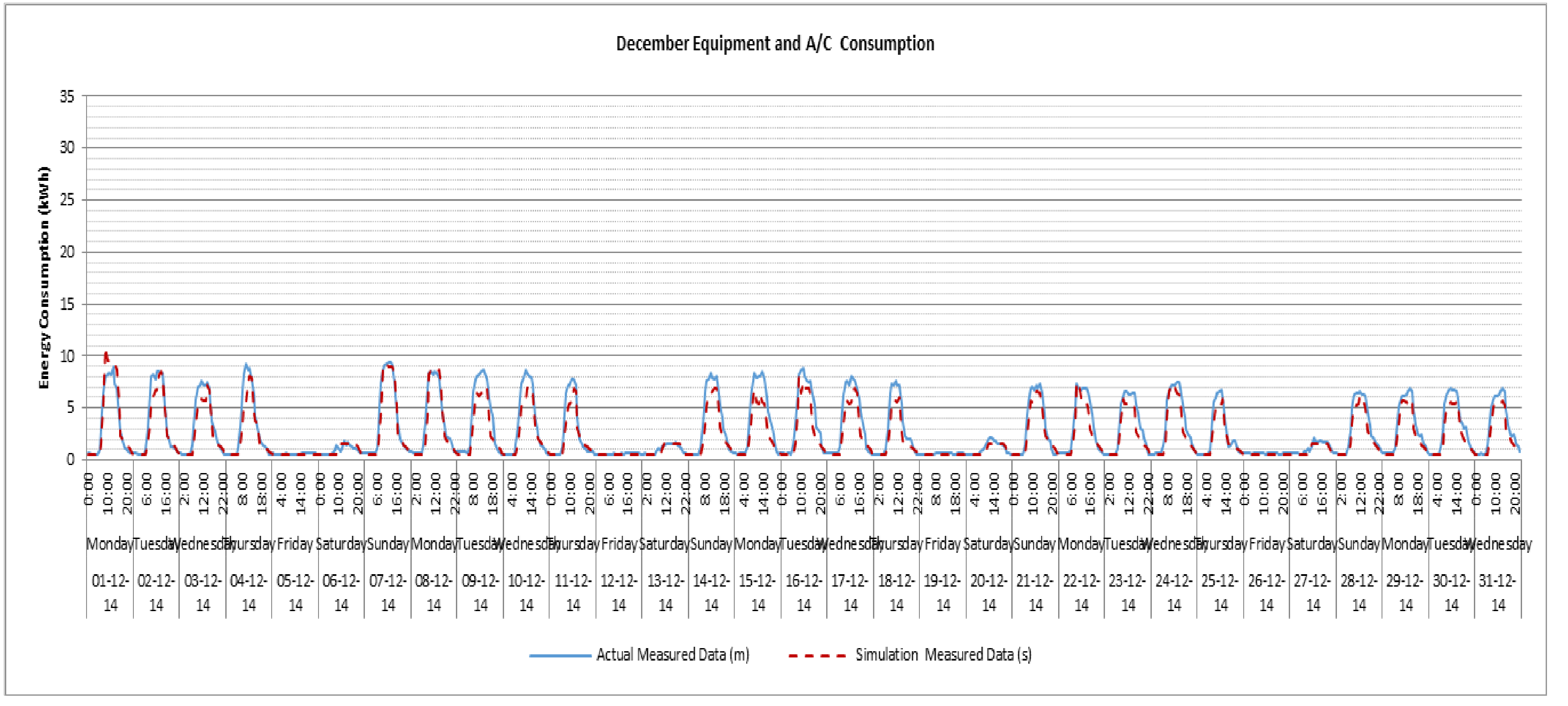


Figure 4-24. Equipment and A/C energy consumption during December.

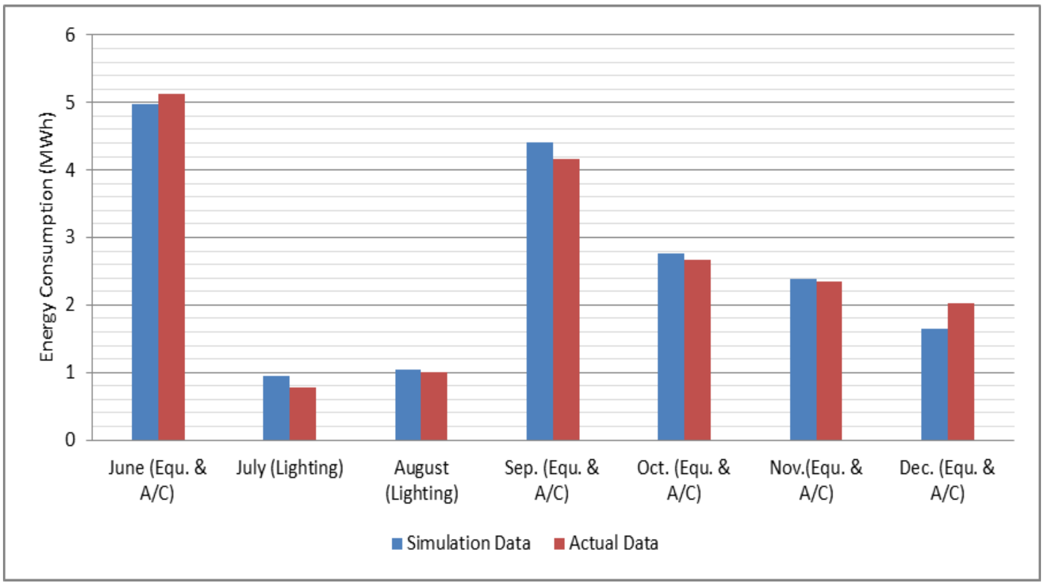


Figure 4-25. Sample of total equipment and lighting energy consumption

The annual energy performance for the building can be characterised by energy use category after performing the calibration process, as indicated in Figure 4-26. The calibrated model showed generally good agreement with the measured data from the survey of the case study building. However, when these results are compared with the Chapter 3 energy survey data for Egyptian buildings of this type (Figure 4-27) it can be seen that the calibrated model does give some monthly energy use results that differ from the survey. The source of the differences may be the case study building's function as an administration building serving a large university, with very high occupancy and energy use in June and August associated with the university calendar. On the other hand, it had lower typical occupancy and activity levels in July in 2014, the measurement year, because of Ramadan.

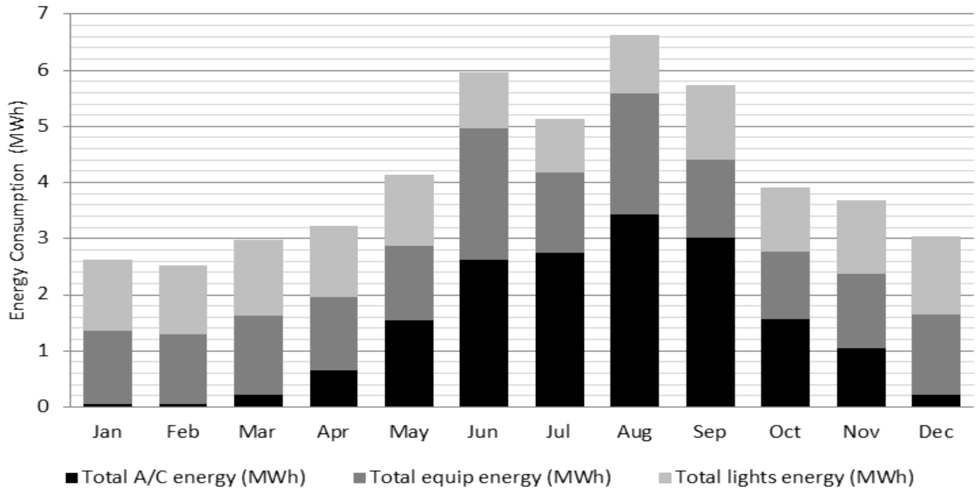


Figure 4-26. Stack-bar-chart of the monthly energy consumption for the calibrated model by category.

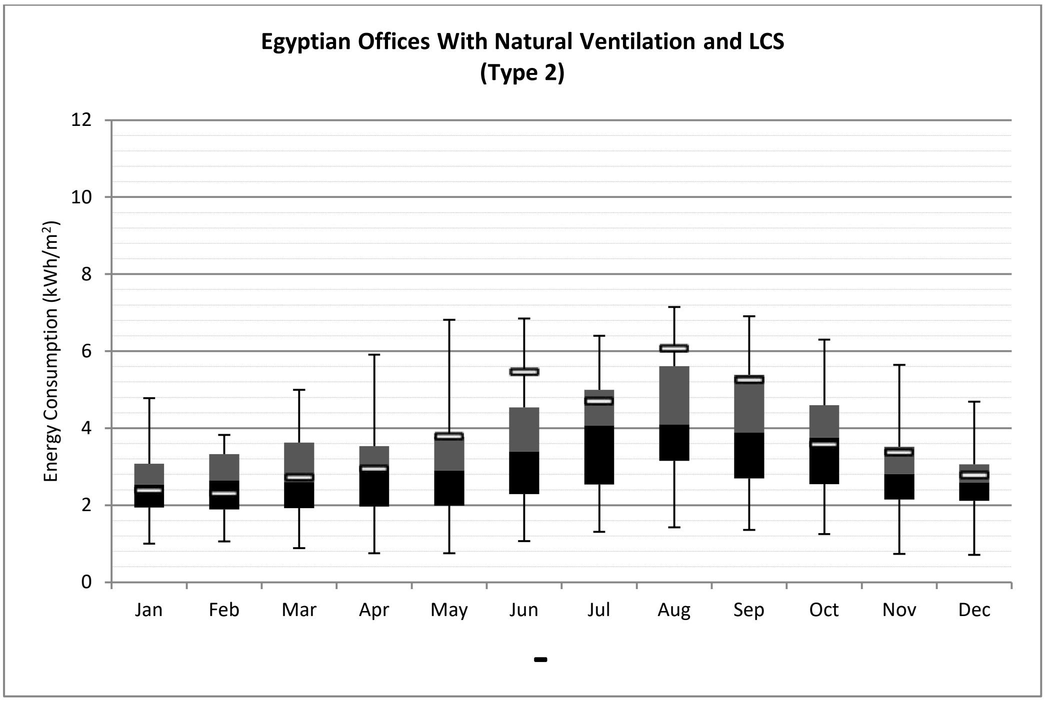


Figure 4-27. Monthly energy consumption for Type 2 offices; survey and calibrated model results. (solid bars are +/- 25 percentiles, lines the range).

4.6 Summary

This chapter introduced the concept of building simulation by discussing the definition, classification, and basics of simulation models. A historical introduction to building simulation models emphasised the need for using building simulation tools. Some commonly used simulation tools were discussed.

A brief discussion of building energy performance simulation in Egypt was provided to emphasise the vital problem that in Egypt there is no genuine interest in energy performance in buildings. This is reflected in the lack of use of building simulation tools and the shortage of the data required.

Based on the energy audit discussed in Chapter 3 an initial base model was created using the IES-VE 2014 simulation tool. As expected, this initial base model showed disagreement between simulated building energy performance and measured performance. This initial model was then subjected to a calibration process summarized in Figure 4-13 and Table 4-3. Despite some limitations in monitored data as a result of budget and access issues the results from the calibration process were broadly sufficient to meet the ASHRAE criteria.

The calibrated model also showed generally good agreement with real measurements by being within the distribution in total energy use found in the multi-building survey of Chapter 3, but it also showed some monthly variations in energy use which differed from the general trend. These may be related to the specific function of the modelled case study building.

To generalize this calibrated model of the case study office to form a model more representative of typical building operation and behaviours according to the general survey, a method will be proposed in the next chapter. This method will provide a typical model plus worst case input parameter sets for capturing uncertainties and variations in operations and behaviours.

Chapter 5 A REPRESENTATIVE BASELINE MODEL: GENERALIZATION OF THE CALIBRATED MODEL INCLUDING THERMAL COMFORT

5.1 Introduction

In Chapter 3 a general energy bill survey was conducted, and a more detailed energy, environmental and indoor air quality survey was performed for an individual case study office building located in Alexandria, Egypt. In Chapter 4 a dynamic simulation model for the case study building was developed, and calibrated using the data gathered through the individual office survey.

In the current chapter the appropriate indoor thermal comfort standard for the Egyptian office building is selected based on the monitored data and simulation results from the calibrated model. Three different thermal comfort models (ASHRAE 55, EN 15251, PMV/PPD) are considered in order to decide which of these models is closer to real occupant behaviour and apparent desired thermal sensation in the Egyptian context.

A process is then developed to for generalizing the calibrated model to form a representative baseline model capturing uncertainties and variations in operations and behaviours in realistic worst case parameter sets. This is applied to create a modelling framework representing typical Egyptian office buildings of the majority type as identified in the survey data, incorporating the appropriate thermal comfort requirements.

5.2 Study Of The Suitability Of Different Thermal Comfort Models For Egyptian Office Buildings

The selection of a thermal comfort model which represents real occupancy behaviour and acceptable comfort sensation has a major impact on the modelled energy consumption of buildings. The models for thermal comfort in hot climates discussed in the literature review of Chapter 2 will be compared to investigate which of these is more representative of conditions in the typical office building. This model will be appled in the study of the energy performance in these buildings.

The comparison will include the two adaptive comfort models which represent the ‘free running’ buildings with occupant control for the indoor environment, e.g. through the opening of windows. These are ASHRAE 55 adaptive comfort standard [112], and EN 15251 adaptive comfort standard [125]. The Fanger model, based on PMV/PPD and applicable to buildings with no control by the occupants, is also included.

Thermal comfort indicators are calculated for the occupied periods using the three standards, and averaged monthly to allow simple comparisons. This data can be conveniently represented graphically and used to evaluate measured or modelled performance against each standard to choose the most representative comfort model.

5.2.1. American Adaptive Comfort Model (ASHRAE 55)

Figure 5-1 and Figure 5-2 both show the acceptable range of thermal comfort based on the ASHRAE Adaptive Model [114] showing the optimal comfort temperature (grey line in the middle) with upper and lower boundaries for the 80% (continuous lines) and 90% (dashed lines) bands of acceptability.

Figure 5-1 and Figure 5-2 also show respectively the average monitored monthly indoor temperature and, to have a wider time period comparison, the average simulated monthly indoor temperatures for the calibrated model. As shown from both figures, based on this result the occupants in the case study model require lower inside room temperatures than recommended by the ASHRAE 55 Standard, with the mean indoor temperatures just within the 80% acceptance level (cool side) of the model.

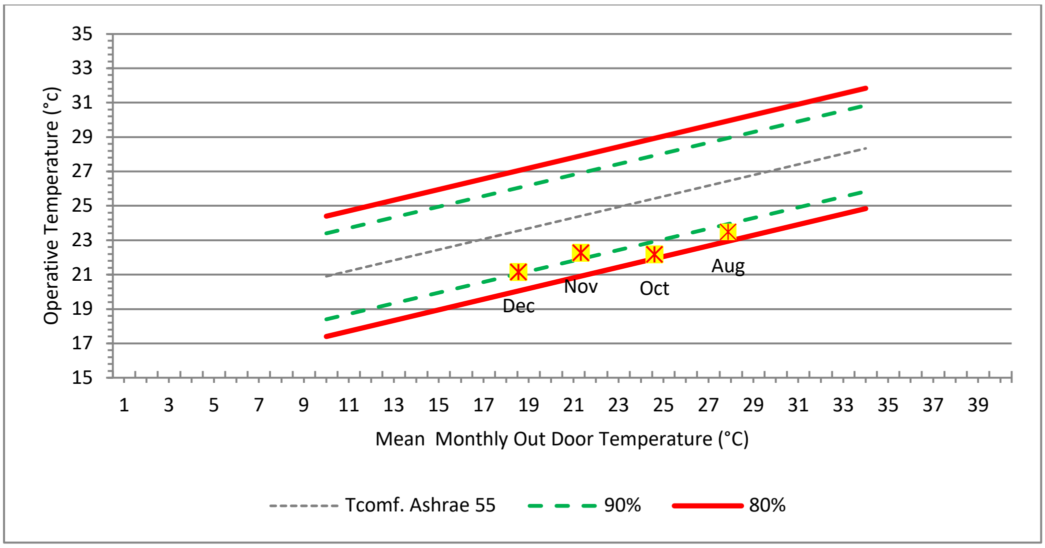


Figure 5-1. Average monitored monthly indoor temperature vs adaptive comfort chart (ASHRAE 55).

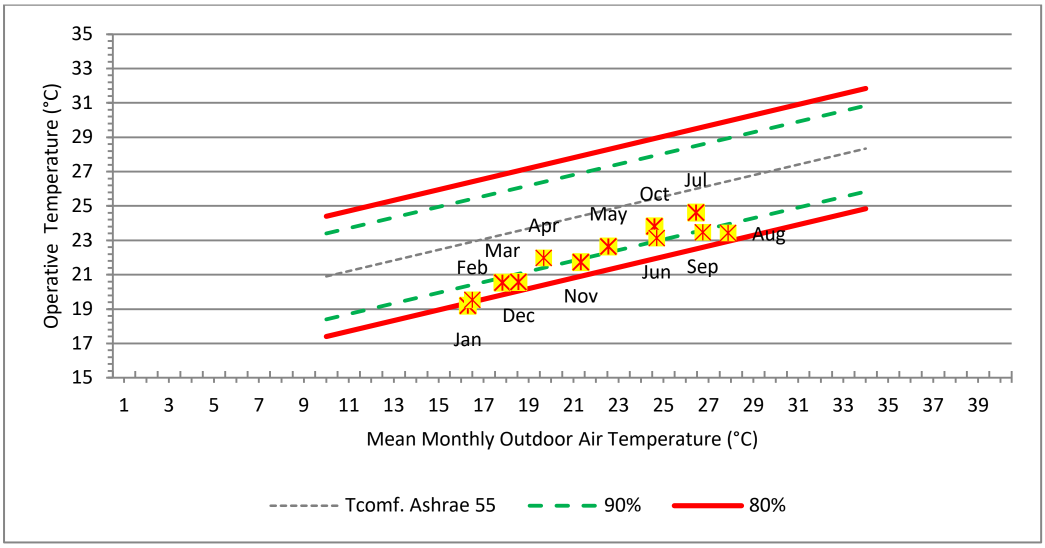


Figure 5-2. Calibrated model average monthly indoor temperature vs adaptive comfort chart (ASHRAE 55).

5.2.2. European Adaptive Comfort Model (EN 15251)

Figure 5-3 and Figure 5-4 show the acceptable range predicted by the thermal EN 15251 comfort model [128]. The optimal comfort temperature (grey line in the middle) is shown with three acceptability level boundaries Level I (dashed line), Level II (long dashed line), and Level III (continuous line).

Figure 5-3 and Figure 5-4 also show respectively the average monitored monthly indoor temperature and average simulated monthly indoor temperature for the calibrated model. As shown from the graphs every monthly average falls between acceptability Level II and Level III or even outside the bounds of level III. This means that the EN 15251 comfort model is not compatible with the occupant requirements in this type of building in Egypt. Required temperatures are cooler than predicted by this standard.

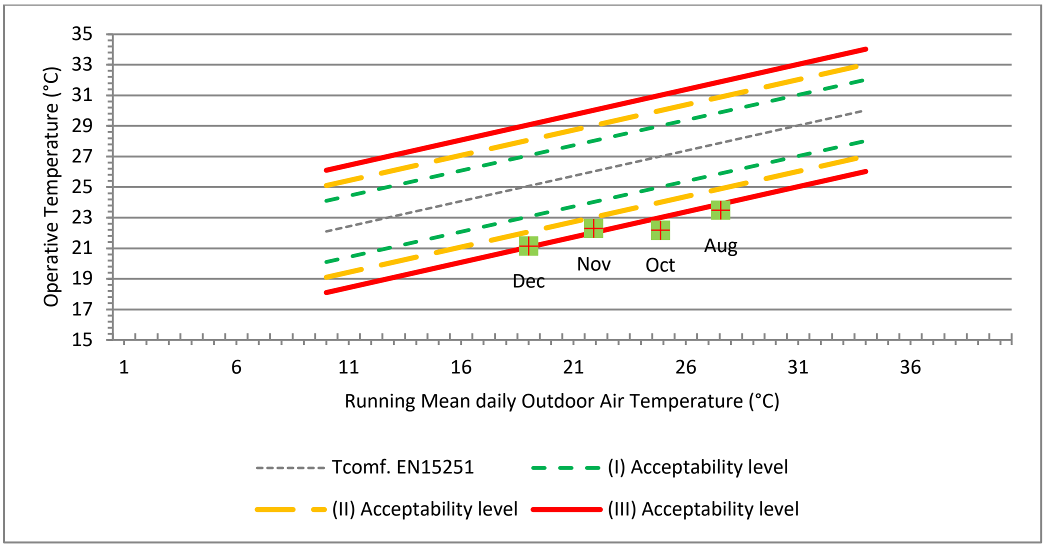


Figure 5-3. Average monitored monthly indoor temperature vs adaptive comfort chart (EN 15251).

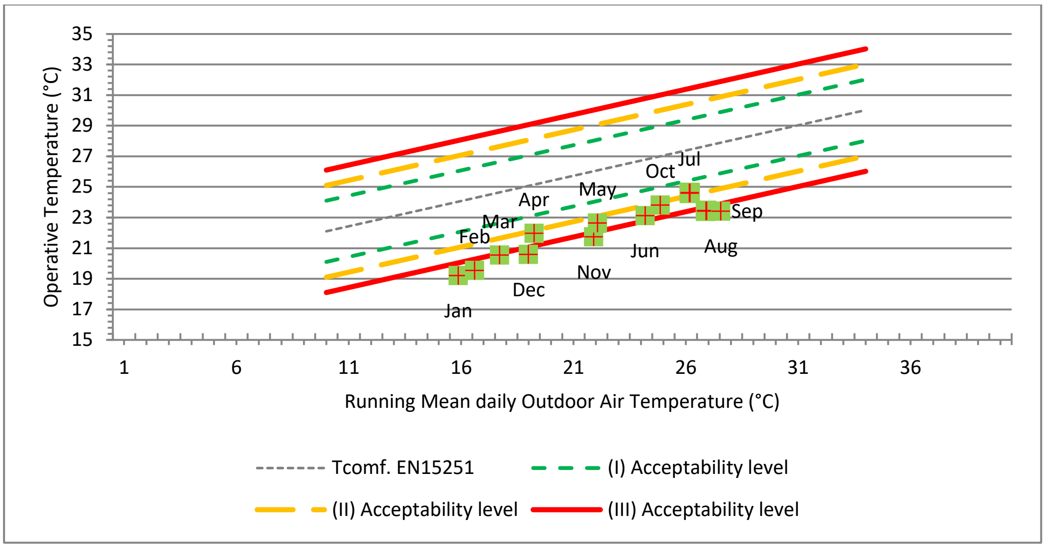


Figure 5-4. Calibrated model average monthly indoor temperature vs adaptive comfort chart (EN 15251).

5.2.3. PMV/PPD Comfort Model

Both the ASHRAE 55 and EN 15251 models take into account the outside air temperature and neglect the other primary factors mentioned by Fanger's equation (metabolic rate (met), clothing insulation (clo), air speed and humidity) which will have an impact on the thermal comfort sensation. The Fanger comfort equation assumes that the air velocity is constant at 0.15m/s, metabolic rate is 1.2 met, external work is zero met and the clothing level is 0.7 clo in summer and 1 clo in winter. It also varies the outside temperature, the surface temperature, and the relative humidity to arrive at the inside room temperature which gives the PPD 0.5 and PMV zero. These values were used in the simulation model to calculate surface and air temperatures to use as new values for the next iteration until there was no change in the surface temperature and air temperature. The final values were used to draw the PPD/PMV comfort chart in Figure 5-5 to Figure 5-7. As shown in Figure 5-6 and Figure 5-7 the PMV/PPD comfort chart is highly representative of the monitored data, and the simulation data.

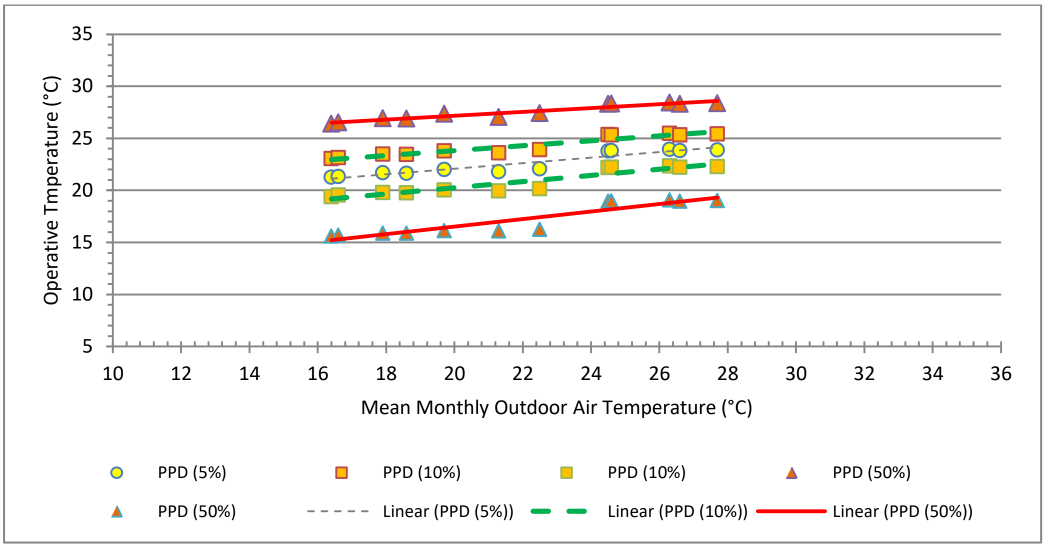


Figure 5-5. PMV/PPD comfort chart.

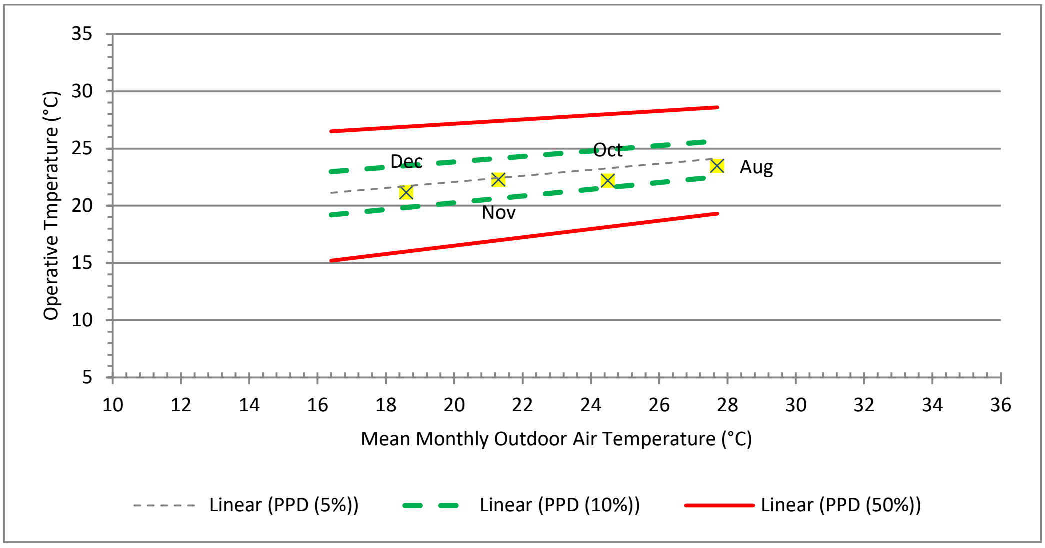


Figure 5-6. Average monitored monthly indoor temperature vs PMV/PPD comfort chart.

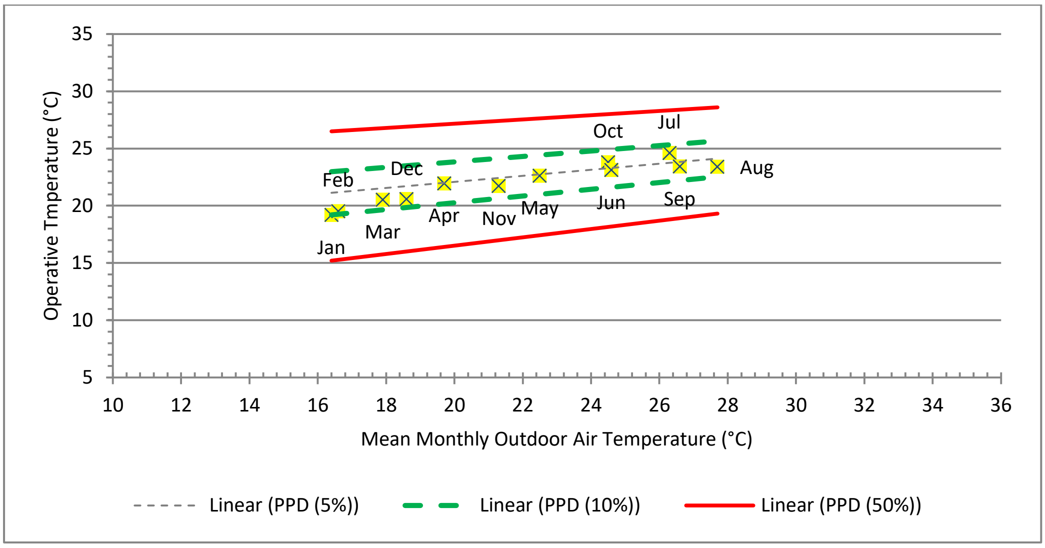


Figure 5-7. Calibrated model average monthly indoor temperature vs PMV/PPD comfort chart

5.2.4. Appropriate Comfort Model For Egyptian Type 2 Offices (PMV/PPD)

The conclusion from applying the three comfort models is that the PMV/PPD model is the most representative for the case study data. The ASHRAE 55 model showed good matching but not as good as that of the PMV/PPD model, while the EN15251 model was the least successful at representing the real occupant sensations.

This conclusion is based on a single sample office and needs to be more extensively validated but will be used as the basis of the work of this thesis. One thought is that the desire for lower temperatures than predicted by the adaptive standards, despite the ability to control windows and A/C could be motivated by factors such as cultural behaviour, or clothing fashions, lack of energy cost to the individual etc. The adaptive standards themselves appear to indicate they are not necessarily applicable when cooling is available, so the choice of the PMV/PPD standard is reasonable.

In the next section, the calibrated model developed in Chapter 4 will be generalized to the majority of the office survey data taking into account the effect on thermal comfort.

5.3 Generalization Of The Calibrated Model And Consideration Of Uncertainties

The monitoring and model calibration process enabled the development of a model representative of the most commonly observed behaviour, indoor environment and energy use in the monitored building. However, this calibrated model is specific to the case study building and to the conditions encountered during the monitoring period such as activities, behaviours, installed equipment, systems, operations, and weather. The calibrated model may not represent general buildings of this type, or may not represent well any buildings (including the monitored building) that have different specifics at any given time.

In order to address this issue, the calibrated model is first reviewed against the general survey data for buildings of this type, reported in Chapter 3. It is then adjusted to be more typical by generating parameter sets which capture likely variations in building specifics. These include operations and behaviour that can then be considered in assessing the energy consumption and indoor environmental performance of such buildings.

As reported at the end of Chapter 4, the model has a different monthly energy use profile from the average observed in the general survey of Type 2 offices, as shown in Figure 4-27. The case study building has noticeably higher than average energy use in June and August, falling in the top 25th percentile of the surveyed offices. This may be associated with the intensive academic related activity in these periods which was noted during the survey. May and September may also be partly affected. During Ramadan, which fell in July, this increased summer energy use appears to be offset by the observed shorter working hours. In the winter period energy use is higher during March, November, and December than the average for the surveyed offices, while generally lying between the mean and 25 per cent below the mean during February.

For future performance analysis a more representative ‘Typical Model’ is required. In the next section, the calibrated model will be generalized based on the range of variation of input parameters to form such a ‘Typical Model’.

5.4 A Baseline Typical Model and Worst Case Input Parameter Sets

In order to adjust the model to be more representative of the average performance seen in the general survey of Type 2 offices, the parameter ranges established from the literature review were used to represent limits within which a normal distribution was assumed to apply. The upper and lower limits were assumed to lie at at three standard deviations above and below the notional mean. The calibrated model input parameters were then adjusted manually towards the mean of these notional distributions to give results closer to the mean of the 59 building survey data. For example, the higher equipment load in summer associated with the academic year was reduced by adjusting the equipment use profile factor (P.F.) to be the same summer and winter, and the installed equipment load was reduced.

Other adjustments were made to move parameters within these notional distributions such that the changes acted to bring the model into line with the mean of the survey data (Table 5-1). It should be noted that this process was based on limited evidence and some engineering judgement was used based on the evidence of the 59 building survey and the case study building physical surveys.

It is recommended that more evidence be gathered in future to help confirm the real input parameter distributions found in the Egyptian context. Such additional data gathering was outside the scope of the current work, which lays the foundation for future work with additional datasets.

The ranges in input parameters are considered to capture the likely variations and uncertainties in building operation and occupancy to be found across the stock. Different parameters have either a positive or negative impact on energy performance and these ranges will be used to construct realistic best and worst case parameter sets. This is described and illustrated in a later section.

With these adjustments, the model results corresponded more closely with the mean of the survey data for Type 2 offices. As shown in Figure 5-8 decreasing the equipment load and diversity factor results in a reduction in the summer load and some smaller reduction in the winter load. This reduction better represents the majority of offices surveyed.

Table 5-1. Primary input parameters and ranges.

Parameter	Unit	Contribution to Power Consumption	Calibrated Model	Mean case Model	Best case (+3 sigma)	Worst case (-3 sigma)
Equipment load (IT + Miscellaneous)	W/m^2	Positive	17.6	14.8	5.9	23.7
Equipment P.F.	---	Positive	0.6 / 0.9	0.45	0.15	0.7
Lighting Load	W/m^2	Positive	12	10	4.0	16.0
Lighting P.F.	---	Positive	0.35 / 0.45	0.3 / 0.5	0.1	0.5
Occupancy Load	m^2/ person	Negative	10	10	16	4.0
Occupancy P.F.	---	Positive	0.6 / 0.8	0.45 / 0.6	0.15	0.7
A/C Setpoint	°C	Negative	21	22	26.0	18.0
A/C CUEER	W/W	Negative	6	8	14.0	2.0
Infiltration Rate (Operation)	$l/s.m^2$	Positive	1	0.5	0.1	1.0
Infiltration Rate (Envelope)	$l/s.m^2$	Positive		0.3	0.3	0.3

The model is readily extendable to represent more intensively serviced office types. The typical model was re-run without cooling and the results compared against those for the Type 1 office in the survey, this also gave good agreement (Figure 5-9). The simulation showed the total annual energy consumption for this type of building to be $29kWh/m^2$ p.a. with 53% of this energy consumed by the IT equipment and the rest by the lighting system (Figure 5-12). The typical model was re-run again by adding a mechanical ventilation system (with the additional energy used derived as described in Chapter 3) and the results compared against those for the Type 3 offices in the survey. This also gave good agreement, as shown in Figure 5-10. The simulated total annual energy consumption for this building type reached 68kWh/m^2 p.a. This energy consumption was made up of 27% IT equipment, 24% lighting, 17% cooling and the rest mechanical ventilation and auxiliary equipment.

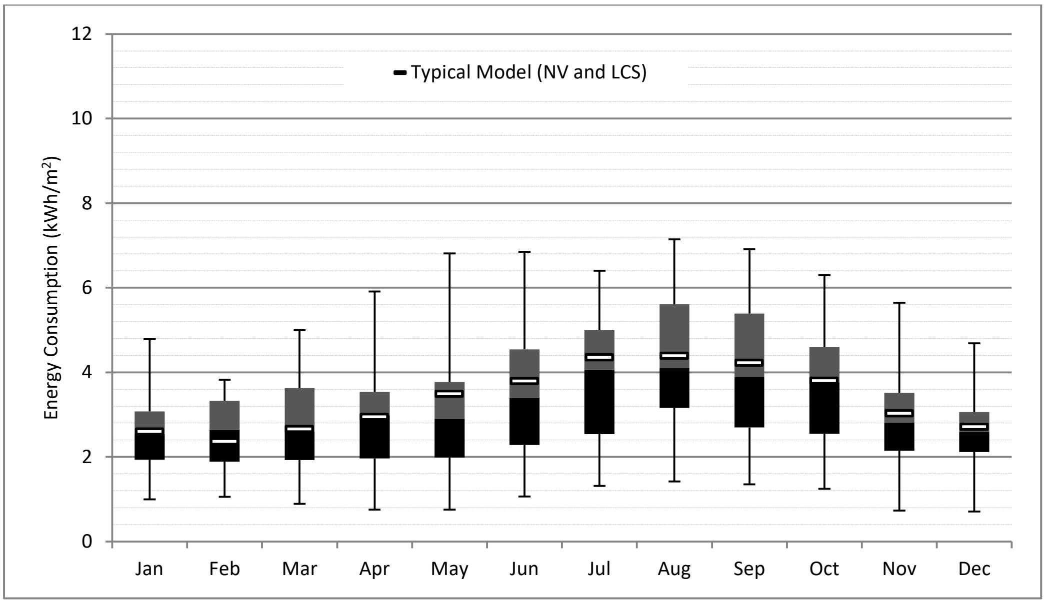


Figure 5-8. Monthly energy consumption for Type 2 offices; survey and typical model results (solid bars are +/-25 percentiles, lines the range).

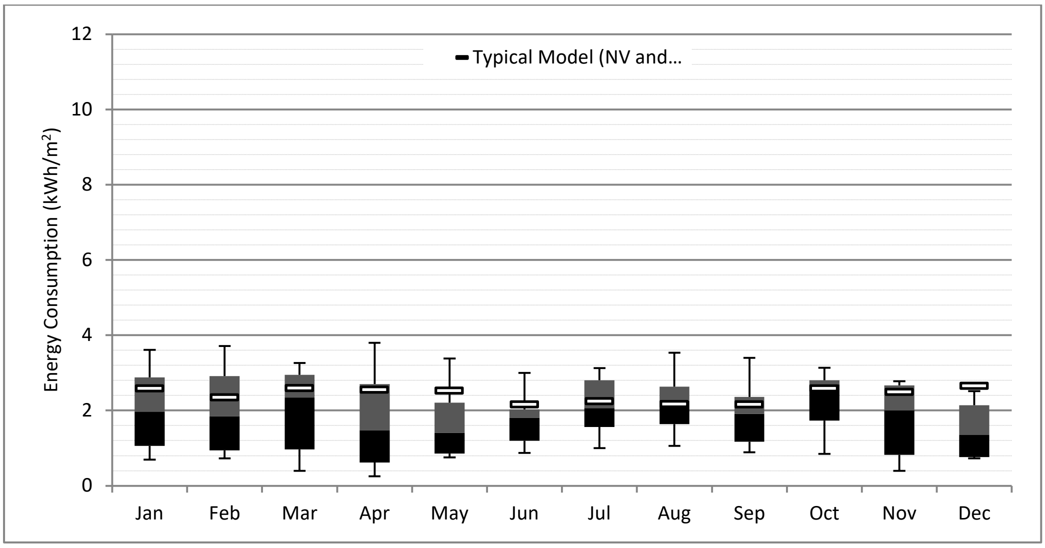


Figure 5-9. Monthly energy consumption for Type 1 offices with natural ventilation (NV) and no cooling system (NCS): survey and typical model results (solid bars are +/- 25 percentiles, lines the range).

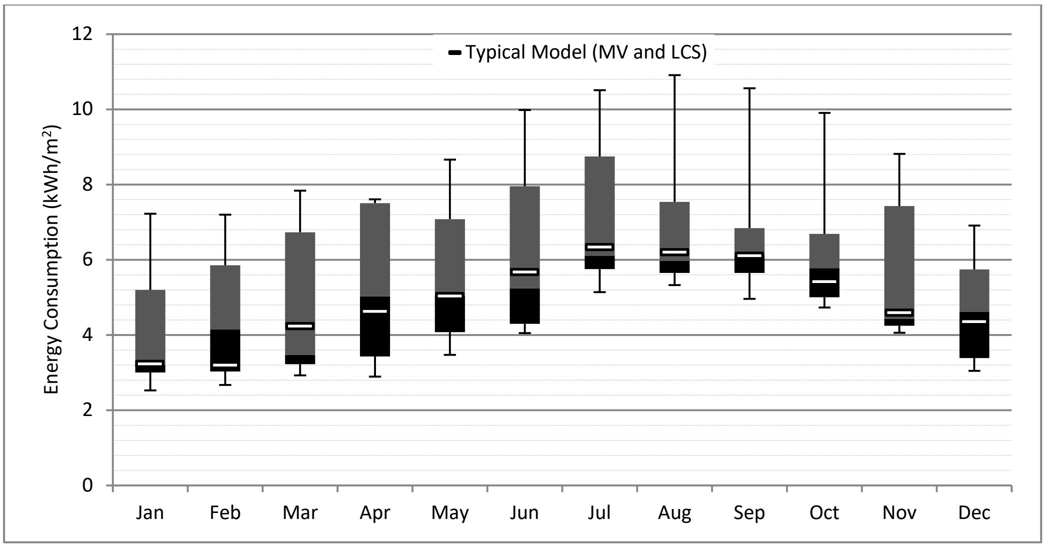


Figure 5-10. Monthly energy consumption for Type 3 offices with Mechanical Ventilation (MV) and Local Cooling System (LCS): survey and typical model results (solid bars are +/- 25 percentiles, lines the range).

The typical model run with mechanical ventilation and a central cooling system (MV & CCS) showed acceptable agreement with the survey data for Type 4 offices (Figure 5-11). The simulated total energy consumption for this type of building was 153kWh/m^2 p.a., of which 30% of the energy was consumed by the cooling system while the ventilation system, Direct Hot Water (DHW), auxiliary energy and facilities consumed about 48%. The lighting and the IT equipment loads consumed about 21% of the total energy used.

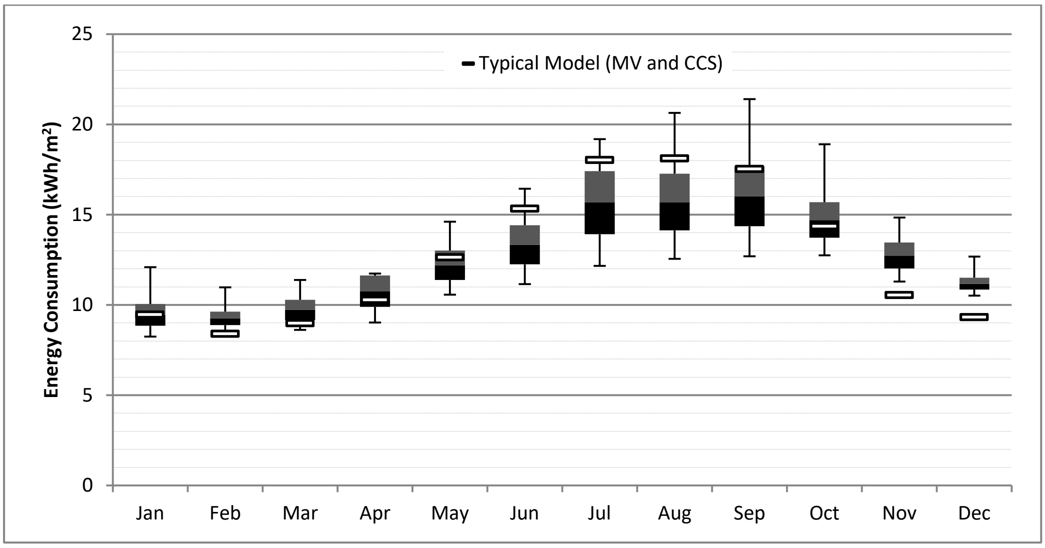


Figure 5-11. Monthly energy consumption for Type 4 offices with Mechanical Ventilation (MV) and Central Cooling System (CCS): survey and typical model results (solid bars are +/- 25 percentiles, lines the range).

Figure 5-12 shows the energy use indices for the four different types of building based on the typical simulation model.

Occupant thermal comfort was tested in the typical model to make sure that it gives results which are similar to those of the calibrated model with respect to the monitored data. The monthly average indoor resultant temperature for occupied hours, based on the typical model was plotted on the PMV/PPD comfort chart. As illustrated in Figure 5-13, the typical model operative temperature shows good matching with the PMV/PPD chart.

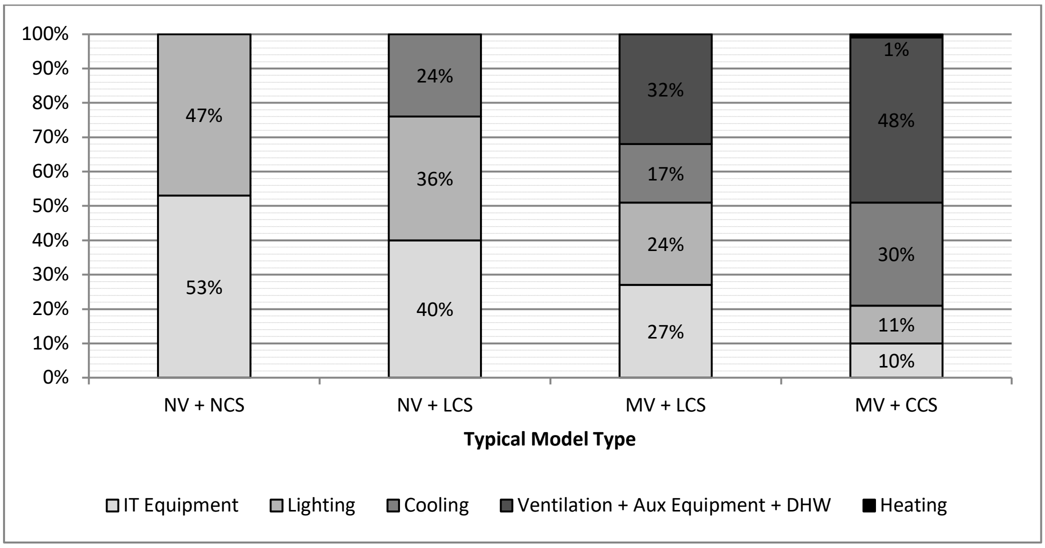


Figure 5-12. Energy Use Indices (EUI) percentage for the four types of building.

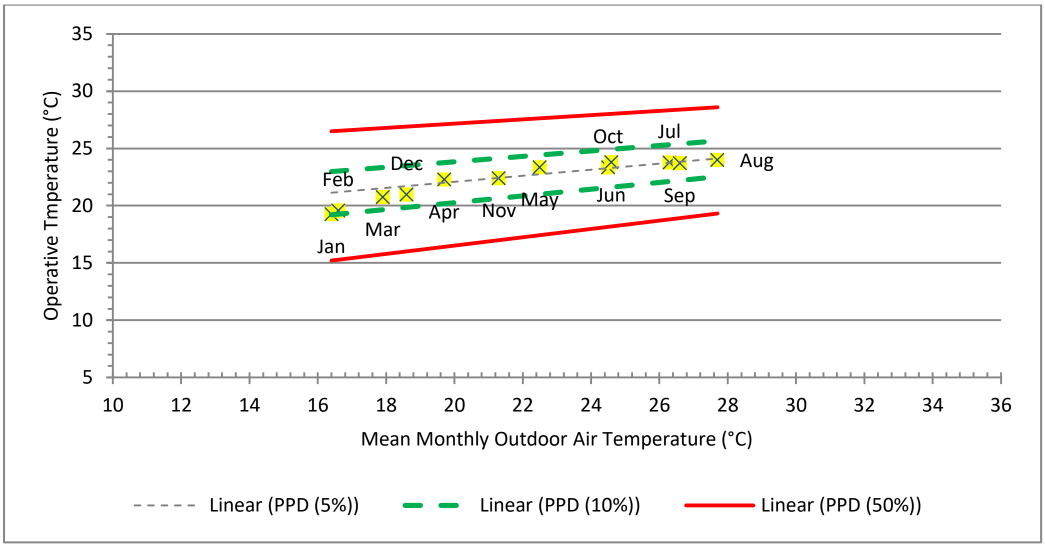


Figure 5-13. Typical model average monthly indoor temperature vs PMV/PPD comfort chart.

This work has shown that the typical model is more representative of the majority of the survey offices of the same type. It also shows good matching with the PMV/PPD comfort chart as did the calibrated model with the monitored data. This typical model will be used in the next step to analyse the variation in the model input parameter ranges which represents the variation in energy consumption found in the office survey data.

5.5 Realistic Model Input Parameter Sets Capturing Likely Variations In Operation And Behaviour

To capture the inherent variability in operation and behaviour, 'best and worst case parameter sets' used in other industries to bracket likely ranges in input parameters were investigated in this section [156]. The ranges previously established by parametric screening were categorized in terms of their positive or negative influence on energy consumption. For zinstance, increasing equipment loads will increase energy consumption while raising the cooling setpoint will reduce it The extremes combine into 'best case' and 'worst case' sets which drive low and high energy consumption, respectively. The ranges were hypothesised to arise from a notional normal distribution of each parameter, with the value of the standard deviation for each distribution assumed to be one-sixth of that parameter's range.

The probability of the occurrence of combinations where all ten parameters are simultaneously at their extreme best or worst case settings is very small. This is unrealistic and too extreme a situation to consider as a likely scenario in modelling. The situation where all ten parameters are simultaneously at +/- 2 standard deviations towards their best or worst case values gives a more realistic spread, as can be seen in Figure 5-14. The range of energy consumption based on +/- 1 standard deviation covers the majority of the survey offices, but there are some cases which are outside this range though covered by the range for the +/- 2 standard deviation case. The +/- 3 standard deviation case shows the hypothetical extremes of energy consumption for this type of building in Egypt, but these extremes are overestimating the actual variation in energy consumption.

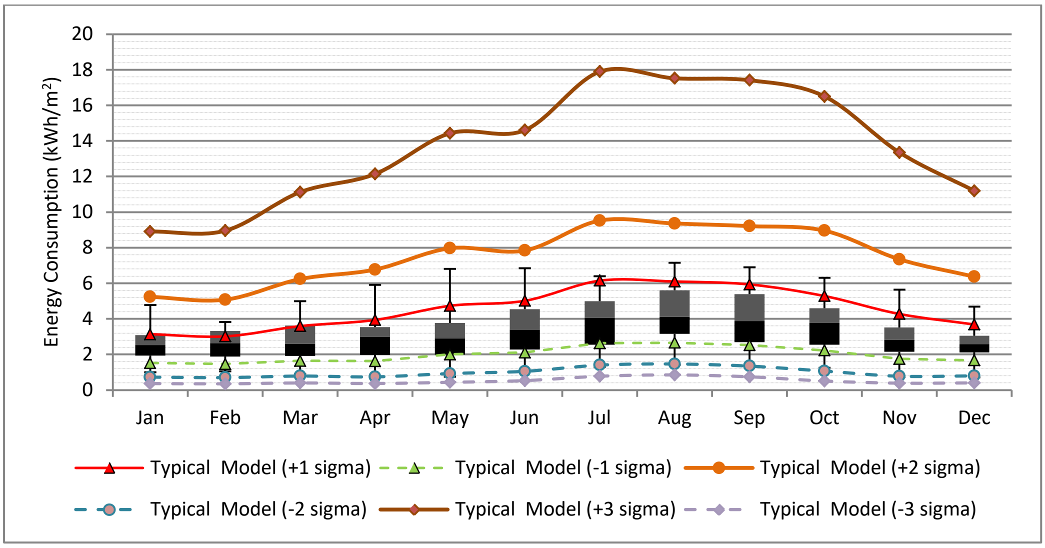


Figure 5-14. Monthly energy consumption for Type 2 offices; survey and typical model results +/- 1,2,3 sigma. (solid bars are +/- 25 percentiles, lines the range).

The worst case parameter sets represent variations in operations and behaviours which are likely to occur. There are obviously other factors, such as weather and building fabric characteristics (e.g. insulation and glazing properties) which cause uncertainties and will have some effect. In the parameter screening exercise the building fabric properties were found to have much smaller effects on energy consumption and IC values than did the worst case parameters (Table 4-2), but this was based on a single case study building. Realistic worst case weather patterns could be readily established.

The worst case model input parameter sets described here give some indication of likely effects of the most influential factors for building performance identified in the screening exercise, and part explain the variation seen in the survey. Of course, the obvious aim would be to minimise the operational energy use through operating in the 'best case' situation. However, realities such as constraints and competing demands for business productivity or improved comfort may not allow this. It is hoped the parameter sets here will allow such situations to be comprehended through modelling.

From the discussion above, the +/- 2 standard deviation case is the most representative for energy consumption in this type of office building in Egypt, and will be used to apply a detailed performance analysis study. In the next chapter, performance analysis for Type 2 Egyptian offices will be applied by classifying the input variables into six groups to study the effect of each group on both the energy consumption and the indoor environmental quality.

5.6 Parametric Input For Uncertainty Propagation In Building Envelope

The previous chapters suggested that building envelope parameters had only a relatively small influence on energy performance. In this section, a further parametric analysis is carried out to gain some insights which further the understanding of this result.

Further parametric analyzes have been conducted for building envelope parameters for the typical Type 2 office building, across typical ranges of values. The following variables have been analyzed:

- External wall construction.
- Roof construction.
- Glazing U and G-solar values.

Each of these variables was investigated for the building oriented in 8 different directions.

5.6.1 External Wall Construction

Two parameters were investigated: (i) U-value, and (ii) thermal mass.

Firstly, to study the effect of the external wall U-value with different building orientations, four wall types with a range of U-values were examined. The wall construction (Figure 5-15) was the same in each case, consisting of cement render (50mm) on the outside, insulation, common brick (120mm), with cement plaster (30mm) on the inside. The thickness of the insulation material was varied (5.6, 18.3, 43.6, and 119.5mm) changing the overall wall U-value across the different cases.

Then to study the effect of the external wall thermal mass three types of construction were examined with different thermal mass but with the same U-value. In this case, the insulation location within the construction was changed but the insulation thickness was not changed (Figure 5-16). This resulted in three different values for the thermal mass exposed on the inside of the insulation layer, able to interact with the room air: a heavy thermal mass wall (Kappa value: 290kJ/(m^2.k)), a medium thermal mass wall (Kappa value: 150kJ/(m^2.k)), and a light thermal mass wall (Kappa value: 45kJ/(m^2.k)); all wall versions have the same thermal bridging coefficient of 0.192W/m^2.k.

The effects of the U-value and thermal mass on total energy use are shown in Figure 5-17 and Figure 5-18 respectively. It can be seen that the effects are relatively small, confirming earlier results.

The variation in thermal mass represented by the range of constructions is quite small as even the least massive construction has 3cm of plaster on the inside surface.

In other studies, it is often shown that night ventilation in conjunction with heavy thermal mass can have a beneficial effect on cooling energy use[157]. It is not common to have night ventilation in Egypt due to security concerns, but here increased night ventilation was investigated to illustrate how this might affect performance if building designs were to be changed to support it.

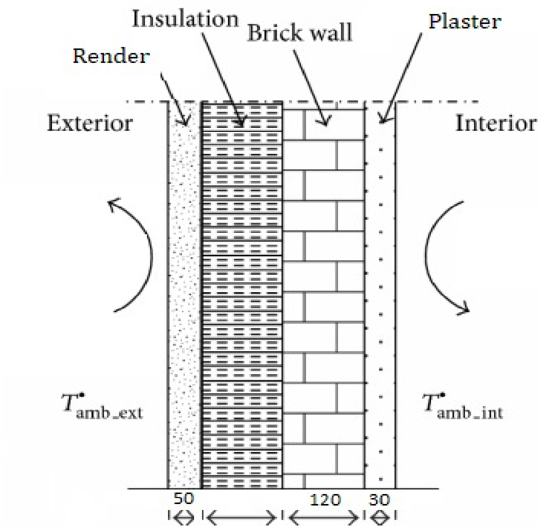
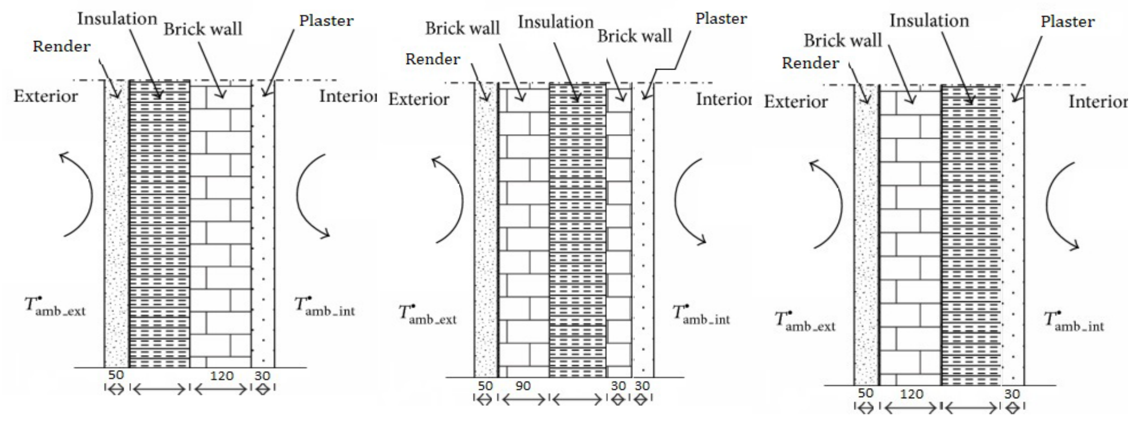


Figure 5-15. External wall composition.



Heavy thermal mass Medium thermal mass Light thermal mass

Figure 5-16. External wall composition with different thermal masses.

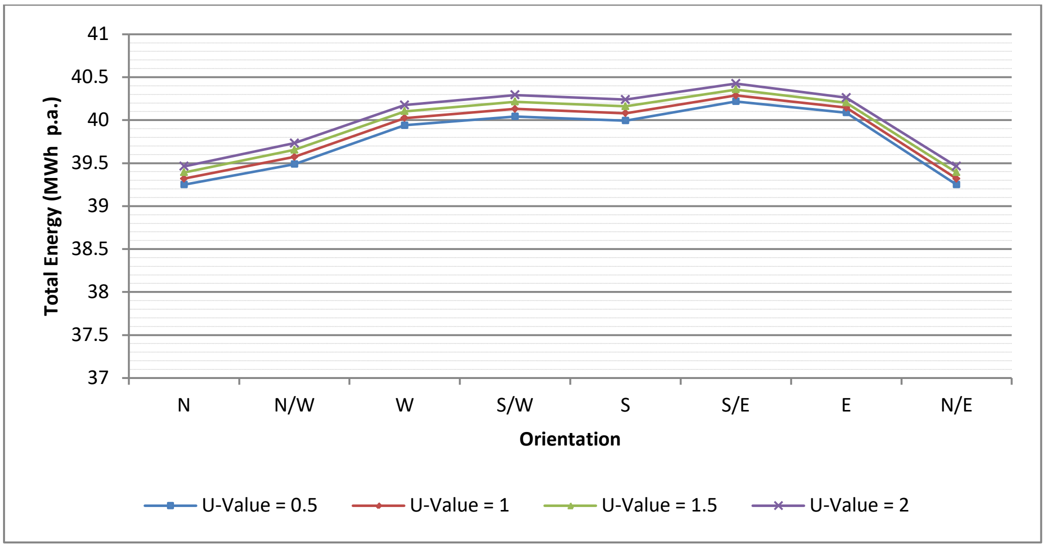


Figure 5-17. Effect of external wall U-value with different building orientation on the total electricity consumption.

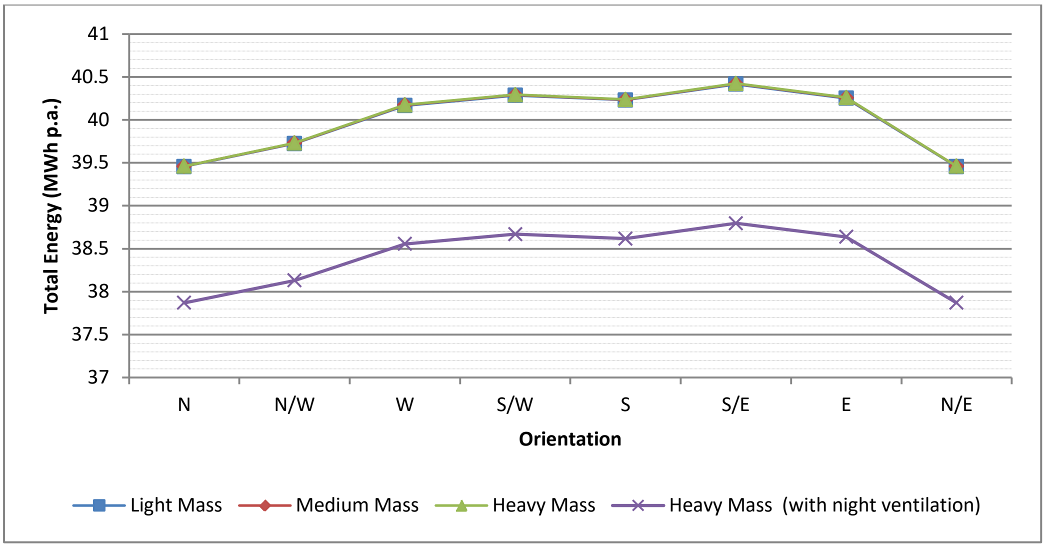


Figure 5-18. The effect of external wall thermal mass, and night ventilation, on total electricity consumption for a range of building orientations.

One case was examined with the heavy thermal mass wall together with night ventilation (25L/s.m^2 during the night from midnight to 6 am, 0.8L/s.m^2 during the daytime). The night ventilation resulted in significant reduction in the energy used as shown in Figure 5-18. However, this ventilation rate would be difficult to achieve in practice so was not pursued further in this work.

Figure 5-17 to Figure 5-20 show the effect of the building orientation. As expected, a north or north-east orientation of the main glazing elements show the lowest energy consumption with a south/east orientation showing the highest energy consumption.

5.6.2 Roof Construction

The effect of changing the U-value of the roof construction (200 mm reinforced concrete with external roof insulation) was examined. The method of changing the roof overall U-value was the same as that used for varying the external wall U-value. The effect of the roof U-value on the energy consumption was sensible as shown in Figure 5-19.

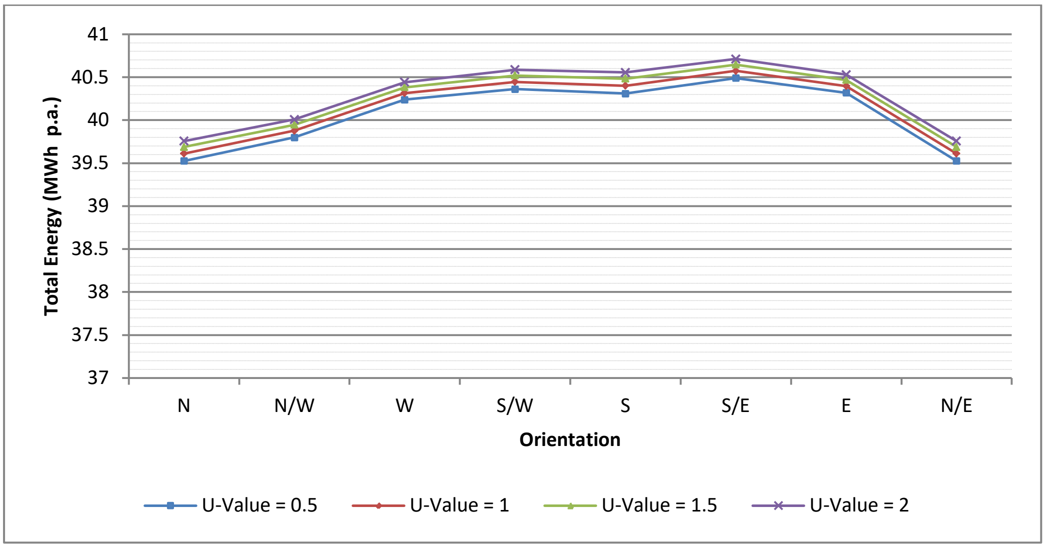


Figure 5-19. Effect of roof U-value with different in building orientation on the total electricity consumption

5.6.3 Window Construction

Finally, the external window specifications were studied; the glazing U-value and the glazing G-solar were examined separately. First, the glazing U-value was changed by changing from single to two variants of double glazing. The glass properties for each layer were adjusted in order to reach the same overall G-solar and Visible Light Transmittance for the different types to allow the effect of U-value to be assessed independently, as shown in Table 5-2. The results are shown in Figure 5-20. During this study the use of the lighting system was not changed in order to study the effect of the glazing U-value only.

Then to study the effect of the glazing G-solar the same type of glazing system was used (single glass) while varying the glass property (glass solar transmittance) which directly changed the glazing G-solar value while other properties were kept constant. The results are shown in Figure 5-21.

Table 5-2 Different glazing unit properties

Glazing Type	**Single Clear 6mm glass**	**Double Clear 3mm glass with 1mm air cavity**	**Double Clear 3mm glass with 3mm air cavity**
Glazing U-value (W/m^2.K)	6	5	4
Glazing G-solar value	0.82	0.82	0.82
Visible light transmittance	0.76	0.76	0.76
Thermal bridging coefficient (W/m^2.K)	0.53	0.45	0.37

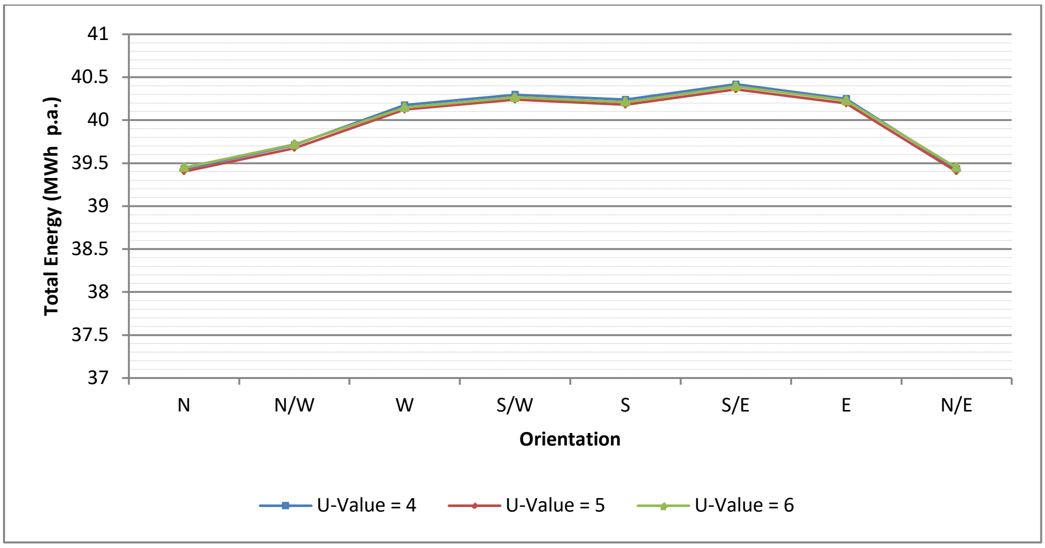


Figure 5-20. Effect of glazing U-value with different building orientation on the total electricity consumption.

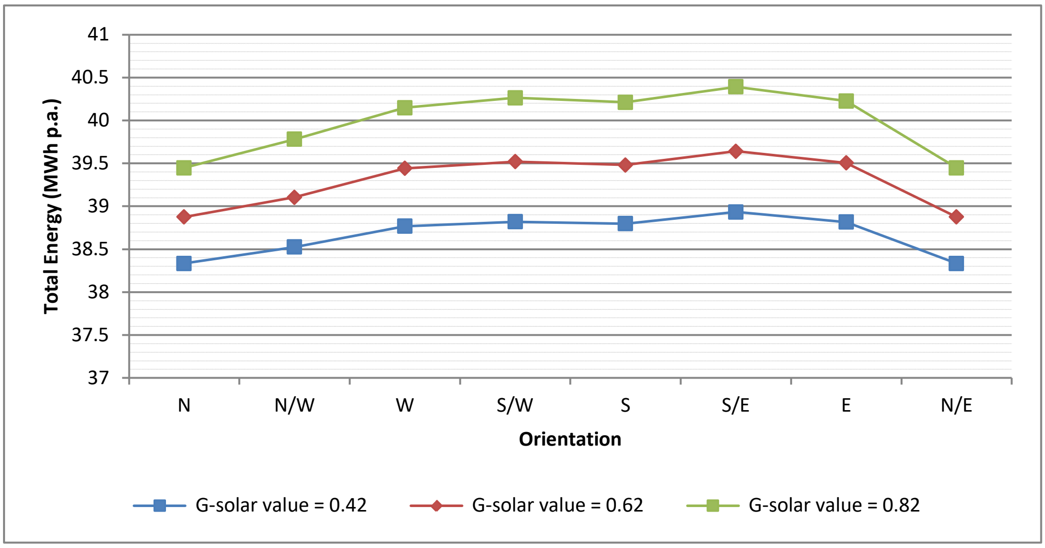


Figure 5-21. Effect of glazing G-solar value with different building orientation on the total electricity consumption.

From this analysis of the building envelope parameters, the window G-solar value has the greatest effect on the energy consumption (around 2.5%) followed by the external wall U-value and the roof U-value. In addition, night ventilation could be useful but was deemed out of the scope of this study due to practical considerations. This study was specific to the geometry of the case study building, which is a very common building type in Egypt. The results will not apply to other building types which would need to be analyzed separately.

5.7 Summary

In this chapter different thermal comfort standards were evaluated to find the most representative model. The PMV/PPD thermal comfort model is the most representative model for the Type 2 building model and the monitoring data. Then the calibrated model created in the previous chapter was shown not to well represent the performance of Type 2 offices recorded by the general office survey. To use the model in future as a foundation for performance analysis, a more typical representative model was required. In this chapter, the calibrated model was generalized based on the range of variation of input parameters to provide a better representation of the general survey.

The typical model results matched more closely the mean of the survey data for Type 2 offices. The typical model was re-run without cooling and the results compared against those for the Type 1 offices in the survey, and this also showed good agreement. The typical model was also re-run by adding mechanical ventilation which caused extra energy use and this again resulted in good agreement with the survey data for Type 3 offices.

To capture the inherent variability in operation and behaviour, ‘best case’ and ‘worst case’ parameter sets (+/- 1, 2 and 3 standard deviations) were used. It was found that from this variation in inputs the range of energy consumption based on +/- 1 standard deviation was representative for the majority of the survey offices but with some cases falling outside this range though still within the +/- 2 standard deviation range.

This would imply that all of the key input parameters were simultaneously at their best and worst case values in the range, which is very unlikely in practice.

Finally, a parametric analysis was applied to each of the most common building envelope parameters to give some insight into the relative impacts on performance. The parameter with the greatest effect on energy consumption was the solar heat gain (G-solar value) of the external windows followed by the roof insulation and the external wall U-value, while the influence of the thermal mass of the external walls was negligible. While these results are interesting and give some insights, they cover only a limited set of the potential performance determinants and do not cover combinatorial effects.

The worst case sets do capture the combinatorial variations but to assess the relative impacts of different individual or groups of parameters a more detailed study is required. In the next chapter, a full factorial analysis is run using the typical model as a base, the intention is to create results which can be useful and inform future policy.

Chapter 6 COMBINATORIAL PARAMETRIC PERFORMANCE ANALYSIS FOR TYPICAL EGYPTIAN TYPE 2 OFFICE BUILDINGS

6.1 Introduction

The preceding chapters described the underpinning modelling framework of a typical model and best and worst case input parameter sets representing existing Type 2 office performance as understood from the data gathered in both the general survey and the detailed case study. The influence of some key variables was identified in the model calibration. A more comprehensive parametric study was then performed to capture the impact of individual or groups of input variables, some of which had been trreated as fixed in the calibration process, and also to investigate parameters associated with occupant behaviour in more detail.

In this chapter, a parametric sensitivity study will be described, dividing the inputs into six main groups, and then running a full factorial analysis of the parameter combinations using the typical model of a Type 2 office as a base model to apply performance analysis looking at both IEQ and energy performance outputs. The outputs of this sensitivity study and performance analysis are then be used in Chapter 7 to determine the policy directions for existing Type 2 offices and to make some informed proposals on how such policy decision should be approached for other building types.

6.2 Input Parameters For Energy And IEQ Parametric Sensitivity Study.

To allow the many individual input parameters to be analyzed and results displayed in a readily comprehensible manner, an initial step was to group input parameters into six categories. As illustrated in Figure 6-1, these categories are: (i) Location e.g. climate zone within the Egypt, (ii) Weather e.g. warm, cool or typical, (iii) Building envelope, e.g. building construction, thermal standards, (iv) Installed systems, e.g. equipment lights and HVAC, (v) Behaviours in terms of required thermal comfort standards and diligence in switching off equipment when not in use, (vi) Intensity of occupancy in terms of occupant density and number. Probable ranges were then established for input parameters in each of the categories to allow single and combinatorial parametric studies to be carried out in order to explore their influence on performance.

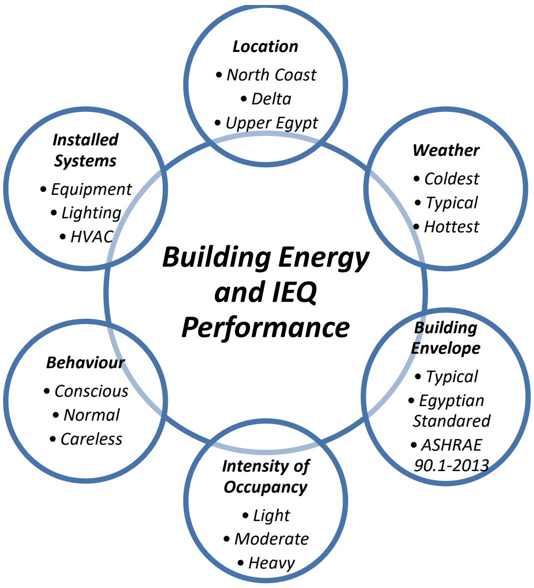


Figure 6-1. Categories for the main drivers of building energy and IEQ performance.

6.2.1 Location

The Egyptian Code for Energy (ECP 306-2005) classifies Egypt into eight regions based on weather [4, 105] as shown in Figure 6-2. . Some of these regions are not populated, for example, the eastern desert and western desert regions. Other regions are border areas, such as part of Sinai and the south of Egypt and are not highly populated. There are some regions that are tourist destinations, such as a large part of Sinai and the coast of Egypt face the Red Sea, and these regions are divided into compounds and resorts with particular characteristics. The three locations which have the highest populations were selected for this study, i.e. Alexandria City (northern coast zone), Cairo City (Cairo and Delta zone), and Asyut City (boundary between northern and southern Upper Egypt zones) (Figure 6-3, Figure 6-4).

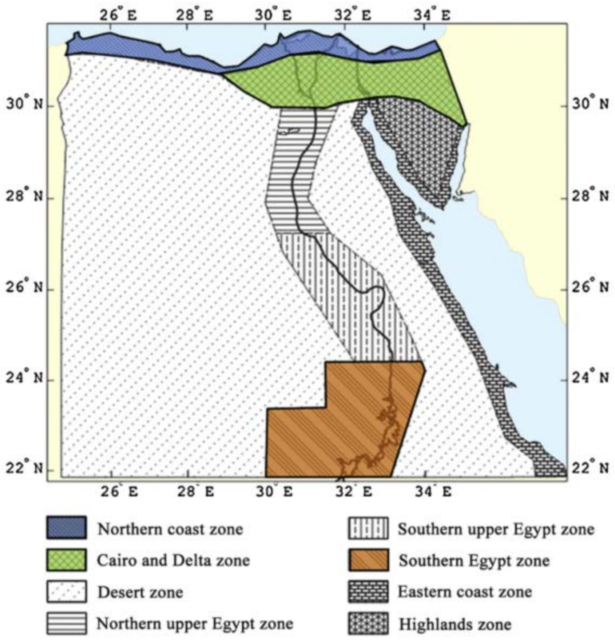


Figure 6-2. Egyptian main regions based on weather conditions described in the Egyptian code for energy [105].

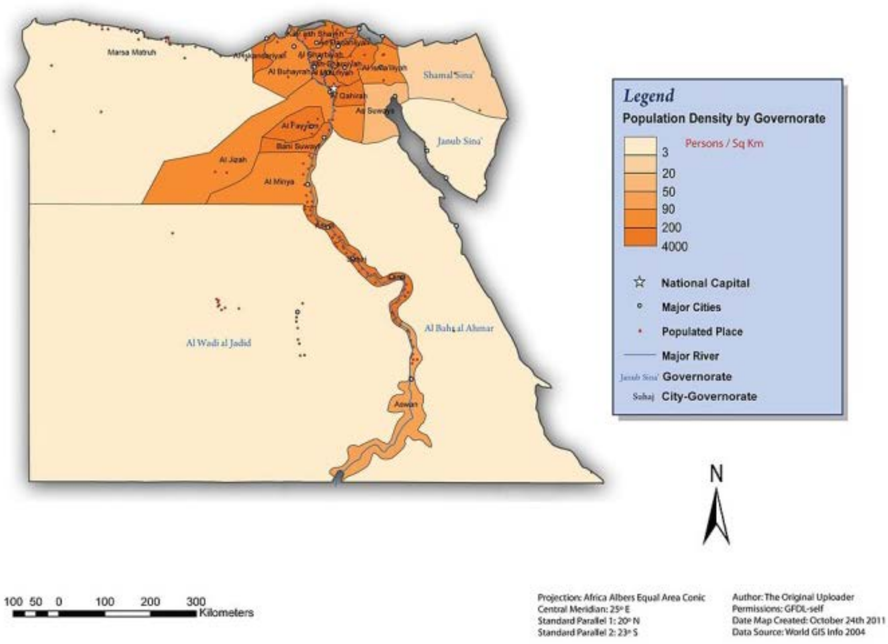


Figure 6-3 Egypt population map [158].

6.2.2 Weather

Energy and environmental performance studies based on a single selected 'typical' weather year, while they may provide useful insights, do not provide any information about how performance will vary as weather conditions inevitably deviate from those on which studies were based. Much research has been applied to study the variation of the weather data file and appropriate methods for capturing this in simulation input files. Several studies have proposed using multi-year weather data to synthesise a 'standard' weather file [159-161]. More recent studies found limitations in this approach, e.g. concerning overheating calculations leading to the generation of design weather files [162-164]. Crawley and Lawrie [13] developed extreme meteorological year (XMY) weather files to represent the extremes of the climate that the building will experience. The available data in Egypt was not sufficient to develop XMY weather files based on this method.

The weather file used in the present study was generated using the following procedures: (i) firstly available weather files for the last 15 years were collected, (ii) for each calendar month the average maximum and minimum dry-bulb temperatures were used to select the extremes of weather from the dataset, (iii) the weather for the identified extremes for each calendar month was then used to construct the hottest weather file based on the 12 highest extreme months and the coldest weather file based on the 12 at the lower extreme. Some manual smoothing was applied to transitions between months. These hottest and coldest years are two extreme years which cover the range of the weather. Due to the limited data available, this method has limitations and should be revised when more data becomes available. However it was chosen as a reasonable representation of the likely weather extremes. Figure 6-4 shows a graph for the two extreme weather files for Alexandria.

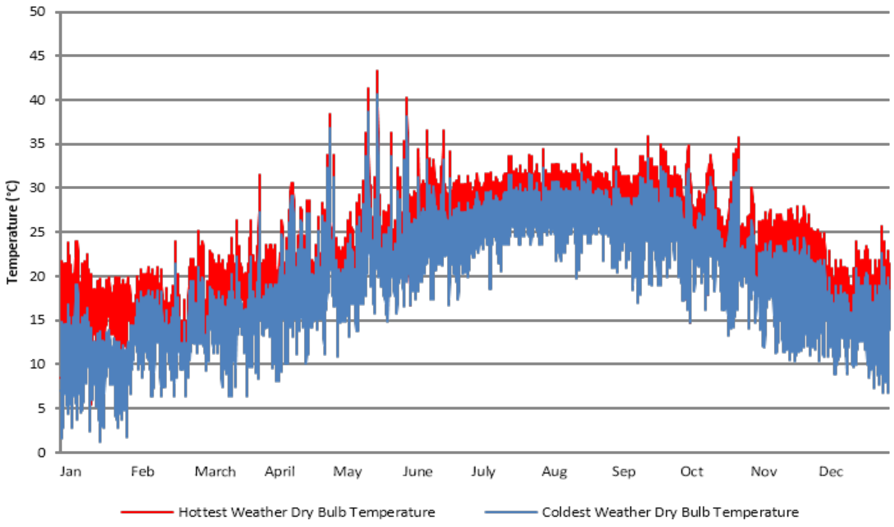


Figure 6-4. Dry-bulb temperature for hottest and coldest weather files for Alexandria.

6.2.3 Building Envelope

The building envelope transfers heat from and to the surrounding environment. Some studies have investigated the effect of the building envelope on the cooling and heating loads [96, 99, 105]. Based on these studies and the parametric sensitivity analysis during the calibration for the monitored office, four parameters were chosen to be varied: external roof U-value [95], external wall U-value [105], external windows U-value, and G-solar [155]. The levels set for these parameters are shown in Table 6-1. They have been aligned with the 'typical' (Type 2) model. Egyptian code (ECP306/2005), ASHRAE 2010 and ASHRAE 90.1-2013 parameter values are also shown in Table 6-1 as a further reference point.

Table 6-1. Building envelope categories.

Variable	Typical	EGYPTAIN CODE (ECP 2005)	ASHRAE 90.1-2010	ASHRAE 90.1-2013
Roof U-Value (W/m^2.K)	0.4	Alex 0.454 Cairo 0.454 Asyut 0.3125	0.28	0.22
External Wall U-Value (W/m^2.K)	2.35	Alexandria 1.11 Cairo 0.714 Asyut 0.588	0.85	0.85
External Glazing U-Value (W/m^2.K)	6	5	4.250	3.69
External Glazing G-SOLAR VALUE (%)	0.82	0.3	0.25	0.25

6.2.4 Installed Loads And Systems

Installed system efficiencies are one of the key drivers for energy use and comfort in offices. Technological advances have allowed for higher efficiency equipment, at the same time working practices are demanding more use of digital equipment. Office installed plug loads and lighting densities are considered to vary based on both installed density and installed system efficiency. The ranges considered in the parametric study are set at the +/- 2 standard deviation extremes based on the earlier review (Table 4-2, Table 6-2).

Similarly, the efficiency of the HVAC systems has a fundamental impact on the energy performance. For the Type 2 offices, the SEER of the cooling system has an effect in combination with the pattern of use associated with the cooling system. SEER values of 3, 3.5 and 4 were selected to represent the current range of low cost unitary and split systems (Table 6-2).

Table 6-2. Installed systems efficiency categories.

Variable	High Efficiency	Typical	Low Efficiency
Equipment Load Density (W/m^2)	8.9	14.8	20.6
Lighting Load Density (W/m^2)	6	10	14
SEER (W/W)	4	3.5	3

6.2.5 Intensity Of Occupation

In office buildings intensity of occupation varies according to the nature of the work in the offices. Some offices are continuously fully occupied with heavy computer and equipment use, lights on and the cooling system required to be constantly on while others are occupied only for a small part of the work time, have low computer use, and lights and cooling only applied during part of the occupied times. Ranges in diversity factors were applied to represent the intensity of occupation (Table 6-3). The cooling usage factor is represented by the diversity factor multiplied by the percentage of the total internal floor area covered by cooling (many office buildings have local cooling in office spaces but no cooling systems implemented in corridors, stairs, and WCs).

Table 6-3. Catagories of intensity of occupancy.

Variable	Light	Typical	Heavy
Equipment D.F.	0.3	0.6	0.9
Lighting D.F.	0.3	0.6	0.9
Occupancy D.F.	0.3	0.6	0.9
Cooling Usage Factor	0.3	0.45	0.75

6.2.6 Behaviour

Most of the current energy performance calculation methods focus primarily on building characteristics delivering a theoretical energy consumption for a standard user. However actual energy consumption may differ greatly from this predicted theoretical consumption [165]. Occupant behaviour in buildings has multiple aspects including the desire for comfortable surroundings and interactions with building systems to restore comfort if needs are not met. Some occupants may be careless in their use of building systems leading to higher energy use, others may be conscious of the need to reduce energy and how to interact with the building to achieve this. Some occupants may be restricted in their use of adaptive opportunities by physical or cultural constraints. To capture the likely variation in occupant behaviour three scenarios were used (energy conscious behaviour, normal behaviour, energy careless behaviour) as described in Table 6-4 [86]. Seasonal adaption in clothing levels as outlined in the model calibration process was not varied between the scenarios but is discussed later.

6.3 Combinatorial Parametric Performance Analysis

A full factorial of the 729 parameter level combinations was then run using the typical model as a base. Figure 6-6 to Figure 6-15 show various snapshots for the Alexandria location. The y-axis represents outputs: total energy use (Figure 6-6 to Figure 6-11), average thermal comfort, summer and winter, (Figure 6-12 and Figure 6-13), average CO_2 concentrations during occupied hours, summer and winter

(Figure 6-14 and Figure 6-15). The vertical range within the box-plot represents the intensity of occupation. Other input variables are indicated along the x-axes. The results for energy use are also summarised in Table 6-5 for Alexandria, Table 6-6 for Cairo, and Table 6-7 for Asyut.

Table 6-4. Categories of behavior.

Occupant Behaviour		Conscious Behaviour	Normal Behaviour	Careless Behaviour
Cooling Setpoint (°C)		25	22	19
Heating Setpoint (°C)		No Heating System	No Heating System	No Heating System
Occupant Control: Lights and Equipment		If occupied: 20% dimming of lights in summer days. If unoccupied: IT, equipment, lights, and cooling off.	If unoccupied: 10% of IT, Equipment and Lights on.	If unoccupied: 20% of IT, Equipment and Lights on.
HVAC Operation Period		April to November	January to December	January to December
External Window Opening – office areas	Summer	If unoccupied, windows closed. If occupied, windows closed while A/C ON	If unoccupied, windows closed. If occupied, windows closed while A/C ON	If unoccupied, windows closed. If occupied, 20 % of windows open while A/C ON
	Winter	If unoccupied, or AC ON: windows closed. If occupied and AC OFF: 20 % of windows open when room T > 20 and outside T < 21	If unoccupied, or AC ON: windows closed. If occupied and AC OFF: 20 % of windows open when room T > 20 and outside T < 21	If unoccupied, or AC ON: windows closed. If occupied and AC OFF: 20 % of windows open when room T > 20 and outside T < 21
Service Window Opening (WCs)		10% open.	10% open	10% open
Background Infiltration (envelope+ operations)	Envelope	0.3 L/S/m^2	0.3 L/S/m^2	0.3 L/S/m^2
	Operation	0.2L/S/m^2	0.5L/S/m^2	0. L/S/m^2

Table 6-5. Categories of behavior.

Occupant Behaviour		Conscious Behaviour	Normal Behaviour	Careless Behaviour
Cooling Setpoint (°C)		25	22	19
Heating Setpoint (°C)		No Heating System	No Heating System	No Heating System
Occupant Control: Lights and Equipment		If occupied: 20% dimming of lights in summer days. If unoccupied: IT, equipment, lights, and cooling off.	If unoccupied: 10% of IT, Equipment and Lights on.	If unoccupied: 20% of IT, Equipment and Lights on.
HVAC Operation Period		April to November	January to December	January to December
External Window Opening – office areas	Summer	If unoccupied, windows closed. If occupied, windows closed while A/C ON	If unoccupied, windows closed. If occupied, windows closed while A/C ON	If unoccupied, windows closed. If occupied, 20 % of windows open while A/C ON
	Winter	If unoccupied, or AC ON: windows closed. If occupied and AC OFF: 20 % of windows open when room T > 20 and outside T < 21	If unoccupied, or AC ON: windows closed. If occupied and AC OFF: 20 % of windows open when room T > 20 and outside T < 21	If unoccupied, or AC ON: windows closed. If occupied and AC OFF: 20 % of windows open when room T > 20 and outside T < 21
Service Window Opening (WCs)		10% open.	10% open	10% open
Background Infiltration (envelope+ operations)	Envelope	0.3 L/S/m^2	0.3 L/S/m^2	0.3 L/S/m^2
	Operation	0.2L/S/m^2	0.5L/S/m^2	0. L/S/m^2

Figure 6-5 is a diagram explaining the output graphs. Figure 6-6 and Figure 6-8 show energy consumption outputs for the coldest and hottest weather with the typical building envelope for various combinations of system efficiencies and behaviours. The typical case combination (normal behaviour and medium efficiency systems) shows the variation in performance as a result of the weather change (e.g. 38.7 to 42.8kWh/m^2 p.a. for average intensity of operations). On the other hand, Figure 6-9 illustrates a relatively smaller effect of weather on energy use.

Figure 6-7 shows energy consumption outputs for typical weather and building envelope for various combinations of system efficiencies and behaviours. The best case combination (energy conscious behaviour and high efficiency systems) shows the best performance (e.g. 19.2kWh/m^2 p.a. for average intensity of operations). While the worst case combination (careless behaviour and low-efficiency systems) shows the worst performance (e.g. 76.6kWh/m^2 p.a. for average intensity of operations). For average intensity of operations these two factors (efficiency of installed systems and behaviours) can account for around a four-fold difference in energy use.

Figure 6-12 and Figure 6-13 show summer and winter average PPD during occupied periods. PPD was calculated based on summer clothing level 0.7 and winter clothing level 1.0 with an assumed metabolic rate of 1.2 met and local air speed 0.15m/s. PPD levels show poorer predicted thermal comfort for both the energy conscious and energy careless behaviour cases for 'slightly warm' PMV reasons in summer and 'slightly cool' reasons in winter.

Figure 6-14 and Figure 6-15 show summer and winter CO_2 levels respectively. The main effect seen here is due to the different window opening behaviours affecting overall ventilation rates. This highlights the potential conflict between indoor air quality and energy use in buildings, which will be discussed further later. All of the average values fall within the range seen in the building survey and within the documented 'acceptable' CO_2 range for existing buildings [84].

Figure 6-16 and Figure 6-17 show the same pattern of energy consumption profile as Alexandria for the two other locations, Cairo and Asyut, with outputs for typical weather and building envelope with various combinations of system efficiencies and behaviours. Additional performance analysis graphs for the three locations (Alexandria, Cairo, and Asyut) are given in Appendix A.1.

Figure 6-18 shows the energy use across the full range of input parameters in the form of energy use indices. Similar to weather, the location has a relatively small effect on the overall variation.

Other HVAC arrangements were also modelled by modifying the typical Type 2 model. Type 1 was modelled by eliminating the cooling systems. Central mechanical ventilation with and without central cooling were applied to represent Type 3 and Type 4 respectively. For the Type 4 case, the whole floor area of the office building was conditioned during occupied hours (i.e. cooling usage factor = 1).

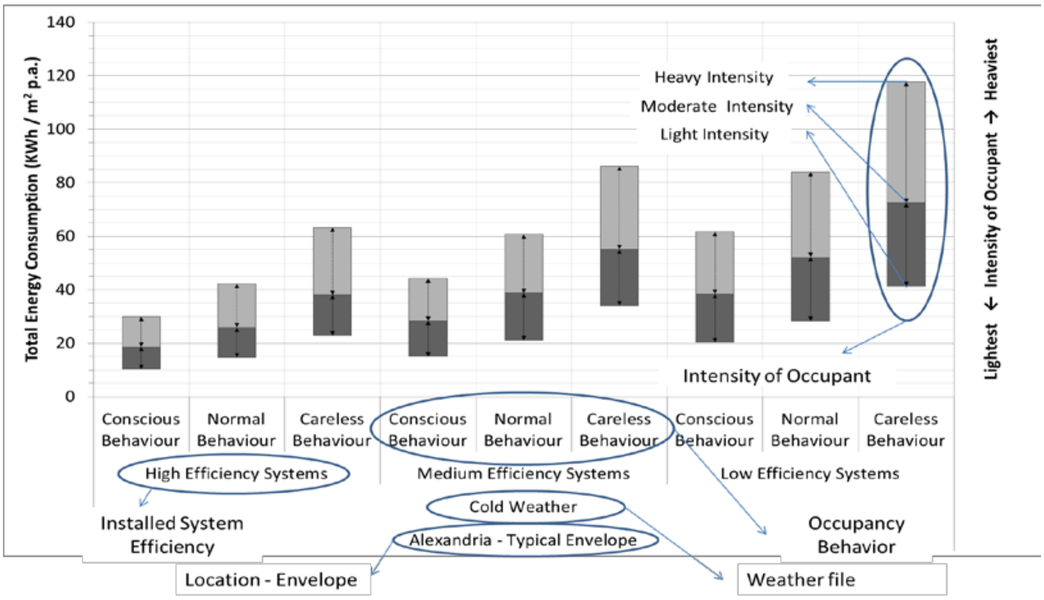


Figure 6-5. Diagram explaining the performance graphs.

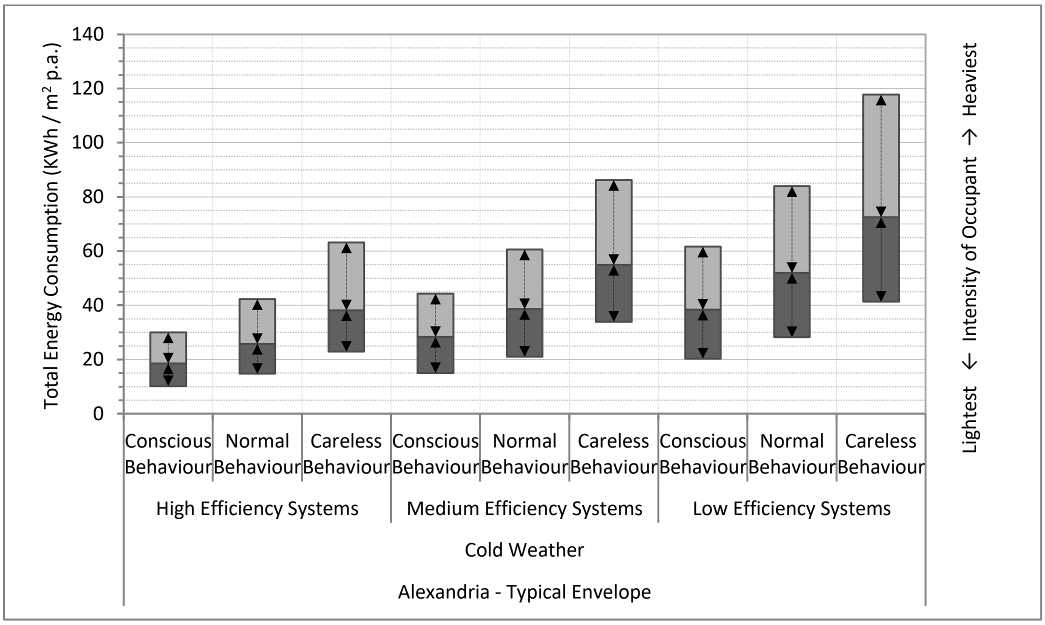


Figure 6-6. Total annual energy consumption per unit area for Alexandria (typical construction, coldest weather).

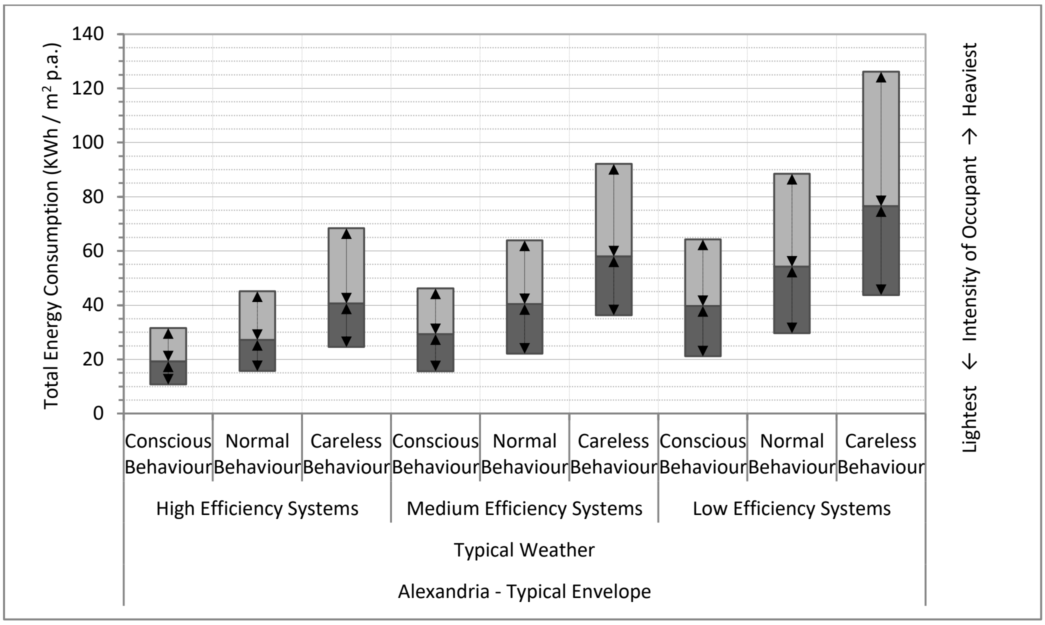


Figure 6-7. Total annual energy consumption per unit area for Alexandria (typical construction, typical weather).

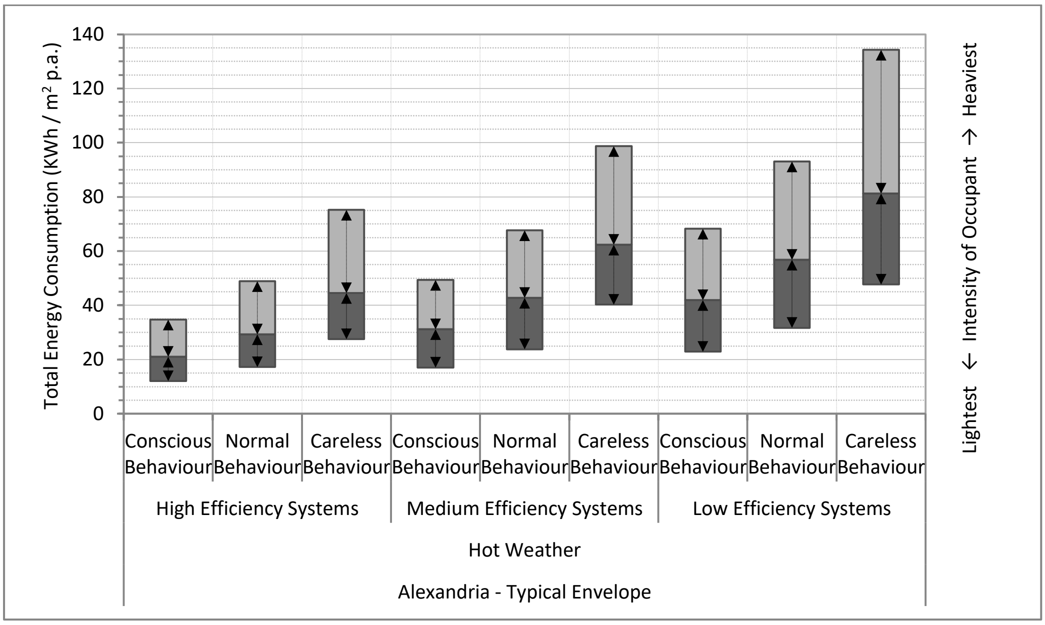


Figure 6-8. Total annual energy consumption per unit area for Alexandria (typical construction, hottest weather).

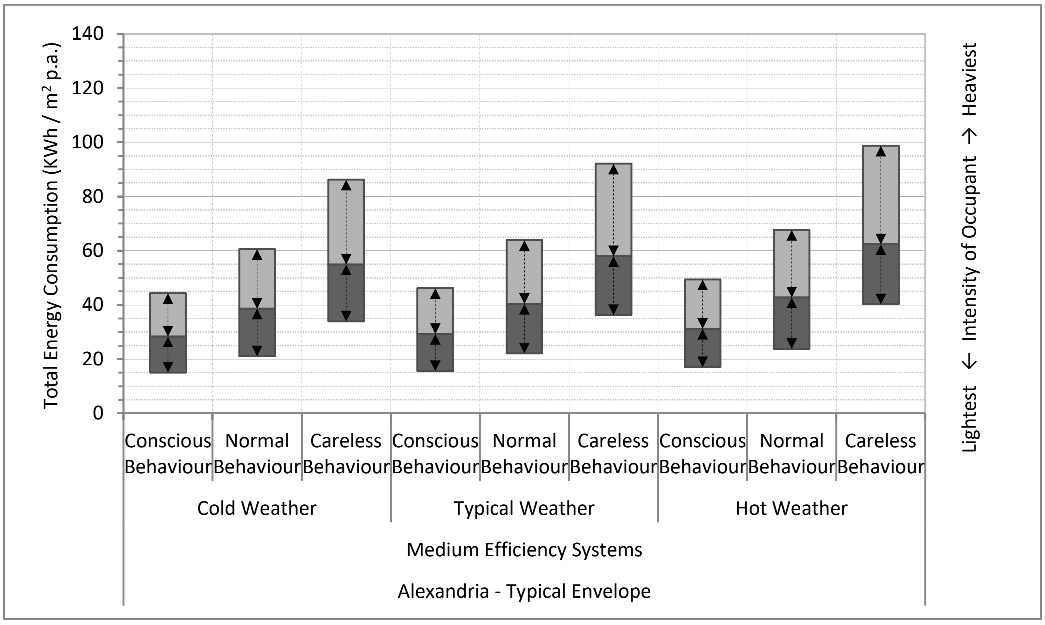


Figure 6-9. Total annual energy consumption per unit area for Alexandria (typical construction, medium efficiencies).

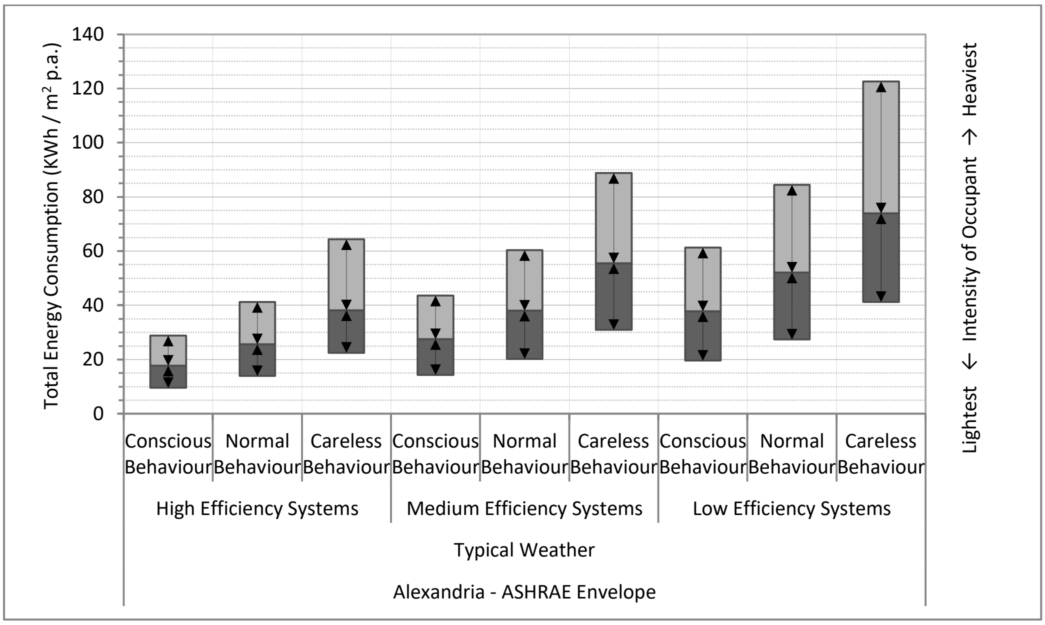


Figure 6-10. Total annual energy consumption per unit area for Alexandria (ASHRAE construction, typical weather).

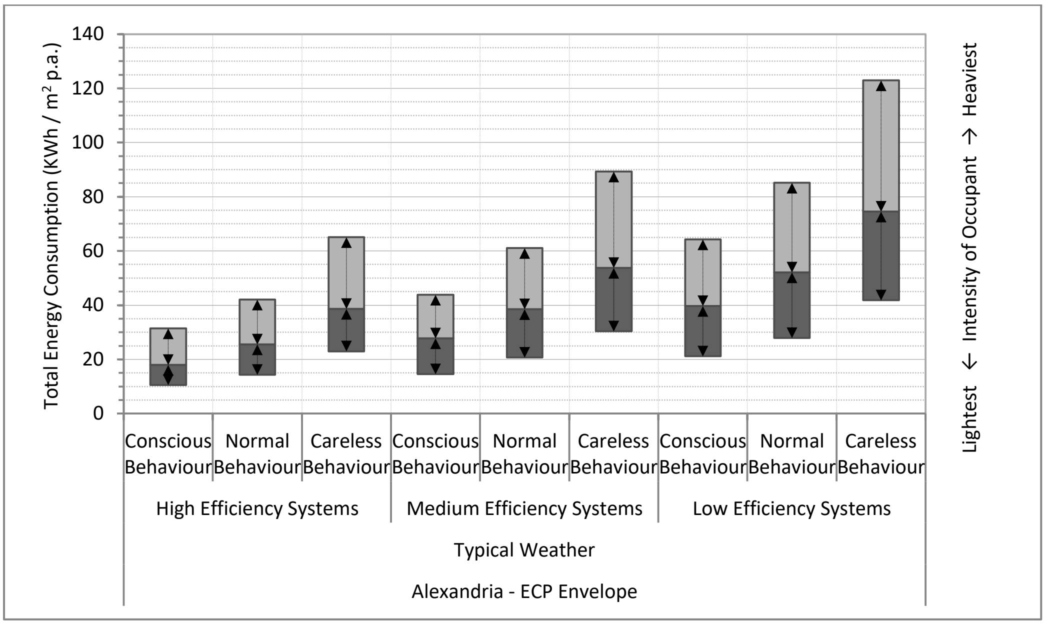


Figure 6-11. Total annual energy consumption per unit area for Alexandria (ECP construction, Typical weather).

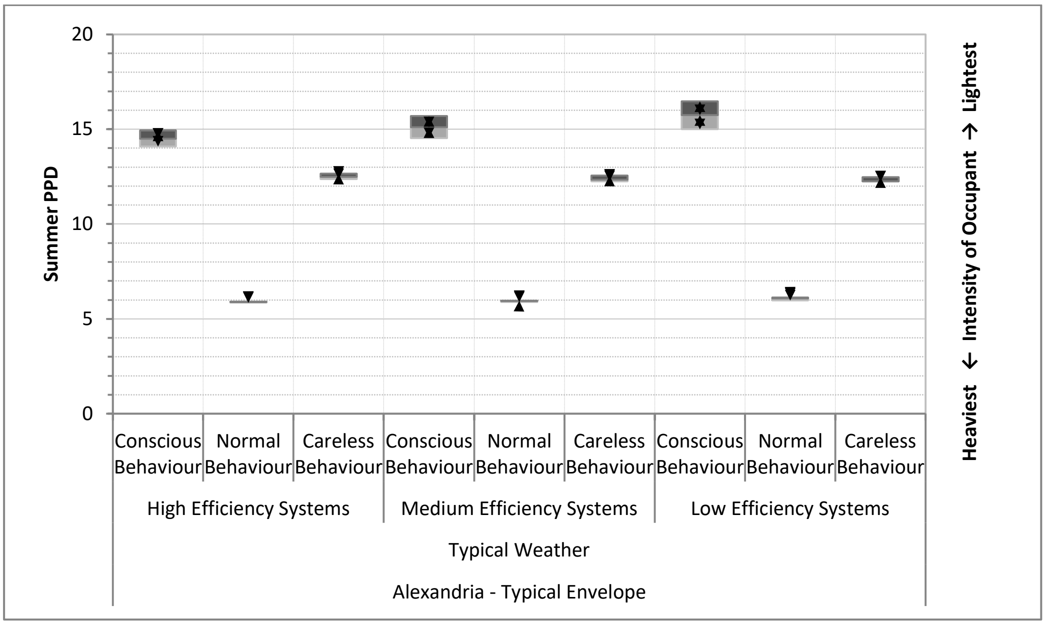


Figure 6-12. Summer PPD for Alexandria (Typical construction, Typical weather).

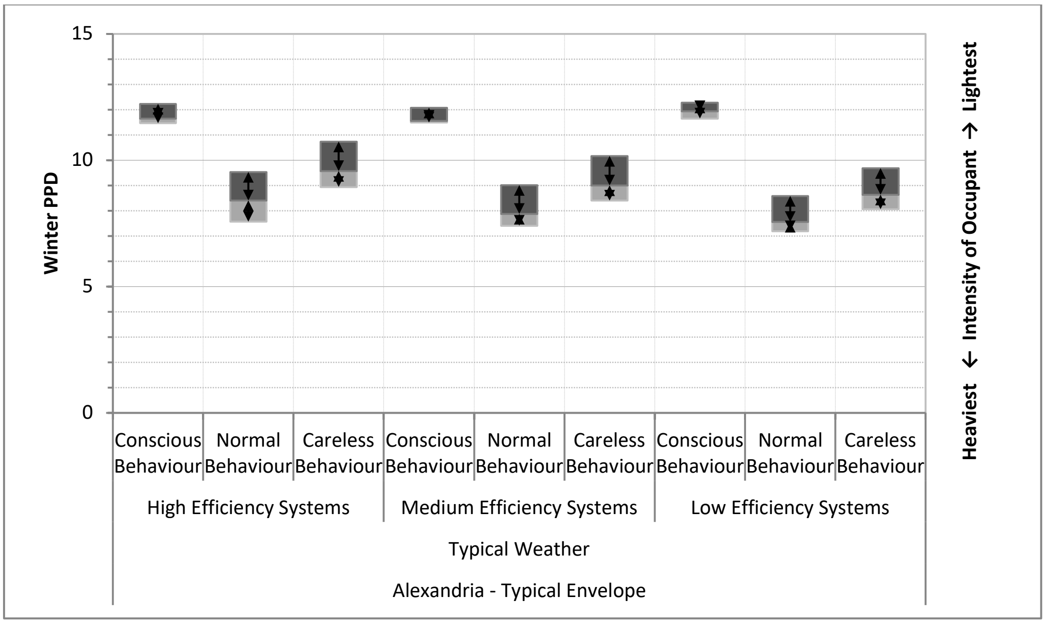


Figure 6-13. Summer PPD for alexandria (typical construction, typical weather).

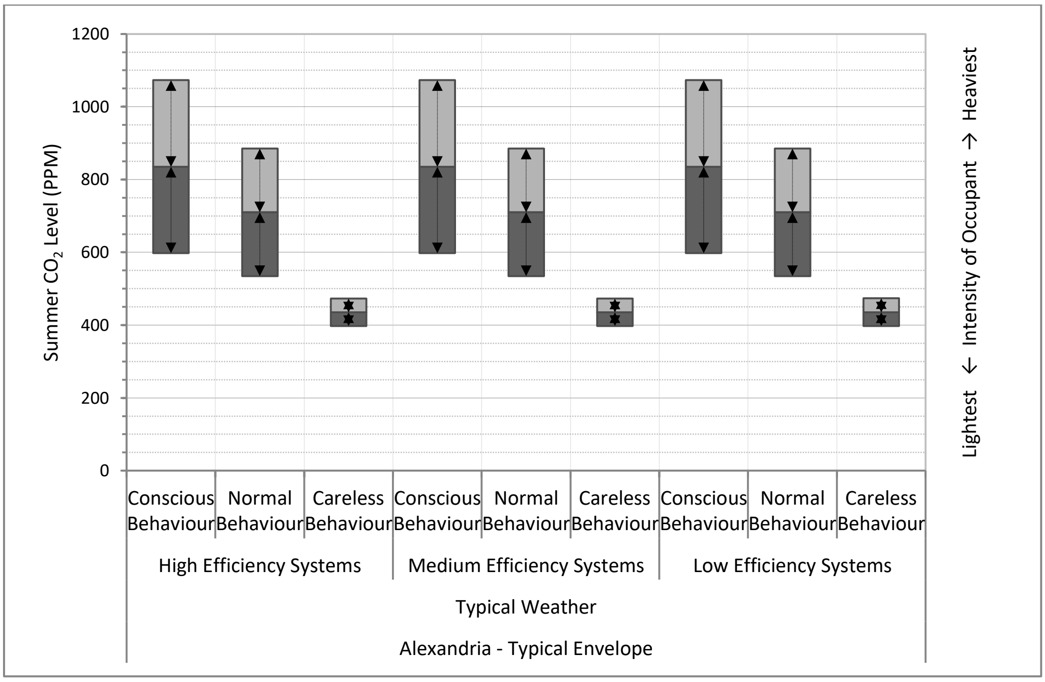


Figure 6-14. Summer CO_2 level for Alexandria (typical construction, typical weather).

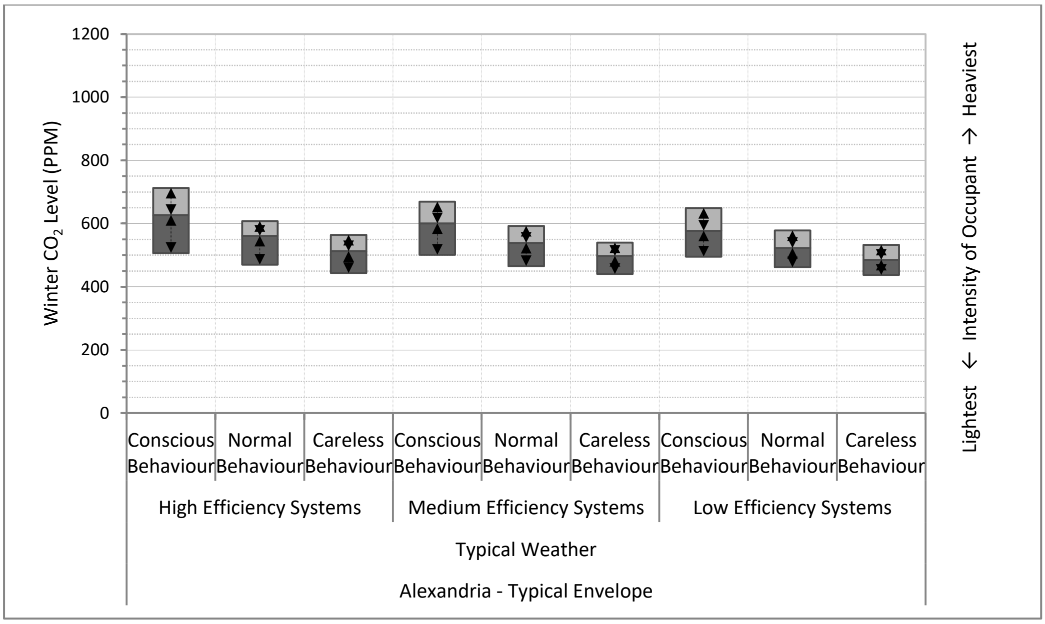


Figure 6-15. Winter CO_2 level for Alexandria (Typical construction, Typical weather).

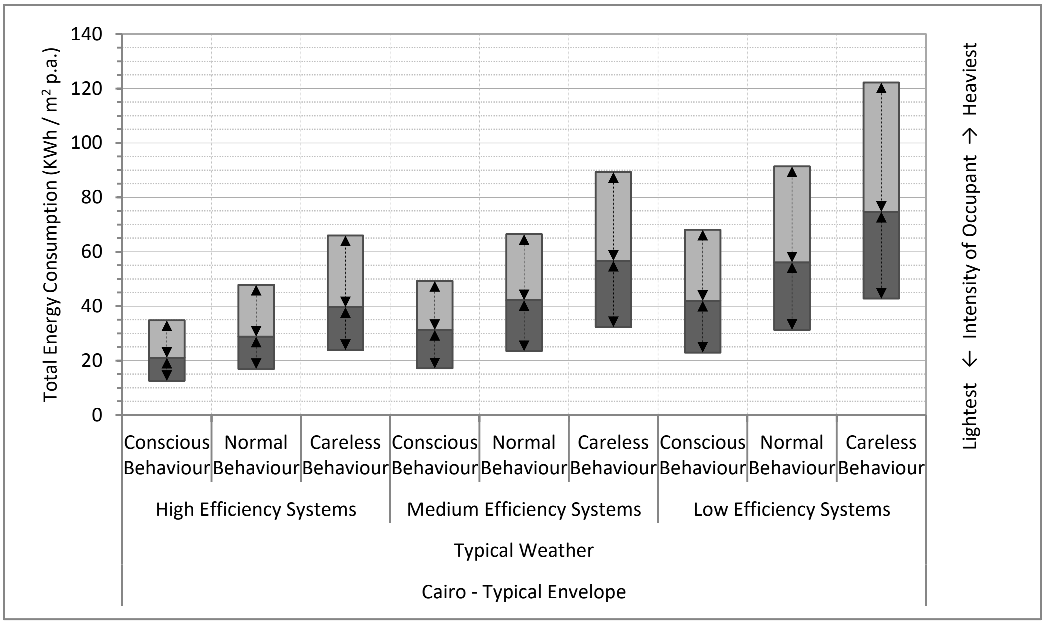


Figure 6-16. Total annual energy consumption per unit area for Cairo (Typical construction, Typical weather).

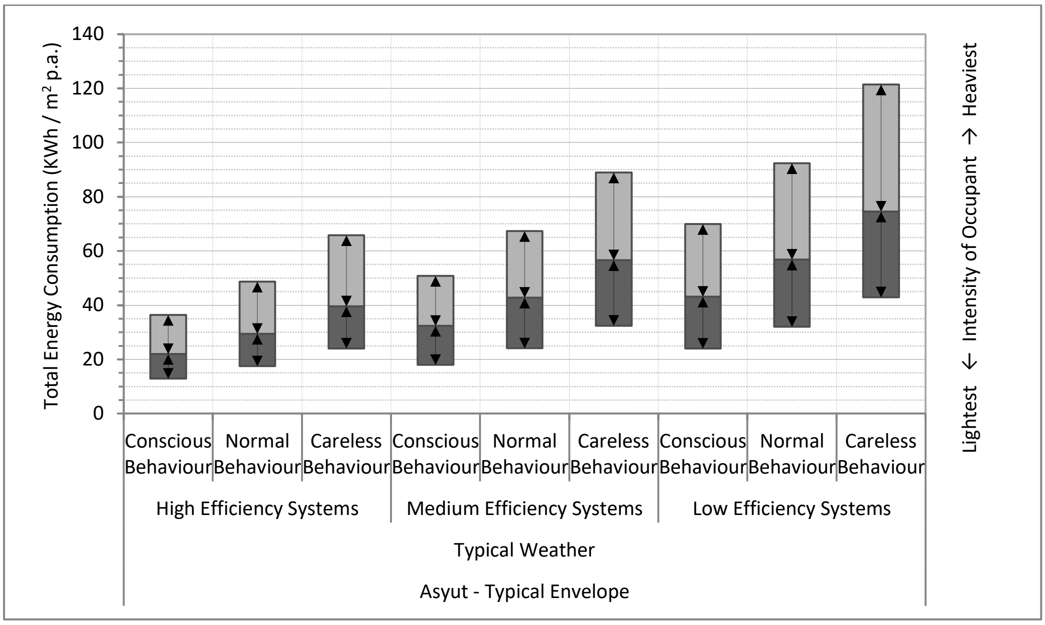


Figure 6-17. Total annual energy consumption per unit area for asyut (Typical construction, typical weather).

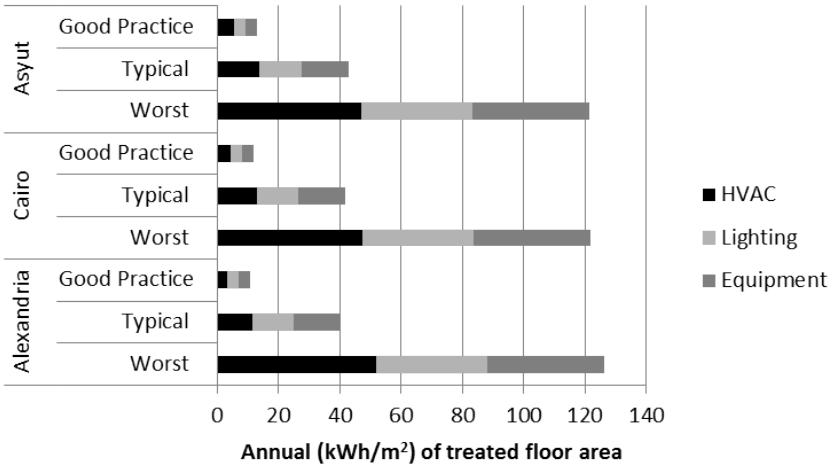


Figure 6-18. Energy use indices (EUIS) for best, typical, and worst combinations for the three locations, office Type 2.

To provide a useful overview, the results were then aggregated into a set of single base multivariate charts such as that shown in Figure 6-19.

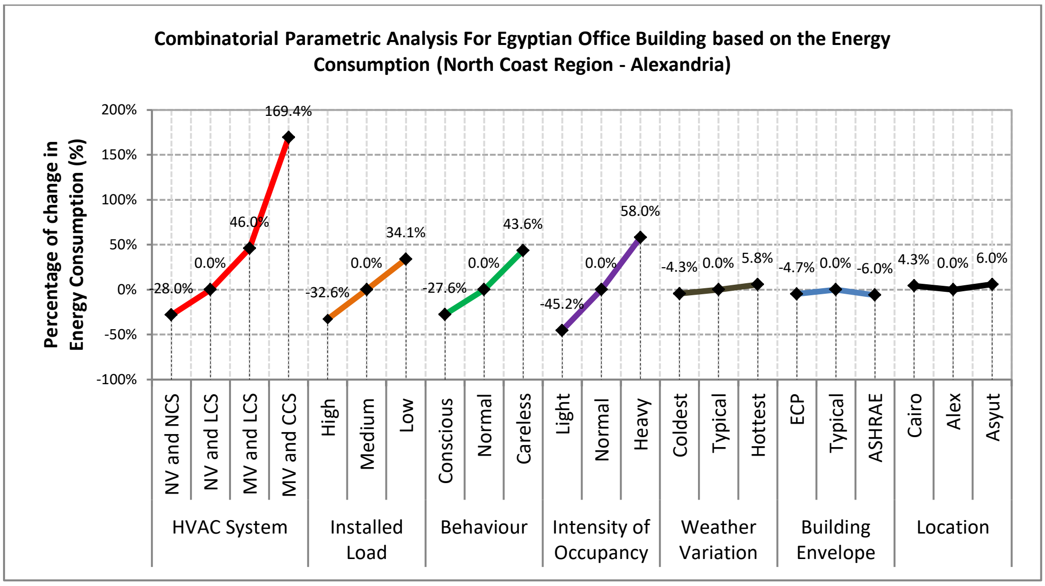


Figure 6-19. Combinatorial parametric analysis for Egyptian offices referenced to typical Type 2 office in north coast region (Alexandria).

In Figure 6-19, conditions represented by the 0% values form the base model, i.e. the typical Type 2 office with medium efficiency installed system loads, normal behaviour and typical weather, typical building envelope and Alexandria location.

The results showed that the HVAC system has the biggest effect on the energy consumption, consistent with the 59 building survey results and elsewhere. In general, the lack of central systems and the provision of local personally controlled systems which are used on an as-needed basis appears to result in lower energy use. Centrally implemented systems which continuously condition the whole space seem to be associated with higher energy use, possibly not a surprising result but one perhaps at odds with the current trajectory in building systems provision. The trade-off with indoor environment quality will be discussed later.

Other variables which have large effects are the intensity of occupancy (+58% to -45%), user behaviour (+44% to -28%), and efficiencies of the installed loads (+34% to -33%). The intensity of operations is representative of the activities carried out in the office. Higher energy use with higher intensity of use is not necessarily a bad thing, rather the energy use per person-hour of activity could be a better measure of effectiveness in energy use when considering different uses of an office space. It is important to understand this effect and not reward apparent low energy use due to space being underutilised [166]. The ‘behaviour’ and ‘efficiency of installed systems' may be categories which can be influenced by policy measures, which will be discussed later.

Table 6-6. Average energy consumption for typical Type 2 office located in north coast region (Alexandria).

Category Classification Based on Installed System (Equipment, Light, Cooling System)									
Installed System Efficiencies	High efficiency			Medium efficiency			Low efficiency		
Energy Consumption (range) (kWh /m^2 p.a.)									
Normal behaviour									
Typical Energy Consumption	27.2			40.4			58.4		
Weather Variation [Coldest / Hottest]	25.8	-	29.3	38.7	-	42.8	52.0	-	56.9
Intensity of Occupancy [Light / Heavy]	15.7	-	45.1	22.1	-	63.9	29.7	-	88.4
Weather + Intensity of Occupancy [Light + Cold / Heavy + Hot]	14.7	-	48.9	21.1	-	67.6	28.3	-	93.1
Careless behaviour									
Typical Energy Consumption	40.6			58.1			76.5		
Weather Variation [Coldest / Hottest]	38.1	-	44.6	54.9	-	62.3	72.5	-	81.3
Intensity of Occupancy [Light / Heavy]	24.5	-	68.4	36.3	-	92.2	43.8	-	126.2
Weather + Intensity of Occupancy [Light + Cold / Heavy + Hot]	22.9	-	75.2	34.0	-	98.8	41.3	-	134.4
Conscious behaviour									
Typical Energy Consumption	19.3			29.3			39.7		
Weather Variation [Coldest / Hottest]	18.5	-	21.0	28.3	-	31.3	38.5	-	41.9
Intensity of Occupancy [Light / Heavy]	10.7	-	31.6	15.6	-	46.2	21.1	-	64.2
Weather + Intensity of Occupancy [Light + Cold / Heavy + Hot]	10.2	-	23.8	15.1	-	49.4	20.4	-	68.3

Table 6-7. Average energy consumption for typical Type 2 office located in delta region (Cairo).

Category Classification Based on Installed System (Equipment, Light, Cooling System)									
Installed System Efficiencies	High efficiency			Medium efficiency			Low efficiency		
Energy Consumption (range) (kWh/m^2 p.a.)									
Normal behaviour									
Typical Energy Consumption	28.8			42.1			58.4		
Weather Variation [Coldest / Hottest]	27.4	-	32.5	40.5	-	46.4	54.1	-	61.1
Intensity of Occupancy [Light / Heavy]	16.9	-	47.8	23.5	-	66.4	31.3	-	91.3
Weather + Intensity of Occupancy [Light + Cold / Heavy + Hot]	15.9	-	54.6	22.3	-	73.6	29.8	-	100.9
Careless behaviour									
Typical Energy Consumption	39.6			56.6			74.6		
Weather Variation [Coldest / Hottest]	37.6	-	45.2	54.4	-	63.1	71.9	-	82.2
Intensity of Occupancy [Light / Heavy]	23.9	-	66.0	32.3	-	89.3	42.7	-	122.2
Weather + Intensity of Occupancy [Light + Cold / Heavy + Hot]	22.5	-	76.5	30.8	-	100.0	40.8	-	135.8
Conscious behaviour									
Typical Energy Consumption	21.0			31.3			41.9		
Weather Variation [Coldest / Hottest]	19.9	-	23.8	30.0	-	34.5	40.4	-	45.6
Intensity of Occupancy [Light / Heavy]	12.5	-	34.7	17.1	-	49.3	22.9	-	68.1
Weather + Intensity of Occupancy [Light + Cold / Heavy + Hot]	11.7	-	23.8	16.2	-	54.6	21.8	-	74.8

Table 6-8. Average energy consumption for typical Type 2 office located in Upper Egypt region (Asyut).

Category Classification Based on Installed System (Equipment, Light, Cooling System)									
Installed System Efficiencies	High efficiency			Medium efficiency			Low efficiency		
Energy Consumption (range) (kWh /m^2 p.a.)									
Normal behaviour									
Typical Energy Consumption	29.4			42.8			58.4		
Weather Variation [Coldest / Hottest]	27.8	-	32.1	40.9	-	45.8	54.6	-	60.3
Intensity of Occupancy [Light / Heavy]	17.5	-	48.7	24.1	-	67.3	32.0	-	92.4
Weather + Intensity of Occupancy [Light + Cold / Heavy + Hot]	16.3	-	53.5	22.7	-	72.2	30.3	-	98.7
Careless behaviour									
Typical Energy Consumption	39.6			56.7			74.6		
Weather Variation [Coldest / Hottest]	37.4	-	42.8	54.2	-	60.2	71.7	-	78.7
Intensity of Occupancy [Light / Heavy]	24.0	-	65.8	32.4	-	88.9	42.9	-	121.4
Weather + Intensity of Occupancy [Light + Cold / Heavy + Hot]	22.4	-	71.6	30.7	-	94.7	40.7	-	128.8
Conscious behaviour									
Typical Energy Consumption	22.0			32.4			43.2		
Weather Variation [Coldest / Hottest]	20.7	-	24.1	30.8	-	34.7	41.3	-	45.9
Intensity of Occupancy [Light / Heavy]	12.9	-	36.4	18.0	-	50.8	24.0	-	70.0
Weather + Intensity of Occupancy [Light + Cold / Heavy + Hot]	11.9	-	23.8	16.9	-	54.7	22.6	-	74.9

Both location and weather effects were seen to be of the order of 6% and, perhaps surprisingly given the focus elsewhere, the effect of building envelope was of a similar order of around 6% of the variation. These small building envelope variations in the Egyptian climate are consistent with the findings from the initial parameter influence screening carried out in the earlier model calibration process where only glazing G-solar value and shading had a significant effect. As indicated in Figure 4-11, it should be noted that this result was for a typical building which already has some roof insulation so roof insulation should not be ignored.

Figure 6-20 and Figure 6-21 present the same approach for the Cairo and Asyut location respectively, with conditions represented by the 0% values forming the base model, i.e. the typical Type 2 office with medium efficiency installed system loads, normal behaviour and weather, and typical building envelope.

These results also showed that the HVAC system has the biggest effect on the energy consumption, the next biggest effects are: the intensity of occupancy (+58% to -44%), user behaviour (+34% to -26%), and efficiencies of the installed loads (+33% to -32%) for Cairo. For Asyut the result showed that the largest effects were: intensity of occupancy (+57% to -44%), user behaviour (+32% to -25%), and efficiencies of the installed loads (+33% to -31%).

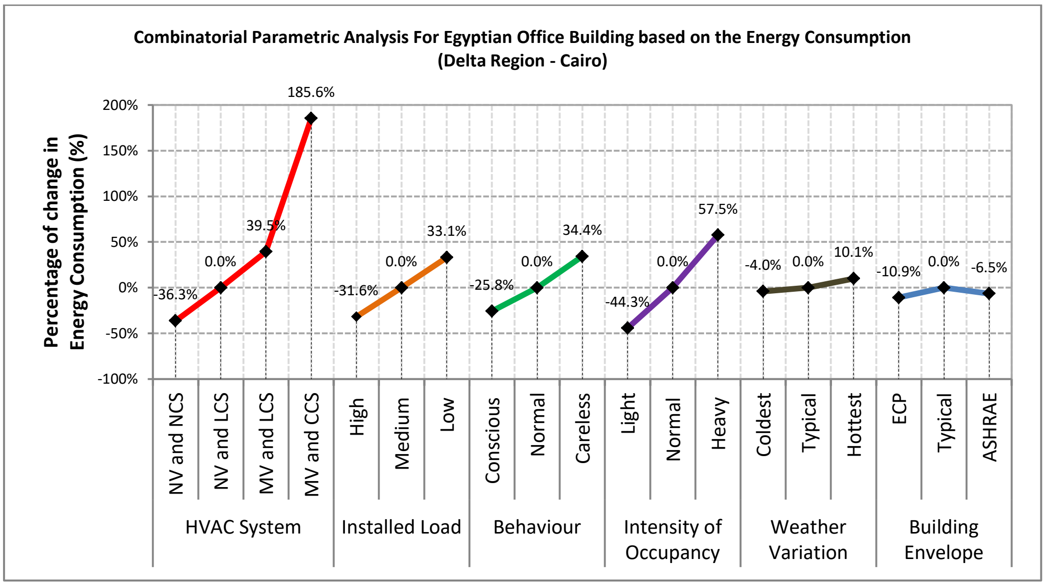


Figure 6-20. Combinatorial parametric analysis for Egyptian offices referenced to typical Type 2 office in delta region (Cairo).

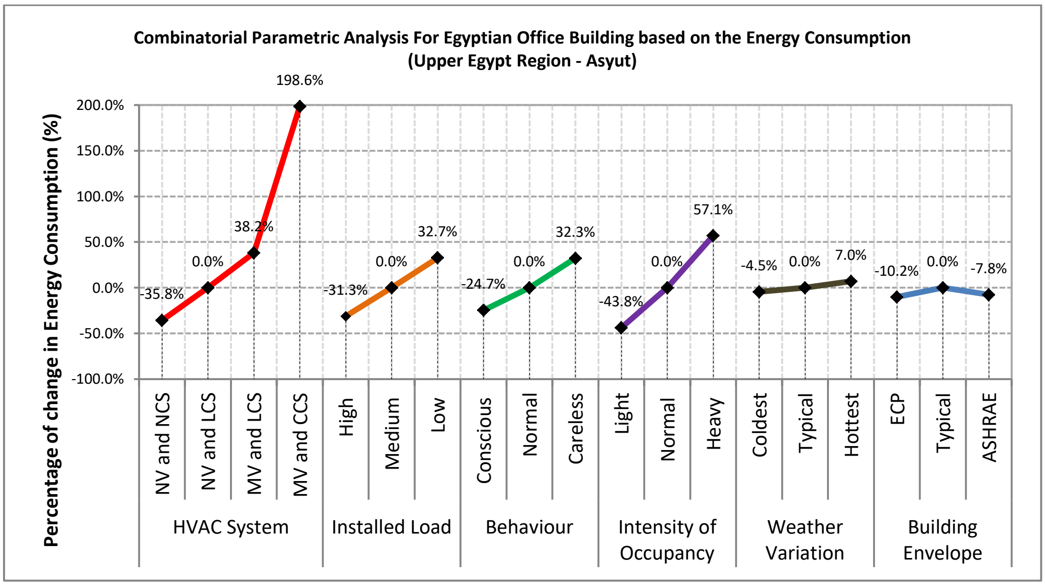


Figure 6-21. Combinatorial parametric analysis for Egyptian offices referenced to typical Type 2 office in upper Egypt region (Asyut).

The intensity of occupancy, user behaviour, and efficiencies of installed loads are within the same range in the three locations, but the ECP envelope shows more saving in energy consumption than the ASHRAE envelope as the ECP requirement in the delta region and upper Egypt is more restricted as shown in Table 6-1.

6.4 Summary

By referring to Table 6-5, it is apparent that the typical Type 2 office in Alexandria has an annual electrical demand of 40.4kWh/m^2 p.a.. This demand could be reduced to 29.3kWh/m^2 p.a. (27% reduction) if the energy-conscious behaviour were adopted. Alternatively, the demand would be reduced to 27.2kWh/m^2 p.a. (33% reduction) if the high-efficiency systems were installed. These two measures combined would reduce the electricity demand of the typical office to 19.3kWh/m^2 p.a. (52% reduction).

Table 6-5 also serves to illustrate how the intensity of occupation can have a confounding effect, e.g. if a building were retrofitted with high-efficiency systems and occupants changed behaviour to energy-conscious then a 52% reduction in electricity demand would be expected. However, if after the refit the building intensity of occupancy was increased from 'typical' to 'heavy' then the reduction in electricity demand would be only 22% (31.6kWh/m^2 p.a.). This highlights the requirement for a representation of the intensity of occupation within performance assessment methods.

These findings were consistent across different base cases. The next chapter discusses how these findings and the modelling framework can be used to inform future policy direction.

Chapter 7 POLICY DIRECTIONS FOR EXISTING TYPE 2 OFFICES

7.1 Introduction

The most prevalent office type, Type 2, was used as the base for the parametric analysis described in Chapter 6. The parameter changes that could most effectively reduce energy use are to system efficiencies and occupant behaviour. The work presented in this chapter will extend the analysis. Some recommendations will be provided as a focus of future work to develop both an advanced energy design guide and policy for the reduction of energy use.

7.2 Improved System Efficiencies

Several scenarios were selected as worth exploring for installed system efficiencies are elaborated in Table 7-1. The Egyptian Code (ECP) [4] covers lighting and cooling systems but does not cover IT and other office equipment. The ECP requires better performance than the low-efficiency case (Table 6-2, Table 7-1) but is less stringent than the typical case. ASHRAE [5] specifies only lighting, and cooling system efficiencies, however in the scenario outlined in Table 6-1 it was assumed that high efficiency IT and other office equipment would also be specified. A further 'High Efficiency' scenario has the high efficiency of the parametric study; here the increased lighting efficiency compared to ASHRAE could represent either increased system efficiency or reduced illuminance.

Table 7-1. Installed systems efficiency categories.

Variable	High Efficiency	ASHRAE	ECP	Typical
Equipment (W/m^2)	8.9	8.9	14.8	14.8
Lighting (W/m^2)	6	8.8	14	10
SEER (W/W)	4	3.8	3	3.5
Cooling use (%)	0.45	0.45	0.45	0.45
CUEER (W/W)	9	8.5	7	8

The performance of these three possible standards compared to the typical case for a Type 2 office is shown in Figure 7-1. The minimum standards required in the ECP would give an 18% increase over the typical office (but 14% better than the low-efficiency case). The reductions in energy use compared to the 'typical' current Type 2 office for ASHRAE and High Efficiency would be 22% and 33% respectively.

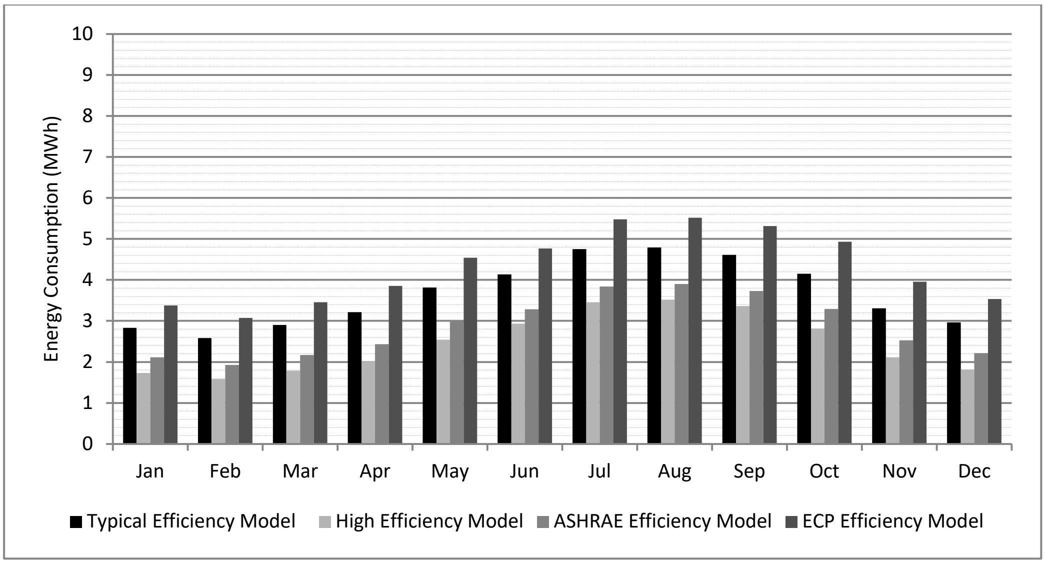


Figure 7-1. Energy consumption for Type 2 office for various equipment efficiency scenarios.

For a Type 3 office the performance of these three possible standards compared to the typical case is shown in Figure 7-2. The minimum standards required in the ECP would give a 13% increase over the typical office (but 11% better than the low-efficiency case). The reductions in energy use compared to the 'typical' current Type

3 offices for ASHRAE and High Efficiency would be 16% and 22%, respectively. The percentage reduction in energy consumption for Type 3 offices is lower than for Type 2 offices; this is due to the additional power required by the HVAC system especially the mechanical ventilation system.

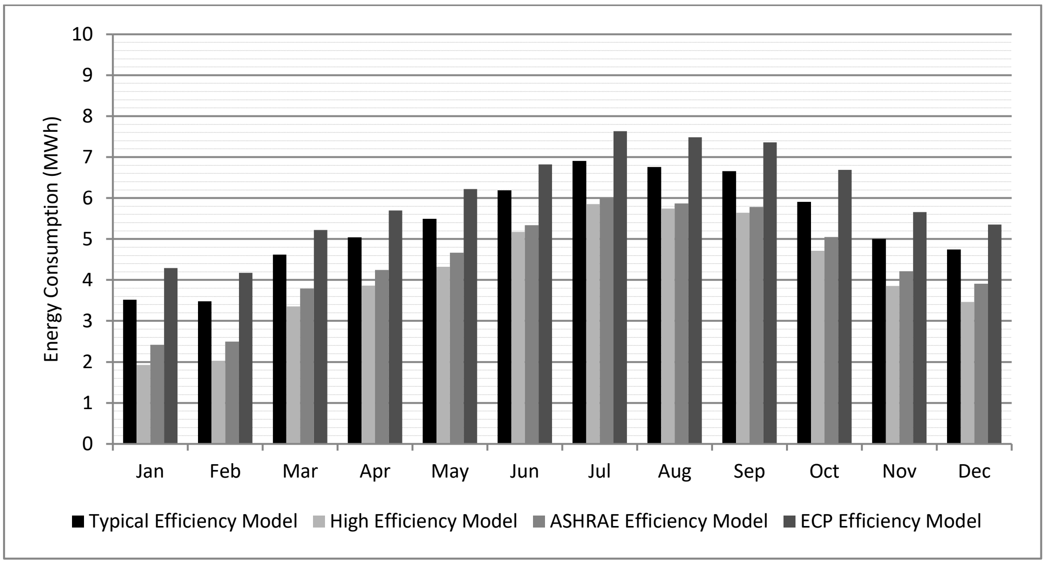


Figure 7-2. Energy consumption for Type 3 office for various equipment efficiency scenarios

7.3 Occupant Behaviour Future Initiative

A principal driver for energy use is the desire for satisfactory thermal comfort through the use of the available controls (cooling systems, windows, fans). The energy conscious behaviour which reduces electricity demand may compromise thermal comfort to some extent as illustrated in Figure 6-12 and Figure 6-13, and this is worth further exploration. Interrelationships between factors influencing thermal comfort have been captured by Paliaga and others [142] [167]. Reducing clothing levels from 1 clo to 0.5 clo can increase the resultant temperature threshold for PMV +0.5 from 24.8^{o}C to 27.6^{o}C, A similar change in thermal comfort threshold can be achieved by increasing local airspeed from 0.15 to 0.8m/s, for example by the use of fans as shown in Figure 7-3 [142]. Clothing flexibility and local airspeed can, therefore, be adaptations allowing the temperature settings for cooling systems to be increased and hence energy demands for cooling reduced. There have been successful initiatives using these effects, e.g. Coolbiz in Japan [145].

Figure 7-3. Traditional Ceiling Fan.

In the parametric analysis it was clear that energy use is significantly reduced (27% for the typical office, Figure 7-4) if energy conscious behaviour is adopted, including a cooling setpoint temperature of 25^{o}C (normal level is 22^{o}C), without possible adaptations to clothing or air velocity for example, this, however, leads to thermal comfort dissatisfaction levels beyond those experienced in the typical office, as given in Figure 7-5. If adaption is allowed through reducing summer clothing levels from 0.7 to 0.5 clo during June to October and from 1.0 to 0.7 clo in May and November then PPD could be maintained in an acceptable range for this higher setpoint, as shown in Figure 7-5.

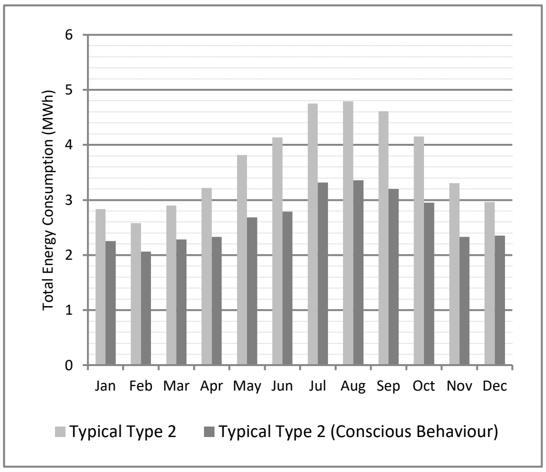


Figure 7-4. Electricity consumption for typical Type 2 office with typical and energy conscious behaviour.

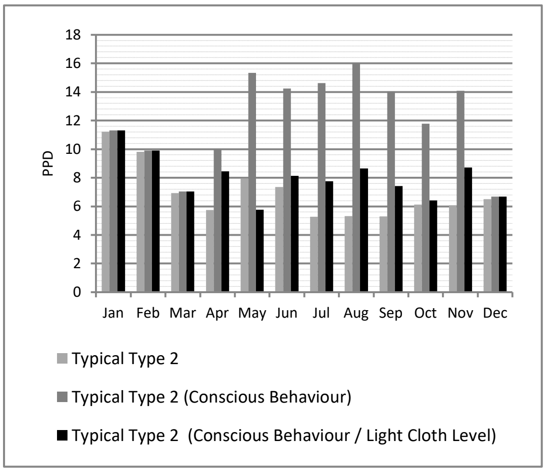


Figure 7-5. PPD for typical Type 2 office with different behaviour and clothing levels.

It is possible to envisage an initiative for a further reduction in energy use through raising the cooling setpoint to 27°C and the use of a ceiling fan to increase air velocity in addition to the clothing adaptation. An air velocity of 0.5m/s instead of 0.15m/s created by user-controlled ceiling fans was found to give both improved energy performance (Figure 7-6) and acceptable comfort (Figure 7-7) (assuming one 55W fan covering a 90m^2 floor area). The annual electricity demand for the scenario with a 27^{o}C cooling setpoint and ceiling fans is reduced by 33% from the typical office case, compared to the 27% reduction for the case with a 25^{o}C setpoint and no fans.

The results for the same initiative applied to the Type 3 office model are shown in Figure 7-8 to 7-11. Figure 7-8 and Figure 7-10 show the reduction in the energy consumption for conscious behaviour and a 27°C setpoint plus fans. Energy use is significantly reduced (27% for the typical office) if energy conscious behaviour is adopted, while the annual electricity demand for the 27^{o}C cooling setpoint with ceiling fans scenario is reduced by 31% from the typical Type 3 office case. This however leads to thermal comfort dissatisfaction levels beyond those experienced in the typical office, as illustrated in Figure 7-9 and Figure 7-11.

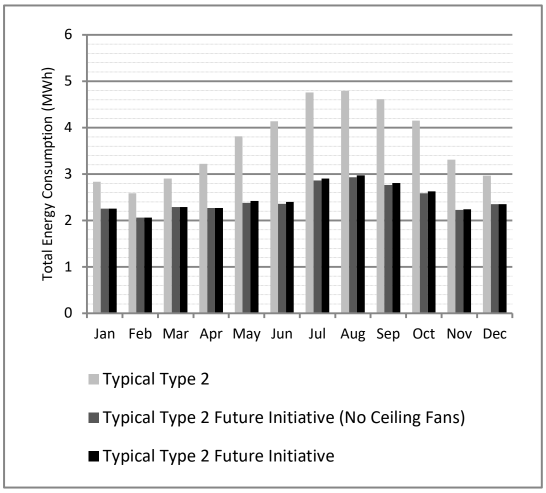


Figure 7-6. Monthly electricity consumption for typical Type 2 office with typical, and 27oC plus fans behaviours.

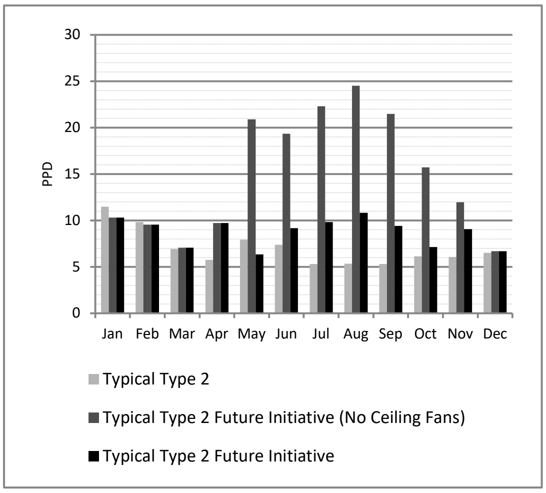


Figure 7-7. PPD for typical Type 2 office with typical, energy conscious, and 27oC plus fans behaviours.

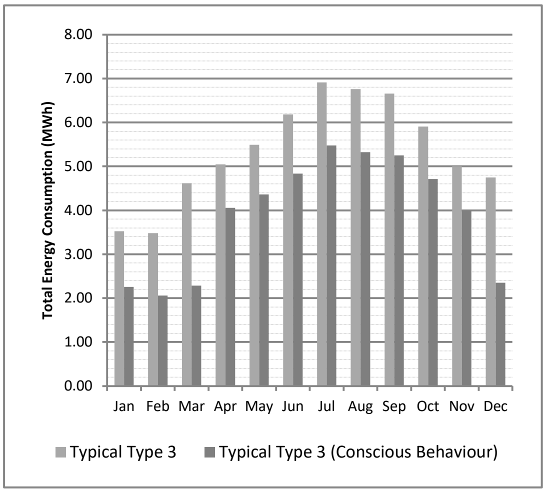


Figure 7-8. Electricity consumption for typical Type 3 office with typical and energy conscious behaviour.

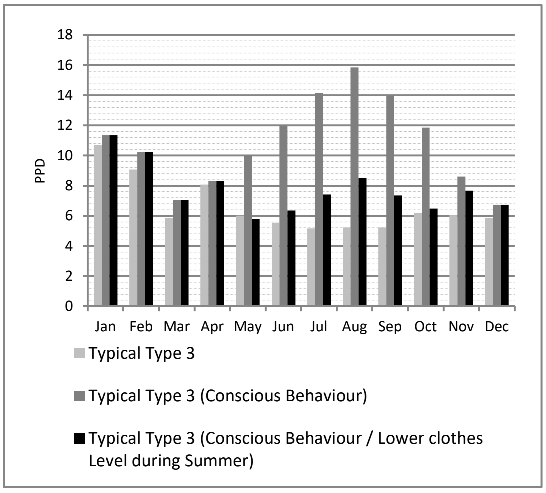


Figure 7-9. PPD for typical Type 3 office with different behaviour and clothing levels

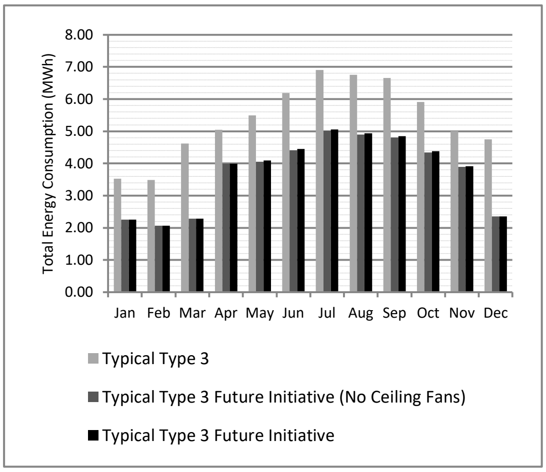


Figure 7-10. Monthly electricity consumption for typical Type 3 office with typical, and 27°C plus fans behaviours.

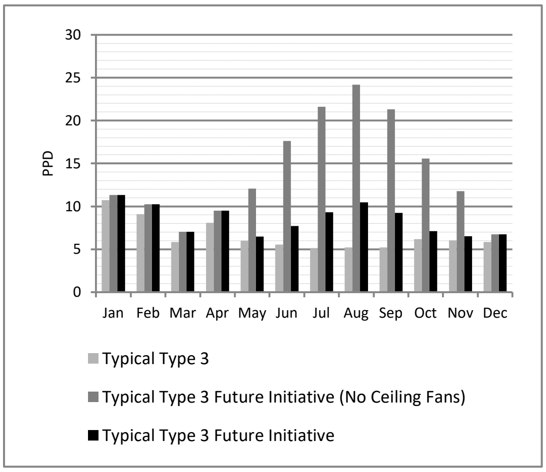


Figure 7-11. PPD for typical Type 3 office with typical, energy conscious, and 27°C plus fans behaviours

7.4 Occupant Behaviour Future Initiative Performance Analysis

The Type 2 office model was tested for two extremes of the weather with different intensities of occupancy to cover the initiative occupant behaviour. Firstly, the future initiative behaviour model described in the previous section (with a 27°C cooling setpoint, light clothing levels during warm periods, and ceiling fans) was run for the hottest year, and then for the hottest year with high occupant intensity. Both models show good comfort levels (PPD) (Figure 7-12). Secondly, the Type 2 office model was run using the coldest year, and also the coldest year with low occupant intensity. Both sets of conditions show high levels of discomfort during December, January, and February (Figure 7-13) exceeds the 30 % PPD which would require increased levels of clothing throughout these months, in addition to the use of a heating system to reach the accepted level of comfort.

A heating system with the setpoint temperature of 19°C was applied to the future initiative model to overcome the predicted discomfort. Figure 7-14 shows the power consumption of the future initiative model through the coldest year with low occupancy intensity and using a heating system. This results in consumption of 26.83kWh/m^2 p.a., 10% less than the typical future initiative model (typical weather, typical occupant intensity, 27 °C set point and ceiling fans), and 44% higher than the same model (coldest weather, low occupant intensity, 27°C set point and ceiling fans) but without using heating system. From this analysis it would seem more appropriate to maintain current practice in the typical office buildings and avoid heating systems through increased winter clothing levels rather than installing heating.

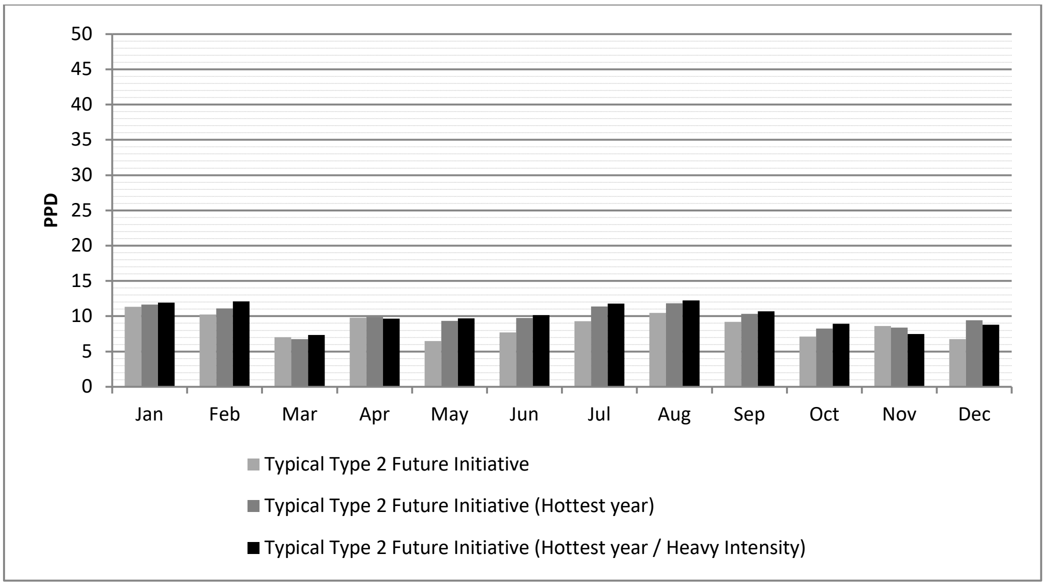


Figure 7-12. PPD for typical Type 2 future initiative office performance through the hottest weather.

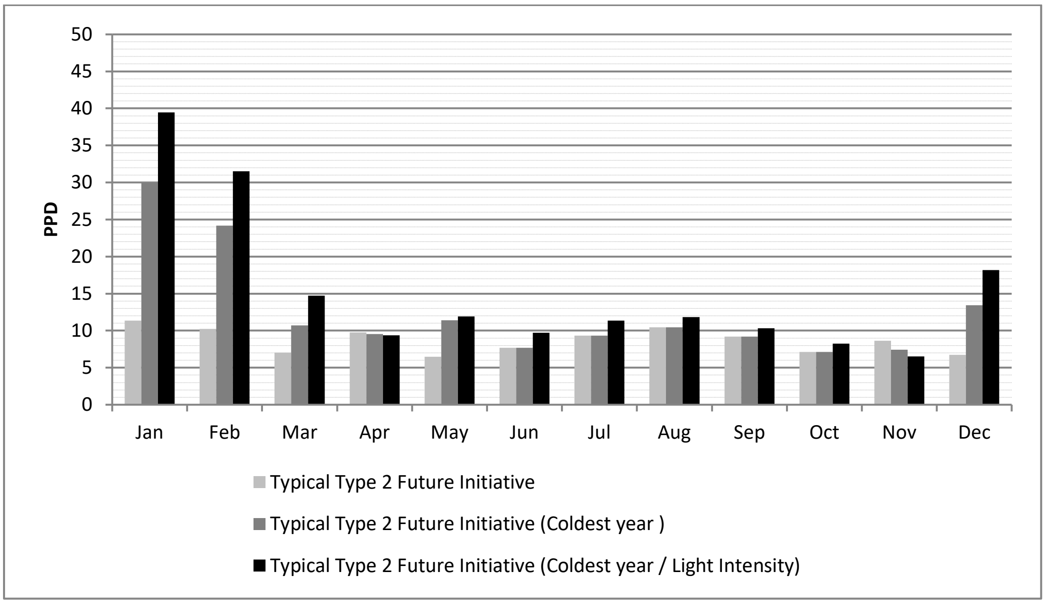


Figure 7-13. PPD for typical Type 2 future initiative office performance through the coldest weather.

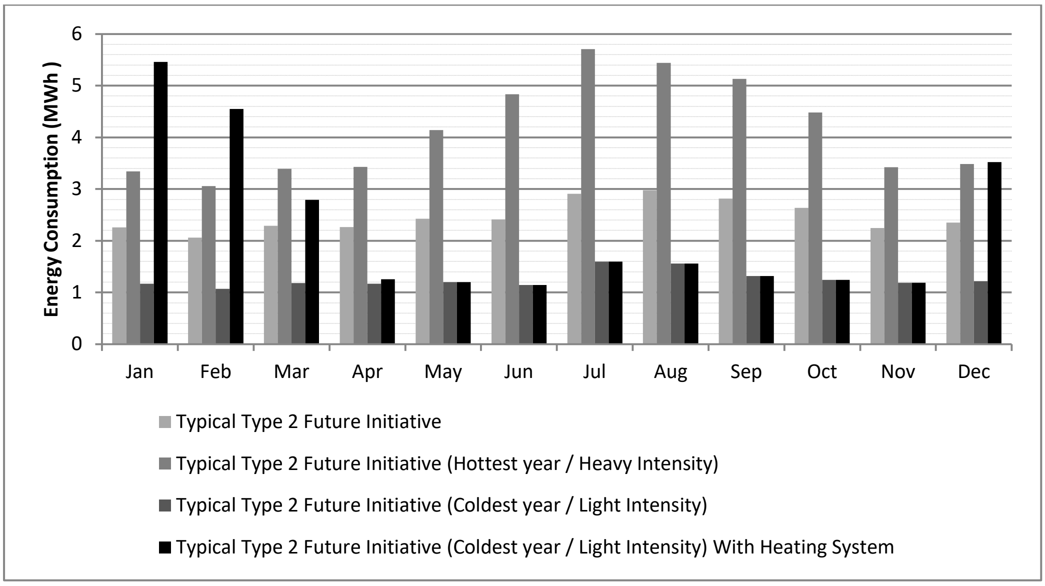


Figure 7-14. Monthly electricity consumption for typical Type 2 future initiative during hottest weather / coldest weather / coldest weather with heating system.

7.5 Summary

The work presented through this chapter has contributed useful insights; this work aims to sit alongside the work of others and be further extended in future to give a sound basis for defining policy. The datasets created in this work provide a foundation; it is important that further studies be conducted on larger samples and in different contexts to advance to a more comprehensive understanding.

These results capture the most influential parameters found in the parametric analysis based on the representative model. This model has a specific geometry and construction, in particular the glazing is not full facade and is set in significant window reveals, and the roof construction includes insulation. For modern buildings which do not fit with these typical vernacular characteristics geometrical and construction factors are likely to have a more significant influence.

To reduce the energy demand of existing Type 2 , Type 3 and other offices the work presented here suggests that the most effective strategies would be to influence (i) the efficiency of the installed loads and (ii) the occupants' behaviour in terms of adoption and efficient use of energy-using systems, including local cooling.

Finally, installed system efficiencies (HVAC, lights, equipment) and occupant behaviours (e.g. use of systems, cooling setpoints) have been identified as having a potential for energy saving of around 30% each or 50% in combination for these typical offices.

Possible policy measures to promote (i) energy efficient systems, and (ii) energy conscious behaviour, have been proposed and discussed, including potential trade-offs between energy conscious behaviour and indoor environmental quality.

Chapter 8 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

8.1 Discussion

The main aims of the thesis were: (i) to provide insights into energy use and IEQ associated with current Egyptian office buildings, (ii) to develop a method for producing a model to represent current Egyptian office performance, for use in the future to inform upgrades and policy directions, (iii) to use this modelling framework to investigate the relative and combinatorial impact of relevant parameters, and to present the results to inform decision makers, (iv) to propose possible future scenarios for Egyptian office buildings to minimize energy use, (v) to illustrate how this process can be usefully extended to other building sectors and contexts.

This thesis has described the steps taken in this exploration; the 59 office energy survey, the single building energy and environmental monitoring, the initial calibration of a base model, the creation of a representative modelling framework including a typical model and parameter sets capturing variations and uncertainties, and the use of that framework to provide further insights beyond the survey and monitoring.

The multi-building energy survey and the detailed case study building evaluation gave useful insights and added to the work of others in describing energy use and indoor environmental quality in existing Egyptian buildings. It highlighted that energy use is higher in more fully serviced buildings, a similar finding to that reported elsewhere [1, 29]. The provision of centrally controlled comfort cooling and ventilation across the entire indoor space continuously throughout the occupied period has an associated energy penalty, in contrast to the situation where individuals have control and only occupied workspaces are conditioned as required.

Interesting observations on thermal comfort from the detailed office survey were that people tended to adjust their clothing level rather than require heating in winter, also that people tended to control the temperature in the case study building to match the expected temperatures in the PMV scale.

The method developed for creating a calibrated model of an Egyptian office was generalized to form a more typical model. Developing realistic best and worst case model input parameter sets provided an interesting route to a baseline model which is grounded in measured data.

The performance analysis explored the energy and IEQ of Egyptian offices and provided insights that can begin usefully to inform future strategy for this sector.

The Type 2 naturally ventilated and locally cooled office buildings are common, if these were to be converted or replaced by fully serviced buildings it appears that this would greatly increase the overall energy demand of the office sector (more than two-fold).

The influence of building fabric improvements on existing Type 2 offices, apart from window shading / solar transmittance and possibly roof insulation, was seen to be relatively small at up to 8%. This result needs to be checked across a range of different building geometries to make sure that this is a general conclusion. For the fully serviced, highly glazed modern design of offices however these factors may have a much greater impact. The G-solar factor showed a clear effect and the reduced G-solar in the Egyptian and ASHRAE standards is a move in the right direction which could be usefully integrated into the upgrade strategies for existing buildings. The impact of G-solar will be much greater in buildings with higher solar exposure, particularly those with large exposed glazing not following the local vernacular design style for smaller windows set in deep reveals.

The modelling approach developed here has potential to inform new building standards, upgrades to existing buildings, to investigate policy options such as the Japanese Coolbiz initiative [57], and the adaptation of equipment or lighting energy efficiency standards.

On the opposite side of this argument against continuously running centralised systems is the potential highlighted in the analysis for indoor environmental conditions to be compromised by energy conscious behaviour, e.g. through lower ventilation rates and associated increases in CO_2 (and possibly other pollutants). This is a conflict inherent in the use of natural ventilation[168],[169]. The provision of desktop CO_2 monitors and guidance to occupants of naturally ventilated buildings is being mandated in some countries as a means of ensuring the appropriate setting of ventilation openings, addressing this concern [170]. In office environments, the use of ventilation to eliminate odours may be sufficient unless there are unusual sources of pollutants dangerous to health. A further potential issue with natural ventilation can be that there is no filtration of the outdoor air which could be problematic depending on the specifics of the location; outdoor air quality is another area which may become an increasing focus for policy.

8.2 Limitations

This work has necessarily been of limited scope but hopes to point forward to expansion and replication of this type of work in Egypt and elsewhere. The building surveys and monitoring carried out have necessarily been constrained by the resources available and the access allowed by the building occupants and managers. The modelling exercise and sensitivity analysis have been based on a single case study office of a single type. Much more work remains to be done to develop the impact of this work and to do follow-on work in other building types and contexts.

8.3 Conclusions

The following conclusions may be drawn from the foregoing survey, analysis and discussions:

1. An energy survey was carried out for 59 Egyptian offices, categorized by servicing strategy into four building types: natural ventilation with no cooling, natural ventilation with local cooling, mechanical ventilation with local cooling, centrally serviced mechanical ventilation and cooling, and energy use benchmarks were provided.
2. It was observed that energy use increases as building services increase, and existing Egyptian offices use less energy than benchmarks.
3. A more detailed investigation for a case study office was carried out to inform model calibration.
4. This provided insight into energy use, thermal comfort and environmental conditions, and revealed high variability in conditions and behaviours.
5. A calibrated model was created for the case study office, then a baseline model and input parameter sets created to represent more generalized performance.
6. The observed indoor environment was compared against adaptive and non-adaptive thermal comfort standards. It was found that the PMV/PPD (non-adaptive) thermal comfort model is the most representative.
7. The typical model was then used to investigate the impacts on the performance of the most common type of office for a range of parameters including location, weather, building envelope, the intensity of occupancy, behaviour, and installed systems including HVAC strategy. HVAC strategy

was identified as the most significant factor followed by system efficiencies (HVAC, lights, equipment) and occupant behaviour (e.g. use of systems, temperatures)

8. Two types of possible policy measures, (i) energy efficient systems and (ii) energy conscious behaviour, are proposed and discussed, including potential trade-offs between energy conscious behaviour and indoor environmental quality.

8.4 Contributions To knowledge

This research makes contributions and gives new insight into:

- Energy, indoor environmental conditions and behaviour in Egyptian office buildings.
- The development of a new method for defining a representative model capturing uncertainties in input datasets.
- The representative model's use to identify the impacts of various parameters for the Egyptian context, illustrated through a combinatorial parametric study.
- Proposals informing future Egyptian policy.
- The method developed in this work has applicability to other contexts and building categories.

8.5 Recommendations For Future Work

This work is intended to stand alongside the work of others and be further extended in future in order to give a sound basis for future policy. The datasets created in this work are only a start, it is important that further studies are conducted across larger samples and different contexts to allow a more comprehensive understanding.

Monitoring must also be used on an ongoing basis to allow actual building performance to be understood and to provide feedback for the buildings sector. Experience elsewhere has highlighted that policy does not always result in the intended results and that monitoring and reporting of actual performance is key if performance gaps are to be avoided [58, 171].

The monitoring carried out in this work was limited due to equipment, cost and access restrictions. It is recommended that instrumentation and protocols such as those suggested by Parkinson, Parkinson, and de Dear are followed; potentially the 'SAMBA' IEQ monitoring kit they have developed could be used [119]. The work also highlights the difficulty in modelling system and human behaviours in buildings, and the need for more work in this area.

References

1. Ezzeldin, S.M.N., *Mixed-Mode Cooling Design for Office Buildings in Arid Climates, Ph.D. Thesis.* 2011, De Montfort University: De Montfort University.
2. EIA, U., *International energy outlook 2013*, in *US Energy Information Administration (EIA)*. 2013: USA.
3. ECP306/1-2005, *The Egyptian Residential Buildings Energy Code*. Housing and Building National Research Center, HBRC 2005 Egypt.
4. ECP306/2-2005, *The Egyptian Commercial Buildings Energy Code*. Housing and Building National Research Center, HBRC 2005 Egypt.
5. Eberhard, A., et al., *Underpowered: the state of the power sector in Sub-Saharan Africa.* Background paper, 2008. **6**.
6. Zhou, Y., et al., *Modeling the effect of climate change on US state-level buildings energy demands in an integrated assessment framework.* Applied Energy, 2014. **113**: p. 1077-1088.
7. ECG19, *Energy consumption guide 19: energy use in offices*, in *Energy*. 2003.
8. Crawley, D.B., *Building Performance Simulation: A Tool For Policymaker*, in *Mechanical And Aerospace Engineering*. 2008, Strathclyde University.
9. Coakley, D., P. Raftery, and M. Keane, *A review of methods to match building energy simulation models to measured data.* Renewable and Sustainable Energy Reviews, 2014. **37**: p. 123-141.
10. *Official Journal of the European Union. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast).* 2010. **18**(06): p. 2010.
11. Baldwin, R., et al., *BREEAM 98 for Offices.* Building Research Establishment, Watfordt, 1998.

12. Hassan, M.A., et al., *Effect of Building Material and Wall Construction on the Energy Consumption*. 2011, Cairo: Housing and Building National Research Center, Industrial Education Faculty.
13. Crawley, D.B. and L.K. Lawrie. *Rethinking The Tmy: Is The 'Typical'meteorological Year Best For Building Performance Simulation?* in *Conference: Building Simulation*. 2015.
14. Yang, L., J.C. Lam, and C.L. Tsang, *Energy performance of building envelopes in different climate zones in China.* Applied Energy, 2008. **85**(9): p. 800-817.
15. Raslan, R.M.S., *Performance based regulations: the viability of the modelling approach as a methodology for building energy compliance demonstration*. 2010, UCL (University College London).
16. ASHRAE, *Standard 90.1-2013 'Energy Standard for Buildings Except Low-Rise Residential Buildings', American Society of Heating, Refrigerating and Air-Conditioning Engineering, Atlanta, GA*. 2013.
17. US Green Building Council, *LEED: Leadership in energy and environmental design*. 2011.
18. EGBC, *Egyptian Green Building Council The GREEN PYRAMID rating system*. 2009, Egypt.
19. *Annual Report 2014/2015, Electricity Holding Company, Egypt*.
20. *EIA, International energy data and analysis (EGYPT Report),* in *Monthly report, June 2015*.
21. *Annual Report 2012/2013, Electricity Holding Company, Egypt*.
22. Attia, S., *A tool for design decision making: zero energy residential buildings in hot humid climates, Ph.D. Thesis*. 2012, Presses univ. de Louvain.
23. *Energy Efficiency Handbook - Environmental Housekeeping Handbook for Office Buildings in the Arab Countries*. 2012, Arab Forum for Environment and Development.
24. Pérez-Lombard, L., J. Ortiz, and C. Pout, *A review on buildings energy consumption information.* Energy and buildings, 2008. **40**(3): p. 394-398.
25. Saidur, R., *Energy consumption, energy savings, and emission analysis in Malaysian office buildings.* Energy Policy, 2009. **37**(10): p. 4104-4113.
26. Menezes, A.C.K.d., et al., *Review of benchmarks for small power consumption in office buildings.* 2012.
27. http://www.emsd.gov.hk/en/energy_efficiency/energy_end_use_data_and_consumption_indicators/hong_kong_energy_end_use_data/index.html, *2016*.

28. Pérez-Lombard, L., et al., *HVAC systems energy comparisons for an office building*. Proceedings of the Climamed, Lisbon, 2004: p. 121-127.

29. Abdelhafez, N.R., et al., *Energy Conservation in Existing Office Building: Case study Petrojet Company Head Office Buildings in Cairo, Egypt*. 2014.

30. Ezzeldin, S.M.N., *Mixed-Mode Cooling Design for Office Buildings in Arid Climates*. 2011, De Montfort University.

31. Dubois, M.-C. and Å. Blomsterberg, *Energy saving potential and strategies for electric lighting in future North European, low energy office buildings: A literature review*. Energy and Buildings, 2011. **43**(10): p. 2572-2582.

32. ASHRAE. *Standard 90.1-2010‘Energy Standard for Buildings Except Low-Rise Residential Buildings’,American Society of Heating, Refrigerating and Air-Conditioning Engineering, Atlanta, GA*. 2010.

33. Hanna, G.B., *Energy Analysis for New Office Buildings in Egypt*. 2013.

34. CIBSE, G.F.E.E.i.B., 3rd ed., The Chartered Institution, *CIBSE, Guide F: Energy Efficiency in Buildings, TM54: Evaluating Operational Energy Use at the Design Stage, The Chartered Institution of Building Services Engineers, London, 2013.*

35. CIBSE, G.F.E.E.i.B., 3rd ed., The Chartered Institution and L. of Building Services Engineers, 2012., *CIBSE, Guide F: Energy Efficiency in Buildings*. 2012, CIBSE.

36. Buswell, R.A., et al., *Analysis of electricity consumption for lighting and small power in office buildings*. 2011.

37. Bray, M., *Review of computer energy consumption and potential savings*. Dragon Systems Software Limited (DssW), 2006.

38. Kawamoto, K., et al., *Electricity used by office equipment and network equipment in the US: Detailed report and appendices*. Lawrence Berkeley National Laboratory, 2001.

39. Menezes, A., et al., *Estimating the energy consumption and power demand of small power equipment in office buildings*. Energy and Buildings, 2014. **75**: p. 199-209.

40. Moorefield, L., B. Frazer, and P. Bendt, *Office plug load field monitoring report*. Ecos Consulting, 2008.

41. Mungwititkul, W. and B. Mohanty, *Energy efficiency of office equipment in commercial buildings: The case of Thailand*. Energy, 1997. **22**(7): p. 673-680.

42. Nordman, B., M.A. Piette, and K. Kinney, *Measured energy savings and performance of power-managed personal computers and monitors*. Lawrence Berkeley National Laboratory, presented at the American Council for an

Energy Efficient Economy Summer Study on Energy-Efficiency in Buildings, 1996.

43. Roberson, J.A., et al., *Energy use and power levels in new monitors and personal computers.* Lawrence Berkeley National Laboratory, 2002.

44. Kawamoto, K., Y. Shimoda, and M. Mizuno, *Energy saving potential of office equipment power management.* Energy and Buildings, 2004. **36**(9): p. 915-923.

45. Attia, S., *A tool for design decision making: zero energy residential buildings in hot humid climates*. Vol. 4. 2012: Presses univ. de Louvain.

46. Zhao, H.-x. and F. Magoulès, *A review on the prediction of building energy consumption.* Renewable and Sustainable Energy Reviews, 2012. **16**(6): p. 3586-3592.

47. Recast, E., *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast).* Official Journal of the European Union, 2010. **18**(06): p. 2010.

48. Saltelli, A., et al., *Global sensitivity analysis: the primer*. 2008: John Wiley & Sons.

49. Young, P., S. Parkinson, and M. Lees, *Simplicity out of complexity in environmental modelling: Occam's razor revisited.* Journal of Applied Statistics, 1996. **23**(2-3): p. 165-210.

50. Reddy, T.A. and K.K. Andersen, *An evaluation of classical steady-state off-line linear parameter estimation methods applied to chiller performance data.* HVAC&R Research, 2002. **8**(1): p. 101-124.

51. Clarke, J.A., *Energy simulation in building design*. 2001: Routledge.

52. Clarke, J., P. Strachan, and C. Pernot, *An approach to the calibration of building energy simulation models.* Transactions-American Society Of Heating Refrigerating And Air Conditioning Engineers, 1993. **99**: p. 917-917.

53. Winkelmann, F., et al., *DOE-2 supplement: version 2.1 E*. 1993, Lawrence Berkeley Lab., CA (United States); Hirsch (James J.) and Associates, Camarillo, CA (United States).

54. Crawley, D.B., et al., *EnergyPlus: creating a new-generation building energy simulation program.* Energy and buildings, 2001. **33**(4): p. 319-331.

55. Laboratory, U.o.W.-.-M.S.E. and S.A. Klein, *TRNSYS, a transient system simulation program*. 1979: Solar Energy Laborataory, University of Wisconsin--Madison.

56. Crawley, D.B., et al., *Contrasting the capabilities of building energy performance simulation programs.* Building and environment, 2008. **43**(4): p. 661-673.

57. Fabrizio, E. and V. Monetti, *Methodologies and advancements in the calibration of building energy models.* Energies, 2015. **8**(4): p. 2548-2574.

58. De Wilde, P., *The gap between predicted and measured energy performance of buildings: A framework for investigation.* Automation in Construction, 2014. **41**: p. 40-49.

59. Reddy, T.A., I. Maor, and C. Panjapornpon, *Calibrating detailed building energy simulation programs with measured data—Part I: General methodology (RP-1051).* Hvac&R Research, 2007. **13**(2): p. 221-241.

60. Karnopp, D.C., D.L. Margolis, and R.C. Rosenberg, *System dynamics: modeling, simulation, and control of mechatronic systems*. 2012: John Wiley & Sons.

61. Raftery, P., M. Keane, and A. Costa, *Calibrating whole building energy models: Detailed case study using hourly measured data.* Energy and Buildings, 2011. **43**(12): p. 3666-3679.

62. ASHRAE, *Guideline 14-2002, Measurement of Energy and Demand Savings, American Society of Heating, Ventilating, and Air Conditioning Engineers, Atlanta, Georgia*. 2002.

63. Reddy, T.A., *Literature Review on Calibration of Building Energy Simulation Programs: Uses, Problems, Procedures, Uncertainty, and Tools.* ASHRAE transactions, 2006. **112**(1).

64. Coakley, D., et al. *Calibration of a detailed BES model to measured data using an evidence-based analytical optimisation approach*. in *Proceedings of the 12th International IBPSA Conference. Sydney, Australia*. 2011.

65. Haberl, J. and T. Bou-Saada, *Procedures for calibrating hourly simulation models to measured building energy and environmental data.* Journal of solar energy engineering, 1998. **120**(3): p. 193-204.

66. Hadley, D.L., *Daily variations in HVAC system electrical energy consumption in response to different weather conditions.* Energy and Buildings, 1993. **19**(3): p. 235-247.

67. Waltz, J.P., *Practical experience in achieving high levels of accuracy in energy simulations of existing buildings.* Strategic planning for energy and the environment, 1995. **15**(2).

68. Yoon, J., E.-J. Lee, and D. Claridge, *Calibration procedure for energy performance simulation of a commercial building.* Journal of solar energy engineering, 2003. **125**(3): p. 251-257.

69. Liu, G. and M. Liu, *A rapid calibration procedure and case study for simplified simulation models of commonly used HVAC systems.* Building and Environment, 2011. **46**(2): p. 409-420.

70. Booth, A., R. Choudhary, and D. Spiegelhalter, *A hierarchical Bayesian framework for calibrating micro-level models with macro-level data.* Journal of Building Performance Simulation, 2013. **6**(4): p. 293-318.

71. Eisenhower, B., et al., *A methodology for meta-model based optimization in building energy models.* Energy and Buildings, 2012. **47**: p. 292-301.

72. Liu, S. and G. Henze. *Calibration of building models for supervisory control of commercial buildings*. in *Proceedings of the 9th International Building Performance Simulation Association (IBPSA) Conference*. 2005.

73. MacKay, D.J., *Bayesian nonlinear modeling for the prediction competition.* ASHRAE transactions, 1994. **100**(2): p. 1053-1062.

74. O'Hagan, A., *Bayesian analysis of computer code outputs: a tutorial.* Reliability Engineering & System Safety, 2006. **91**(10): p. 1290-1300.

75. Sun, J. and T.A. Reddy, *Calibration of building energy simulation programs using the analytic optimization approach (RP-1051).* HVAC&R Research, 2006. **12**(1): p. 177-196.

76. Rosen, R., *Life itself: a comprehensive inquiry into the nature, origin, and fabrication of life*. 1991: Columbia University Press.

77. Macdonald, I.A., *Quantifying the effects of uncertainty in building simulation*. 2002: University of Strathclyde.

78. Persily, A.K., *Airtightness of commercial and institutional buildings: blowing holes in the myth of tight buildings*. 1998: Building and Fire Research Laboratory, National Institute of Standards and Technology.

79. Persily, A.K., *Myths about building envelopes.* ASHRAE journal, 1999. **41**: p. 39-48.

80. Heo, Y., R. Choudhary, and G. Augenbroe, *Calibration of building energy models for retrofit analysis under uncertainty.* Energy and Buildings, 2012. **47**: p. 550-560.

81. Bourgeois, D., C. Reinhart, and I. Macdonald, *Adding advanced behavioural models in whole building energy simulation: a study on the total energy impact of manual and automated lighting control.* Energy and buildings, 2006. **38**(7): p. 814-823.

82. Chong, A. and K.P. Lam, *Uncertainty Analysis And Parameter Estimation Of HVAC Systems In Building Energy Models*, in *Proceedings of BS2015: 14th Conference of International Building Performance Simulation Association, Hyderabad, India, Dec. 7-9, 2015.*

83. Hoes, P., et al., *User behavior in whole building simulation.* Energy and Buildings, 2009. **41**(3): p. 295-302.

84. Tuohy, P.G., et al., *Comfort driven adaptive window opening behaviour and the influence of building design*, in *Comfort driven adaptive window opening behaviour and the influence of building design. In: Proceedings of Building Simulation 2007, 10th IBPSA Conference. IBPSA.* 2007.

85. Aerts, D., et al., *A method for the identification and modelling of realistic domestic occupancy sequences for building energy demand simulations and peer comparison.* Building and environment, 2014. **75**: p. 67-78.

86. Karjalainen, S., *Should we design buildings that are less sensitive to occupant behaviour? A simulation study of effects of behaviour and design on office energy consumption.* Energy Efficiency, 2016: p. 1-14.

87. Webber, C.A., et al., *Field surveys of office equipment operating patterns.* Lawrence Berkeley National Laboratory, 2001.

88. Masoso, O. and L.J. Grobler, *The dark side of occupants' behaviour on building energy use.* Energy and buildings, 2010. **42**(2): p. 173-177.

89. Zhang, T., P.-O. Siebers, and U. Aickelin, *Modelling electricity consumption in office buildings: An agent based approach.* Energy and Buildings, 2011. **43**(10): p. 2882-2892.

90. Attia, S., et al., *Selection criteria for building performance simulation tools: contrasting architects' and engineers' needs.* Journal of Building Performance Simulation, 2012. **5**(3): p. 155-169.

91. Attia, S.G.M., et al., *Towards strategic use of BPS tools in Egypt.* IBPSA, 2011. **1**.

92. Attia, S., A. Evrard, and E. Gratia, *Development of benchmark models for the Egyptian residential buildings sector.* Applied Energy, 2012. **94**: p. 270-284.

93. Elharidi, A.M., P.G. Tuohy, and M.A. Teamah. *Facing the growing problem of the electric power consumption in Egyptian residential building using building performance simulation program*. in *Building Simulation Cairo 2013 Conference*. 2013.

94. ElDabosy, M.M. and M.M. AbdElrahman, *Evaluation of Office Spaces Ventilation using Simulation software El-Dakahlia Governmental Headquarter as a Pilot Renovation.* 2013.

95. Dabaieh, M., et al., *Reducing cooling demands in a hot dry climate: A simulation study for non-insulated passive cool roof thermal performance in residential buildings.* Energy and Buildings, 2015. **89**: p. 142-152.

96. Mahdy, M.M. and M. Nikolopoulou, *Evaluation of fenestration specifications in Egypt in terms of energy consumption and long term cost-effectiveness.* Energy and Buildings, 2014. **69**: p. 329-343.

97. El Mohimen, M.A., G. Hanna, and M. Krarti, *Analysis of daylighting benefits for office buildings in Egypt.* Journal of solar energy engineering, 2005. **127**(3): p. 366-370.

98. Saleem, A.A., et al., *An Analysis of Thermal Comfort and Energy Consumption within Public Primary Schools in Egypt.*

99. Sheta, W. and S. Sharples. *A Building Simulation Sustainability Analysis to Assess Dwellings in a New Cairo Development*. in *Fourth National Conference of IBPSA-USA, New York City, New York.* 2010.

100. Belda, M., et al., *Climate classification revisited: from Köppen to Trewartha.* Climate research, 2014. **59**(1): p. 1-13.

101. Crawley, D.B. *Creating weather files for climate change and urbanization impacts analysis*. in *Building Simulation*. 2007. IBPSA Beijing.

102. Peel, M.C., B.L. Finlayson, and T.A. McMahon, *Updated world map of the Köppen-Geiger climate classification.* Hydrology and earth system sciences discussions, 2007. **4**(2): p. 439-473.

103. ASHRAE, *Standard 90.1-2007 'Energy Standard for Buildings Except Low-Rise Residential Buildings', American Society of Heating, Refrigerating and Air-Conditioning Engineering, Atlanta, GA.* 2007.

104. Beck, C., et al., *Characterizing global climate change by means of Köppen climate classification.* Klimastatusbericht, 2005. **51**: p. 139-149.

105. Fahmy, M., M.M. Mahdy, and M. Nikolopoulou, *Prediction of future energy consumption reduction using GRC envelope optimization for residential buildings in Egypt.* Energy and Buildings, 2014. **70**: p. 186-193.

106. Robaa, S., *Evaluation of sunshine duration from cloud data in Egypt.* Energy, 2008. **33**(5): p. 785-795.

107. Levermore, G. and J. Parkinson, *Analyses and algorithms for new Test Reference Years and Design Summer Years for the UK.* Building services engineering research and technology, 2006. **27**(4): p. 311-325.

108. Pedersen, L., *Use of different methodologies for thermal load and energy estimations in buildings including meteorological and sociological input parameters.* Renewable and Sustainable Energy Reviews, 2007. **11**(5): p. 998-1007.

109. Westphal, F.S. and R. Lamberts, *The use of simplified weather data to estimate thermal loads of non-residential buildings.* Energy and buildings, 2004. **36**(8): p. 847-854.

110. Marion, W. and K. Urban, *User's Manual for TMY2s: Typical Meteorological Years: Derived from the 1961-1990 National Solar Radiation Data Base*. 1995: National Renewable Energy Laboratory.

111. Forejt, L., et al. *Weather data around the world for design of field hospital HVAC*. in *Proceedings international air-conditioning and ventilation conference*. 2006.

112. CIBSE, *TM24 Environmental factors affecting office worker performance: A review of evidence, The Chartered Institution of Building Services Engineers*. 1999.

113. Fanger, P.O., *Thermal comfort. Analysis and applications in environmental engineering.* Thermal comfort. Analysis and applications in environmental engineering., 1970.

114. ASHRAE/ANSI, *Standard 55-2004, Thermal environmental conditions for human occupancy, American Society of Heating, Refrigerating and Air-Conditioning Engineering, Atlanta, GA*. 2004.

115. Nicol, J.F. and M.A. Humphreys, *Adaptive thermal comfort and sustainable thermal standards for buildings.* Energy and buildings, 2002. **34**(6): p. 563-572.

116. ASHRAE/ANSI, *Standard 55-2013, Thermal environmental conditions for human occupancy, American Society of Heating, Refrigerating and Air-Conditioning Engineering, Atlanta, GA*. 2013.

117. ISO7726, *Ergonomics of the thermal environment. Instruments for measuring physical quantities, 2001. P5*.

118. Lomas, K.J. and S.M. Porritt, *Overheating in buildings: lessons from research*. 2017, Taylor & Francis.

119. Parkinson, T., A. Parkinson, and R. De Dear, *Introducing the SAMBA indoor environmental quality monitoring system*, in *49th International Conference of the Architectural Science Association*. 2015: Sydney, Australia. p. 1139–1148.

120. de Dear, R. and G.S. Brager, *The adaptive model of thermal comfort and energy conservation in the built environment.* International Journal of Biometeorology, 2001. **45**(2): p. 100-108.

121. Hellwig, R., S. Brasche, and W. Bischof. *Thermal Comfort in Offices–Natural Ventilation vs. Air Conditioning*. in *Proceedings of congress Comfort and Energy Use in Buildings–Getting it Right, Winsor*. 2006.

122. Attia, S. and S. Carlucci, *Impact of different thermal comfort models on zero energy residential buildings in hot climate.* Energy and Buildings, 2015. **102**: p. 117-128.

123. Nicol, F., *Adaptive thermal comfort standards in the hot–humid tropics.* Energy and Buildings, 2004. **36**(7): p. 628-637.

124. Givoni, B., *Climate considerations in building and urban design*. 1998: John Wiley & Sons.

125. De Dear, R.J. and G.S. Brager, *Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55.* Energy and buildings, 2002. **34**(6): p. 549-561.

126. Oseland, N.A., *Predicted and reported thermal sensation in climate chambers, offices and homes.* Energy and Buildings, 1995. **23**(2): p. 105-115.

127. Van der Linden, A., et al., *Adaptive temperature limits: A new guideline in The Netherlands: A new approach for the assessment of building performance with respect to thermal indoor climate.* Energy and buildings, 2006. **38**(1): p. 8-17.

128. EN15251, *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. European Committee for Standardization, Brussels, Belgium*. 2007.

129. Fanger, P.O. and J. Toftum, *Extension of the PMV model to non-air-conditioned buildings in warm climates.* Energy and buildings, 2002. **34**(6): p. 533-536.

130. Nicol, F. and I. Raja, *Thermal comfort, time and posture: exploratory studies in the nature of adaptive thermal comfort*. 1996: Oxford Brookes University, School of Architecture.

131. Janda, K.B. and J.F. Busch, *Worldwide status of energy standards for buildings.* Energy, 1994. **19**(1): p. 27-44.

132. Iwaro, J. and A. Mwasha, *A review of building energy regulation and policy for energy conservation in developing countries.* Energy Policy, 2010. **38**(12): p. 7744-7755.

133. Fong, K.F., V.I. Hanby, and T.-T. Chow, *HVAC system optimization for energy management by evolutionary programming.* Energy and Buildings, 2006. **38**(3): p. 220-231.

134. Arens, E., et al., *Are ‘class A’temperature requirements realistic or desirable?* Building and Environment, 2010. **45**(1): p. 4-10.

135. Chow, T. and J. Lam, *Thermal comfort and energy conservation in commercial buildings in Hong Kong.* Architectural Science Review, 1992. **35**(2): p. 67-72.

136. Mui, K.W.H. and W.T.D. Chan, *Adaptive comfort temperature model of air-conditioned building in Hong Kong.* Building and environment, 2003. **38**(6): p. 837-852.

137. Nicol, F. and S. Roaf, *Pioneering new indoor temperature standards: the Pakistan project.* Energy and Buildings, 1996. **23**(3): p. 169-174.

138. Roussac, A.C., J. Steinfeld, and R. de Dear, *A preliminary evaluation of two strategies for raising indoor air temperature setpoints in office buildings.* Architectural Science Review, 2011. **54**(2): p. 148-156.

139. Sadineni, S.B. and R.F. Boehm, *Measurements and simulations for peak electrical load reduction in cooling dominated climate.* Energy, 2012. **37**(1): p. 689-697.

140. Zmeureanu, R. and A. Doramajian, *Thermally acceptable temperature drifts can reduce the energy consumption for cooling in office buildings.* Building and Environment, 1992. **27**(4): p. 469-481.

141. ISO7730, *Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, Ergonomics of the thermal environment, International Organization for Standards, Geneva (2005): P52.* 2005.

142. Paliaga, G., *Moving air for comfort.* ASHRAE journal, 2009. **51**(5): p. 18.

143. Toftum, J., *Air movement–good or bad?* Indoor Air, 2004. **14**(s7): p. 40-45.

144. https://www.energyinst.org/home.

145. Haneda, M., et al., *A field measurement of thermal environment in COOL BIZ office and the evaluation on productivity by a questionnaire survey*. Journal of Environmental Engineering, 2009. **74**(637): p. 389-396.

146. Westphal, F.S. and R. Lamberts. *Building simulation calibration using sensitivity analysis*. in *Ninth International IBPSA Conference*. 2005. Citeseer.

147. ASHRAE, *Standard 90.1-2010'Energy Standard for Buildings Except Low-Rise Residential Buildings',American Society of Heating, Refrigerating and Air-Conditioning Engineering, Atlanta, GA*. 2010.

148. Nicol, F. and M. Humphreys, *Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251.* Building and Environment, 2010. **45**(1): p. 11-17.

149. Taleghani, M., et al., *A review into thermal comfort in buildings.* Renewable and Sustainable Energy Reviews, 2013. **26**: p. 201-215.

150. https://energyplus.net/weather-location/africa_wmo_region_1/EGY//EGY_Alexandria.623180_ETMY.

151. Zhang, Q., J. Huang, and S. Lang, *Development of typical year weather data for Chinese locations/Discussion.* ASHRAE transactions, 2002. **108**: p. 1063.

152. Royapoor, M. and T. Roskilly, *Building model calibration using energy and environmental data.* Energy and Buildings, 2015. **94**: p. 109-120.

153. IES-VE, *Virtual Environment (VE) by Integrated Environmental Solutions (IES)*. 2014.

154. Tahmasebi, F., et al., *Simulation model calibration: an optimization-based approach.* BauSIM 2012, 2012. **1**.

155. Ali, A.A.E.-M.M., *Using simulation for studying the influence of vertical shading devices on the thermal performance of residential buildings (Case study: New Assiut City).* Ain Shams Engineering Journal, 2012. **3**(2): p. 163-174.

156. Iqbal, I. and M.S. Al-Homoud, *Parametric analysis of alternative energy conservation measures in an office building in hot and humid climate.* Building and environment, 2007. **42**(5): p. 2166-2177.

157. Givoni, B., *Effectiveness of mass and night ventilation in lowering the indoor daytime temperatures. Part I: 1993 experimental periods.* Energy and Buildings, 1998. **28**(1): p. 25-32.

158. *http://www.msrintranet.capmas.gov.eg*.

159. Hui, S.C. and K. Cheung. *Multi-year (MY) building simulation: is it useful and practical*. in *Proc. of the IBPSA Building Simulation'97 Conference*. 1997.

160. Crawley, D.B., J.W. Hand, and L.K. Lawrie. *Improving the weather information available to simulation programs*. in *Proceedings of Building Simulation'99*. 1999. Citeseer.

161. Dorm, M. and R. Amor, *The creation of weather data files to fulfil the simulation needs of New Zealand.* 1993.

162. Kershaw, T., M. Eames, and D. Coley, *Comparison of multi-year and reference year building simulations.* Building Services Engineering Research and Technology, 2010. **31**(4): p. 357-369.

163. Narowski, P., M. Janicki, and D. Heim. *Comparison of Untypical Meteorological Years (UMY) and their influence on building energy performance simulations*. in *Proc. of Conference "Building Simulation–BS2013", Le Bourget-du-Lac*. 2013.

164. Georgiou, G., et al., *A study of the effect of weighting indices for the development of TMY used for building simulation.* 2013.

165. Corrado, V., H.E. Mechri, and E. Fabrizio. *Building energy performance assessment through simplified models: application of the ISO 13790 quasi-steady state method*. in *Proceedings of building simulation*. 2007.

166. Morton, E.M. and P.G. Tuohy. *Embracing variations in patterns of use, pre and post design phase, to improve tenant energy performance*. in *4th Annual CIBSE ASHRAE Technical Symposium*. 2014.

167. Rijal, H.B., et al. *An algorithm to represent occupant use of windows and fans including situation-specific motivations and constraints*. in *Building Simulation*. 2011. Springer.

168. Persily, A. and W.S. Dols, *The relation of CO 2 concentration to office building ventilation*, in *Air change rate and airtightness in buildings*. 1990, ASTM International.

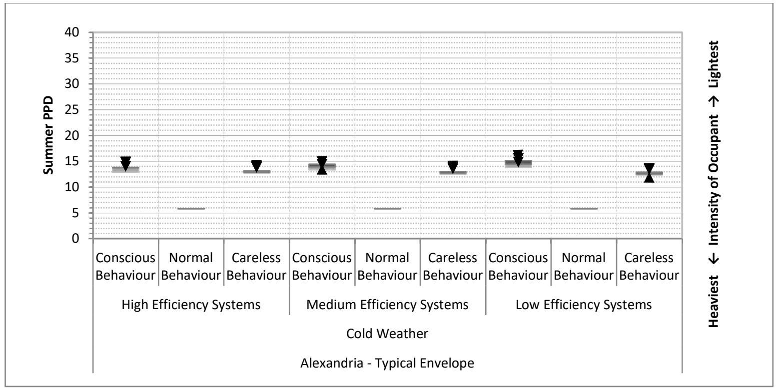
169. Persily, A.K., *Evaluating building IAQ and ventilation with indoor carbon dioxide.* Transactions-American society of heating refrigerating and air conditioning engineers, 1997. **103**: p. 193-204.

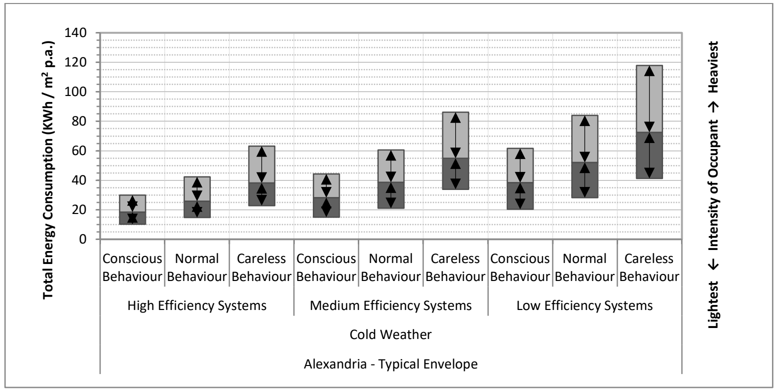
170. Seppänen, O., W. Fisk, and M. Mendell, *Association of ventilation rates and CO2 concentrations with health andother responses in commercial and institutional buildings.* Indoor air, 1999. **9**(4): p. 226-252.

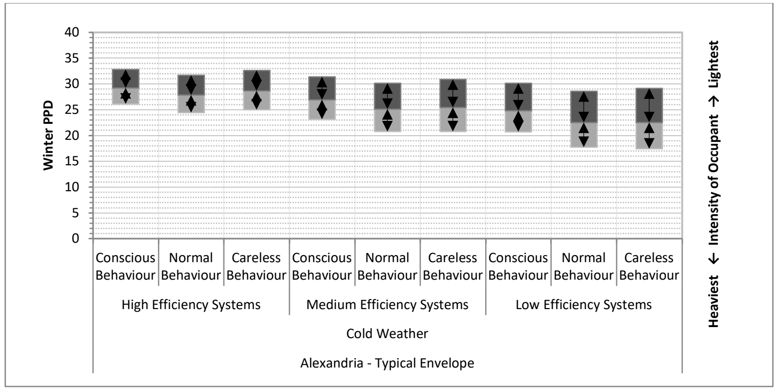
171. Menezes, A.C., et al., *Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap.* Applied Energy, 2012. **97**: p. 355-364.

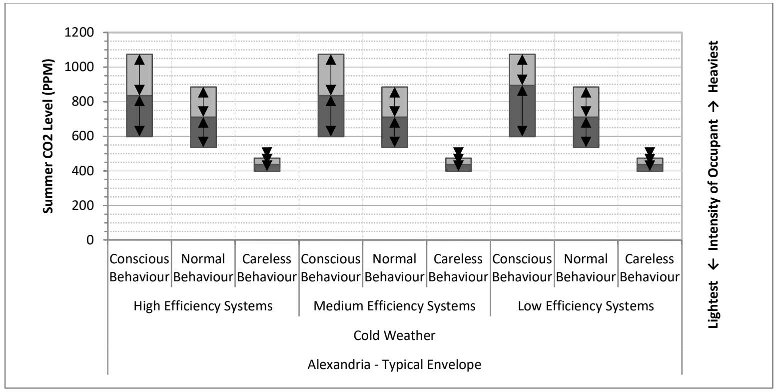
Appendices

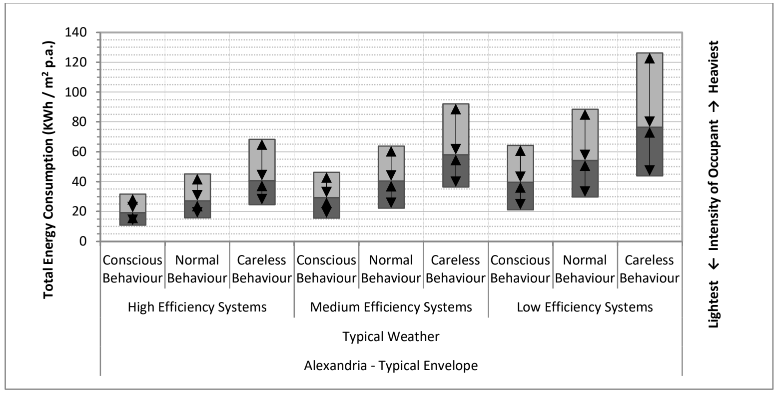
Appendix A (Performance Analysis Results)

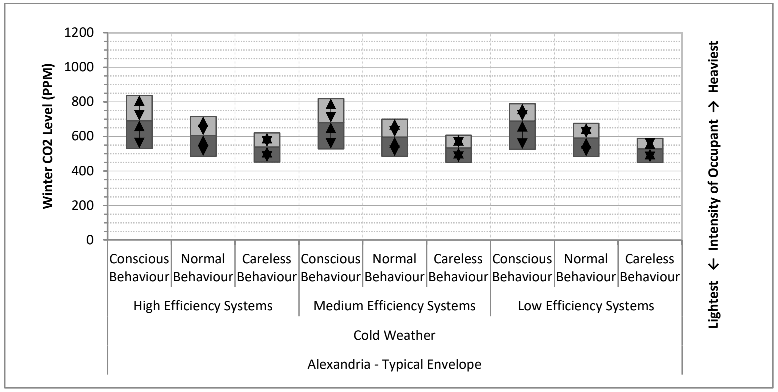


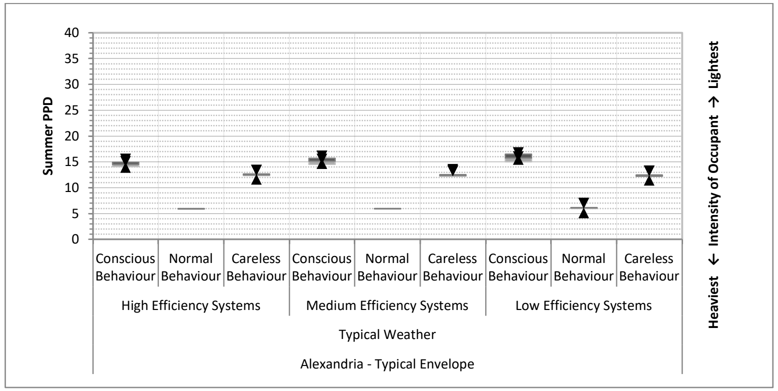


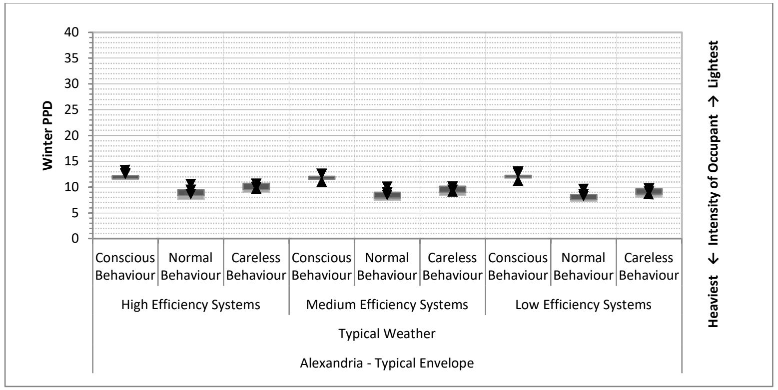


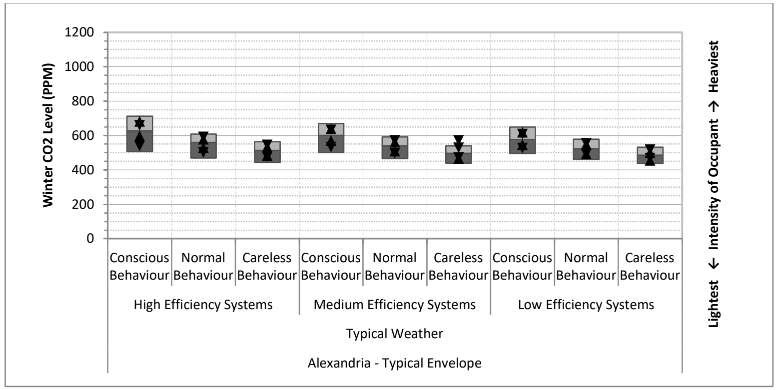

Summer CO2 Level (PPM)
1200
1000
800
600
400
200
0
Conscious Behaviour
Normal Behaviour
Careless Behaviour
High Efficiency Systems
Medium Efficiency Systems
Low Efficiency Systems
Cold Weather
Alexandria - Typical Envelope
Lightest ← Intensity of Occupant → Heaviest

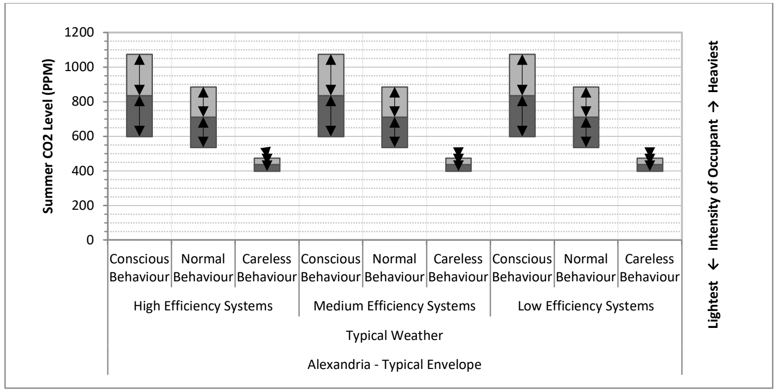

Total Energy Consumption (KWh / m² p.a.)
140
120
100
80
60
40
20
0
Conscious Behaviour
Normal Behaviour
Careless Behaviour
High Efficiency Systems
Medium Efficiency Systems
Low Efficiency Systems
Typical Weather
Alexandria - Typical Envelope
Lightest ← Intensity of Occupant → Heaviest

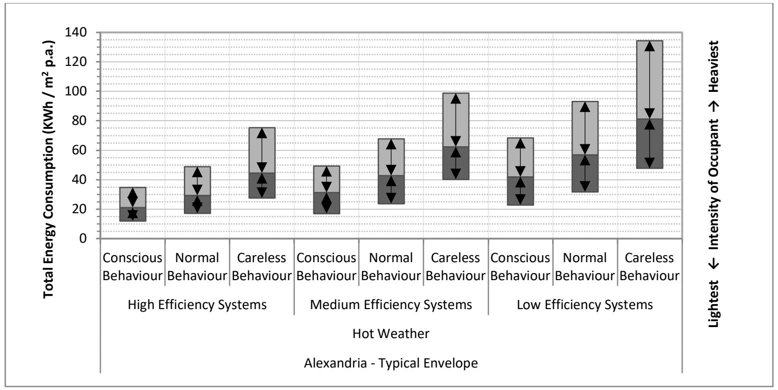

Winter CO2 Level (PPM)
1200
1000
800
600
400
200
0
Conscious Behaviour
Normal Behaviour
Careless Behaviour
High Efficiency Systems
Medium Efficiency Systems
Low Efficiency Systems
Cold Weather
Alexandria - Typical Envelope
Lightest ← Intensity of Occupant → Heaviest

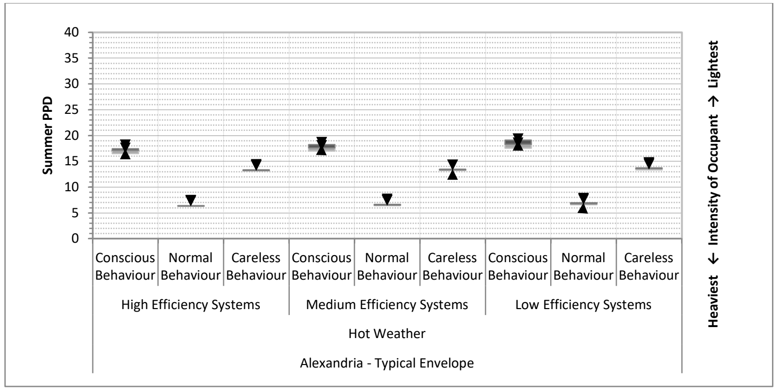

Summer PPD
40
35
30
25
20
15
10
5
0
Conscious Behaviour
Normal Behaviour
Careless Behaviour
High Efficiency Systems
Medium Efficiency Systems
Low Efficiency Systems
Typical Weather
Alexandria - Typical Envelope
Heaviest ← Intensity of Occupant → Lightest


Winter PPD
Conscious Behaviour
Normal Behaviour
Careless Behaviour
High Efficiency Systems
Medium Efficiency Systems
Low Efficiency Systems
Typical Weather
Alexandria - Typical Envelope
Heaviest ← Intensity of Occupant → Lightest


Winter CO2 Level (PPM)
Conscious Behaviour
Normal Behaviour
Careless Behaviour
High Efficiency Systems
Medium Efficiency Systems
Low Efficiency Systems
Typical Weather
Alexandria - Typical Envelope
Lightest ← Intensity of Occupant → Heaviest


Summer CO2 Level (PPM)
Conscious Behaviour
Normal Behaviour
Careless Behaviour
High Efficiency Systems
Medium Efficiency Systems
Low Efficiency Systems
Typical Weather
Alexandria - Typical Envelope
Lightest ← Intensity of Occupant → Heaviest


Total Energy Consumption (KWh / m² p.a.)
Conscious Behaviour
Normal Behaviour
Careless Behaviour
High Efficiency Systems
Medium Efficiency Systems
Low Efficiency Systems
Hot Weather
Alexandria - Typical Envelope
Lightest ← Intensity of Occupant → Heaviest


Summer PPD
Conscious Behaviour
Normal Behaviour
Careless Behaviour
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Medium Efficiency Systems
Low Efficiency Systems
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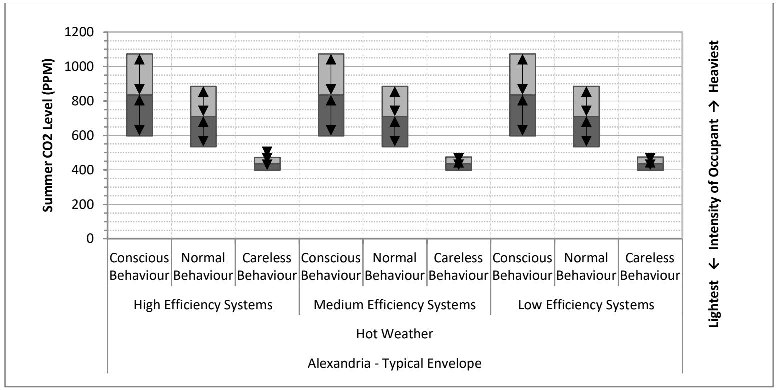
Summer CO2 Level (PPM)
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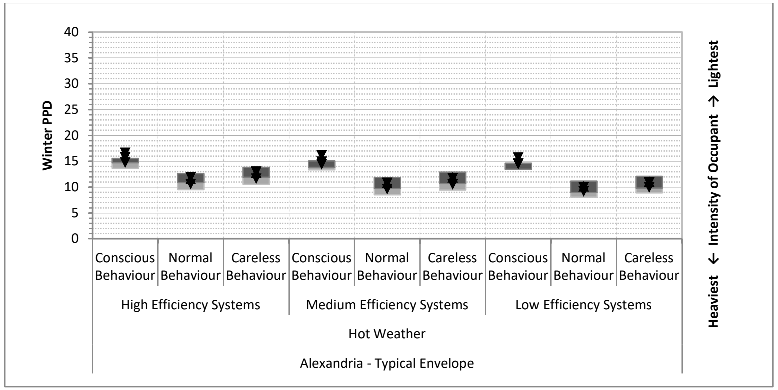
Winter PPD
Conscious Behaviour
Normal Behaviour
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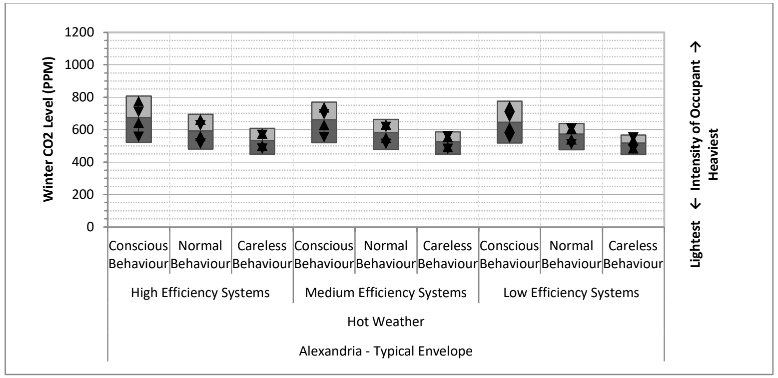
Winter CO2 Level (PPM)
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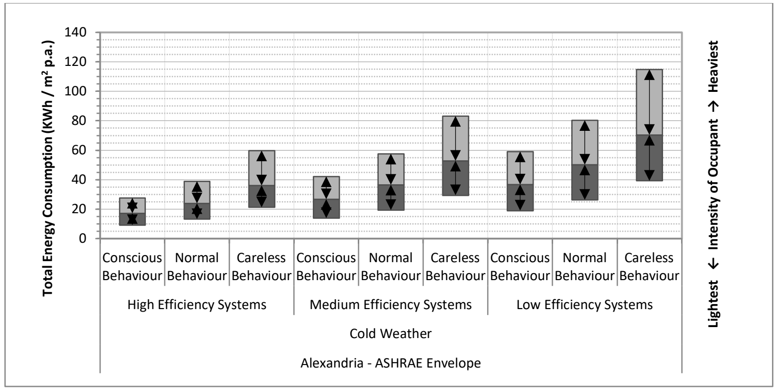
Total Energy Consumption (KWh / m² p.a.)
140
120
100
80
60
40
20
0
Conscious Behaviour
Normal Behaviour
Careless Behaviour
High Efficiency Systems
Medium Efficiency Systems
Low Efficiency Systems
Cold Weather
Alexandria - ASHRAE Envelope
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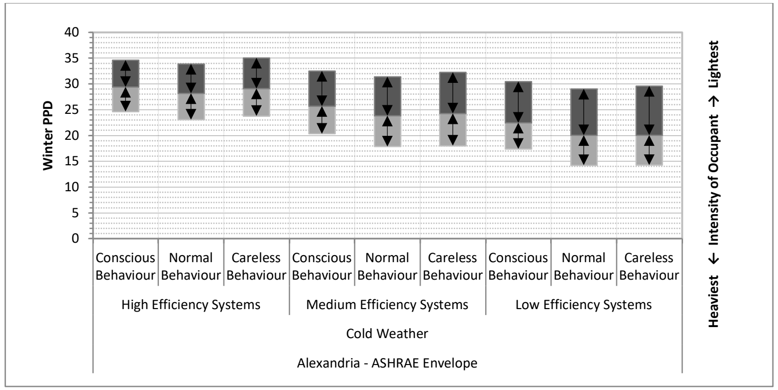
Winter PPD
40
35
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25
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15
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5
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Conscious Behaviour
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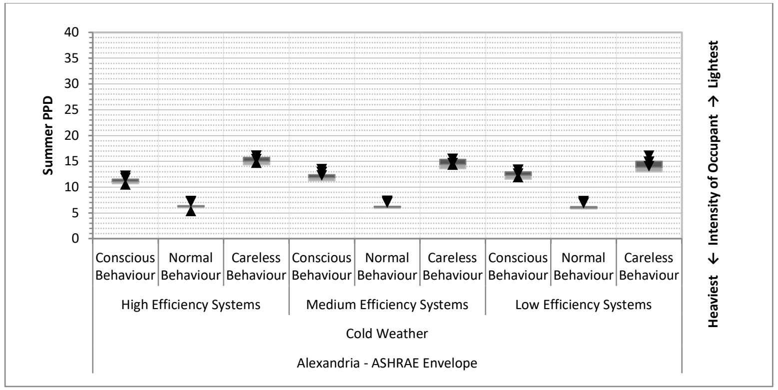
Summer PPD
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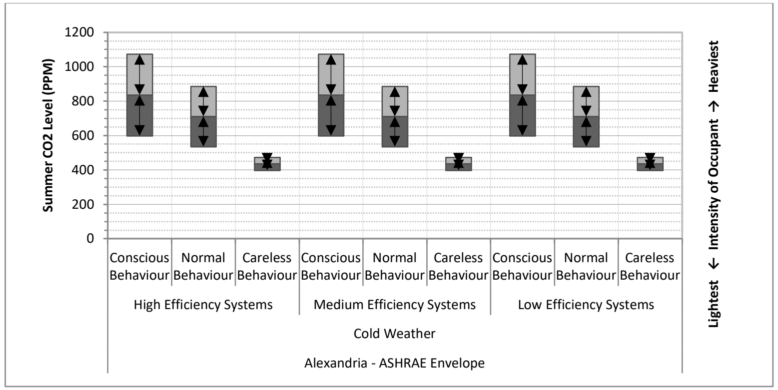
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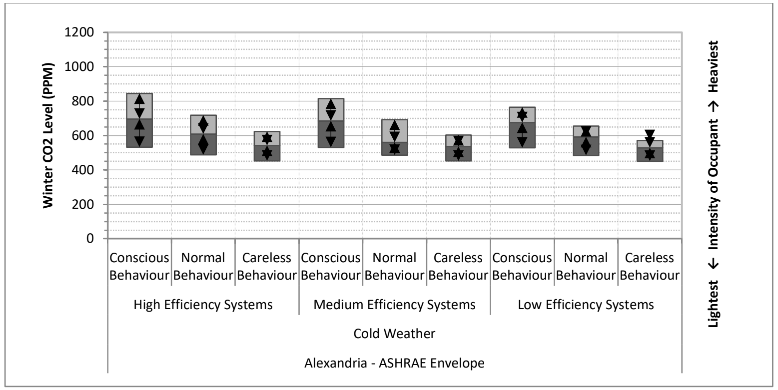
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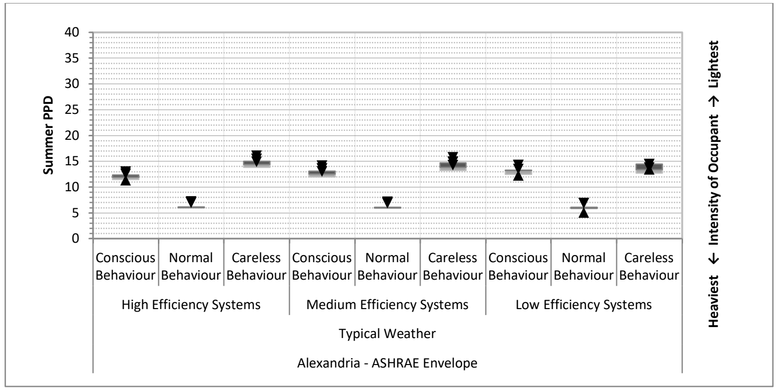
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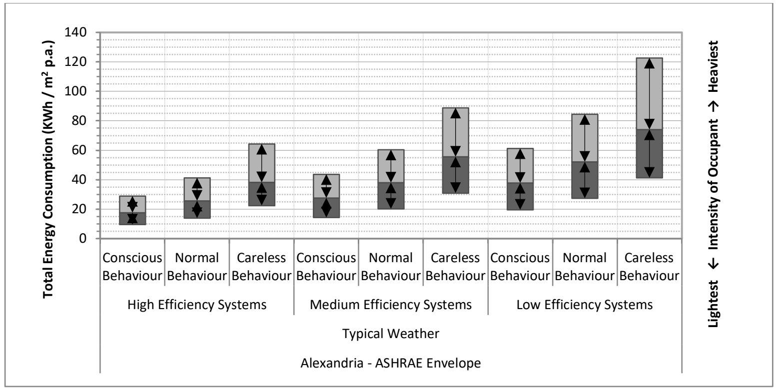
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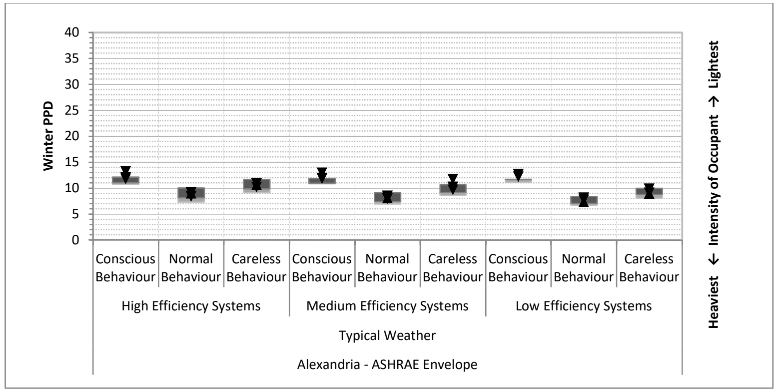
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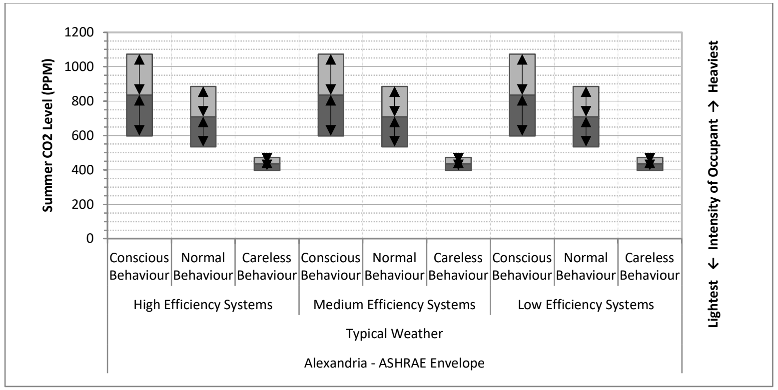
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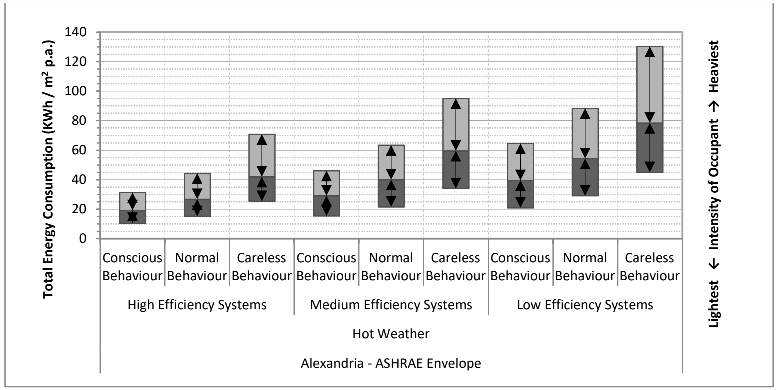
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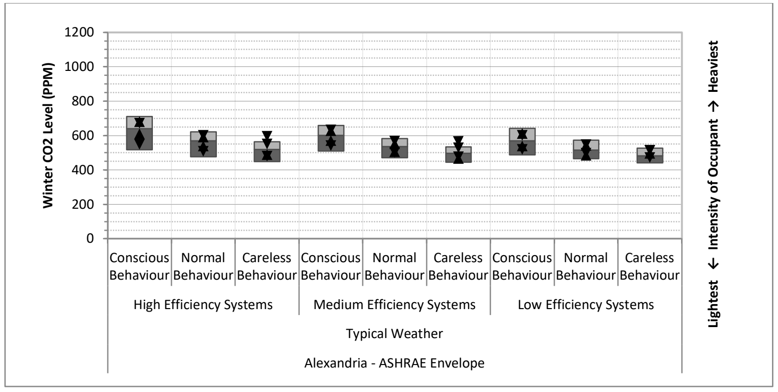
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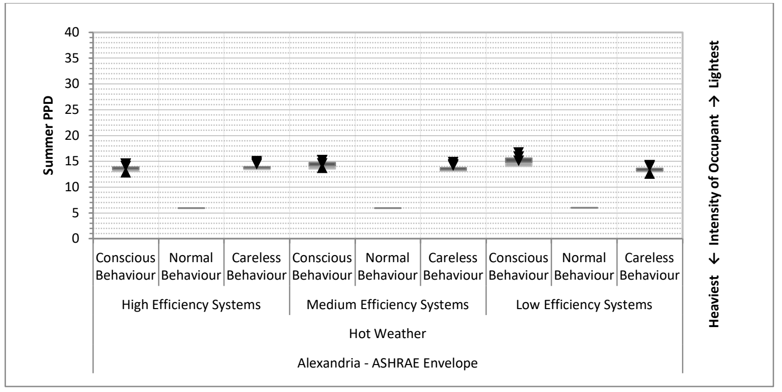
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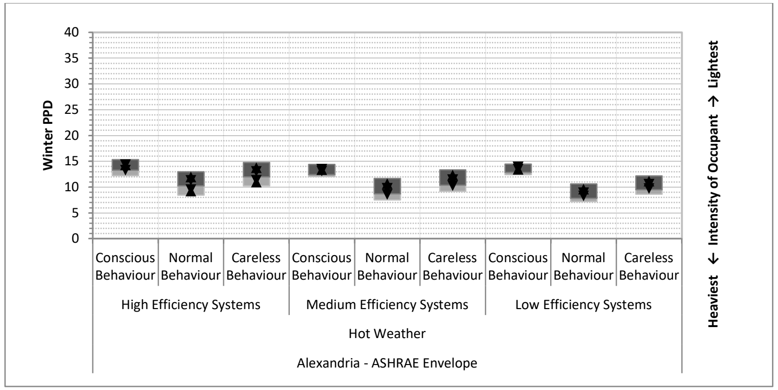
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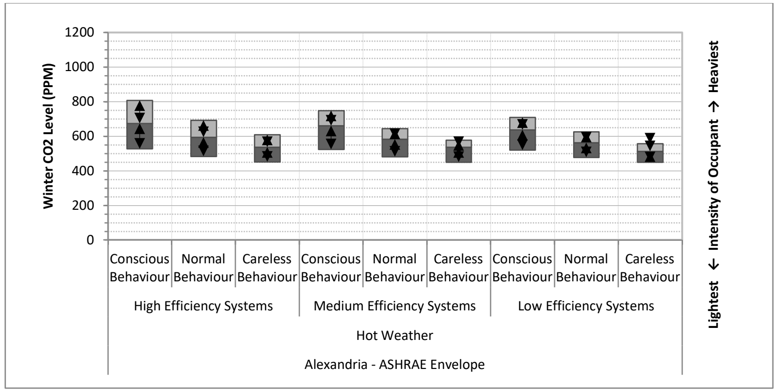
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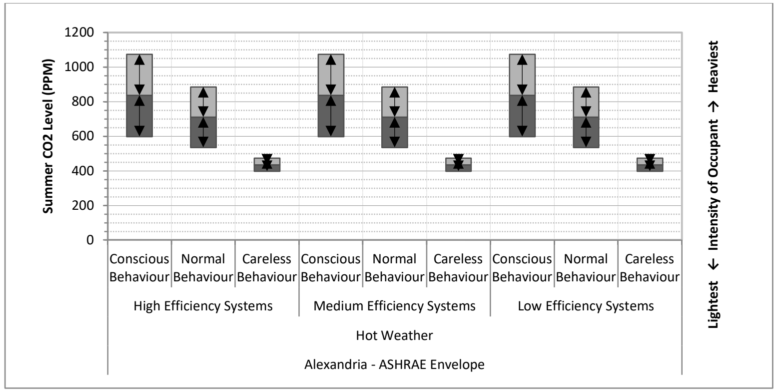
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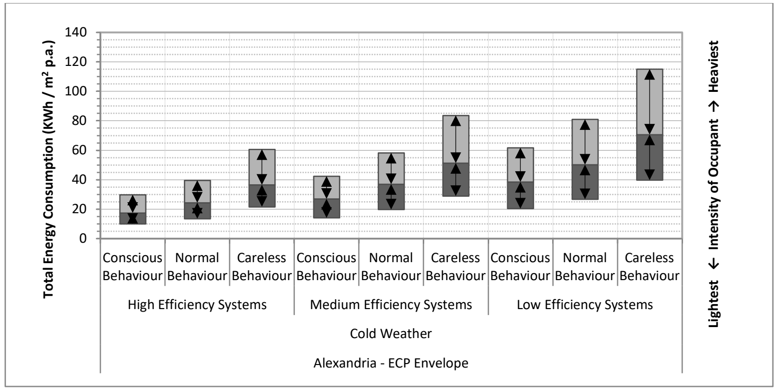
Total Energy Consumption (KWh / m² p.a.)
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Low Efficiency Systems
Cold Weather
Alexandria - ECP Envelope
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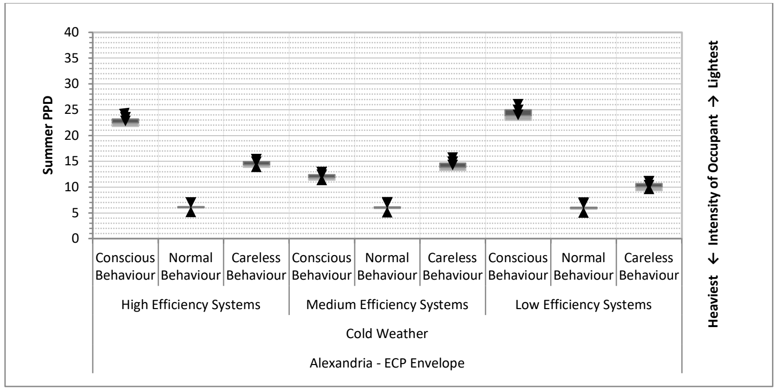
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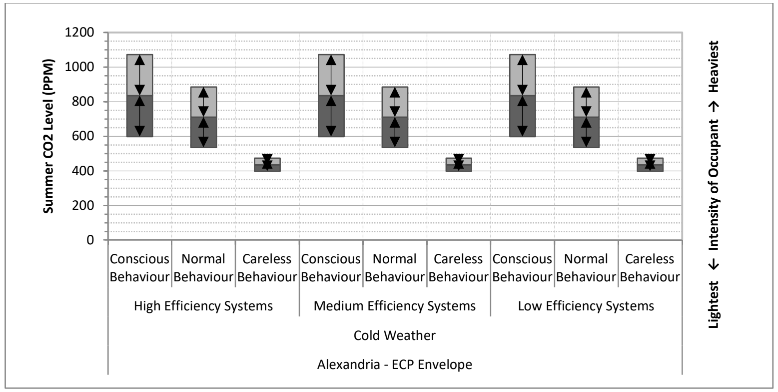
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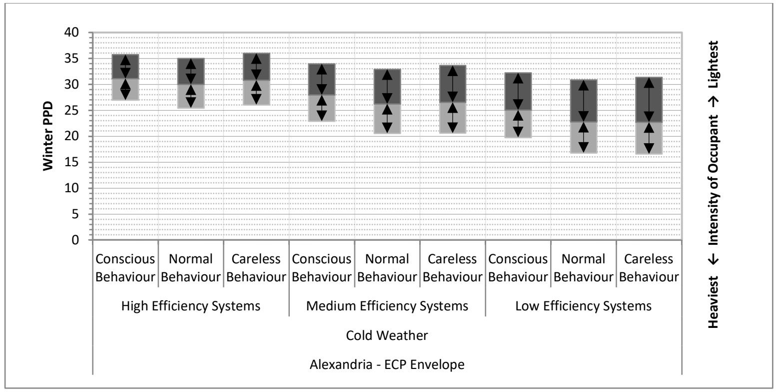
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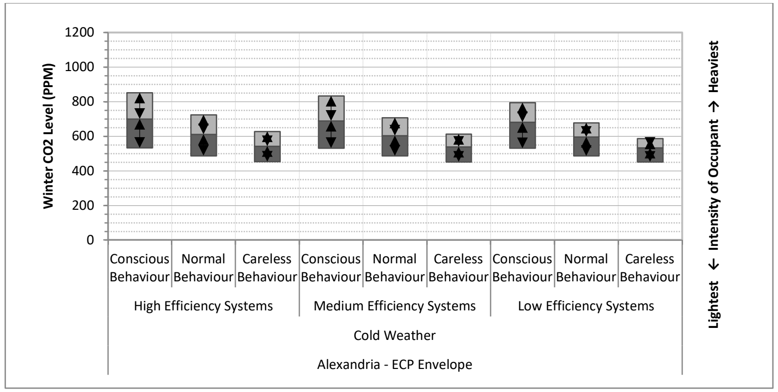
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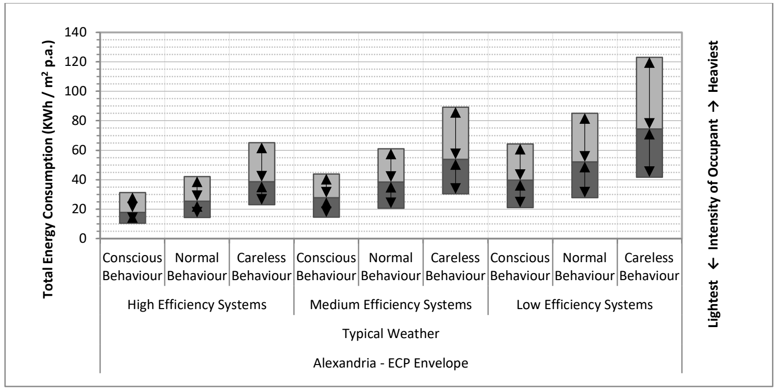
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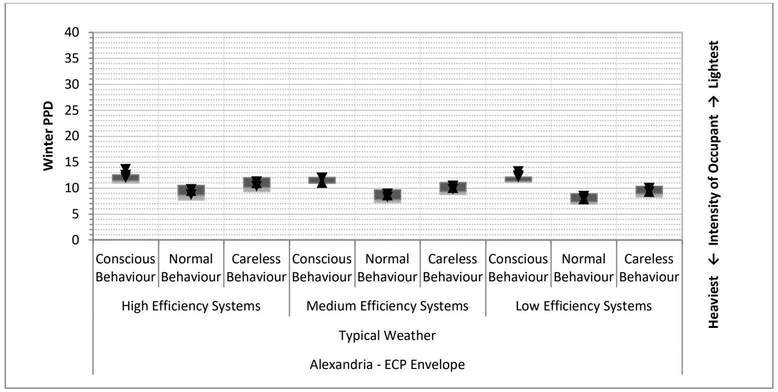
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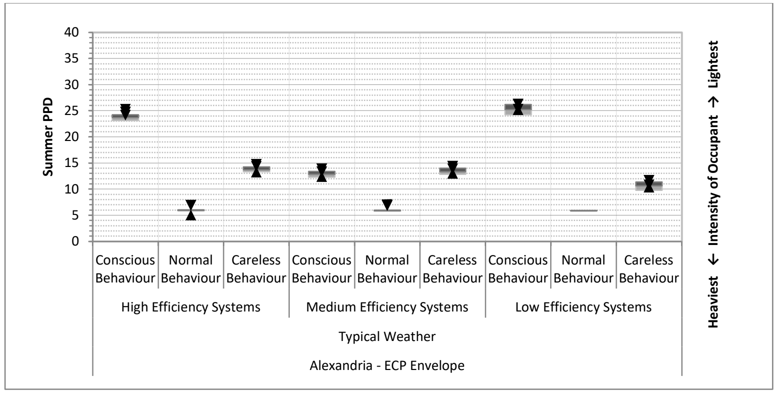
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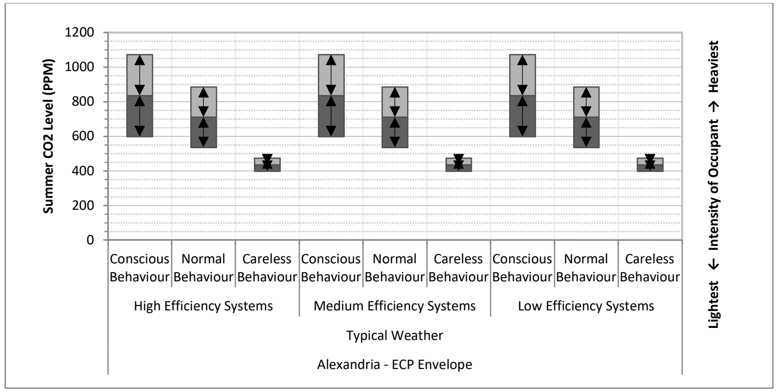
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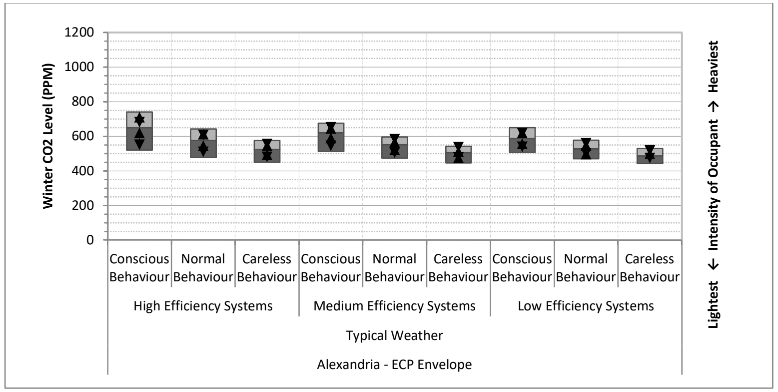
Winter CO2 Level (PPM)
0
200
400
600
800
1000
1200
Conscious Behaviour
Normal Behaviour
Careless Behaviour
High Efficiency Systems
Medium Efficiency Systems
Low Efficiency Systems
Typical Weather
Alexandria - ECP Envelope
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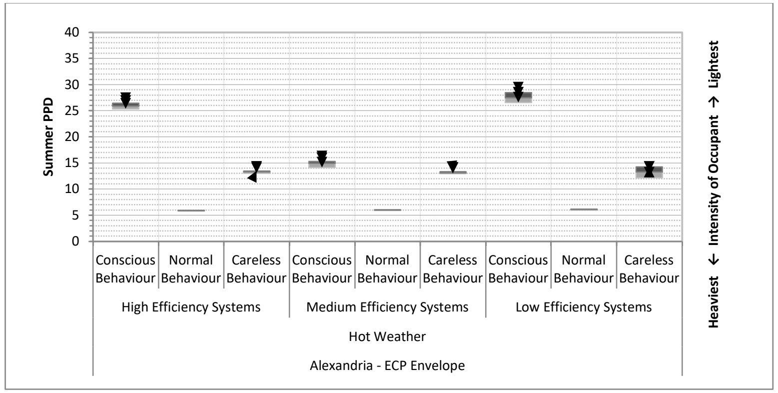
Summer PPD
0
5
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15
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25
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35
40
Conscious Behaviour
Normal Behaviour
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High Efficiency Systems
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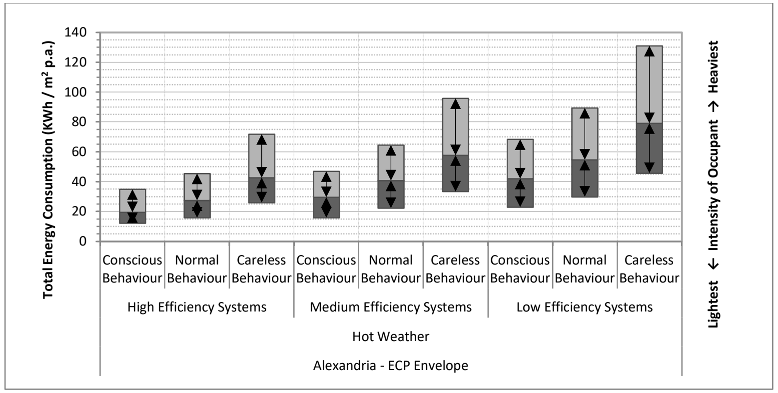
Total Energy Consumption (KWh / m² p.a.)
0
20
40
60
80
100
120
140
Conscious Behaviour
Normal Behaviour
Careless Behaviour
High Efficiency Systems
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Hot Weather
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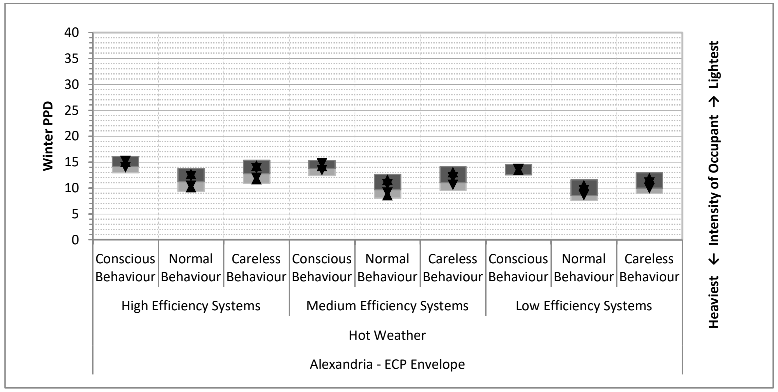
Winter PPD
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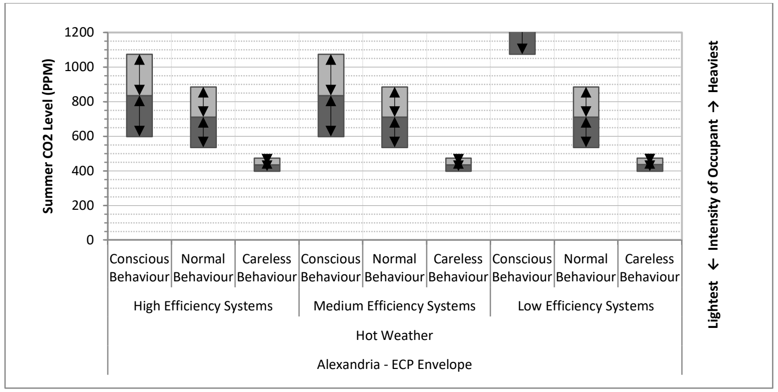
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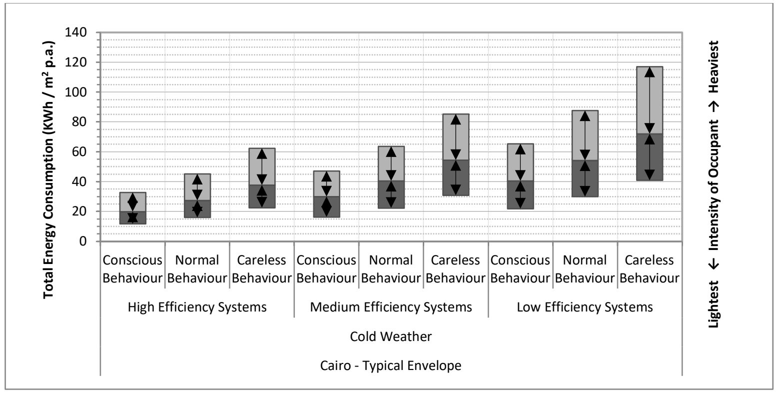
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Cold Weather
Cairo - Typical Envelope
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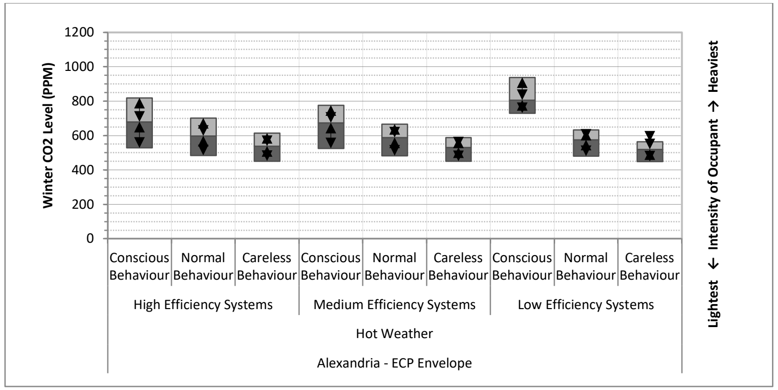
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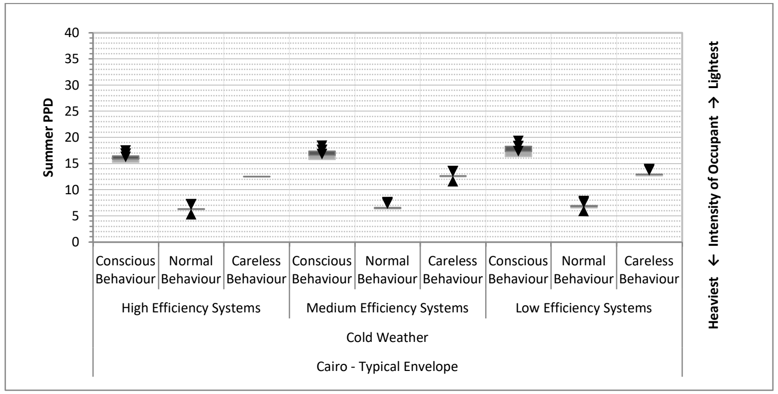
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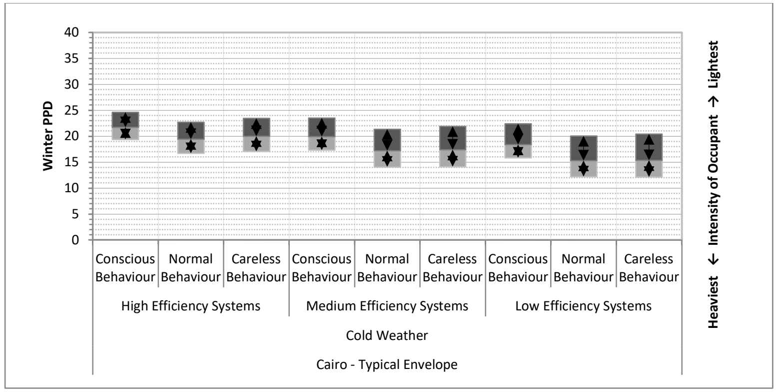
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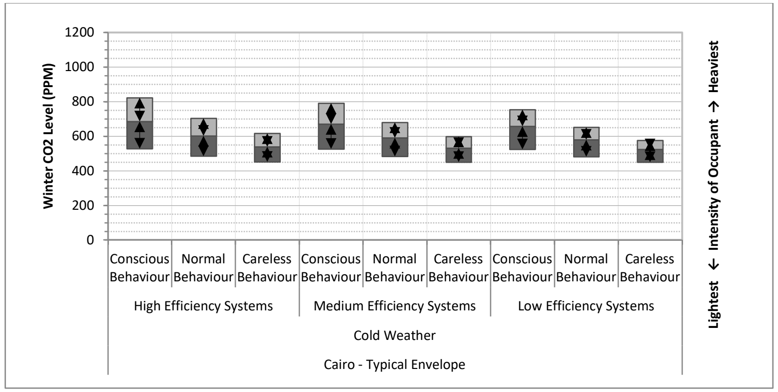
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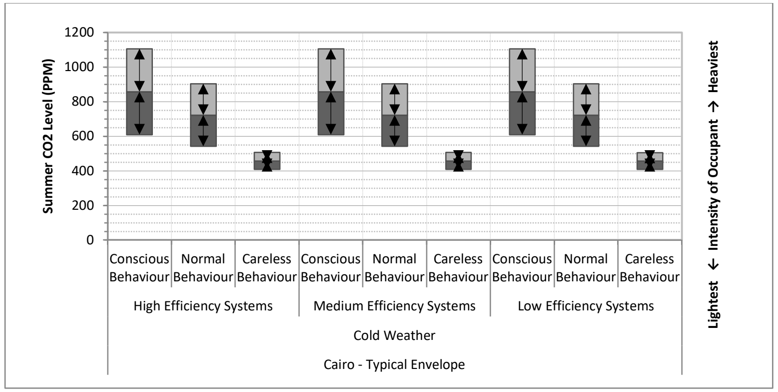
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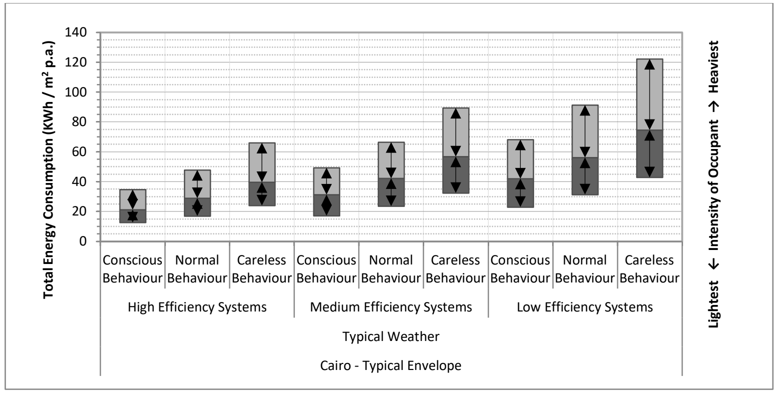
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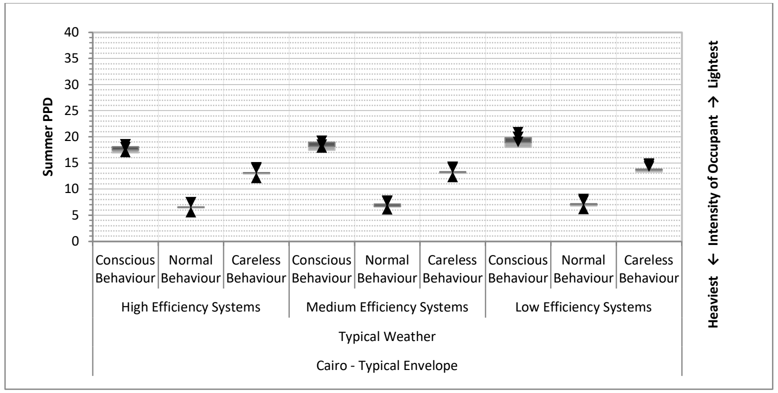
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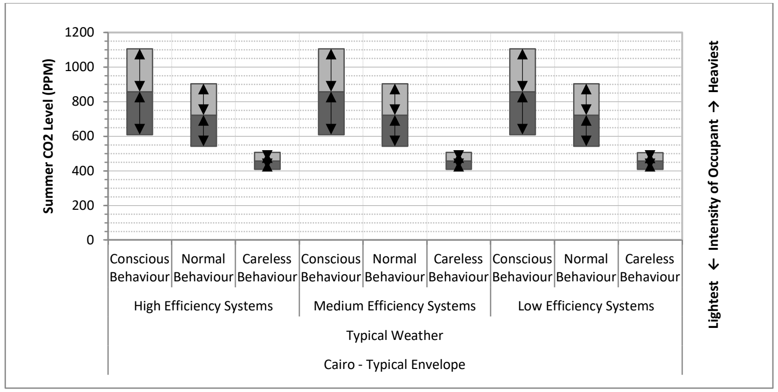
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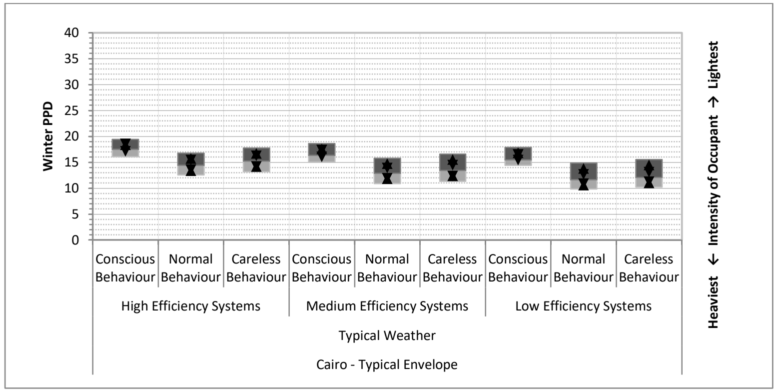
Winter PPD
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Conscious Behaviour
Normal Behaviour
Careless Behaviour
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Medium Efficiency Systems
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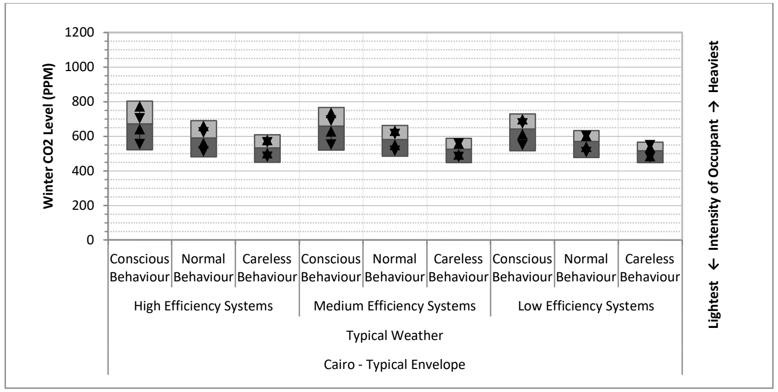
Winter CO2 Level (PPM)
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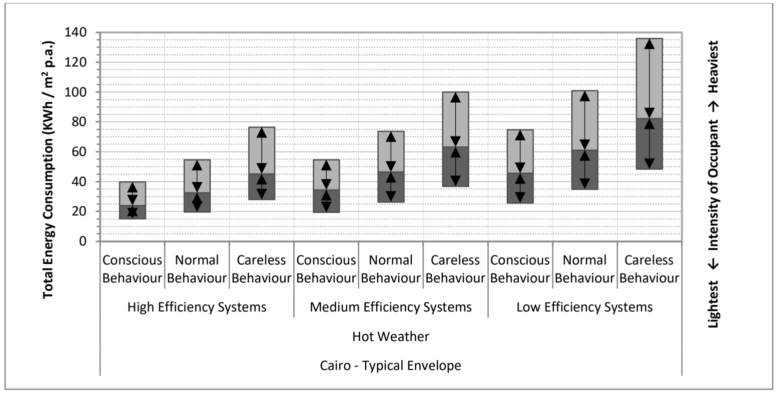
Total Energy Consumption (KWh / m² p.a.)
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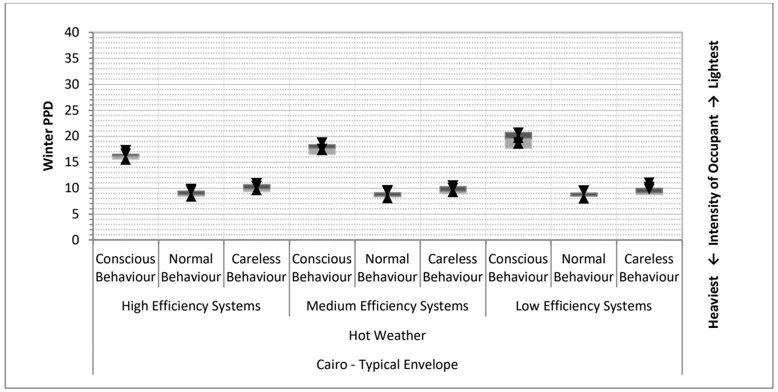
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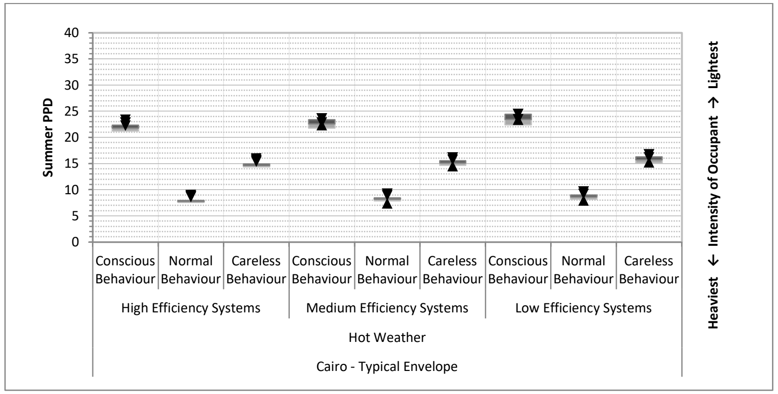
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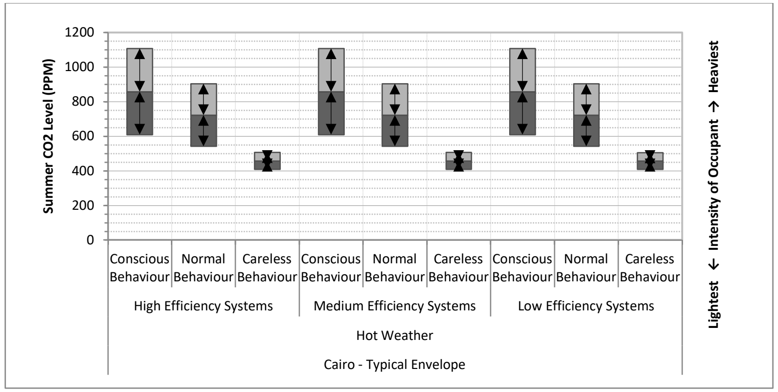
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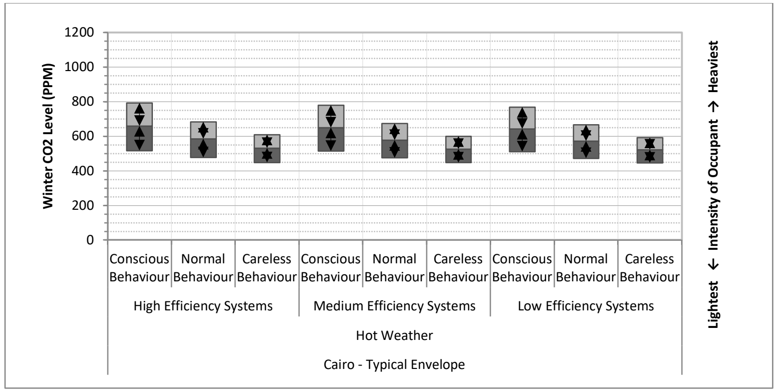
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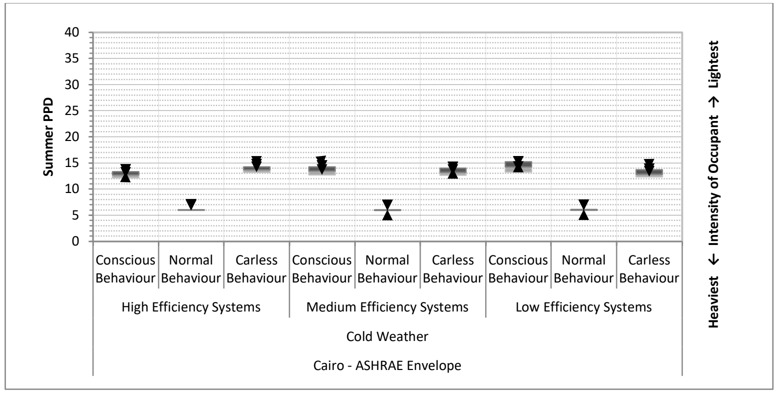
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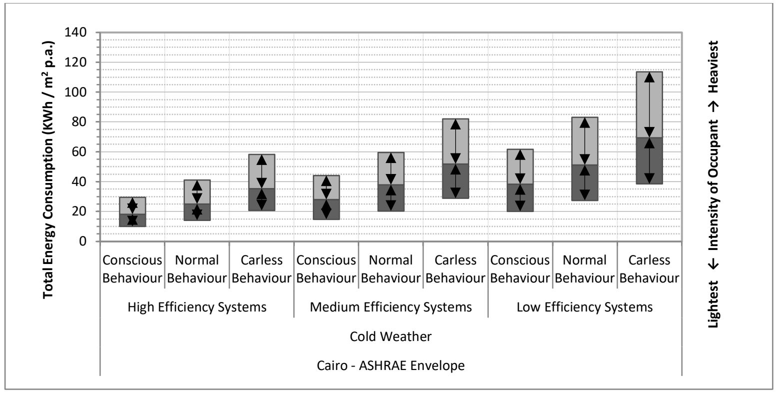
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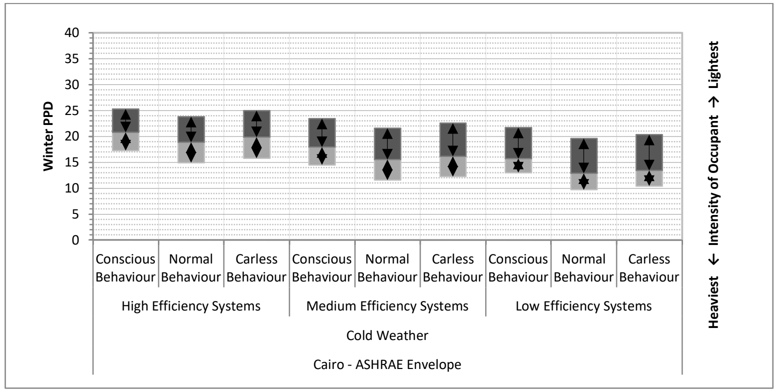
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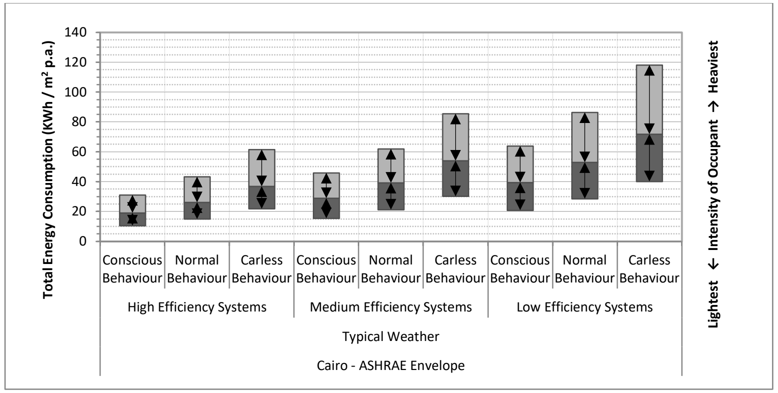
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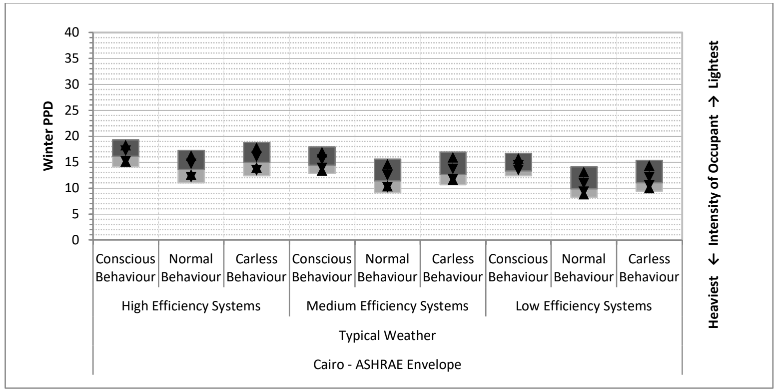
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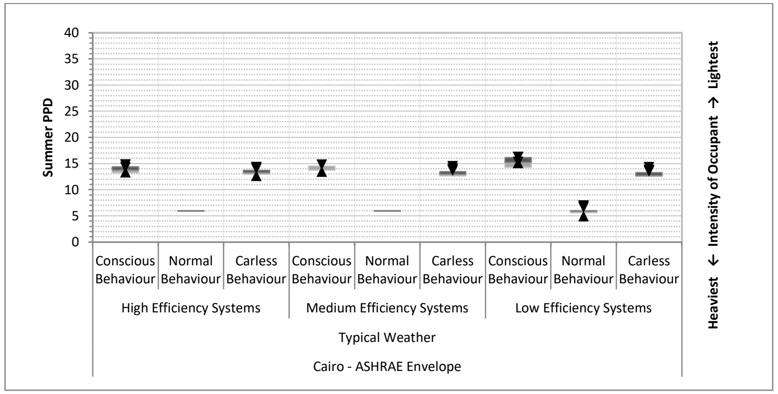
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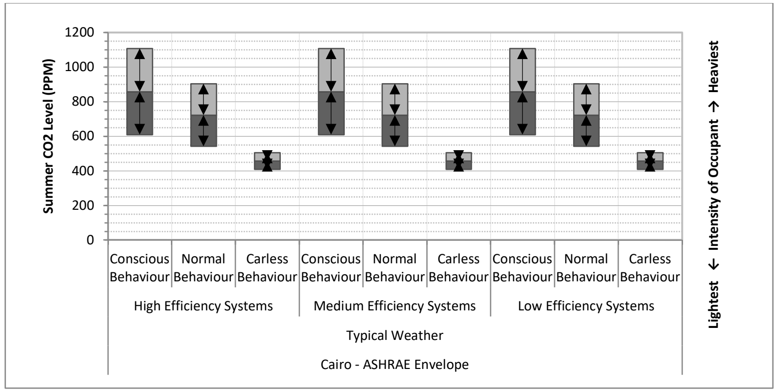
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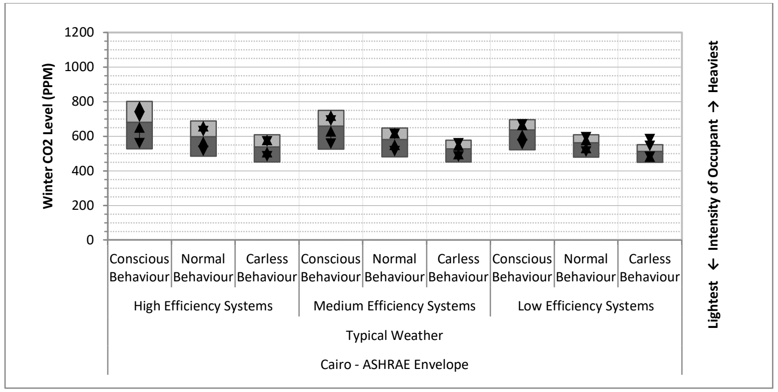
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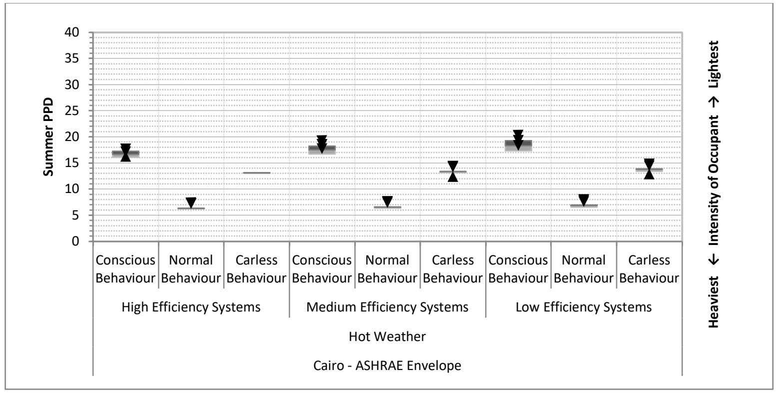
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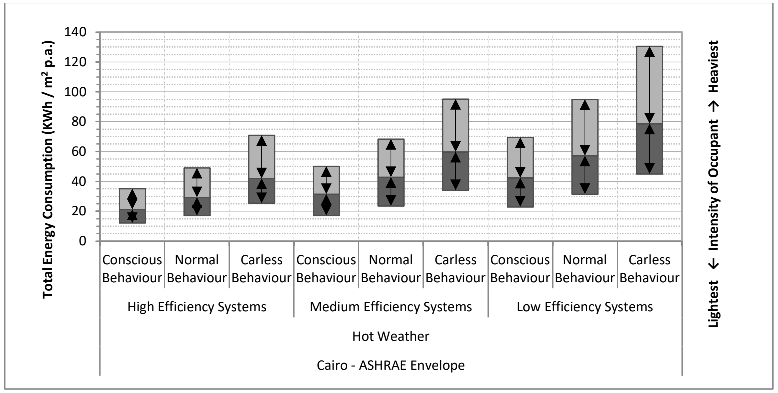
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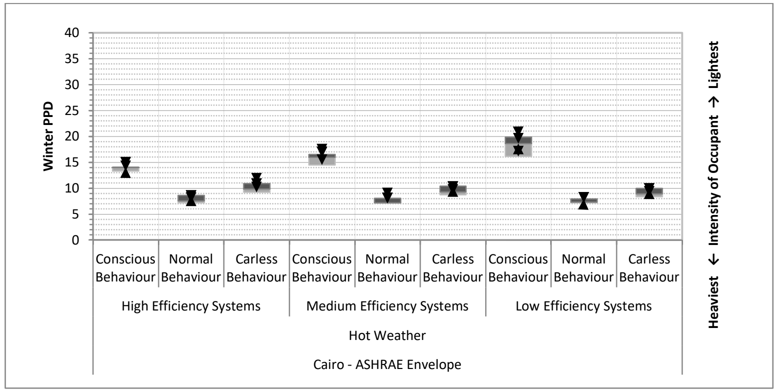
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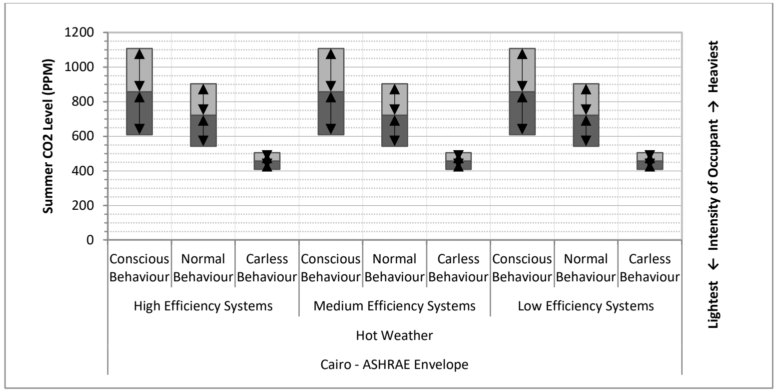
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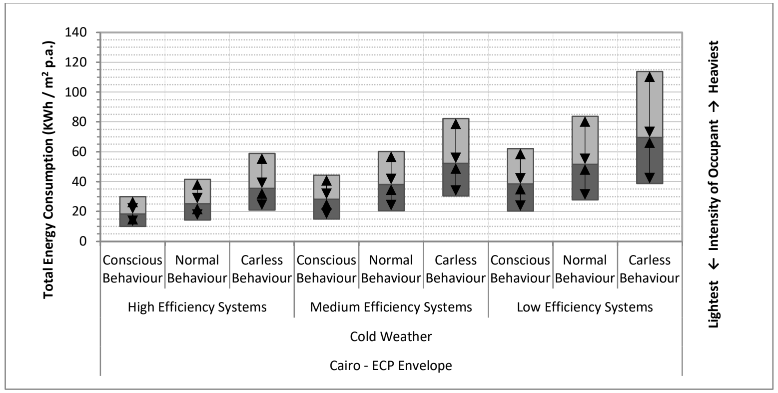
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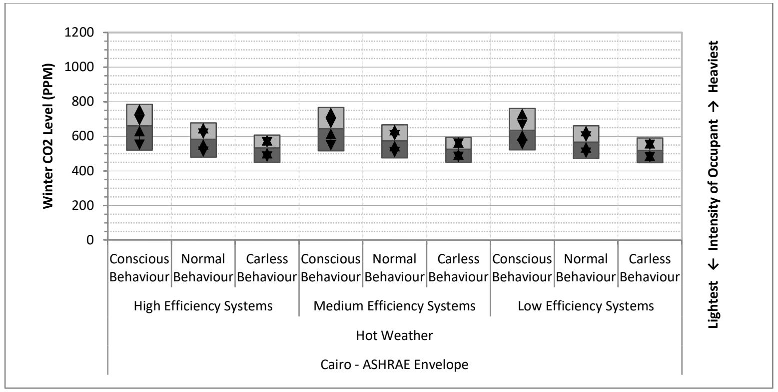
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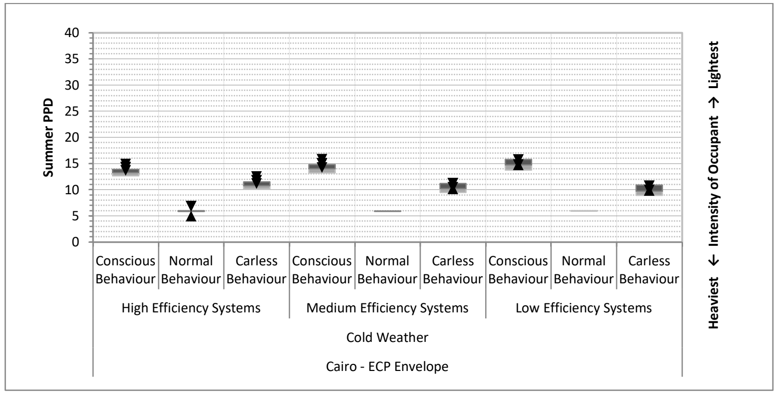
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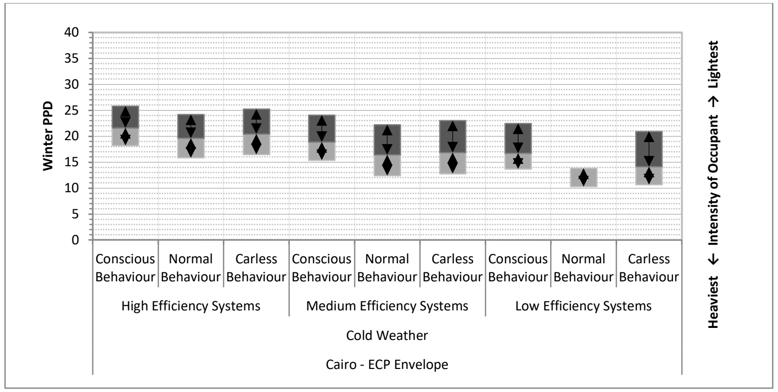
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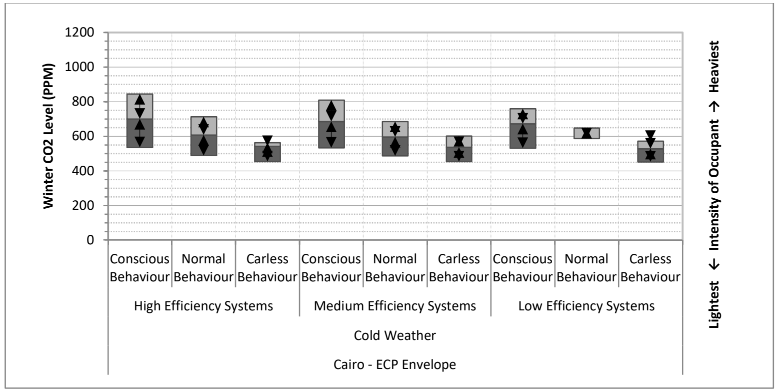
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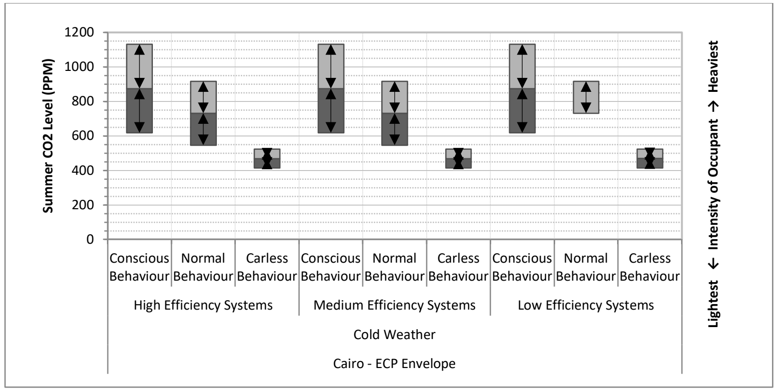
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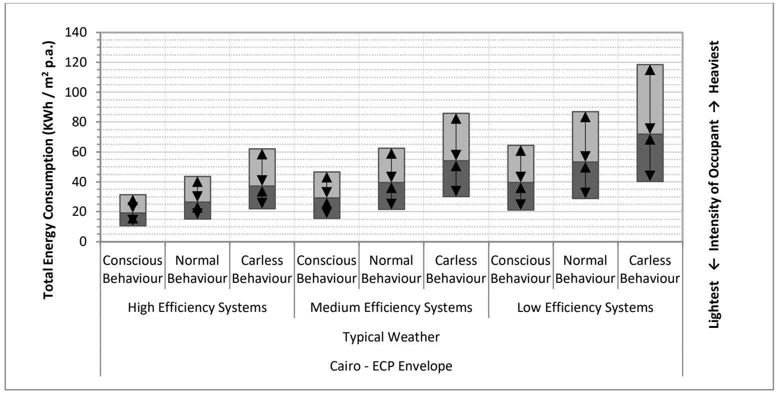
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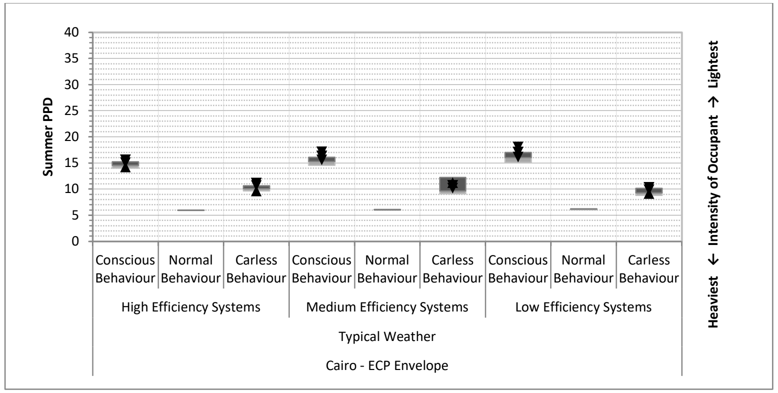
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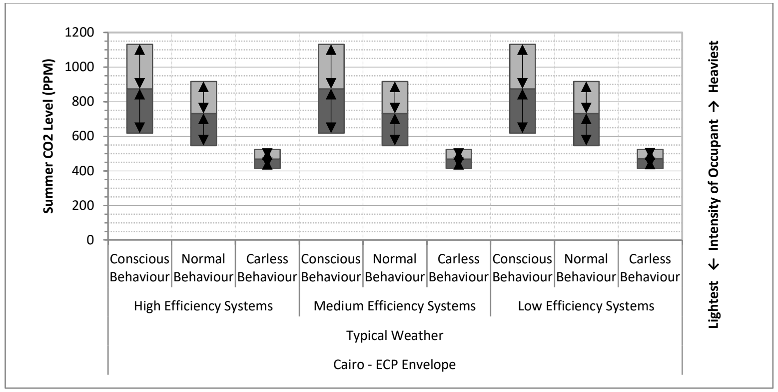
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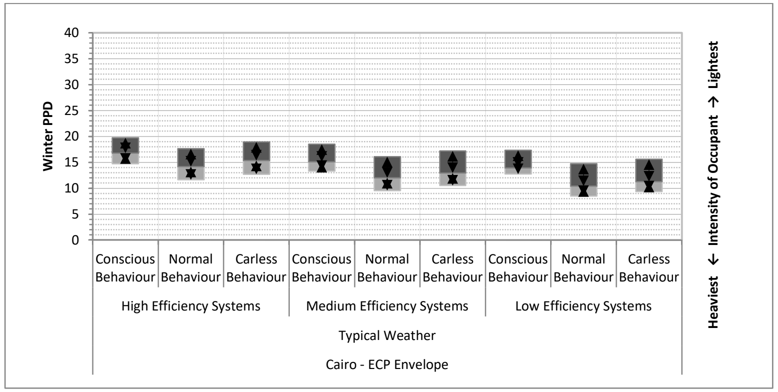
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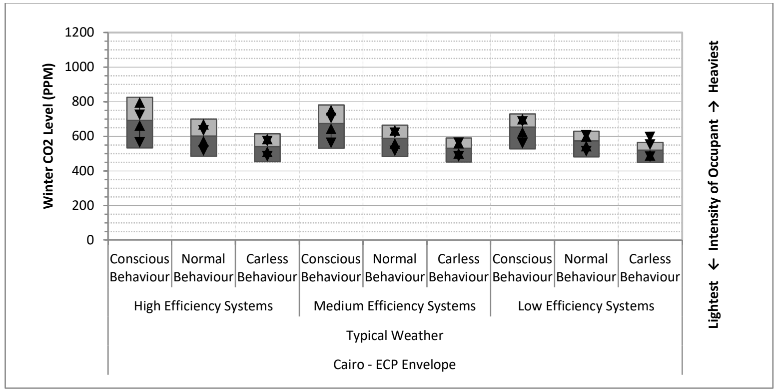
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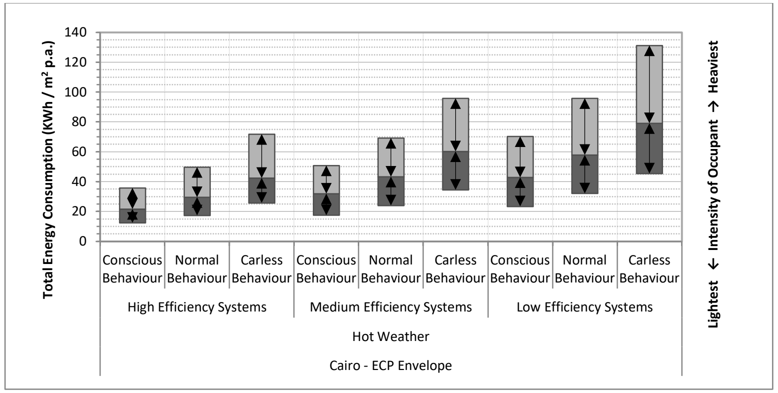
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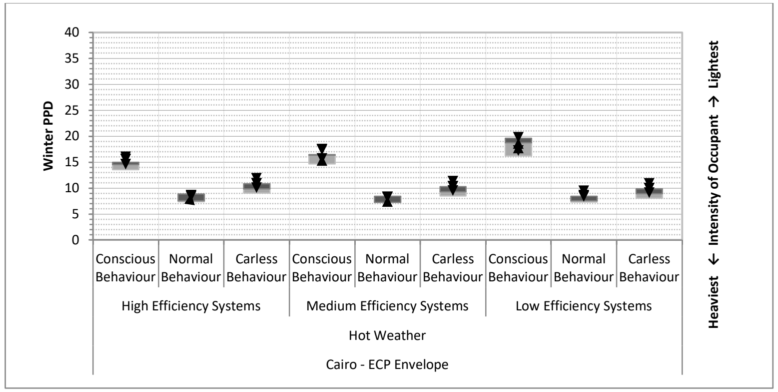
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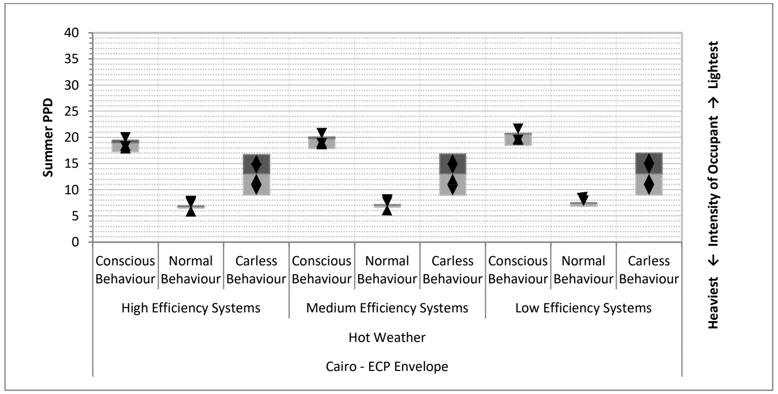
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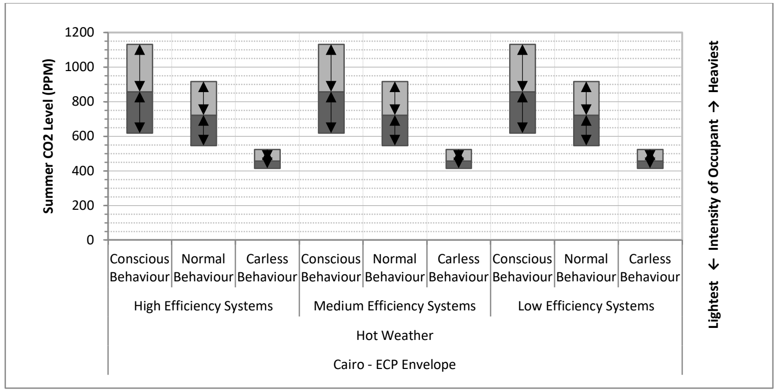
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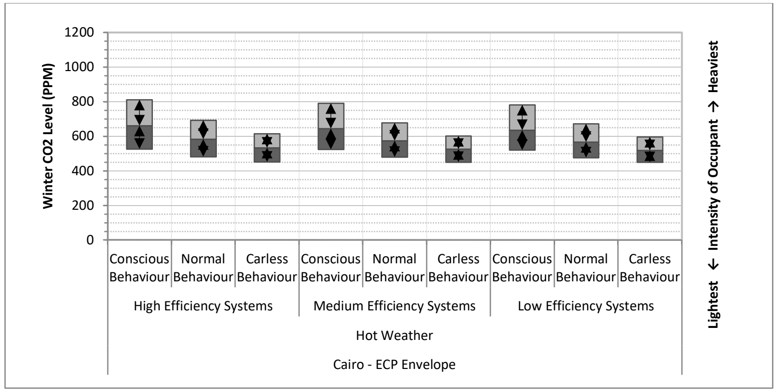
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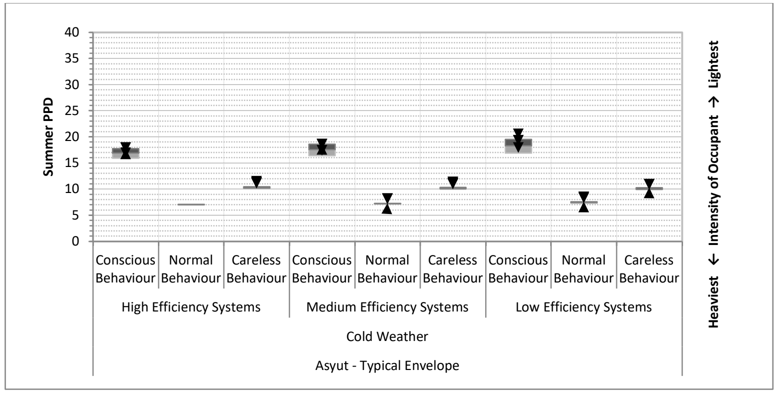
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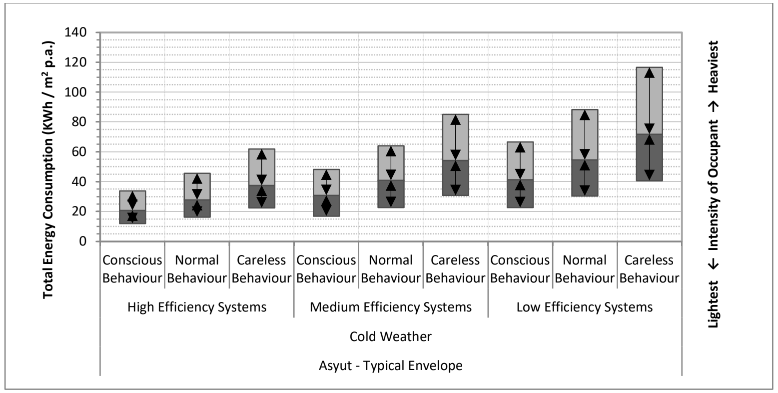
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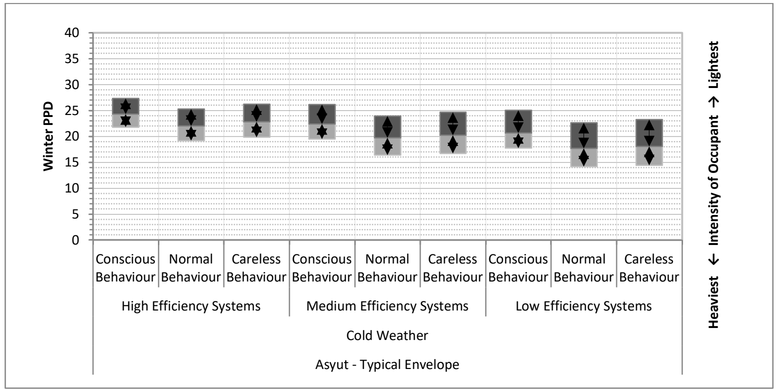
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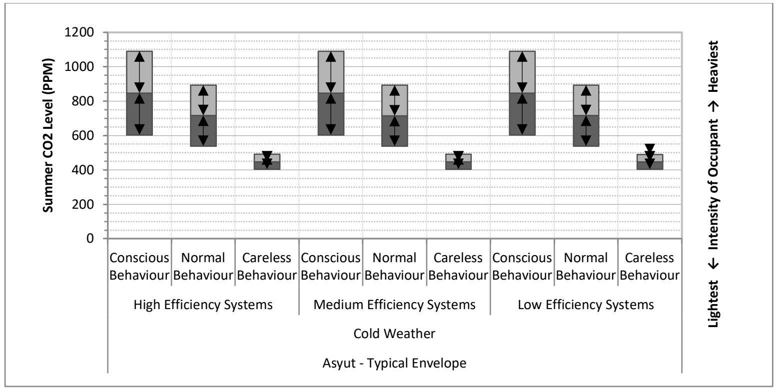

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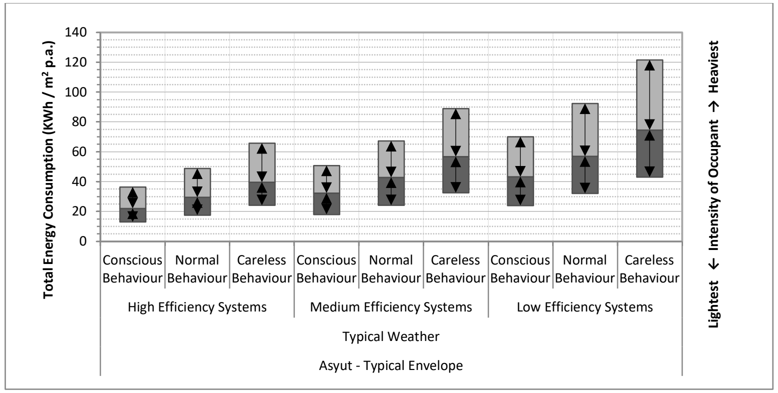

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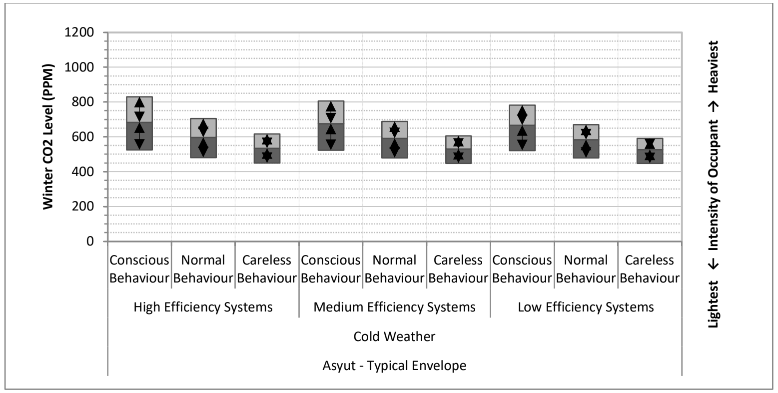

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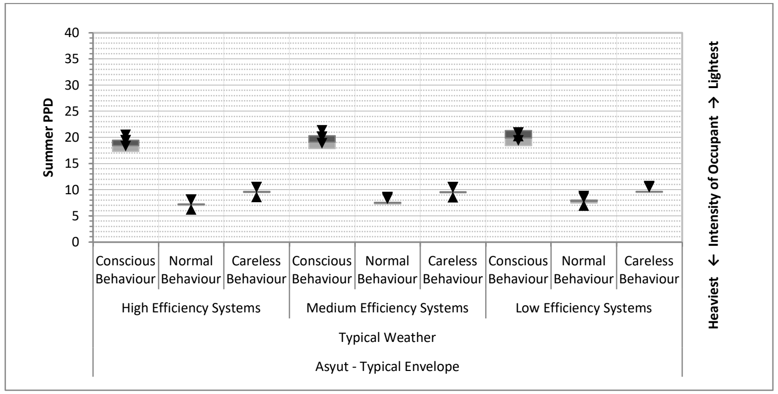
Lightest ← Intensity of Occupant → Heaviest



Summer PPD
40
35
30
25
20
15
10
5
0
Conscious Behaviour
Normal Behaviour
Careless Behaviour
High Efficiency Systems
Medium Efficiency Systems
Low Efficiency Systems
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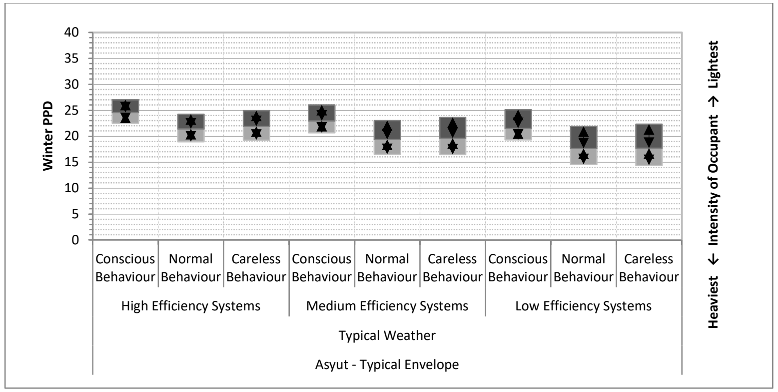
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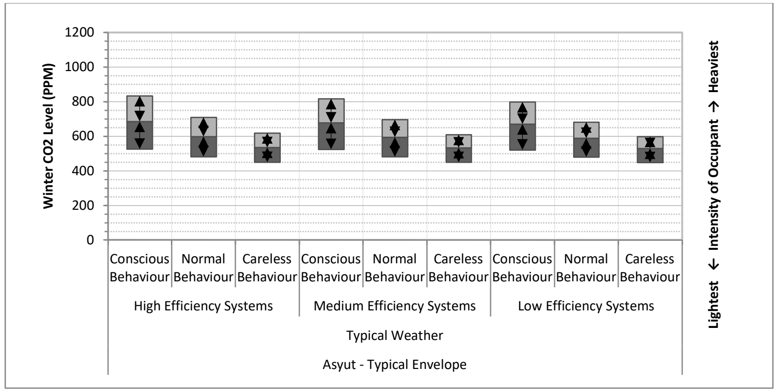
Winter CO2 Level (PPM)
1200
1000
800
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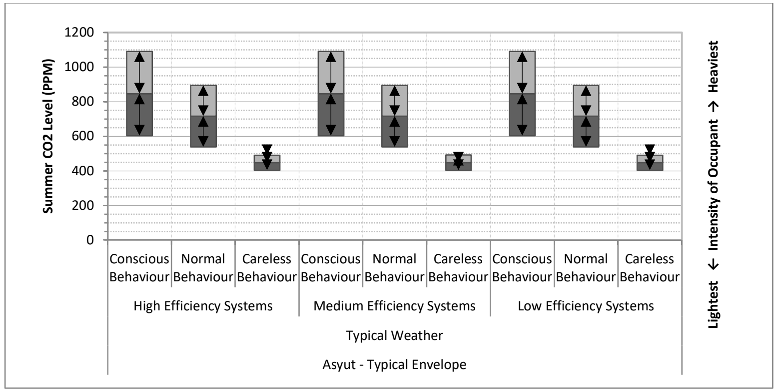
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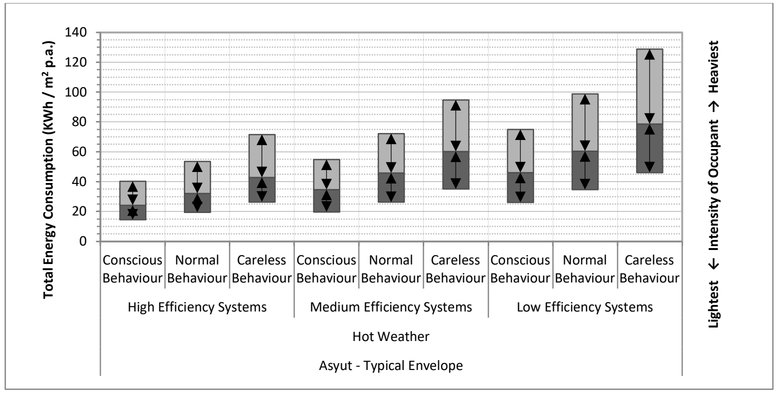
Total Energy Consumption (KWh / m² p.a.)
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120
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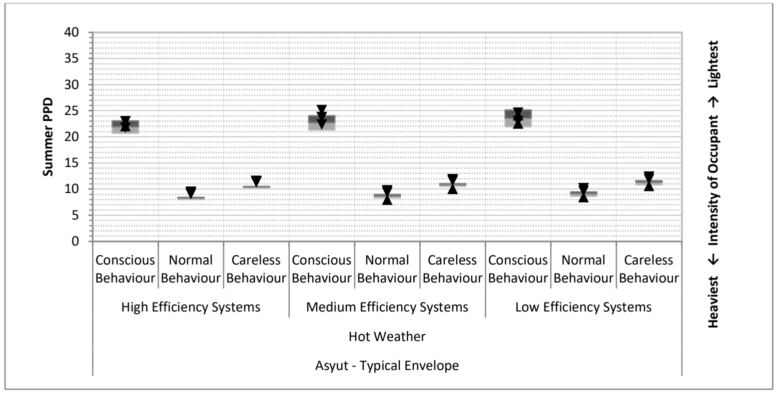
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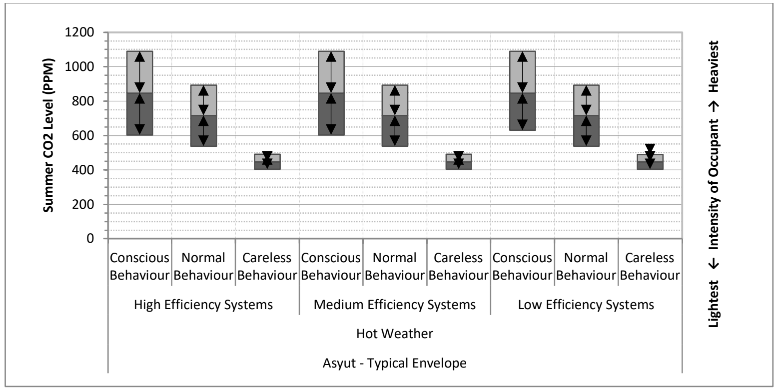
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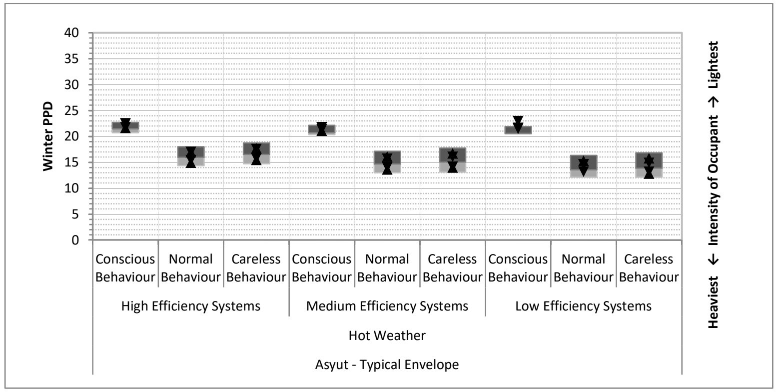
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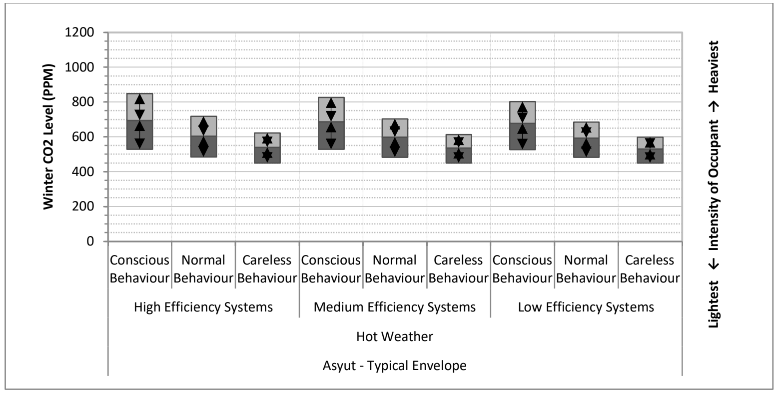
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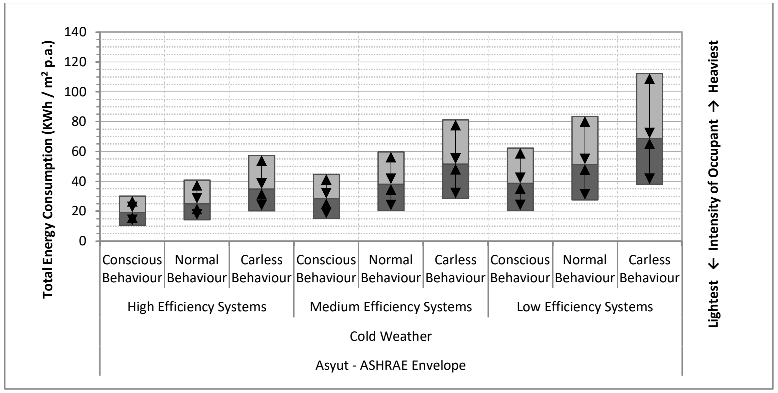
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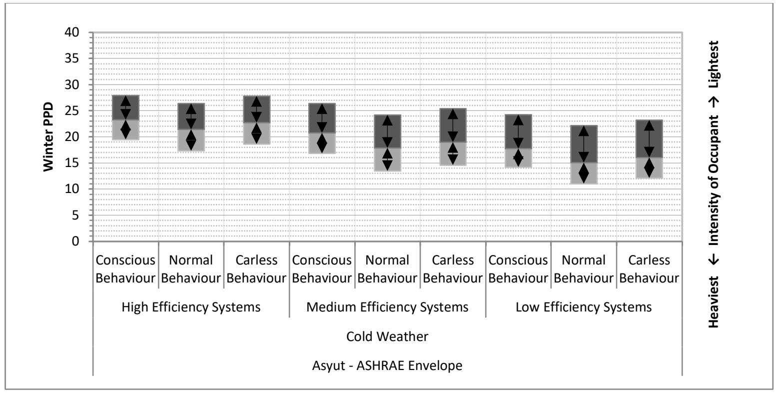
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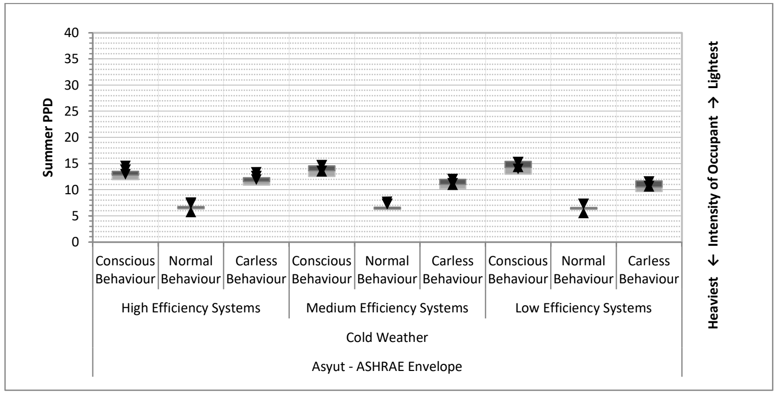
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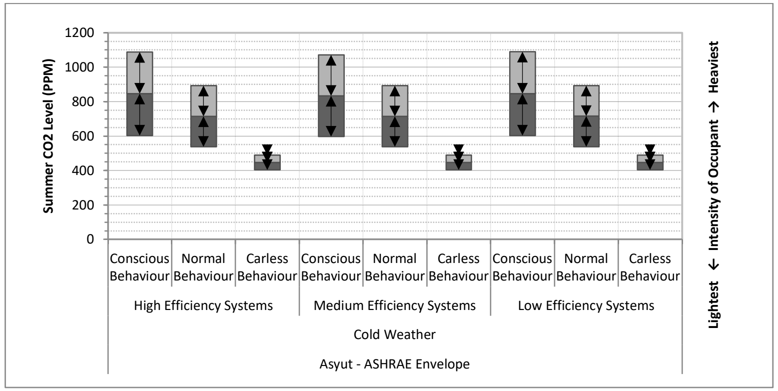
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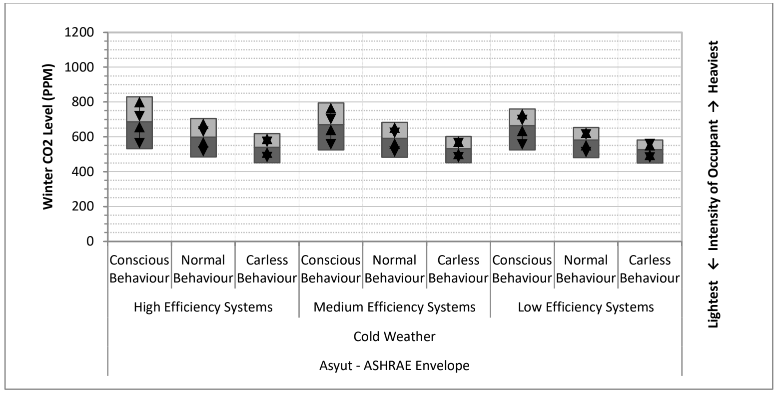
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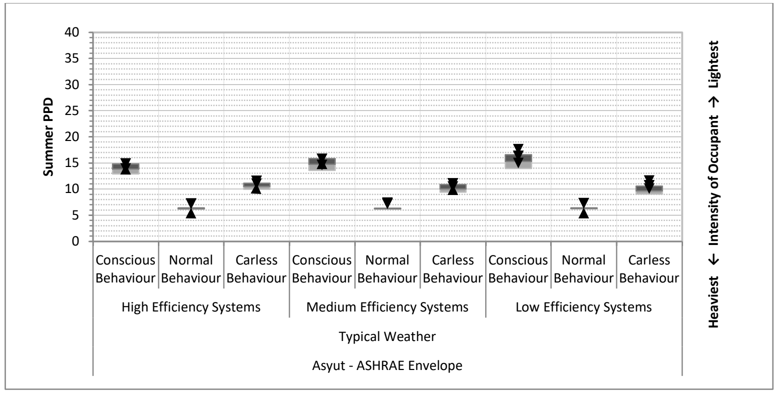
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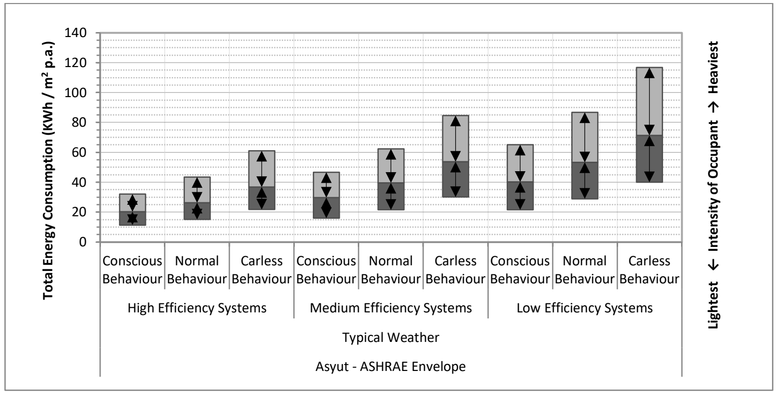
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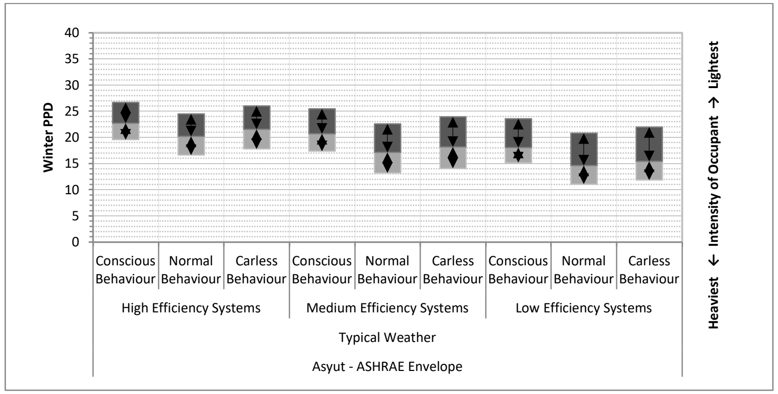
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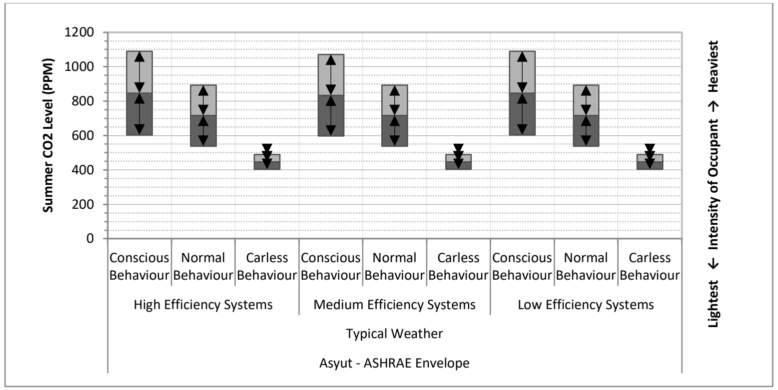
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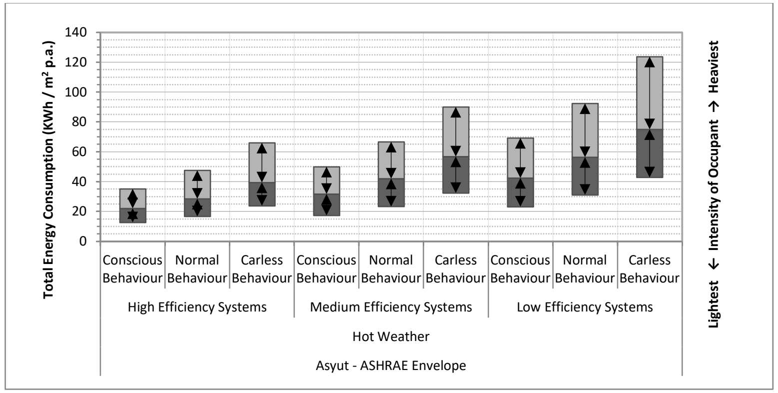
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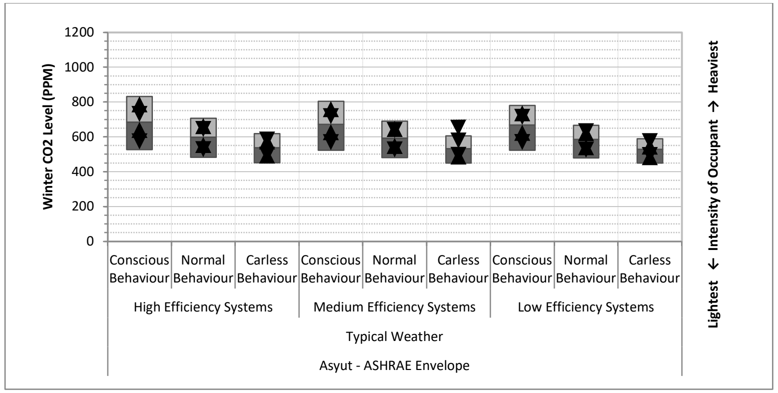
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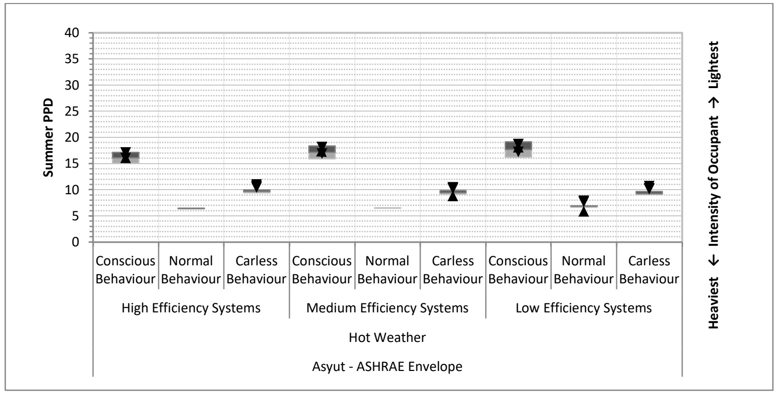
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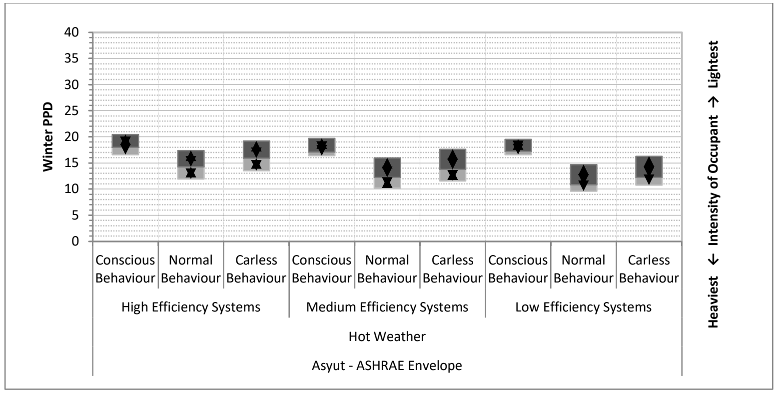
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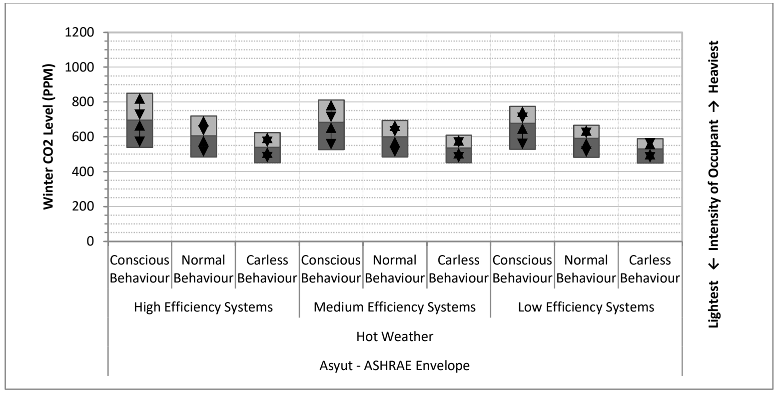
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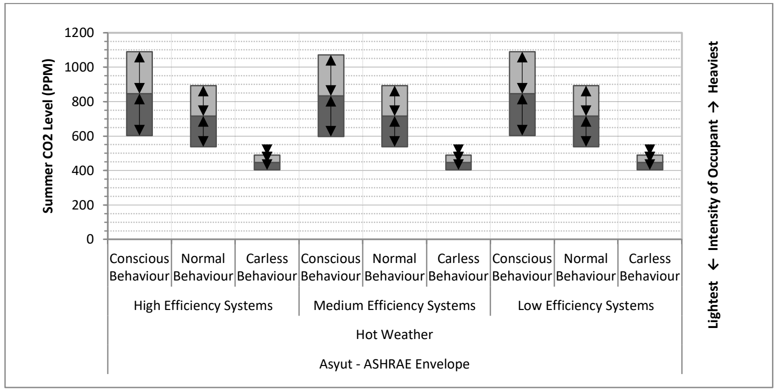
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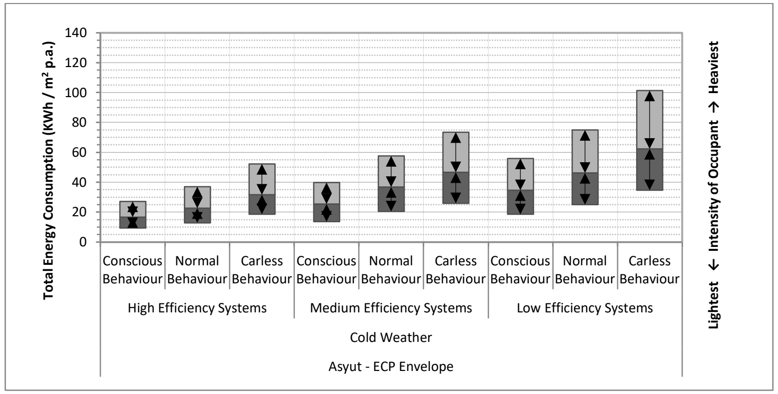
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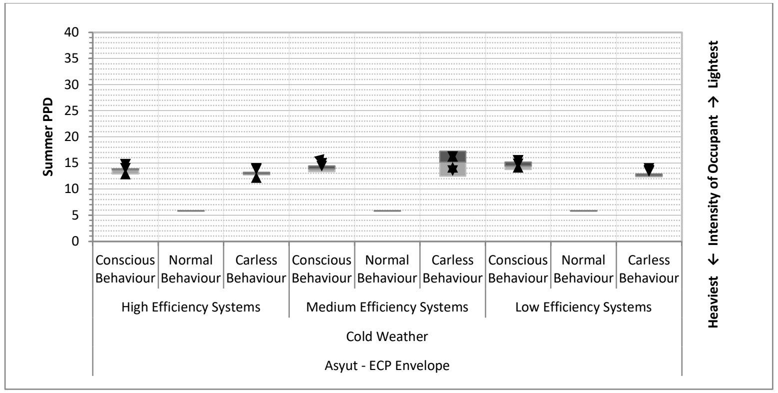
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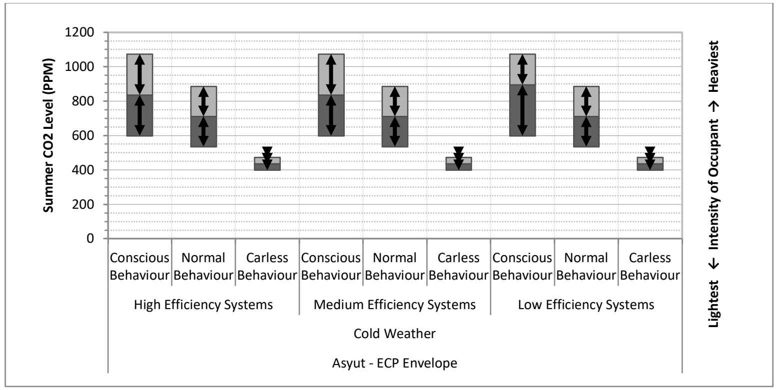
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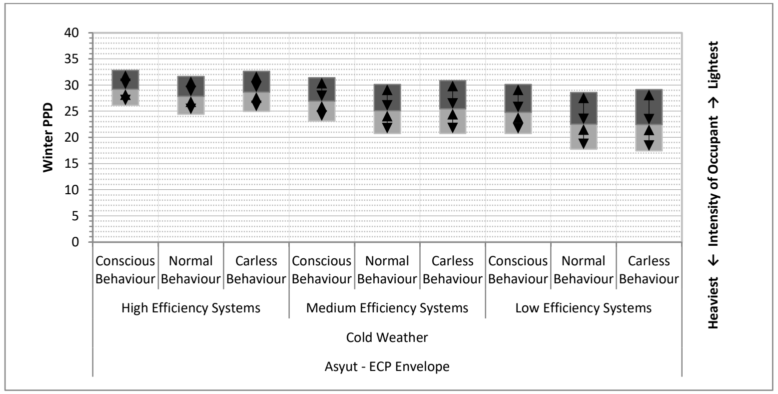
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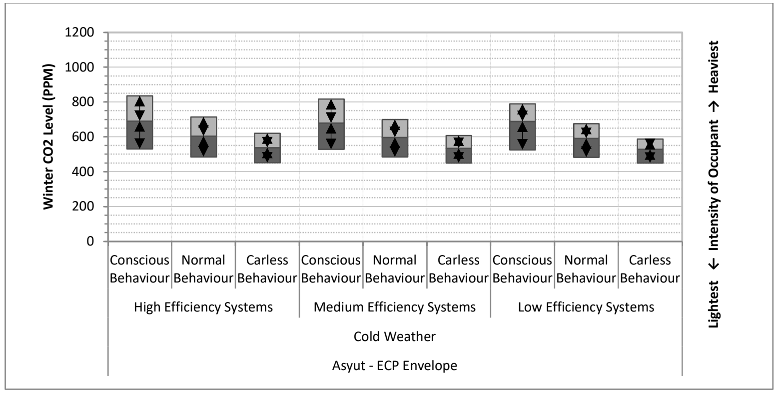
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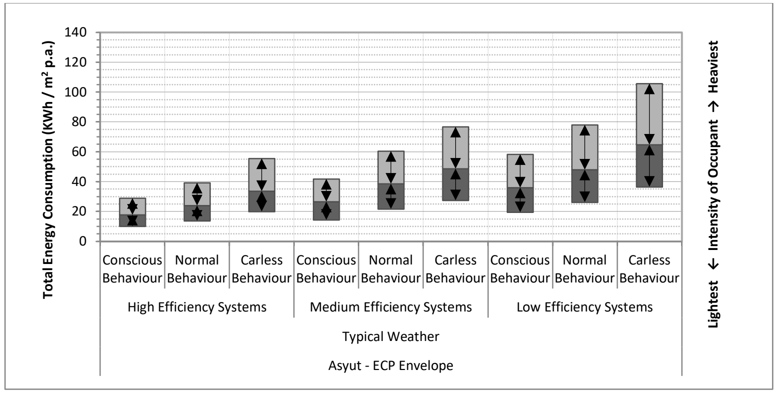
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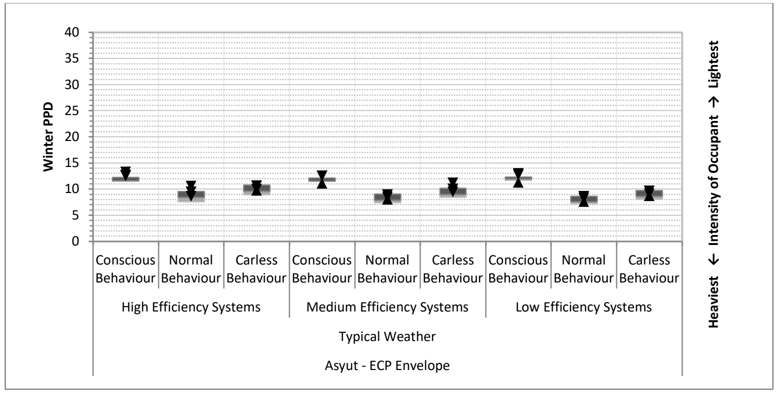
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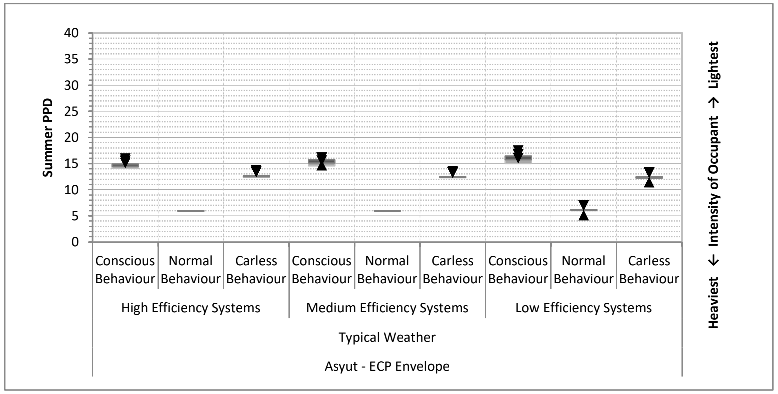
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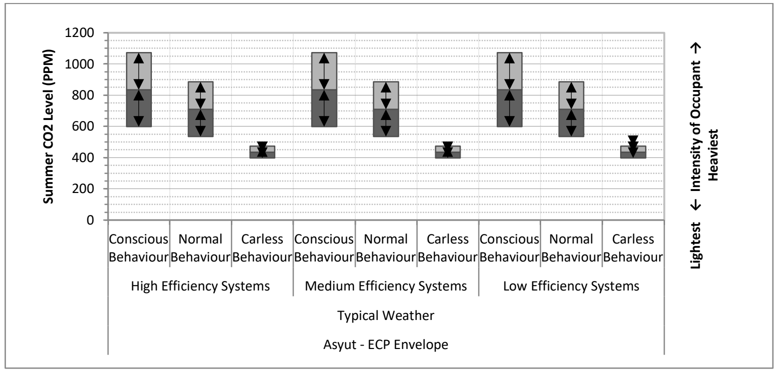
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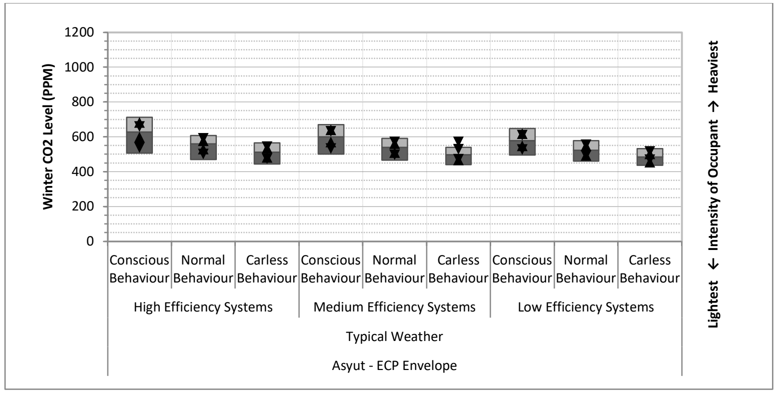
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0
200
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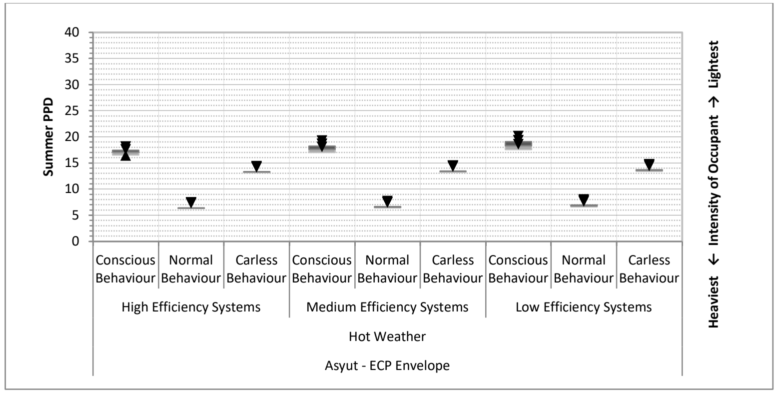
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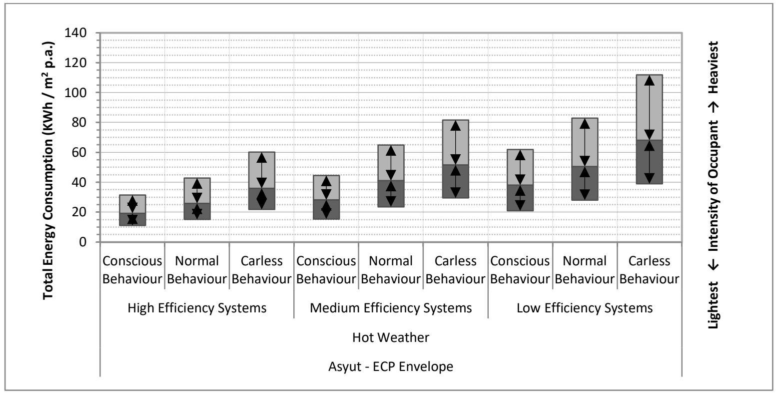
Total Energy Consumption (KWh / m² p.a.)
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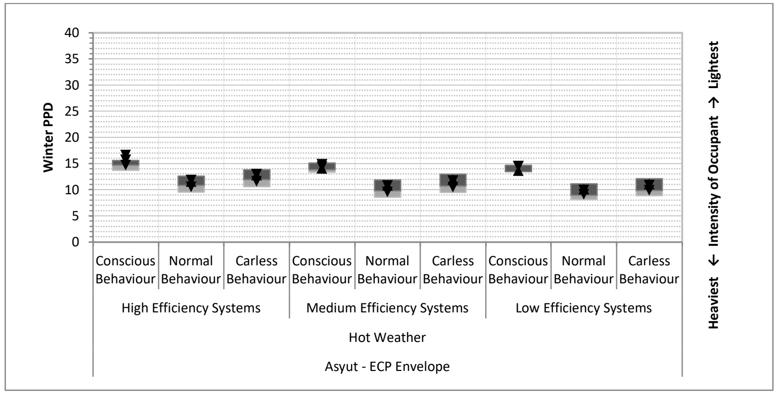
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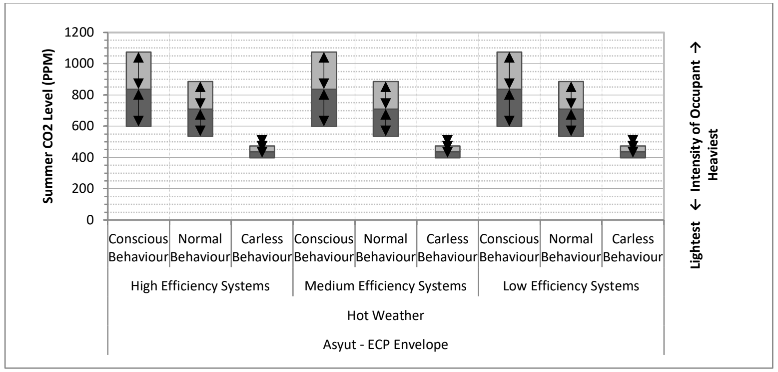
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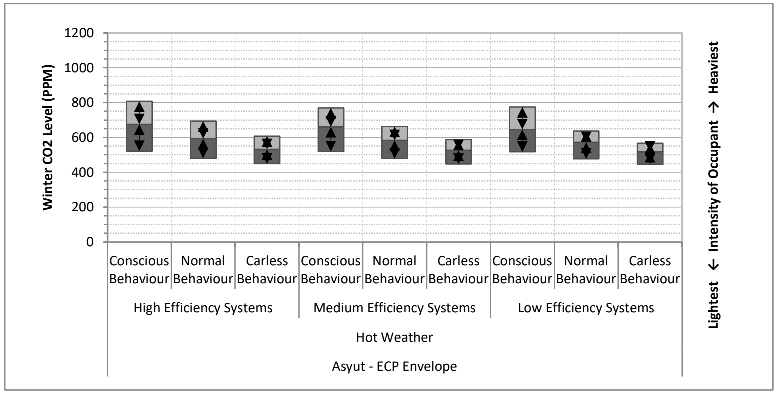
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