ABSTRACT

Achieving thermal comfort in buildings has currently become an urgent need, because of excessive demand in energy consumption across the length and breadth of the world. Accordingly, academics, policy-makers, regulators and governments are striving to find solutions that can be applied to achieve thermal comfort in buildings without excessive consumption of energy. Corollary to this, thermal comfort and energy efficiency in buildings are two faces on the same coin.

Egypt is characterised by haphazard utilisation of prototypical design in public housing projects. The haphazard utilisation of prototypical strategy is in stark contrast with the conventional strategy, which takes into account the various climatic design issues in carrying out social housing projects. Previous studies indicated that the thermal behaviour of same building stock varies across Egypt due to different climatic regions. This evidence overtly illuminates that in order to ensure thermal comfort in residential buildings in Egypt, a combined strategy that takes into consideration the prevailing climatic condition is imperative. It is therefore, against this backdrop that this study examined how the combination of natural ventilation behavioural strategies and insulation retrofitting technique influences indoor thermal comfort without using any mechanical cooling or heating systems.

In order to accomplish the research aim, the problem of thermal comfort in the prototype design social housing building stocks within the hot arid climate of Egypt was identified. Further, the Integrated Environmental Solution – Virtual Environment (IESVE) was adopted to predict the building thermal behaviour whilst applying natural ventilation behavioural strategies on the one hand and its combination with insulation retrofitting technique on the other hand. Predictions were comparatively analyzed to identify the optimum strategy during each month of the year. Cross analyses were carried out to ascertain either this strategy highlights the differences among building orientations or otherwise. In addition, a comparison between typical and upper floor was conducted to highlight their differences.

By applying natural ventilation behavioural strategies, scenarios of natural ventilation were categorized into three; the base case scenario, the actual behavioral scenarios and the hypothetical suggested scenarios. The results illuminated that, In terms of the summer season, the hypothetical suggested scenario of cross night purge ventilation revealed a considerable improvement in indoor thermal comfort. Moreover, whilst natural ventilation scenarios had a modest improvement in thermal comfort in spring-autumn period, it had a negative effect in winter season.

In regards to the combination strategy, simulation results revealed that whilst this strategy played a major role in increasing indoor thermal comfort and reducing cooling demand in summer period, it had very slight impact on enhancing indoor comfort and reducing heating demand (in winter) and heating or cooling demand (in spring-autumn periods). However, by comparing the combined strategy with natural ventilation only, it was deduced that the insulation technique had relatively small impact on thermal comfort enhancement in all periods of the year.

The study further assessed the effect of orientation on indoor thermal comfort via the utilisation of natural ventilation only as well as the combined strategy in winter, summer and spring-autumn periods. The observable fact illuminated that the orientation has no significant effect on indoor thermal comfort in winter, summer and spring-autumn seasons. Finally, the comparison between typical and upper floor confirmed that the difference between them is negligible in terms of thermal comfort.

Keywords: Thermal comfort, residential buildings, hot-arid climates, natural ventilation, external insulation

RIASSUNTO

Il raggiungimento del comfort termico negli edifici sta diventando una problematica sostanziale del dibattito odierno, data la sempre crescente domanda energetica, proveniente da tutto il mondo. Di conseguenza, il mondo scientifico, accademico e politico-amministrativo, ricerca soluzioni per raggiungere un maggior comfort termico all'interno degli edifici, limitando l'eccessivo consumo di energia. E' evidente quindi come il raggiungimento del comfort termico sia direttamente collegato al concetto di efficienza energetica.

L'Egitto è caratterizzato da un uso non programmatico della progettazione prototipizzata per gli interventi di edilizia residenziale pubblica (*social housing*). Questo utilizzo inadeguato di strategie di prototipazione è in netto contrasto con quelle che sono invece le procedure convenzionali, che tengono conto in modo integrato dei vari problemi di natura climatico-ambientale per la realizzazione di progetti di *social housing*. Studi precedenti a questo, hanno evidenziato come il comportamento termico di uno stesso edificio risulti variabile, se collocato nelle diverse regioni climatiche che caratterizzano l'Egitto. Questo evidenzia quindi che, al fine di garantire il comfort termico negli edifici residenziali in Egitto, l'applicazione di una strategia combinata, che tenga conto delle condizioni climatiche prevalenti della zona di insediamento, è condizione imprescindibile. In effetti, la presente ricerca si pone come obiettivo lo studio di combinazioni di strategie comportamentali, attraverso l'inserimento della ventilazione naturale e di tecniche di isolamento in esterno (*Retrofit*), tali da influenzare il comfort termico interno, senza però utilizzare sistemi di climatizzazione e riscaldamento meccanici (impianti).

Al fine di raggiungere tale obiettivo per la presente ricerca, è stato necessario analizzare e porre in evidenza il problema del comfort termico nei casi studio di *social housing* in aree a clima caldo-arido in Egitto. A tale scopo, per l'analisi e la previsione del comportamento termico dei edifici, in situazioni di applicazione di strategie comportamentali di ventilazione naturale da un lato, combinate con tecniche di isolamento in esterno dall'altro, è stato utilizzato il programma Integrated Environmental Solutions – Vertual Environmental (IESVE). Per una analisi più dettagliata ed una simulazione più realistica, al fine quindi di identificare la migliore strategia di intervento per l'efficientamento di tali edifici, sono stati studiati i dati ottenuti dal IESVE sia in un analisi mese per mese, durante tutto l'anno, sia in base ai diversi orientamenti degli edifici stessi. Inoltre, l'analisi ha riguardato anche il confronto fra i dati emersi per gli appartamenti posti al piano tipo degli edifici, e quelli posti all'ultimo piano, analizzando quindi il solaio di copertura, evidenziandone i differenti comportamenti termici.

L'applicazione al modello di simulazione di strategie comportamentali di ventilazione naturale, ha individuato tre principali scenari di applicazione della ventilazione naturale: il scenario di caso base, gli scenari dettati dai comportamentali allo stato attuale degli edifici e gli scenari suggeriti dalle ipotesi di efficientamento individuate. I risultati più significativi emergono nella stagione estiva, l'ipotesi di simulazione ipotizzato attraverso l'inserimento di "*cross night purge ventilation*" mostra un notevole miglioramento del comfort termico interno. Inoltre, è stato possibile osservare che le ipotesi di inserimento di ventilazione naturale hanno invece evidenziato un modesto miglioramento del comfort termico nel periodo primavera-autunno.

Per quanto riguarda le valutazioni circa le strategie di combinazione delle ipotesi di efficientamento, i risultati della simulazione hanno dimostrato che, tale strategia ha giocato un ruolo importante nel migliorare il comfort termico interno e nel ridurre la domanda di climatizzazione nel periodo estivo, ma è emerso ulteriormente che nel periodo invernale, invece, ha avuto un impatto molto debole sia sul miglioramento del comfort termico che sulla riduzione del fabbisogno di riscaldamento. Inoltre nel periodo primavera-autunno e stato osservato una leggera riduzione del fabbisogno del riscaldamento o della climatizzazione estiva.

La ricerca ha inoltre valutato l'effetto dell'orientamento degli edifici sul comfort termico interno attraverso l'utilizzo della sola strategia della ventilazione naturale e l'uso della strategia combinata in inverno, in estate e nel periodo di primavera-autunno. E' emerso che l'orientamento non sembra contibuire significativamente sul comfort termico all'interno sia in inverno che nelle altre stagioni. Infine, il confronto dei dati ottenuti tra il comportamento piano tipo e quello del'ultimo piano a contatto con la chiusura superiore ha confermato che la differenza tra loro è trascurabile per ciò che riguarda il comfort termico all'interno.

Parole chiave: comfort termico, edifici residenziali, clima caldo-arido, ventilazione naturale, isolamento esterno.

ACKNOWLEDGEMENTS

First and foremost, I thank Allah, the Almighty, for having made everything possible by giving me strength and courage to do this work and for giving me the power to believe in my passion and pursue my dreams. I could never have done this without the faith I have in Him.

I would like to express my special appreciation and thanks to my advisor Prof. Theo Zaffagnini, you have been a tremendous mentor for me. I would like to thank you for encouraging my research and for allowing me to grow as a research scientist. I would like to express my deep and sincere gratitude to my dear advisor Dr. Neveen Hamza (Newcastle University), for giving me the opportunity to work under her supervision and tutelage at Newcastle University. Thank you for being always keen to me and guiding me sincerely throughout my research.

I would like to take this opportunity to thank each one of my friends at Ferrara University without whom I would not enjoy my stay in Ferrara. First, a special thank to Otuo Agyemang for his support during last phase of my work. Thanks for all my friends; Ali Edris, Houda Oudouche, Mostafa Tarek, Yasmin Qaraqish, Anahita Sassani, Irena, Sayda, Anahita Lohrasbi, Geeta, Afsaneh, Leila, Ayman, Mohammed, Ika, Ahmed Rjoob, Haseeb, Awad, Eleonora, Hamed, etc.

I would like to thank the staff of University of Ferrara, particularly, Lena Fabbri, Elena Caniato, Raffaella. A special gratitude to Loay Kamel for his assistance during the data gathering stage in Egypt. Thanks to my Italian friend Cristiano Ferrari for being a good friend during my participation in Climate-KIC program in Reggio Emilia.

My special thanks to all my friends at Newcastle University and Nurthumbria University, who made my stay in England a special one especially, my friend Yasser Said- who made me to feel at home and supported me during my stay at Newcastle.

Less I forget, I would like to express my sincere appreciation to the people and the institutions that voluntarily collaborated with me to finish my work in Cairo.

I am speechless! I can barely find words to express all the wisdom, love and support given me by my parents and siblings (especially my twin sister, Ahlam) who have played instrumental role in my academic life. I am really grateful for the immeasurable assistance and encouragement from my childhood days to where I am now. I am indebted to my brother, Mostafa for helping me gather data during the data collection phase of this work in Egypt.

Dedication

To my father's soul

To my mother

To my brothers and sisters for their endless support

I dedicate this study...

TABLE OF CONTENTS, LIST OF FIGURES AND TABLES

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER ONE

LIST OF TABLES

CHAPTER ONE

1. INTRODUCTION AND METHODOLOGY

1. INTRODUCTION AND BACKGROUND TO THE STUDY
2. STATEMENT of PROBLEM
3. RESEARCH OBJECTIVES
4. RESEARCH QUESTIONS
5. RATIONALE OF THE STUDY
6. RESEARCH LIMITATIONS
7. PROPOSITIONS
8. RESEARCH CONTEXT
9. RESEARCH METHODOLOGY

1.0 INTRODUCTION AND BACKGROUND TO THE STUDY

> "Analysis of the climatic conditions of a given place is the starting point in formulating building and urban design principles aimed at maximizing comfort and minimizing the use of energy for heating and cooling." (Givoni, 1998, p.3).

If this assertion by Givoni is anything to go by, then it is worth noting that the relevance of thermal comfort in both indoor and outdoor spaces cannot be underestimated. Practically, ensuring thermal comfort naturally in residential buildings in hot arid climates, without using any mechanical cooling or heating systems makes buildings energy efficient by not sacrificing the comfort of occupants. Achieving thermal comfort in buildings has currently become an urgent need, because of excessive demand in energy consumption across the length and breadth of the world. Accordingly, academics, policy-makers, regulators and governments are striving to find solutions that can be applied to achieve thermal comfort in buildings without excessive consumption of energy (Kordjamshidi, 2010). Corollary to this, thermal comfort and energy efficiency in buildings are two faces on the same coin. Almusaed (2010, p.V) opines:

> A high quality of building model brings the thermal comfort primarily up-to-date to the user of the building with lowest energy costs. In this vision; all buildings can be one of the three conceptual categories relating to; energy, natural and physical surrounding, and building design…

Presently, technology has furnished the building sector with advanced structural techniques, insulation materials and renewable energy mechanisms, which serve as a breakthrough mechanism to ensuring energy efficiency and achieving human comfort in buildings. This mechanism has gone farther to reconfigure existing building as well as creating new buildings that can produce their own energy needs renewably (Sala, 1999; Almusaed, 2010).

The 1970s witnessed a paradigm shift in public consciousness toward energy conservation. Domestic oil production reached its pinnacle in 1970 that eventually resulted in a titanic reliance on foreign exports. Many researchers point to the Arab oil embargo of 1973 and 1974 as the catalyst for the energy crisis (Bynum, 2000, p.7). A second sharp rise in oil prices occurred in 1979 following the Iranian revolution, further contributing to public discussion as well as new energy programs. After the oil shock in the 1970s, the club of Rome issued a caveat that there would be a shortage of natural gas in few decades (Meadows, Meadows and Randers, 1972). But there are diverse views in regards to the exact period the production of fossil fuels will last. In consequence, the International Energy Agency holds the view that there will be adequate fossil fuels until at least 2030 (OECD/IEA, 2006).

Even though there are several sources of CO_2 emissions into the atmosphere, the building industry and building systems are among the vitally important. Accordingly, it is incumbent on governments across the globe to put forth policies to minimize

carbon emissions. (Waters, 2008). Over some decades, there has been a spate of efforts to fashion out a well-organized methodology for adapting built environment for human needs and climatic conditions. Some of these efforts encompass the development of Mahoney tables1 and bioclimatic charts, which are aimed at defining suitable built environment for inhabitants (Sayigh A., Hamid A. M., 1998, p.3).
Egyptian oil production peaked over a decade ago and has since been in decline. In our Reference Scenario, production is projected to fall from 0.7 mb/d in 2010 to 0.5 mb/d 2030. Egypt, currently a minor oil exporter, is expected to become a net oil importer by 2015. (OECD/IEA, 2005)

Energy significantly plays a role within buildings, but this role differs across countries and climatic zones. Currently, building sector consumes 40 percent of the world's energy use (World Business Council for Sustainable Development, 2008). For instance, whilst OECD countries consume 30 percent in the building sector, non-OECD Europe and developing countries consume 50 percent and 70 percent respectively (OECD/IEA, 2006). The global building stock (commercial and residential) accounts for more than 33 percent of worldwide carbon dioxide emissions and a significant number of solutions have been identified (de la Rue du Can and Price, 2008; Urge-Vorsatz and Novikova, 2008). In order to realize CO2 reduction targets, such as the 20 per cent reduction target by 2020 by the European Union or the United Kingdom's 60 per cent reduction by 2050, will demand the execution of deep-seated building upgrades, new technology exploitation and change in lifestyle.

The electricity demand in residential building sector in Egypt has been increasing from 7-10% a year in the period between 1998 to 2008, and it is expected that it will increase by 35% in the future (George and Soliman, 2007). The residential building sector in Egypt consumes more than 47% of the total nationally generated electricity. It was also found that increasing of outside air temperature one degree above 35 °C causes increasing in the energy consumption by 100 MW/Hour. By exploration, if the outside air temperature reached 42 °C it may increase the energy consumption by 800 MW/Hour. This will necessitate electricity generation capacity at a cost of 2 billion Egyptian pounds and four years for construction. In addition, energy could be saved by 10% if the air-conditioning set point raised by 1 °C. ECP306, 2005; Kimura et al, 1994).

The existing building sector in developing countries, particularly Egypt, is worse and still needs practical solutions and viable methods based on local available techniques and materials that could be employed to achieve human comfort and energy efficiency in buildings. Accordingly, this study intends to put a step towards ameliorating the situation in Egyptian residential building sector. Therefore, this study seeks to examine the combination of natural ventilation, occupants' behavioural strategies and insulation technique as a passive technique to ameliorate thermal conditions in the social housing building stocks in hot-arid climatic regions within the context of Egypt.

[1] The Mahoney tables are a set of reference tables used in Architecture. used as a guide to climate-appropriate design. It was later developed by Koenigsberger, Mahoney and Evans (1970).

This chapter highlights the fundamental themes that guide the study. It brings out the statement of problem, research objectives, research questions, rationale of the study, limitations, propositions and a brief description of the context of the study. It further presents the methodology and research methods of the study, and the organization of the study. Finally, a summary of this chapter is provided.

1.1 STATEMENT OF PROBLEM

"Energy and architecture form a natural marriage if indoor comfort and respect for environment are secured." (Sala, 1999, p.1). Ensuring thermal comfort in residential buildings in hot arid climate is extremely important in that it makes buildings energy efficient by not sacrificing the comfort of occupants. Thus any enhancement strategy to improve energy efficiency of residential buildings needs to take into consideration thermal comfort issues. A number of studies has been conducted to address the problem of thermal comfort in hot arid climatic countries in particular, Egypt. These studies have either concentrated on energy performance issues (Al-Ragom, 2003; Attia, 2009; Attia, 2010; Michelle, 2006; Attia, 2012) or achieving thermal comfort during summer (Sakka, 2012; Nicol, 1974; Indraganti, 2010; Gado, 2009; Ali, 2012). In addition, Thermal comfort in winter is researched in fewer studies (Cena, 2001; Herrara, 2011; Kruger, 2010). Further, none of these studies has examined how the combination of natural ventilation strategy and local material insulation techniques improve indoor thermal comfort. However, it is worth noting that this combination offers one of the passive design major keys to ensuring sustainable buildings, which will eventually make residential buildings to be energy efficient without using any mechanical cooling or heating systems.

Egypt is characterized by haphazard utilization of prototypical design in public housing projects (see figure 1.1). In simple terms, a considerable number of Egyptian governmental social housing projects across the length and breadth of the country have been constructed using the same prototype without taking into account the prevailing social and climatic conditions of the Egyptian situation. Consequently, this has made these prototypes unpleasant for their occupants in relation to thermal comfort and social needs. The haphazard utilisation of prototypical strategy is in stark contrast with the conventional strategy, which takes into account the various climatic design issues in carrying out social housing projects (Givoni, 1998). A study by Gado (2000) indicates that the thermal behaviour of same building stocks varies across Egypt due to different climatic regions. This evidence lucidly illuminates that in order to ensure thermal comfort in residential buildings in Egypt, a worthwhile strategy that takes into consideration the prevailing condition of the buildings (without any radical change) and the use of extant ecological materials for insulation is imperative. It is therefore, against this backdrop that this study sought to examine how the combination of natural ventilation, occupants' behavioural strategies and insulation retrofitting technique influences indoor thermal comfort.

Figure 1.1 public housing prtotype project

1.2 RESEARCH OBJECTIVES

The main objective of the study is to examine how indoor thermal comfort can be improved in existing social housing projects in hot arid climates within the context of Cairo, Egypt. In order to address this goal, a division into three main specific research objectives was made. These were to:

- Evaluate different behavioural natural ventilation strategies to enhance indoor thermal comfort; and
- Assess the combination of natural ventilation strategies and insulation retrofitting technique to improve indoor thermal comfort.
- Suggesting significant issues to improve comfort in social housing without any mechanical cooling or heating systems.

1.3 RESEARCH QUESTIONS

Given the importance of indoor thermal comfort in hot arid climate, the main research question of this study was: How can the combination of natural ventilation and insulation retrofitting technique improve indoor thermal comfort?

1.3.1 SPECIFIC RESEARCH QUESTIONS

In addressing the main research question, a division into three specific questions was made:

- What are the occupants' behavioural strategies for natural ventilation available in the extant literature that can improve the indoor thermal comfort in hot arid climates?
- What are the appropriate insulation materials that can improve the thermal performance of building envelope and available or can be available in future in Egypt? and;
- How can the combined strategy of natural ventilation and insulation technique improve building thermal performance and consequently indoor thermal comfort?

- What significant issues could be suggested as auxiliary for improving indoor thermal comfort in social housing existing buildings without any mechanical cooling or heating systems?

1.4 RATIONALE OF THE STUDY

Adapting the existing residential buildings to the prevailed climate is essential in the sense that, it reduces energy consumption as well as ameliorating the living condition for the local inhabitants in terms of thermal comfort. Unlike cold climates, little studies of this kind have been conducted in hot arid climates which Egypt is of no exception. Due to the excessive demand on housing in Egypt, the country adopted a prototype design massive production strategy for social housing across the length and breadth of the country that does not correspond with climate considerations in each part of the country. As a result, the study put an effort to improve the indoor environment of this type of projects. The rationale behind choosing natural ventilation behavioural strategies and insulation retrofitting technique lies in their effectiveness in hot arid climate. Literature review evidences the significant effect of natural ventilation in improving comfort in hot arid climate; Furthermore, due to the poorly adapted building fabric to climate, envelope insulation is a tentatively available technique among others to improve the thermal performance of the building envelope to reduce solar heat gain to the indoor spaces in summer and probably heat loss from the indoor spaces in winter. The research intends to examine the validity of these claims in a hot arid climate aiming to predict the impact of combining natural ventilation as a behavioural zero cost strategy and insulation retrofitting as an available technique to reduce cooling and heating demand for these buildings and improve indoor thermal comfort.

1.5 LIMITATION

This study examines how to improve indoor thermal comfort in social housing buildings in the hot arid climate of Greater Cairo, thus the observable facts do not apply to other climates. Also, the sample does not represent all social housing in Egypt therefore; the empirical evidence cannot be generalized to cover the social housing buildings in other places that have not been included in this study. However, the findings can be applied to other similar buildings within the same climate in Egypt in an analytical sense. With the application of inductive reasoning, the results can be applied to provide important appreciation in an effort to improve indoor thermal comfort in social housing buildings in hot arid climate regions.

1.6 PROPOSITIONS

A research proposition is defined as ‘a tentative and conjectural relationship between constructs that is stated in a declarative form’ (Bhattacherjee, 2012, p. 13). Propositions of the current study are represented by hypotheses that were formulated in order to link the questions to the body of the research study. Hypothesis according to Ragin are explained as ‘an educated guess about what the investigator expect to find in a particular set of evidence. It is an ‘educated guess’ in the sense that it is based on the investigator's knowledge of the phenomena' (Ragin, 1994: p.14). Yin (2009; 2003) asserts that propositions reflect relevant theoretical issues and evidence about individual(s). To assess the effectiveness of natural ventilation and insulation retrofitting technique in social housing stocks within hot arid climate, the following hypotheses were formulated:

Hypothesis one:
Behavioural strategies of natural ventilation control have a significant impact in reducing cooling demand in residential building stocks within hot arid context.

Hypothesis two:
Using external insulation in residential buildings will reduce heating and cooling demand in buildings.

Hypothesis three:
The combination of natural ventilation behavioural strategies and insulation retrofitting technique can significantly improve indoor thermal comfort.

1.6.1 THE VARIABLES

Variables are divided into dependant and independent variables. The independent variable is the exploratory variable that causes changes in the value of the dependant variables. **The dependant** variables in this study will be used to measure changes in heating and cooling demand. It was represented by the weather profile and building operational profile. **The independent** variables are the building envelope materials and openings. The Changing will be done in natural ventilation behavioural control by opening and closing windows in different time during day and night, more so, changing in building envelope material layers will be done by adding external insulation.

1.6.1.1 THE DEPENDENT VARIABLES

1.6.1.1.1 THERMAL COMFORT

Chapter two addressed the variables that affect thermal comfort and adaptive thermal comfort in free running buildings, furthermore, chapter three discussed issues underpinning the range of thermal comfort temperatures that are required in the case study to provide satisfactory level of thermal comfort to occupants. The analysis in chapter three showed the comfort range of indoor air temperature for each month over the year, however, the employed adaptive range of comfort in this study considered by the lowest level of comfort for the month of January (19.6 °C) and the highest level of comfort during July and August (29 °C) (see section 3.4.3)

1.6.1.1.2 OCCUPANCY

It was observed from the questionnaire analyses that house occupancy patterns varied. For this reason, in order to code these data into simulation software, average occupancy percentages were calculated for each hour during day and night (see section 3.1.3). It is assumed in this study that the occupancy sensible gains are at 90 W/person.

1.6.1.1.3 LIGHTING AND EQUIPMENT

The lighting profile was obtained from questionnaire analyses (see section 3.1.4). As the traditional assumption of lighting were 30 – 20 W/m^2 (Meckler, 1992), the lighting in this study were assumed as 20 W/m^2 and coded in the simulation software. As some of respondents had a computer in their homes, computer was added to the living room internal heat gains and was assumed as 50 W/m^2, this assumption is quite high because it was observed that these computers were early models with less energy saving features. Furthermore, miscellaneous appliances sensible gains were assumed as 10 W/m^2.

1.6.1.1.4 WEATHER PROFILE

The weather profile that was used for simulation obtained from the IESVE simulation software database. This file is an average for the weather data over a period of 28 years (1971 – 1999) (figure 1.2). This weather profile includes hourly dry bulb temperature, relative humidity, atmospheric pressure, direct normal solar irradiation, diffuse horizontal solar irradiation, wind direction, wind speed and cloud cover. However, the first intention was to obtain the weather data for the year 2012 from the meteorological station of Cairo airport, but the Egyptian authorities requested a large amount of money that is equal to 400,000 EGP (approximately 57,500£). Accordingly, it was only affordable to the researcher to get the weather data for the month of January, 2013 (to represent winter season) and for the month of June, 2013 (to represent summer season) and then a validation study using paired T test was made to check the significance of using the 28 years average data (see section 3.4.1 and 3.4.2).

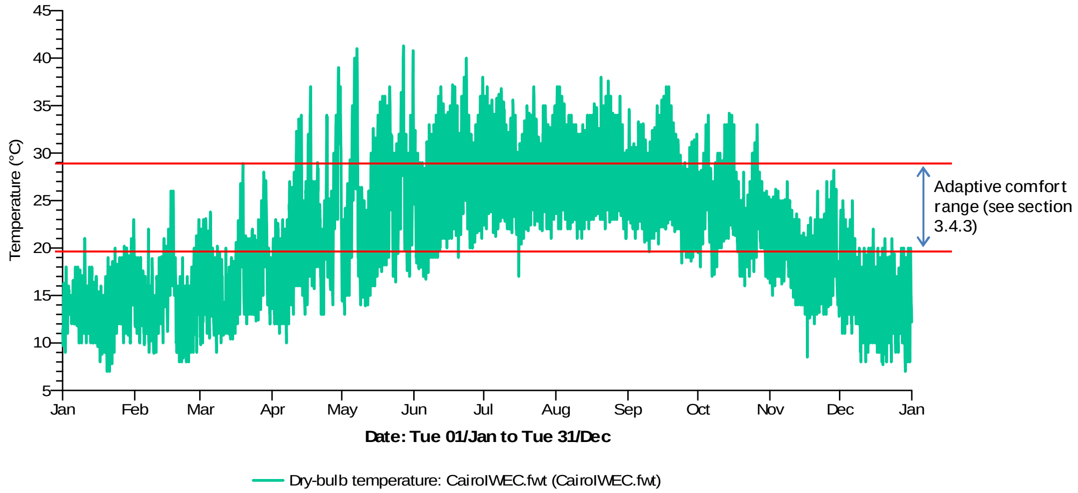

Figure 1.2 Cairo 28 years average weather profile for dry bulb temperature (IESVE database)

1.6.1.2 THE INDEPENDENT VARIABLES

In this study there are two independent variables; the behavioural strategies and the building envelope material layers. In regards to the behavioural strategy, the indicators applied in measuring them were opening and closing the external windows, and internal doors. It is argued that the night purge ventilation can significantly improve indoor thermal in hot arid climate regions (Givoni, 1994; 1998). On the basis of this, the study applied different scenarios of opening and closing windows to allow natural ventilation. These scenarios were categorized into three categories; the base case scenario, the based questionnaire scenarios and the hypothetical suggested scenarios of single and cross night purge ventilation.

In respect of the building envelope material layers, the study applied the external insulation of maize fiber panels in order to evaluate its effectiveness on reducing heating and cooling demand. The external insulation was recommended to be used in hot arid climate regions (Roaf, 2001; Gado, 2000; El-Hefnawi, 2000; Attia, 2010). In view of this, maize fiber panels were employed in this study to evaluate its effectiveness on reducing heating and cooling demand. The insulation materials efficiency was measured by thermal conductivity (k or λ W/mk). The lower conductivity value leads to more efficiency for the insulation material (Smith, 2004).
For both independent and dependent variables, heating and cooling demand were measured by the simulation tool of IES<VE> software (see section 1.8.7.2).

1.7 RESEARCH CONTEXT

This section addresses the research geographical and climatic context. The geographical context describes about the location where the study was conducted whilst climatic context explains the climatic zone where the study location belongs to.

1.7.1 RESEARCH GEOGRAPHICAL CONTEXT

Egypt has a unique location in the north Eastern corner of Africa that is considered the crossroads between East and West, Africa and Asia (see figure 1.3). The country can be divided into five regions: the Nile River Valley, the Nile Delta, the Western Desert, the Eastern Desert, and the Sinai Peninsula (Goldschmidt, 2008, p.1). The country allocates in the region between the northern latitudes of 23° and 32°, and eastern longitudes of about 25° and 36°.

Figure 1.3 6th of October city as one of the biggest settlements around Cairo (source: google maps)

Figure 1.4 Egypt location (source: google maps)

The area of Egypt is about 1,010,000 sq km. the Egyptian population is concentrated in the Nile valley and Delta that only represents an area of 3.3% from all Egyptian lands. The largest number of population is in Cairo city that make expanding with new settlements around it. One of the biggest and oldest settlements around Cairo is 6th of October .The city is located about 35 km west of central Cairo (the original plan covered a gross area of 3500 hectares) and the construction began in the 1980s aiming at absorbing 500,000 of population out of Cairo (NUCA, 2012). As a result, 6th of October city was chosen to be the specific research geographical context (see figure 1.4).

The research selected a part of the city where a large prototypical housing projects (is called the National Housing Project) was built up by the Egyptian government (2005 – 2011). The Egyptian government adopted this project to produce over 500,000 for low income residential units all over the country (see figure 1.5).

Figure 1.5 housing project prototypes location and perspective view

1.7.2 RESEARCH CLIMATC CONTEXT

According to Köppen's climate classification, Egypt is located in the hot arid climate region (see figure 1.6). It allocates the symbols of **BWH**; the letter **B** points to hot dry (subtropical desert climate and constantly dry), the letter **W** specify that precipitation < ½ water consumption and the letter **H** indicates that average annual temperature is greater than 18°C (Henderson and Robinson, 1986). Furthermore, according to the Egyptian Meteorological Authority report (1976 – 2005) obtained from Cairo airport station number 366, the annual average temperature in Cairo is 22.4 °C with a maximum average temperature of 35.4 °C and minimum average temperature of 20 °C in the peak summer month (July) and a maximum average temperature of 18 °C and minimum average temperature of 10.2 °C in the peak winter month (January). The annual average relative humidity is 55% with a maximum monthly average of 61.7% in December and minimum monthly average of 45.5% in May.

Generally, there is a prevailing northern wind with a cooling effect on the country, except in spring the renowned *khamsin* winds may blow from the southwest currying sand, dust, and hot air through the Nile Valley and Delta, making people feel miserable until the winds calm down (Goldschmidt, 2008).

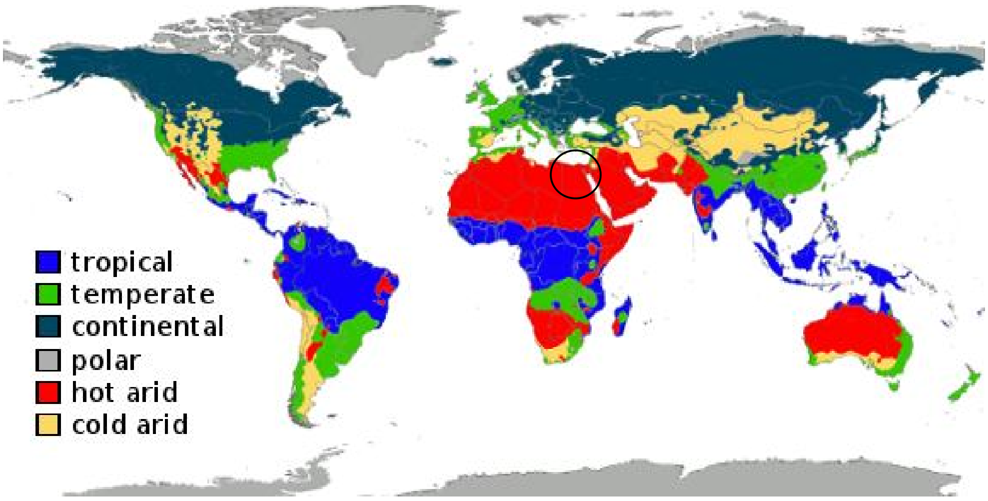

Figure 1.6 world climate classification according to Koppen classification

Egypt has a significant variation in climate conditions from region to another. The Egyptian climate is divided by the the Egyptian Organization for Energy Conservation and Planning (EOECP) into 7 climate zones that were increased recently by to be 8 climatic zones (ECP, 2008) (see figure 1.7)

- **lower Egypt** (region no. 1 – the most famous city is Alexandria) the warmest average maximum temperature is 30 °C in July, August & September and the coolest average minimum temperature is 11 °C in January & February.
- **Greater Cairo** (region no. 2 – the most famous city is Cairo) the warmest average maximum temperature is 35 °C in June, July & August and The coolest average minimum temperature is 9 °C in January & February.
- **Northern part of upper Egypt** (region no. 3 – the most famous city is Al-Minya) the warmest average maximum temperature is 38 °C in June, July, August and the coolest average minimum temperature is 2 °C in January.
- **Middle part of upper Egypt** (region no. 4 – the most famous city is Luxor city) the warmest average maximum temperature is 40 °C in June, July, August and the coolest average minimum temperature is 5 °C in January.
- **The red sea coastal area** (region no. 5 – the most famous city is Suez) the warmest average maximum temperature is 36 °C in July & August and the coolest average minimum temperature is 9 °C in January.
- **Sinai** (region no. 6 the most famous city is El-Tor) the warmest average maximum temperature is 34 °C in August and the coolest average minimum temperature is 9 °C in January.

- **The desert region** (region no. 7 – the most famous city is El-Dakhla oasis) the warmest average maximum temperature is 39 °C in June and the coolest average minimum temperature is 4 °C in January.
- **The Southern part of Upper Egypt** (region no. 8 – the most famous city is Asswan) the warmest average maximum temperature is 41 °C in June and the coolest average minimum temperature is 9 °C in January.

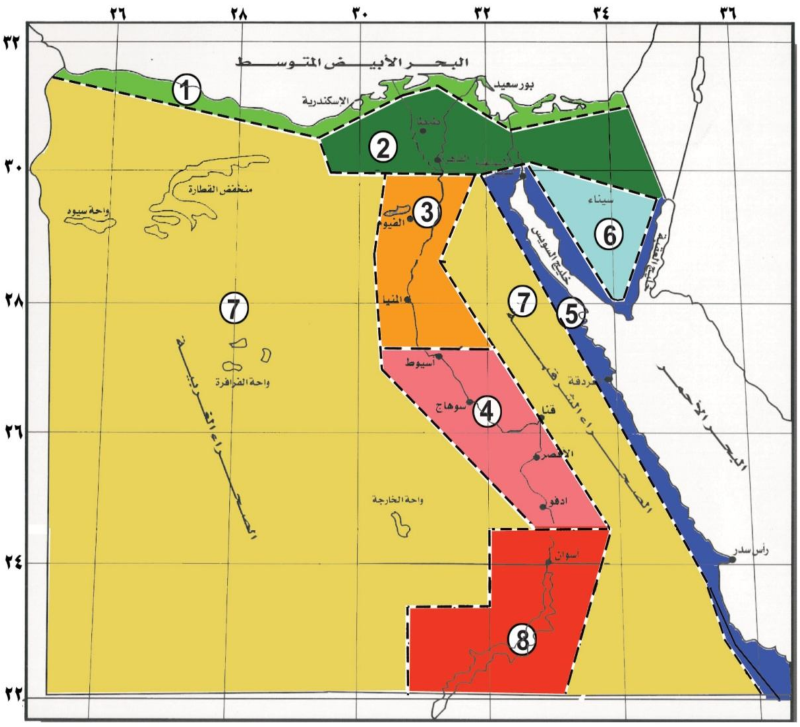

Figure 1.7 Egypt's climatic zones according to ECP (2008)

Zone no. 2 that includes the Greater Cairo and a big part of the delta and Sinai desert is the most populated place in Egypt. Therefore, it was particularly chosen to be the climatic context of this research. 6th of October city was chosen to represent this climatic zone as it is one of the largest satellite city around Cairo includes prototypical social housing design projects.

1.8 RESEARCH METHODOLOGY

The major objective of carrying out a research is contributing to extant knowledge by developing, testing or refuting theories. Research methodology is the manner an individual strives to examine and attain catholic appreciation about the reality (Burrell & Morgan, 1979). The most germane aspect of a research methodology emanates from the assertion that it offers the logic behind the chosen techniques. Kothari (1985, p.8) asserts that;

> When we talk about a research methodology, we not only talk about research methods, but consider the logic behind the methods we use in the context of our research and explain why we are using a particular method or technique so that research

> results are capable of being evaluated either by the researcher him/herself or by others".

Formulating the research question basically determines the methodology and methods that are suitable and considered necessary for the empirical part of the research (Aaltio & Heilmann, 2010). In dealing with the goal, objective and research questions of the study, a multi-method research technique was needed to support how the combination of natural ventilation strategies and external insulation retrofitting technique improves indoor thermal comfort in residential buildings in hot arid climate regions in the context of Egypt. This research strategy offered the researcher a platform to get access to extensive and sufficient data relevant for addressing the research questions of this research (See section 1.3). This research design was characterized by two fundamental facets: Mixed methods and case study. These facets and the rationale behind their selection are discussed in detail in the next segment of this chapter.

1.8.1 MIXED METHODS

A mixed-mode research strategy is a technique for gathering, analyzing, and "mixing" both qualitative and quantitative analyses and procedures in a study to appreciate a research problem (Creswell, 2012). This method aids in generating unique insight into a social phenomenon that cannot be obtained from the application of a single research analysis (Bhattacherjee, 2012). Accordingly, the study applied this method and the major premise was that the application of mixed-mode offered the researcher a better appreciation of whether occupants of the social housing projects feel thermally comfortable or otherwise in their apartments.

In regards to the quantitative aspect of this work, data was obtained about number of occupants, lighting use profile, occupation profile, windows and internal doors profile, domestic appliances and building orientations. Furthermore, the indoor dry bulb temperature, globe temperature and relative humidity were monitored in three hour intervals over one week in both winter and summer seasons. With respect to the qualitative facet, the researcher observed the buildings in terms of building materials used and building distribution on site to validate the archival records obtained. More so, the researcher had experienced the microclimate condition for one of the apartments over one week in both winter and summer seasons. The next sub-section addresses the other fundamental aspect that typified this study: Case study

1.8.2 CASE STUDY

Case study design allows a researcher to comprehensively examine data within a specific context. Yin (2003, p.13) defines a case study 'as an empirical inquiry that investigates a contemporary phenomenon within its real-life context; especially when the boundaries between phenomenon and context are not clearly evident'. To Yin, case study is applied in many circumstances to contribute to knowledge of individual, group or an organization. Case studies can also be applied in architecture related topics such as examining the effect of the combination of natural ventilation and insulation technique on indoor thermal comfort. Zaidah (2007) explains that case studies explore and examine contemporary real-life phenomenon through contextually analyzing a limited number of events and how they are connected. Dul and Hak (2008) also describe it as a study in which a single case or a smaller number of cases in their actual life context are being selected, and scores obtained from these cases are analyzed. To the authors, a case study means a project whereby a theory-oriented or practice-oriented objective is developed and attained.

The study employed this design in that, unlike other strategies, it adds other sources of data such as direct observation of events (Yin, 2009). Also, it is distinctive in the sense that it has the capability to deal with lots of evidence. For example, documents, observations as well as artifacts. Lastly, since this study's aim was to 'get under the skin' of thermal performance of social housing building stocks within the context of Egyptian climate (that is, to scrutinize the case from the inside out) these social housing projects, it was considered suitable to apply this strategy. The next sub-section will address the logical sequence of this study.

Research design ultimately consists of a logical sequence that serves as a nexus between empirical data and the study's initial research questions and eventually, to its conclusion (Yin, 2003). It also deals with the whole purpose of the study (Maxwell, 1996). In case study research method, a catalog of research design has not yet been developed (Yin, 2003). To Yin (2003), there are no textbooks that encapsulate the various research designs for quasi-experimental circumstances. The most important constituents of a case study research design are: a) the study's question, b) the propositions of the study; c) the units of analysis; d) the logical sequence that links the data to the propositions, and e) the benchmarks for implementing the findings (Yin, 2003). Each of these constituents is dealt with in the subsequent sections.

1.8.3 RESEARCH QUESTION

The conceptual part of this study was addressed by identifying the central research question. Case study research is connected to 'how', 'why', and 'what' questions. The study attempted to improve thermal comfort in residential buildings in hot arid climate regions by combining natural ventilation and insulation retrofitting techniques. In consequence, the primary question that was identified was 'How can the combination of natural ventilation and insulation retrofitting technique affect indoor thermal comfort?' From this, the following sub-questions were asked 'what are the behavioural strategies of natural ventilation available in the extant literature that can improve the indoor thermal comfort in hot arid climates?', 'what are the appropriate insulation materials that can improve the thermal performance of building envelope and available or can be available in future in Egypt?' and 'how can the combined strategy of natural ventilation and insulation technique improve building thermal performance and consequently indoor thermal comfort?'. The study answered these questions by employing a case study research as a conduit to appreciate nature and the usage of the theories of indoor thermal comfort.

1.8.4 CASE STUDY SELECTION

The selection of cases is relevant to case studies. For instance, in order to control extraneous variation as well as to help define the limits for extrapolating the findings, the selection of more suitable cases is deemed necessary (Eisenhardt, 1989a). Accordingly, this study employed a criterion-based sampling technique where cases were selected to provide rich evidences, but not for statistical reasons. The rationale behind this selection was that this technique furnishes the investigator a combination of circumstances to alter the emphasis of the study at early stages so that the data collected are a mirror image the instead of conjecturing about what is supposed to have happened (Coyle, 1997; Glaser, 1978; Straus & Cobin, 1990).

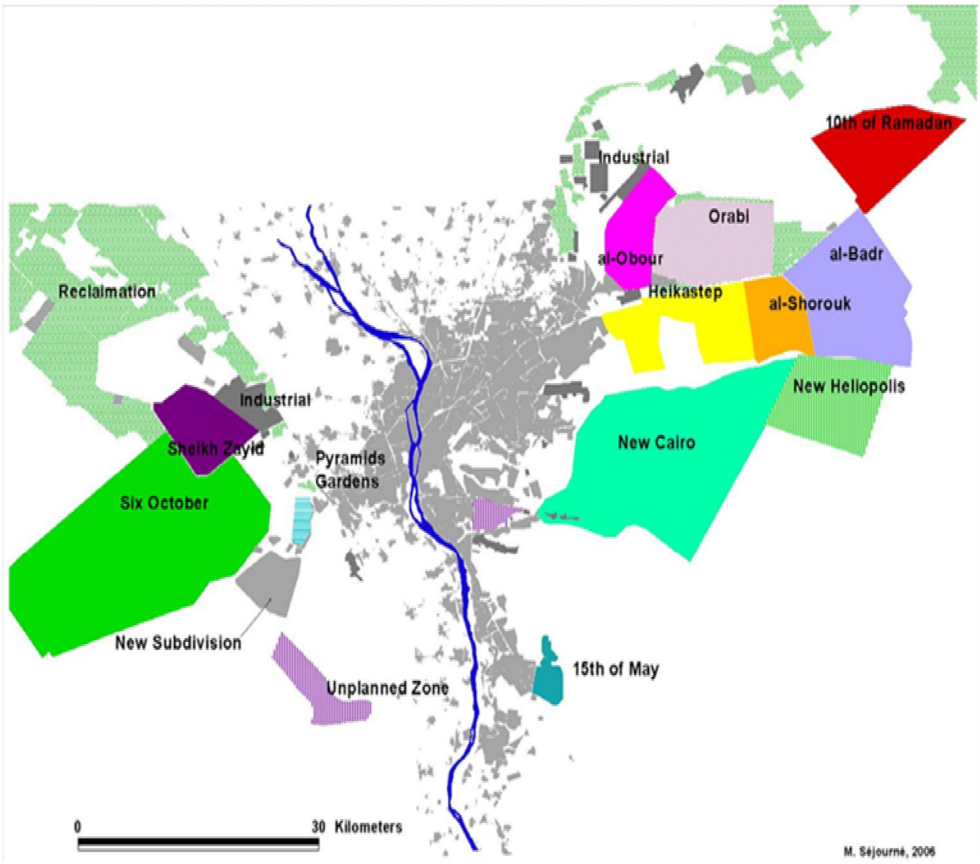

Figure 1.8 Cairo satellite communities (World Bank 2008, p.52)

6th of October city was chosen as it is considered one of the oldest and largest satellite development among twenty-two developments that were constructed around Greater Cairo in three phases from 1977 to 2000 (Forty cities are planned to be built in the future in order to solve the housing problem and to reduce the pressure on services in Cairo city), it was announced in 1979 to be built on 3500 hectares on the western side of Cairo (see figure 1.8) and was planned to absorb a number of population of 500,000 (NUCA, 2012).

The selected buildings represent one of the social housing projects that were built in 6th of October City. The site is a small part of the city and has been constructed in 2005 as a part of a large scale urban development project launched by the Egyptian government for the youth under 'the National Housing Project'. The project includes

500,000 residential units for low income distributed throughout Egypt within 7 different ownership or rental schemes.

In order to apply the criterion-based sampling technique in this study, by reviewing the various satellite cities around Cairo, it was found that 6th of October city is one of major and oldest cities (see figure 1.8). Furthermore, 63 m2 prototypical dwellings was chosen as it encompasses the largest number of residential units (see table 1.1) that is posed to the youth that are the major part of Egyptian population.

Table 1.1 national housing project schemes

type	Project schemes	Number
63 m2 prototypical dwellings	Ownership of housing units	201233 dwellings
	dwellings for rent	136925 dwellings
	Investors land scheme	218931 dwellings
36 m2 dwellings	dwellings for rent	76000 dwellings
Plots 75 m2 for each	Build your own house scheme	91736 houses
Attached houses	Family houses for rent	3020 houses
Attached houses	Ownership of rural houses	7389 houses

The apartments were chosen in different orientations. The orientations were north, south, east and west and their percentages from the chosen sample were 30%, 30%, 20% and 20% respectively (see figure 3.2 in chapter 3). The reason behind the disparity between north and south orientations, East and West orientations is that the north was assumed to be the worst orientation in winter season (as it is less exposed to the sunlight) while the south was assumed to be the worst orientation in summer season (as it is the most exposed to sunlight).

1.8.5 DATA COLLECTION TECHNIQUES

Generally, case studies draw on multiple sources of evidence. These include documents, archival records, interviews, observations (direct or participant) and physical artifacts. Rowley (2002) points out three (3) principles of data collection in case study that this study followed: triangulation, case study database and chain of evidence. Triangulation is one of the major strengths of case studies as compared to other methods (Rowley, 2002) since it is of significant importance for 'interpreting, embedding and validating results' (Huse et. al., 2011, p. 21). With this principle, evidences are collected from multiple sources. This technique therefore, serves as validity procedure to fashion out categories and themes in a study (Creswell, 1994).

Furthermore, the study made use of a case study database during data collection. This was to ensure that the unprocessed data were available to other researchers. Davis (2010, p.79) asserts that '[a] formal case study database not only enables researchers who are not involved in the case study project to juxtapose data collected and cited in the database with claims made and conclusions drawn, but such a database also increases the reliability of the overall case study'. Therefore, the preparation of reliable and practical case study database for further analysis was imperative for ensuring accurateness of the data gathered and analysis.

Following Davis (2010), the study's case study database included notes that were made by the researcher, case study documents collected during the entire period of the study, case study tabular materials and case study narratives. The notes that were taken included messages gathered from interviews, observations and document analysis compiled throughout the entire research. Case study document was also gathered by the researcher by developing an annotated bibliography. Furthermore, tabular materials were obtained from quantitative data from each of the companies' annual reports such as percentage shareholdings of shareholders, company performance and other quantitative records. Lastly, the researcher employed case study narratives in documenting the answers to the various questions in the case study protocol. This was done by footnoting important evidences from the archival records, interviews and observations.

Finally, the researcher required maintaining a chain of evidence that would be easily accessible in the database. This was important because with this technique, an explicit link among the various questions that were asked, the data collected and the conclusions that were drawn was established.

Based on the aforementioned three principles, the study employed three main sources of data collection: Archival records, observation, questionnaire and field measurements.

1.8.5.1 ARCHIVAL RECORDS

Patton (1990, p.245) posits that archival records "analysis provides behind-the-scenes look at the program that may not be directly observable and about which the interviewer might not ask appropriate questions". Lincoln and Guba (1985, p.27) also viewed archival records as "a stable source of information……[in] that they may accurately reflect situations that occurred at sometime in the past and that they can be analyzed and re-analyzed without undergoing changes in the interim". Prior to this research, archival research on secondary resources such as architectural drawings of the project, project specifications, materials and quantities were gathered to identify the project design, materials used, building adjacencies and skeleton structure for the buildings. (figure 1.9)

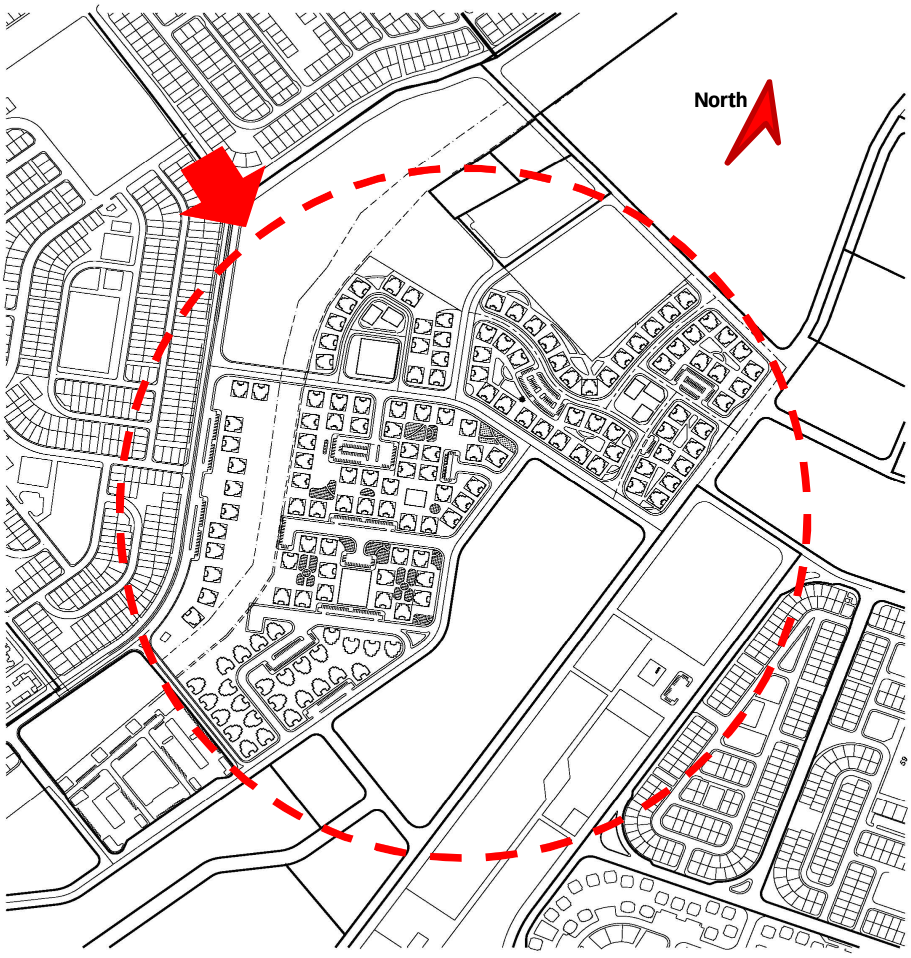

Figure 1.9 case study site map (Archival records)

1.8.5.2 OBSERVATION

Observation, as a data collection technique means an active engagement with a phenomenon in its natural setting. It ‘can be an invaluable way of collecting data because what [the researcher] sees with [his/her] own eyes and perceive with [his/her] own senses is not filtered by what the author of some document might have seen’ (Yin, 2011, p.143). Adler & Adler (1994) point out that the trademark of observation is its non-meddling feature that lessens any intrusion in the behavior of those observed, neither wangling nor provoking them. For this study, the researcher had direct experience of the utilization of building materials and building distribution on site to validate the archival records obtained from the governmental authorities who are in charge of this project. Furthermore, the researcher had experienced the microclimate condition for one of the apartments over one week in both winter and summer seasons.

1.8.5.3 QUESTIONNAIRE

A questionnaire is a data collection instrument comprising a set of questions intended to grab hold of responses from respondents in a standardized way (Bhattacherjee, 2012). It was invented by Sir Francis Galton. Questions will probably be unstructured, semi-structured or structured. In this study, a semi-structured questionnaire was applied to elicit data from the inhabitants of the buildings about occupant's thermal sensation, number of occupants, occupant's activity profile, lighting use profile, occupation profile, windows and internal doors profile, domestic appliances and building orientations. The semi-structured questionnaire used in order to open spaces for the respondents to give a triangulated aroma to the data gathering technique in this research.

The questionnaire was self-administered, where the same questions were administered to respondents who were willing to partake in this study, at their own convenient time. This offered the study's respondents the opportunity to ask for clarifications to specific questions they did not easily decipher. The study's respondents were chosen regardless of sex. The total response rate was 30%, which was low. The reason was at the time of the data gathering, there was social and political unrest in Egypt. Accordingly, the people were afraid to welcome strangers to their homes. These respondents live in different apartments in various buildings. The percentage of male respondents was 80% and female, 20%. Appendix (8.5) entails the questions that were posed to respondents.

1.8.5.4 FIELD MEASUREMENT

According to ASHRAE standard 55 (2003) Measurements should be made in occupied zones of the building at locations where the occupants are known to or are expected to spend their time. Furthermore, it should be taken in locations where the most extreme values of the thermal parameters are estimated or observed to occur. Furthermore, Measurements should be made sufficiently away from the boundaries of the occupied zone and from any surfaces to allow for proper circulation around measurement sensors. In addition, Air temperature should be measured at 1.1 m level above the ground corresponding to the average height of the center of gravity for adults (ASHRAE, 2003; Mayer and Hoppe 1987)

Considering the above literature, the living room of one of the apartments was chosen to carry out the measurements because it the most occupied place in the apartment where people were expected to spend their time and do their various activities. The apartment was located in the typical floor of one of the prototypical dwellings of 63 m^2 for rent in October 6th city. The field measurements were conducted during both winter and summer season in the same apartment. The apartment was naturally ventilated without any cooling or heating systems.

The winter field measurements were conducted during one week in the first half of January, 2013 (from 4th of January to 10th of January, 2013). According to the climatological reports for climate data averages over thirty years from 1976 to 2005, January is the coldest month of the year in Cairo. Air temperature was monitored in three hour intervals. **The summer field measurements** were conducted during the last week of June. Air temperature and globe temperature were monitored in three hour intervals. The external air temperature during the time of measurements in both winter and summer seasons was obtained from Cairo international airport meteorological station no. 623660.

The field measurements were used to validate a commercial simulation software program; the building performance simulation commercial code IES<VE> (Integrated Environmental Solutions - Virtual Environment) that was chosen to simulate the thermal performance of one of the chosen residential buildings. The validation was done by comparing the air temperature between field measurements and simulation predictions. Figure (1.10) shows the place of measurements.

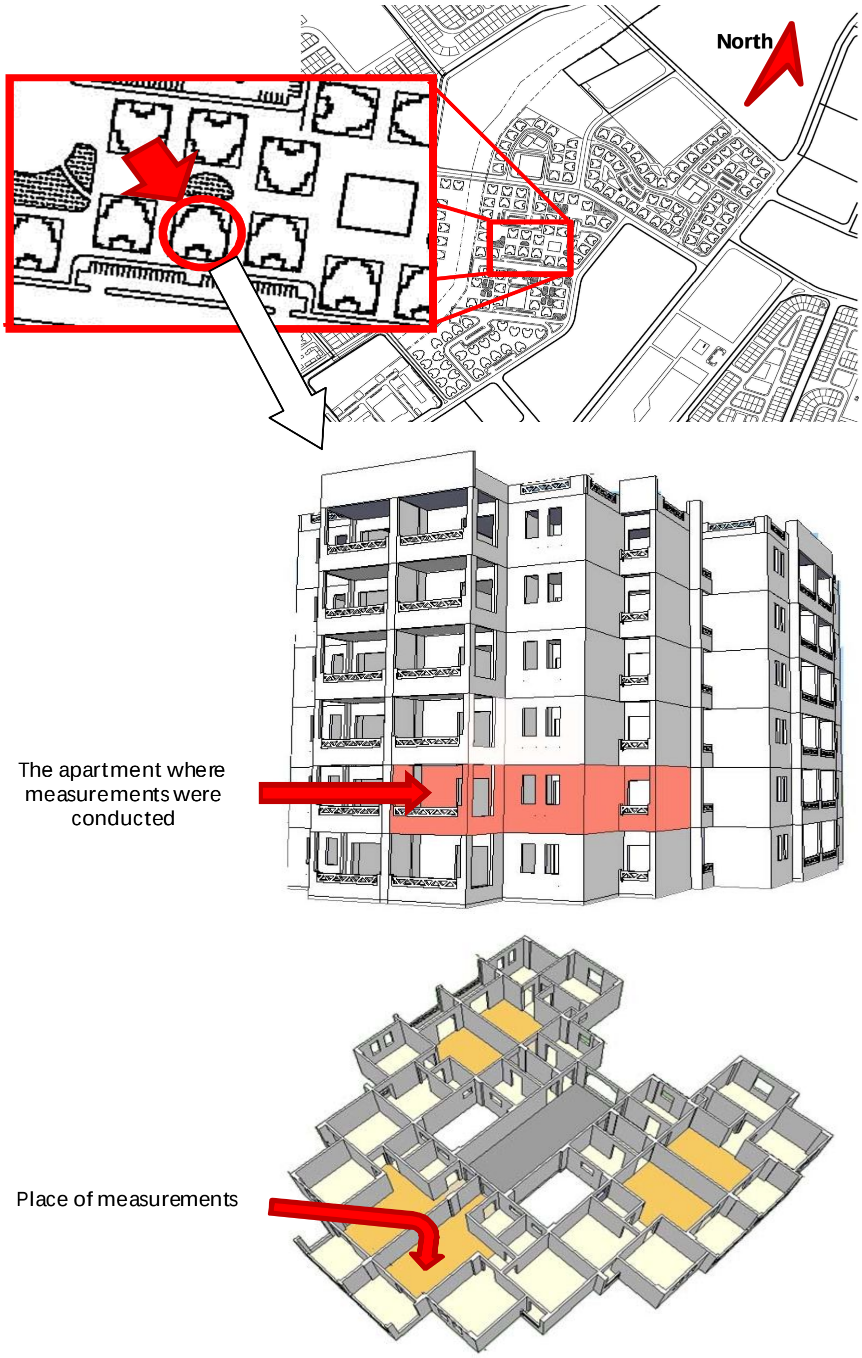

Figure 1.10 the place of measurements

1.8.5.4.1 MEASUREMENT TOOLS

Davis weather station (figure 1.12) was used to record the indoor air temperature in three hour intervals. Davis device can provide temperature readings from --40°C to +65°C with sensor accuracy of ±1°F (±0.5°C). It also measures relative humidity from 0 to 100% with accuracy of ±3% (0 to 90% RH), ±4% (90 to 100% RH). Further, the heat index WBGT meter (model 8778) (see figure 1.11) was used to monitor the black globe temperature during the summer field measurements. It can provide indoor black globe temperature readings range from 0°C to 80°C with sensor accuracy of ±1°C when temperature ranges from 15°C to 40°C and sensor accuracy of ±1.5°C when otherwise.

Figure 1.12 Davis weather station

Figure 1. 11 heat index WBGT meter

1.8.6 UNIT OF ANALYSIS

The unit of analysis is a constituent or component that is connected to the central problem of what the case is to the researcher. In case study research, the researcher ought to be able to identify the unit to be analyzed be it individual, a group, department or an organizational level (Yin, 2009; Teegavarapu & Summers, 2008). In the current study, the unit of analysis was limited the prototypical buildings that were distributed on site, the apartments and the occupants.

1.8.7 THE CRITERIA FOR INTERPRETING FINDINGS

1.8.7.1 ANALYSIS

There were three sets of data analyses were conducted in this research and were presented visually in graphs format within the study:

1- The data gathered from the semi-structured questionnaire were analyzed using EXCEL sheets in order to be coded into the simulation software program; furthermore, they were used to predict the thermal sensation of the local inhabitants that can help to know about the microclimate condition and people satisfaction in both winter and summer.

2- The data gathered from field measurements in both winter and summer seasons were collected by data logger and were turned into EXCEL sheets and then used to validate the simulation predictions generated by IESVE simulation software program in terms of indoor air temperature. Furthermore, the monitored globe temperature was used to check the isothermal condition of the apartment where measurements were conducted.

3- The simulation tool IESVE (integrated environmental solution – virtual environment) was used as a consistent quantifying mechanism to predict and compare the increasing in comfort level and the reductions in cooling and heating demand in the case study when applying a specific scenario of natural ventilation or insulation technique or to combine them together. Furthermore, comparing the differences between the different major orientations; North, East, West, South and, eventually, showing the differences between typical and upper floor. All simulation results were converted into EXCEL sheets where parametric analyses were employed. The simulation output provided monthly three set of data - that were compared to the base case - for each examined scenario; percentage of hours of cooling demand, percentage of hours within comfort range and percentage of hours of heating demand.

4- The data were linked to the proposition to confirm or disconfirm the hypothesis of the study (see section 1.7 for the hypothesis).

1.8.7.2 SIMULATION TOOL

Building performance simulation is now being used in support of policy development. The goal is to provide decision makers with the means to compare energy supply and demand, at a local or regional level, in terms of the match at present or as it may exist under some future scenario (Santamouris, 2009). According to the U.S. Department of Energy (DOE) there are 393 software tools available for assessing the performance of buildings regarding energy efficiency, renewable energy system integration, adaptive occupant comfort, ventilation, indoor air quality and sustainability credentials in buildings.

The current study chose the Integrated environmental solution – virtual environment (IES<VE>) that uses the calculation engine of Apache thermal analysis module, which provides either steady-state or dynamic analysis of energy consumption and indoor thermal conditions (Crawley, 2008; University of Cambridge, 2013). IES <VE> is considered one of the 20 major building energy simulation programs. It includes ApacheSim, a dynamic thermal simulation tool based on first-principles mathematical modeling of building heat transfer processes. It is a validated tool using the ASHRAE Standard 140 and authorized as a Dynamic Model in the CIBSE system of model classification (Crawley et al. 2005). Furthermore, previous studies by Sedki, (2013a,b) conducted in residential buildings in hot arid climates confirmed the credibility of IES<VE> for estimating the indoor air temperature in both winter and summer seasons. A study by Leng (2012) proved the credibility of IESVE within Malaysian context.

Since the real buildings are complicated in systems, sophisticated in variables and the results of simulation are dependent on data inputs, the results are considered as a realistic approximation for the real building. The complexity of data inputs was reduced into a manageable data entry for internal loads, occupancy, activities and so on (see chapter 3). Furthermore, the building model was approximated to the real building in terms of façade details and building fabric (see figure 1.13)

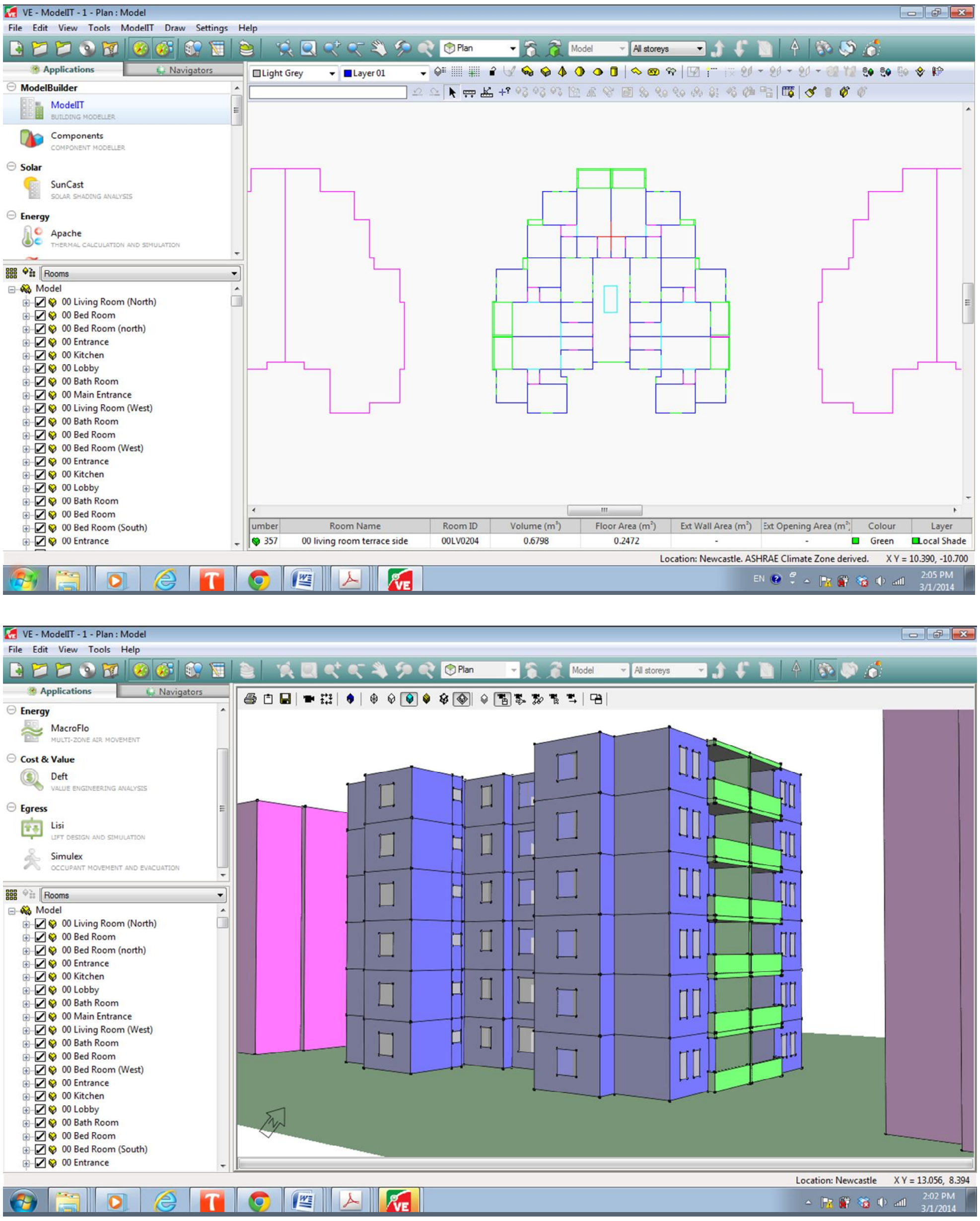

Figure 1.13 modeling analyses on IESVE simulation tool

1.8.8 CRITERIA FOR JUDGING RESEARCH QUALITY

Yin (2009) points out that construct validity is relatively difficult test to pass in case study research. However, the author further suggests three main tactics to increase construct validity when conducting a case study research: 1) The use of multiple sources of evidence; 2) establish chain of evidence; and 3) have key informants review draft report (member checking). An application of multiple sources of evidence is relevant during data collection and also serves as a tool to encourage convergent lines of enquiry (Yin, 2009). This method is termed, triangulation. Accordingly, the study applied four techniques of data collection; archival records, questionnaire, observation and field measurements.

In order to ensure reliability in this study, a case study database was developed. Yin (2009) argues that with no case study database, the unprocessed data will probably be accessible to independent researchers and may result in major setbacks, which will probably affect the credibility of the study. In order to avoid this shortfall, the study employed a case study database during its data collection period. Also, teamwork with a research assistant during the process of data gathering and analysis of the study, and with the supervisor of the thesis during the entire period of the research, reliability was achieved.

For the internal validity, the study constructed connections between the gathered data in inferential structure, explanations and understandings in order to insure that deductions made were methodologically explored and examined.
For the External validity, the study constructed connections between the gathered data in inferential structure, explanations and understandings in order to insure that deductions made were methodologically explored and examined.

1.8.9 ETHICAL CONSIDERATION

Science has more often than not been stage-managed in unethical manner by people and organizations to convey or bolster their private agenda and engage in actions that are in stark contrast with the norms of scientific conduct (Bhattacherjee, 2012). Therefore, ethical issues in research are imperative. This study applied certain forms of ethical behavior that are universally accepted in the scientific society. First, before gathering the required data for the analyses of the study, respondents were informed that their participation in the study was voluntary, that they had the freedom to quit any time without any adverse effects, and that they were not going to be harmed in consequence of their partaking or non-partaking in the study. Also, prior to eliciting information from the respondents, the purpose, data collection techniques and significance of the research were communicated to them.

Second, since one of the data collection techniques of the study was face-to-face questionnaire, anonymity was impossible. However, respondents were assured of confidentiality in that they were promised their identities would not be divulged in any report, paper, or public seminars. This study did not claim that the application of confidentiality is akin to the use of anonymity, but it could offer a relevant help to curb unethical issues in scientific community. Finally, science has been argued to progress through sincerity, credibility and honesty, and investigators can best contribute their quotas to the benefit of science and the science community by wholly highlighting the weaknesses associated with their works so that other investigators could be saved from similar issues (Bhattacherjee, 2012). In the course of carrying out this work, the investigator encountered some limitations and they have been unequivocally and consistently itemized throughout the entire write-up.

1.9 METHODOLOGICAL FRAMEWORK OF THE STUDY

This section of this chapter summarizes the overall design, activities and sources of data for this research approach. Figure (1.14) below illustrates the methodological framework that was employed in this study. This methodological framework mirrors the sequential flow from preliminary activities that introduced the study and the research development.

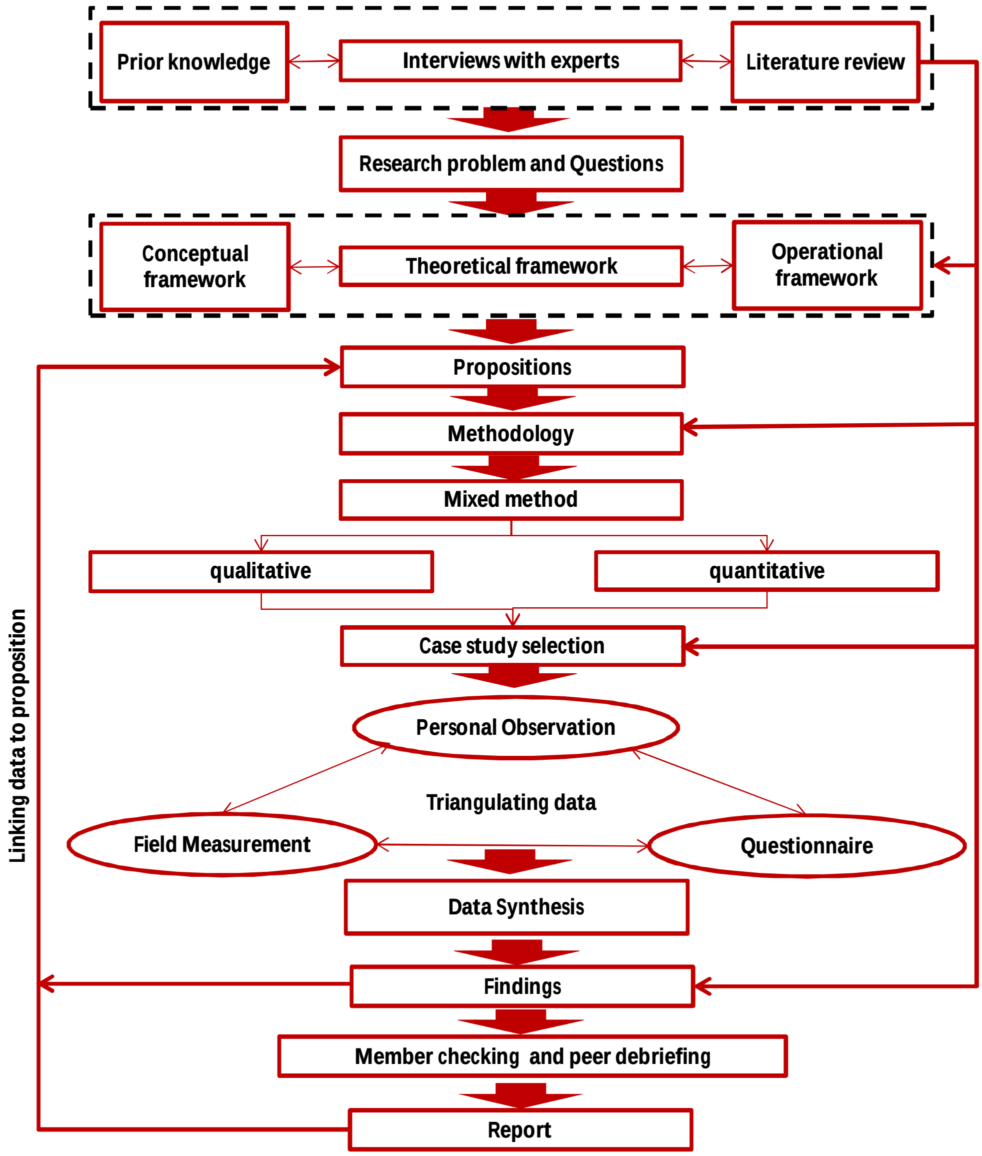

Figure 1.14 Research methodological sequence

1.10 RESEARCH STRATEGY AND ORGANIZATION OF THE STUDY

Research design is defined by Bhattacherjee (2012) as the comprehensive plan for data gathering in an empirical research project. It is also defined as a "*blueprint*" that intend to respond explicit research questions or examine research hypothesis. It has to deal with three progressions; data gathering, instrument progress and sampling. In regards to current study, the research design is portioned into three major frameworks; 1) the conceptual framework, 2) the theoretical framework, 3) the operational framework (see Figure 1.14).

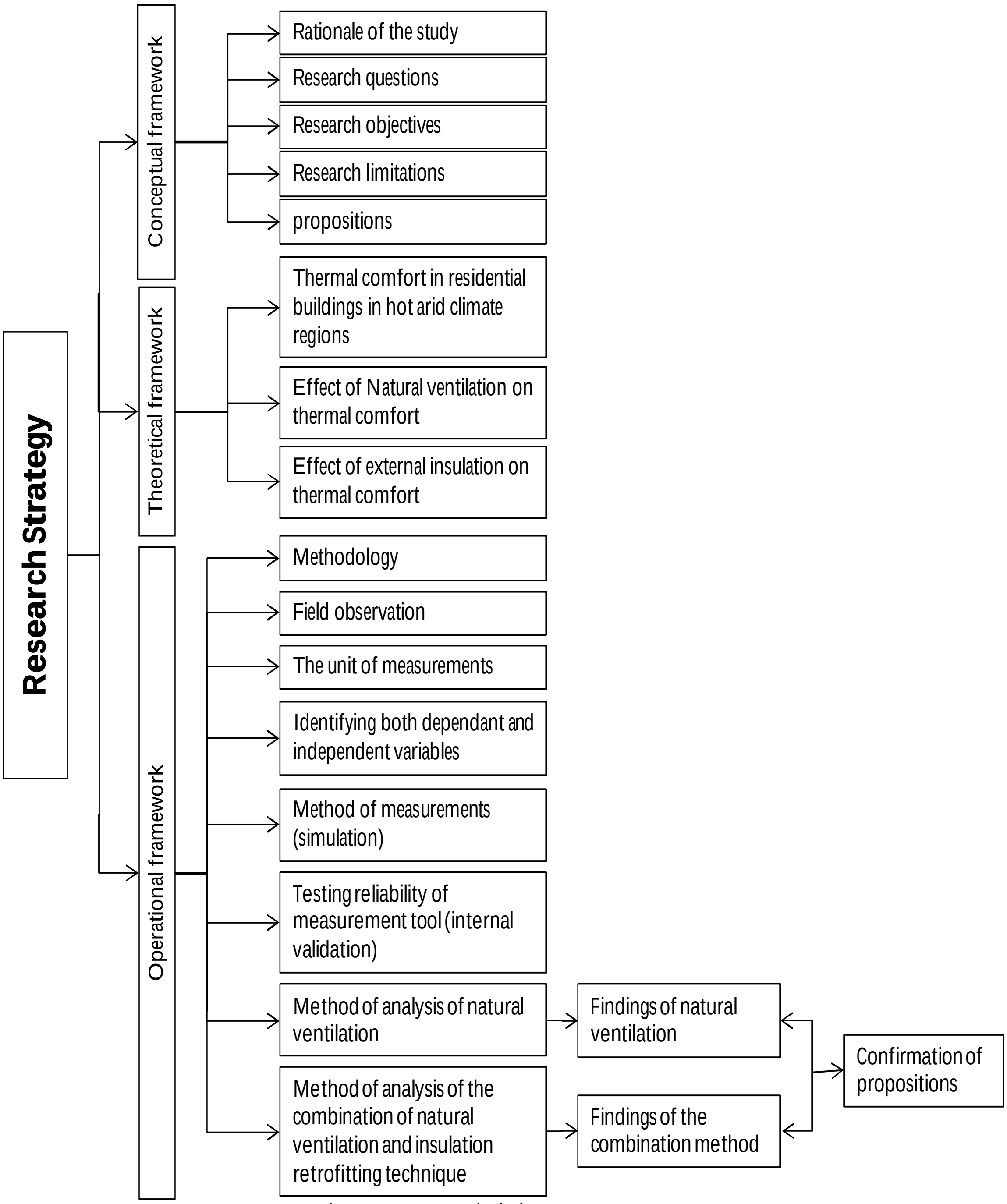

Figure 1.15 Research design

The research organized into six chapters that cover the previously mentioned frameworks. The summary of each chapter contents and structural framework are explained below:

Chapter one: It highlights an introduction to the study and outlines the fundamental themes that lead the study. It brings out the background of the study, a brief description of the context of the study, statement of problem, research objectives, research questions, rationale of the study, and research propositions. It further presents the methodology and research methods of the study, and the organization of the study.

Chapter two: It presents a literature review about thermal comfort, the main factors that affect thermal comfort, the approaches that were used to study thermal comfort, overview on the previous studies that were conducted on residential buildings in hot arid climates.

Chapter three: It comprises the questionnaire analysis, validation studies for the synthetic simulation weather profile in terms of indoor air temperature in IES<VE> simulation tool by comparing the indoor dry bulb temperature between field measurements and simulation predictions in both winter and summer seasons under the hot arid climate conditions of greater Cairo in Egypt and eventually it discusses the comfort zone limits for Cairo climate condition in each month for the whole year.

Chapter four: It identifies the interrelationship between natural ventilation and thermal comfort in hot arid climates; furthermore, it discusses the effectiveness of natural ventilation different scenarios on indoor thermal comfort of the research case study.

Chapter five: It examines the effectiveness of the combination of natural ventilation and insulation retrofitting technique to improve indoor thermal comfort.

Chapter six: It outlines a conclusion and recommendation for the whole research work. It also presents the contributions of the study, overview on research propositions and finally highlights areas for future research.

1.11 CONCLUSION

This chapter presented an introduction to the study and outlined the fundamental themes that guide the study. It encompassed the background of the study, statement of problem, research objectives, research questions, rationale of the study, limitations, propositions, and context. It also presented the methodology and research methods of the study. Finally it brought out the research design and organization of the study. The next chapter will present an extensive literature review about thermal comfort, particularly, thermal comfort in residential buildings in hot arid climates.

CHAPTER TWO

2. THERMAL COMFORT: DEFINITION, APPROACHES AND OVERVIEW

1. THERMAL COMFORT DEFINITIONS
2. THERMAL COMFORT PARAMETERS
3. THERMAL COMFORT APPROACHES
4. OVERVIEW ABOUT RESIDENTIAL BUILDINGS IN HOT-ARID CLIMATES
5. CONCLUSION

2.0 INTRODUCTION

Achieving Thermal comfort became an urgent need because of excessive demand in Energy consumption all over the world in the last decades that urged scientists to come across other solutions can adaptively achieve thermal comfort without consuming more energy in buildings, in addition using renewable energy and energy saving techniques in the built environment.

Nowadays, Building sector consumes 40% from the world's energy use (World Business Council for Sustainable Development (WBCSD, 2008). The electricity demand in residential building sector in Egypt has been increasing from 7-10% a year in the period between 1998 to 2008, and it is expected that it will increase by 35% in future (George and Soliman, 2007). Residential building sector in Egypt consumes more than 47% of the total nationally generated electricity. It was also found that increasing of outside air temperature one degree above 35 °C causes increasing in the energy consumption by 100 MW/Hour. It means if the outside air temperature reached 42 °C it will increase the energy consumption by 800 MW/Hour which needs electricity generator costs 2 billion Egyptian pounds and four years to be constructed. In addition, energy could be saved by 10% if the air-conditioning raised be 1 °C. In this context, there was an urgent need to indoor improve thermal condition of residential buildings in Egypt that can positively reflect on energy consumption (ECP306, 2005; Mourtada, 2009; Kimura, 1994).

This chapter is a literature review that aiming to explore four main questions; first, what is thermal comfort? Second, what are the main factors that affect thermal comfort? Third, what are the approaches used to study thermal comfort criteria? Fourth, what are the studies that were conducted on residential buildings in hot arid climates? The conclusion of this chapter will be useful to specify acceptable comfort condition for residential buildings in hot arid climates and that will lead to further explorations of interventions and materials to improve the performance of the base case.

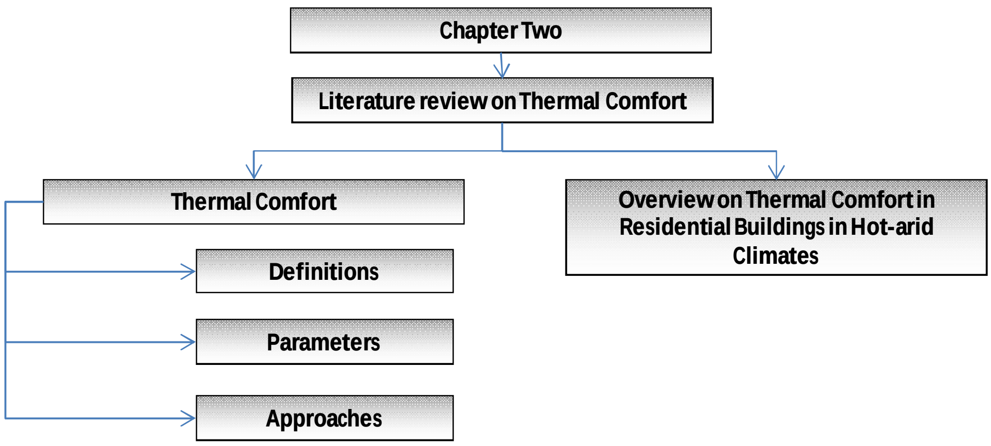

Figure 2.1 Chapter two structure

2.1 THERMAL COMFORT DEFINITIONS

A considerable number of definitions of thermal comfort have been introduced by scholars. Olgyay (1953) defined thermal comfort as the "Conditions wherein the average person does not experience the feeling of discomfort". Givoni (1976) considered thermal comfort as the absence of irritation and discomfort due to heat or cold and the state of pleasantness. Hensen (1991) defined thermal comfort as "a state in which there are no driving impulses to correct the environment by the behaviour". Thermal comfort is also defined by ASHRAE standard 55 (the American Society of Heating, Refrigerating and Air-Conditioning Engineers) as that "the condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation". The definition of thermal comfort leaves open as to what is meant by condition of mind or satisfaction they acknowledge that thermal comfort as a state of mind then, they emphasized that it is being affected by other physical, physiological, psychology factors. the state of mind depends on person's general feeling that affect his judgment according to many environmental or personal factors such as air motion, humidity level, person's attitude, experiences, expectations, and so on (Hijis, 1994; ASHRAE, 2001; Lin and Deng, 2008; Djongyang et al., 2010). Humphreys (1992) simplified the definition of thermal comfort to be 'the absence of discomfort' referring that the criteria of discomfort depends on wide range of physiological, behavioural and cultural factors while Givoni (1992) considered the role of economical and technological factors in understanding comfort and discomfort criteria.

The cause of discomfort happens when the air temperature turn out to be more than the skin temperature of the human body, and then, it reduces the heat loss by convection and radiation from the body into the surrounded environment to maintain thermal balance (Hamza, 2004).
There is no absolute standard for thermal comfort. Research indicates that people who occupy very similar spaces, exposed to the same environment, and belonging to a common culture, issue very different opinions due to their thermal sensation (Brager and De Dear, 1998; Kuchen and Fisch, 2009; Djongyang et al. 2010).

From literature, achieving thermal comfort is highly sophisticated issue and yet not completely understood, furthermore, a worldwide definition of thermal comfort is unattainable because of the diverse wide range of thermal preferences from person to another and the specific characteristics for each climate zone (Kordjamshidi, 2010).

2.2 THERMAL COMFORT PARAMETERS

According to Macpherson (1962) the first observation that there are other factors affecting the thermal sensation rather than air temperature alone was highlighted by Ellis in 1758 as he said that,

"This same thermometer I have had in the equatorial parts of Africa . . . at Jamaica, and the West Indian Islands, and on examination of my journals I did not find that the quicksilver ever rose above the 87 Fahrenheit and to that but seldom. And yet I think that I have felt those degrees with moist air more disagreeable than what I now feel".

At the beginning of the nineteenth century the effect of air movement started to be taken in consideration measured firstly by Leslie's anemometer. The radiation started to take its importance as a significant factor when Stefan Boltzmann published his law on the relationship between thermal radiation (H) and temperature (T) ($H = \delta T^4$) (Bedford and Warner, 1934).

It wasn't until the end of the nineteenth century that the impacts of the four environmental factors (air temperature, relative humidity, air speed, radiation) together on human sensation were acknowledged.
Macpherson (1962) specified six factor that affect thermal comfort; four physical variables (air temperature, air velocity, relative humidity and mean radiant temperature) and two personal variables (clothing insulation and activity level).

According to Szokolay (2008) the variables that affect heat dissipation from the body and consequently thermal comfort can be grouped into three sets; Environmental (Air temperature, Air movement, Humidity, Radiation), Personal (Metabolic rate, Clothing, State of health, Acclimatization) and Contributing factors (Food and drink, Body shape, Subcutaneous fat, Age and Gender). Figure (2.2) shows thermal comfort variables.

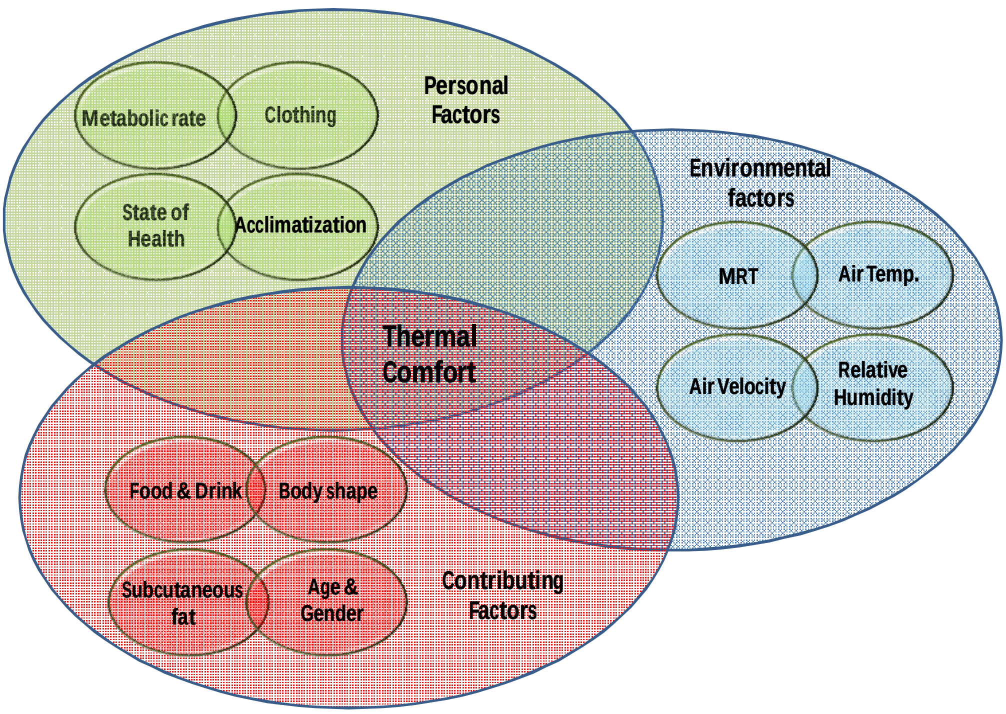

Figure 2.2 Thermal comfort variable sets according to Szokolay, 2008

However, according to Brager and de Dear (1998) in their extensive literature review about thermal adaptation in the built environment, personal variables could be divided into three sets; behavioral adjustments (including personal, environmental, technological and cultural adjustments), physiological adaptation (including genetic adaptations and acclimatization) and psychological adaptation (including habituation or expectations).

Behavioral adjustments comprise all changes that person intentionally or unintentionally does to modify heat fluctuations that affect body's thermal balance with surrounded environment (Wohlwill, 1974). it comprises: 1) personal adjustments that includes activities, clothing, eating, drinking and so on, 2) technological or environmental adjustments such as opening/closing windows, shading, switching on fans or heaters, operating HVAC systems and so on, 3) cultural adjustments that is related to cultural aspects and habituations in like dressing, activities schedule (siesta), etc (CIBSE Guide A; Brager and de Dear, 1998).

Physiological acclimatization includes all transformations which can occur in human body thermoregulatory system as a result of exposure to external thermal factors. Unlike thermal sensors (receptors), the heat flux sensors do not exist in human body. However, receptors are more sensitive to cols than warm conditions in temperature flux (Benzinger, 1979). In hot arid climates, the initial physiological reaction to heat stress is the augmentation in sweating ability for a certain heat load. Furthermore, it causes a drop in body temperature set point that makes change in sweating thermoregulatory in the sense that it makes it better distributed on skin. There are also other physiological responses happen for the acclimatized body such as heart rate reduction, blood volume augmentation and lessening blood flow (Wyndham, 1969). Usually, discomfort sensation occurs when skin temperature exceeds 33 °C and witness less than 25% (Berglund, 1994).

Psycological adaptation is considered as the factors beyond physics and physiology. it has a significant role for the person's thermal preferences, expectations and acceptability (Fountain, 1998). It is strongly related to cognitive and cultural variables that form person's habituation and expectation which affect his perception in a specific thermal environment (Sundstorm, 1986).

2.2.1 ENVIRONMENTAL VARIABLES

This subsection addresses the Environmental variables that affect thermal sensation and human body heat exchange. These variables encompass all the factors of the surrounding environment such as air temperature, mean radiant temperature, relative humidity and air speed. Below is the explanation of these factors.

2.2.1.1 AIR TEMPERATURE (Ta)

Air temperature is known also as the dry bulb temperature of the air in the space (CIBSE guide A, 2006) and it is defined by ASHRAE standard 55 (2003) as "*the temperature of the air surrounding the occupant*".

As air temperature determines convective heat dissipation, it is then considered the most dominant environmental variable affecting thermal comfort (Auliciems, 2007;

Carr et al., 2003; Szokolay, 2008). A change of three degrees will change the response on the thermal sensation scale by about one scale unit for the inactive person (CIBSE Guide A, 2006). There are different ways and scales to measure air temperature (see appendix 8.1).

2.2.1.2 MEAN RADIANT TEMPERATURE (MRT)

Mean radiant temperature is defined by ASHRAE standard 55 (2003) as "the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space"
MRT expresses the radiation exchange between the human body and the surrounding surfaces which basically depends on the average temperature of the surface elements around the subject and the angle between them in the measuring point (Szokolay, 2008).

In hot and sunny climate conditions, MRT is considered a major factor influencing human energy equilibrium. Furthermore, in warm climatic conditions when using lighter clothing, MRT is almost double in significance than the air temperature, whereas in cooler climates its impact is equal to the air temperature (Szokolay, 2008)
MRT also has a strong effect on thermophysiological comfort indexes such as PET (physiological equivalent temperature) and PMV (predicted mean vote) (Fanger, 1970).

The way to measure MRT is quite difficult because it refers to human body shape and its angles with the surrounding surfaces (Fanger, 1970). In this case it is being measured by the following equation:

$$\mathrm{MRT} = T_1 F_{p-1} + T_2 F_{p-2} + \cdots + T_n F_{p-n} \qquad (2.1)$$

While T1 is the surface temperature and Fp-n is the angle between the surface and a person.

The more simple way to measure the MRT is to calculate it indirectly by measuring the Globe temperature using the globe Thermometer which is a thermometer covered its bulb by black copper ball with 150 mm diameter (see figure 1.11 in chapter 1) then the following equation can be used to calculate the MRT (this is the method used in this research):

$$\mathrm{MRT} = \mathrm{GT} \times \left(1 + 2.35\sqrt{v}\right) - 2.35 \times \mathrm{DBT}\sqrt{v} \qquad (2.2)$$

While GT is the globe temperature and DBT is the dry bulb temperature and v is the air velocity.
According to equation (2) if the air velocity is equal to zero, the MRT will be equal to GT.

Operative temperature (which is equivalent to dry resultant temperature) was presented first by Winslow, Herrington and Gagge (1937) and defined as the temperature of a uniform, isothermal black enclosure in which man would exchange heat by radiation and convection at the same rate as in the given non-uniform environment. The operative temperature is adopted by both ASHRAE and ISO 7330 standards especially when the air speed is negligible, in this case it is equal to the average temperature of the indoor air temperature ($T_{a,in}$) and the mean radiant temperature (T_{mrt}):

$$\text{Operative Temperature (OT)} = ½\, T_{mrt} + ½\, T_{a,in} \qquad (2.3)$$

2.2.1.3 RELATIVE HUMIDITY (RH)

Humidity is defined as the weight of water vapor per unit weight of dry air (measured by g/kg, grams of moisture per kg of dry air) or vapor pressure in a given atmosphere (measured by Pascal (Pa)) while the relative humidity (RH) in a given atmosphere is the ratio between the actual water vapor to the maximum vapor that the air can support (in this case it is called saturated air) in same atmosphere and same dry bulb temperature (expressed in a percentage % RH) i.e at a given air temperature of 25°C the saturation humidity (or the absolute humidity AH) is equal to 20 g/kg (CIBSE Guide A, 2006; ASHRAE standard 55, 2003; Szokolay, 2008, Auliciems, 2007).

Humidity affects thermal comfort in the sense that the high level of humidity limits evaporation from skin of the human body and from breathing process, and consequently the dissipation mechanism. Furthermore, Humidity raises wetness on diverse areas of the body that consequently causes discomfort sensation. Whereas the very low level of humidity causes drying effect on the skin and in the mouth and throat of human body and accordingly causes discomfort. The medium level of humidity (RH from 30% to 65% or from 40% to 70%) does not have much effect on human sensation (Szokolay, 2008; CIBSE Guide A, 2006).

Fang, Clausen and Fanger (1999) studied the acceptability of air quality on 36 untrained subjects in climate chambers with various levels of air temperature and humidity in the ranges 18–28°C and 30-70% respectively. The results indicated that the acceptability becomes less with increasing air temperature and humidity. Furthermore, a linear relation between acceptability and enthalpy of air was observed and the subjects felt thermally neutral with 23.5 °C and 60% RH while they felt unacceptable thermal conditions with 26 °C and 60% RH. Humidity is measured by revolving a psychrometer (see appendix 8.2).

2.2.1.4 AIR VELOCITY

The mean velocity of the air is defined by ASHRAE standard 55 as the average of the direct air velocity over a specific period of time.
The difference in pressure between two areas can generate natural air flow as the air can move from higher to lower pressure areas. However, air movement can affect thermal comfort as it accelerates convection and exchanging heat between the body and Environment and accordingly it changes the heat transfer coefficient for the skin

and the clothing surfaces. Furthermore, it increases evaporation from the skin and as a result it creates cooling effect for the human body surface. (Szokolay, 2008).

Air speed is measured by Meter per second (m/s or $m.s^{-1}$). Usually, the unacceptable air speeds are not more than 0.3 $m \cdot s^{-1}$ except in naturally ventilated buildings when higher air speeds causes desirable cooling effect in summer season. However, the fluctuations of air speed have a significant impact on dissatisfaction aside with the air temperature and mean air speed. People are mostly sensitive if the frequency of air speeds fluctuations between 0.3 and 0.6 Hz (CIBSE guide A, 2006). Furthermore, There are individual differences between people about the preferable air speed depends on the activity level and clothes insulations (ASHRAE, 2003).

There are many thermal comfort indices and models were made to predict thermal comfort sensation for either indoor and outdoor spaces by combining two or more from the above mentioned environmental variables.

2.2.2 PERSONAL VARIABLES

The personal variables such as metabolic rate, clothing insulation, state of health and acclimatization play a significant role to keep heat balance for human body thermoregulatory system.

Metabolic rate affects the thermal comfort level of a person as increasing physical activity causes more heat production in the human body and subsequently the need to dissipate this heat. Furthermore, the circumstances under which activities are being practiced can substantially affect the range of variation of the metabolic rate.

Metabolism rate for a specific activity is measured by "met" unit, for example a seated quiet person is producing which equal to 1 met (the 1 met = 58.2 W/m^2) while the standing relaxed person is producing 1.2 met. The one hour of different activities for same person could be calculated by summing the average metabolic rate for all these activities together while the period which exceeds one hour should be calculated separately as distinct metabolic rates. (Table 2.1) (CIBSE Guide A, 2006; ASHRAE standard 55, 2003; Szokolay, 2008; Auliciems, 2007).

Table 2.1 various activities and its met units

Activity	met units	W/m^2	($BTU/h.ft^2$)
Sleeping	0.7	40	13
Seated, quite	1.0	60	18
Standing, relaxed	1.2	70	22
Cooking	1.6 – 2.0	95 - 115	29 - 37

Clothing insulation has a significant impact on thermal comfort depending on the amount of worn by the subject. Acclimatization by clothing is probably the most important available technique that can keep the heat-balance of human body (Schiavon and Lee, 2012). Clothing insulation is measured by the units of clo which means a U-value of 6.45 W/m2K (or a resistance of 0.155 m^2K/W). Each piece of clothing (garment) gives a specific value of clo units, for example, Shorts and short-sleeved shirts are calculated by 0.5 clo. The heaviest kind of arctic clothing can give 3.5 clo.

Clothing is an important adjustment mechanism. Sometimes it faces some cultural or safety constrains in hot areas (for example women in the Islamic countries and workers who wear special clothes safety rules in dangerous work) and then it should be substituted by other cooling mechanisms (Szokolay, 2008).

Table 2.2 clothing garments and its clo units

Garment description	I_{clo} (Clo)
Half-slip	0.14
T-shirt	0.08
Men's briefs	0.04
Long sleeves sweatshirt	0.34
Short sleeve dress shirt	0.19
Short shorts	0.06
Strait trousers (thin)	0.15
Strait trousers (thick)	0.24

The state of health has an important impact on thermal comfort. Unfortunately there is limited knowledge about the comfort requirements for the sick people. Nevertheless, research indicates that the disabled people are more diverse in their thermal responses than able people, so they should be given an individual consideration about their thermal environment (CIBSE, 2006; Parsons, 2002)

2.2.3 CONTRIBUTING FACTORS

Thermal comfort is affected substantially by the person's physical characteristics. For example the Body shape has an important impact on heat production which is relative to body mass. Body surface plays also a big role in heat dissipation according to body surface. Furthermore, females prefer a little bit warmer temperatures than males, but recently this has been related to clothing habits. In addition, age makes very little effect on thermal comfort in the sense that the older people are less tolerant for differences from the optimal. Food and drink can indirectly affect thermal sensation as they have an important influence on metabolic rate (Szokolay, 2008).

2.3 THERMAL COMFORT APPROACHES

Thermal comfort models depend mainly on heat exchange between human body and the surrounding environment (Figure 2.2). Its main aim is to offer a single index that involves all related parameters that affect thermal comfort to predict the human sensation. Thermal comfort models became the basis for thermal comfort standards such as ASHRAE, ISO and others. These models have been created in a various formulas from a simple linear equation to complex algorithms. However, there are some limitations for both simple and complex models that affect the precision of simulation systems as well as the inputs to the models (Jones, 2001). The models that are more complex are not always more accurate than the simple models as well as the simple ones are not probably easier to use. The accuracy of the model is subjected to the target that it is being used for (Holm and Engelbrecht, 2005) (For heat balance equation, see appendix 8.3).

Thermal comfort was studied within two different approaches and models; the rational or Heat balance approach and adaptive approach. The two different approaches are explained as following:

2.3.1 HEAT BALANCE APPROACH AND MODELS

The heat balance approach refers to the steady state condition or the constancy model and the two node model that were studied earlier by Gagge et. al. (1967; 1986) and Fanger (1970). This approach looks for obtaining physical and physiological responses of people to the surrounding thermal environment in terms of heat transfer (see figure 2.3). The heat balance model points out that the human thermal sensation is strongly correlated to the thermal load on the effect mechanisms of the human thermoregulatory system.

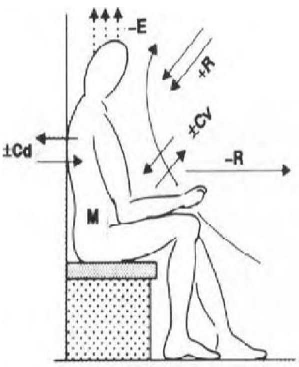

Figure 2.3 human body heat exchange (szokolay, 2008)

Among the most recognized models is the predicted mean vote (PMV) that has been developed by Fanger (1967, 1970). It was developed using principles of heat balance theory and therein the data gathered from extensive American and European experiments applied earlier by Fanger on 1296 Danish students under steady state conditions in a well-controlled climate chamber. The Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD) model has been used internationally to predict and measure indoor thermal comfort in buildings. Accordingly, since the 1980s the PMV model has become a worldwide standard (ISO, 1994) (see appendix 8.4).

Scholars evaluated and criticized the heat balance models. The model is based on data from controlled climate chambers; they consider the person as a passive recipient for the thermal parameters around. They were evaluated as they are accurate only for people who are involved in light or sedentary activity and steady sate one. In other words, Climate chambers tried to simplify comfort issues to make it appropriate for chamber studies and, so that, they didn't succeed to combine with the human experience or with the so called "experiential realism" such as human expectations and attitude to deal with thermal comfort problems; People's expectations can specify the way in which people respond to a specific environment. So that, People expectations or experience when they are exposed to the same environment in a well-controlled climate chamber differs from the real situation as people compare their actual sensation depending on their expected sensation. In addition, people uses some environmental controls to adjust the environment according to their own preferences considering the natural differences preferences between person to another which make it difficult to fit with imposed standards. Likewise, heat balance model doesn't correlate the clothes insulation to different climates and/or cultures. (Doherty and Arens,1988; Cena and De Dear, 2001). Williamson et al. (1995) stated that the PMV strongly overestimates warm comfort, especially in warm climates.

In conclusion, the heat balance model is unable to take into account the social and cultural factors that are important in the real situation that can be included by the field surveys.

In the 1970s, Humphreys and Nicol suggested a way to solve the above problems (Humphreys and Nicol 1970, Nicol and Humphreys 1972, Humphreys 1976, 1978) which can allow the social factors to be combined into comfort standards. Their suggested approach has been called the adaptive approach of thermal comfort (Humphreys and Nicol 1998).

2.3.2 ADAPTIVE APPROACH AND MODELS

Human reaction to environment in real buildings is affected by a wide range of complicated factors that is not considered in the heat balance theory. These factors can comprise environmental interaction (lighting, acoustics, and indoor air quality), context (building design, building function, season, climate, and semantics), cognition (attitude, preferences, expectation) and demographics (gender, age culture, and economic situation) and so on (Oseland, 1994; Baker 1993; McIntyre, 1982).

The number of field studies on adaptive thermal comfort has been substantially increased over the last two decades (Mishra and Ramgopal 2013). Unlike the heat balance approach, the adaptive approach collects the data directly from the field studies to predict the acceptable level of thermal sensation for the inhabitants. The condition in buildings is more dynamic than the climate chambers, hence it is being affected by both thermal environment (ecological valency) the occupants activities (ecological potency) (Mahdavi, 1996).

Baker and Standeven (as cited in Givoni, 1998) reviewed many studies based on observations on un-air conditioned structures that were conducted within the European PASCOOL project framework. Whilst they observed the occupants of the structures in daytime, the indoor temperature and air velocity were recorded. With an exception of one study, clothing adjustments were included in the observations in all the studies. The results indicated that 70% of the inhabitants in one study were comfortable at high temperatures of 27.8 °C by adaptive behavior such as clothing modification. The other study highlighted that 89% of occupants were satisfied at temperature of 30.5 °C. However, these results contradicted the conventional comfort

hypothesis in that the temperatures recommended by this theory are less than the observed temperatures.
Adaptive approach doesn't comprise the problems of climate chambers as it is being conducted in actual buildings with a sample of real occupants and takes in consideration the behavioral adaptation, the physiological adaptation and the psychological adaptation of the occupants (Cena 1994; Brager and de Dear 1998; Djongyang et al. 2010). Furthermore, getting the data from field studies has the advantage that the inhabitants can acclimatize themselves freely without any restrictions and they can react naturally in the way to reduce discomfort. Furthermore, they can practice their everyday activities, put on their everyday clothes and so on (Cena and de Dear 2001; Nicol and Humphreys 2002). Figure (2.4) shows The psycho-physiological model of thermal perception (Szokolay, 2007).

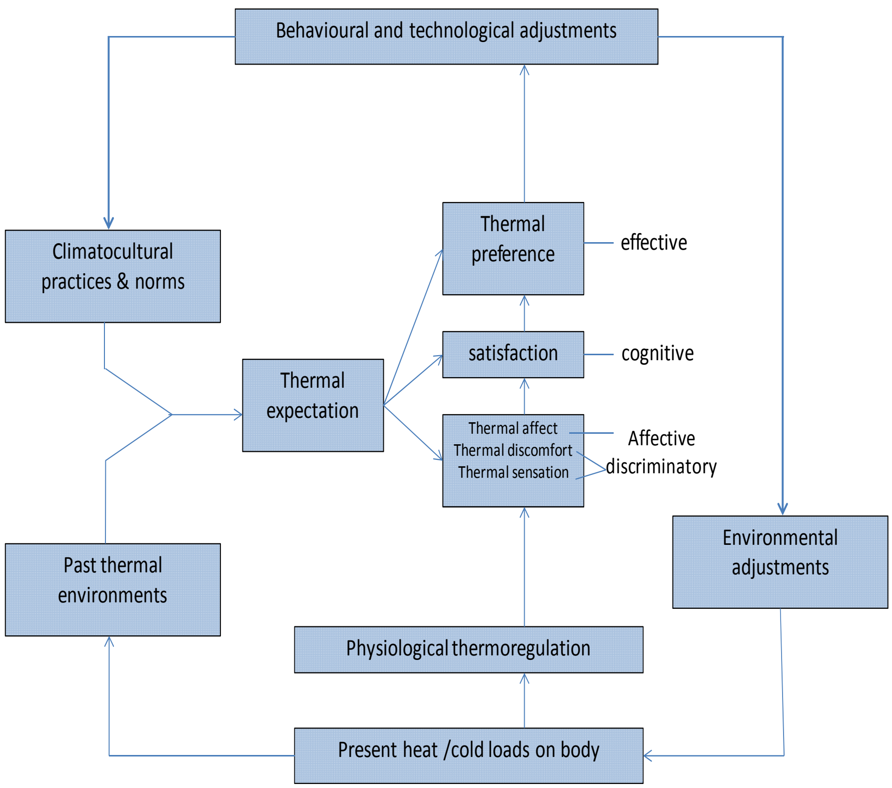

Figure 2.4 The psycho-physiological model of thermal perception (Szokolay, 2007).

The adaptive model of thermal comfort (see figure 2.5 below) was developed to be used in naturally ventilated buildings specifying the acceptable indoor environment in a given monthly mean outdoor air temperature this is specify the acceptability of indoor environment and used as an index for inhabitants' adaptation to outdoor conditions. The model considers clothing adaptation of the occupant in naturally ventilated spaces by linking the acceptable range of indoor temperatures to the outdoor climate, so it is not necessary to estimate the clothing values (ASHRAE 55-2010; CEN 15251, 2007). Furthermore, humidity and limits of air-speed are not required therein.

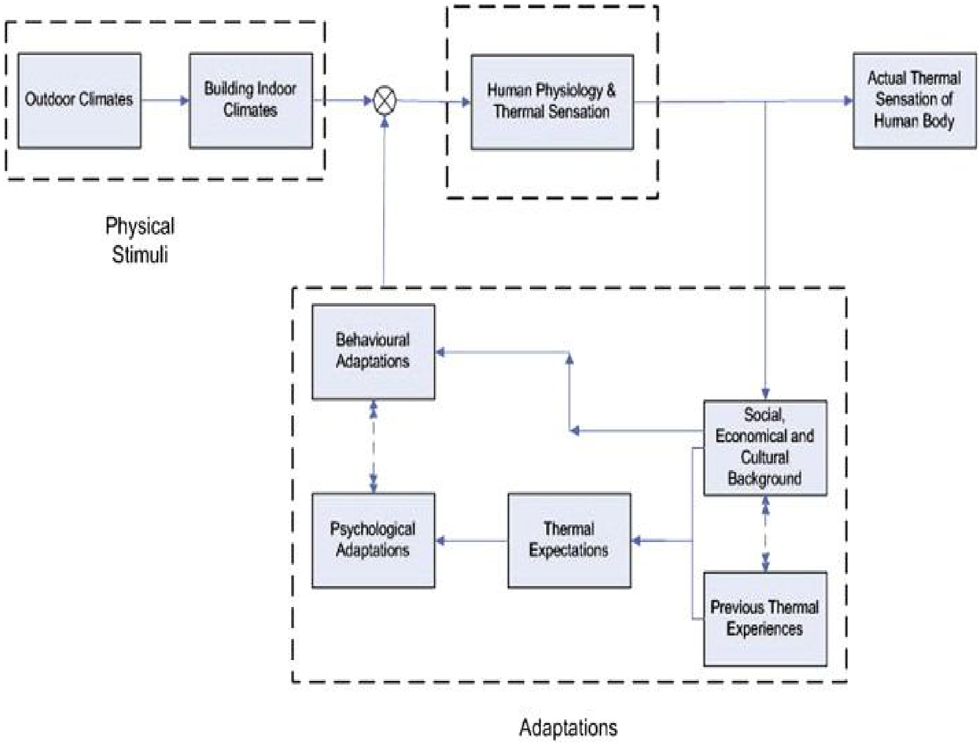

Figure 2.5 Thermal comfort adaptive model mechanism

Adaptive models of thermal comfort consider that there is dynamic interaction between subjects and their environment using clothing or window-opening to control thermal comfort level. This is different from comfort in closed air-conditioned buildings, in which occupants respond passively to the environment (Djamila et. al. 2013).

The neutrality temperature (T_n) has been considered as an indication for the comfort zone for human body considering with a range of + / - 2.5 °C.
A large number of field studies were conducted to correlate the outdoor temperature with the indoor thermally comfortable conditions for free running buildings. The field studies showed that the indoor thermal neutrality and comfort range have strong statistical dependence on the mean outdoor temperature (Auliciems, 1981; Auliciems and de Dear, 1986; Brager and de Dear, 1998; Nicol and Roaf, 1996; Dear et al., 1997; de Dear and Brager, 1998).

Humphreys (1978) investigated the relationship between indoor thermal neutrality and the prevailing outdoor climate. He found that this relationship can be obtained with equation (2.4) below.

$$T_n = 11.9 + 0.534\ T_o \qquad (2.4)$$

(where $T_{o.av}$ is the month's mean outdoor temperature)
Auliciems (1981) reviewed Humphrey's equation by excluding some of his field studies and including others were conducted in various climatic zones and countries.

Based on total number of 53 field studies, he derived the equation (2.5) for comfortable temperature.

$$T_n = 0.48\ T_i + 0.14\ T_o + 9.22 \quad (2.5)$$

Auliciems and de Dear (1986) suggested the equation (2.6) for thermal neutrality in both naturally and air-conditioned buildings.

$$T_n = 0.31\ T_o + 17.6 \quad (2.6)$$

Nicol and Roaf (1996) conducted a field study in Pakistan and developed equation (2.7) between neutral temperature and outdoor temperature.

$$T_n = 0.38\ T_o + 17.0 \quad (2.7)$$

In another survey in Pakistan, Nicol et al. (1999) suggested equation (2.8)

$$T_n = 0.36\ T_o + 18.5 \quad (2.8)$$

Eventually, after several regressions by de Dear et al. (1997) to relate indoor neutral temperature by effective temperature (ET*), de Dear and Hart (2002) recommended the model that is formulated based on mean monthly outdoor temperature (equation 2.8). this model is more applicable and accurate than the one which based on ET*. Equation (2.9) is the most applicable and was adopted by ASHRAE standards (**This is the equation used in this research**).

$$T_n = 17.8 + 0.31\ T_{a,out} \quad (2.9)$$

(Where $T_{a,out}$ is the mean monthly outdoor average temperature).
However, the adaptive comfort models for naturally ventilated buildings still need more development to combine all environmental and personal factors that affect thermal comfort (Kordjamshidi, 2010).

2.4 OVERVIEW ON RESIDENTIAL BUILDINGS IN HOT-ARID CLIMATES

Although numerous studies are undertaken worldwide on thermal comfort, research is still limited on thermal comfort in hot arid climates and sub-Saharan African regions (Cena & de Dear 2001; Djongyang et al. 2010; Mishra and Ramgopal 2013). The international standards for thermal comfort such as ASHRAE and ISO are almost exclusively based on theoretical analyses of human heat exchange performed in mid-latitude climatic regions in North America and Northern Europe (Djongyang, Tchinda et al. 2010) ASHRAE standard 55, 2003). Although ASHRAE and ISO7730 are based on Fanger's equation for thermal comfort yet it ignored the adaptive approach which has been proved by many other scholars later to be as much important as the heat balance approach (Nicol 2004, Nicol 2005).

Interest to study and research adaptive thermal comfort increased in the mid 70's as a reaction to the oil shock and it this concern has increased recently again over human impact on the global climatic environment. Controlling the indoor environment can have significant impacts on both improving comfort and reducing energy consumption (Brager and de Dear 1998).

Sakka et al. (2012) investigated the indoor thermal condition in fifty low income non air conditioned different type houses in Athens, Greece, during the extremely hot summer of 2007. The study was carried out from May to October 2007. The indoor data were recorded each 30 minutes by data loggers installed inside the buildings while the outdoor data were taken from the national observatory of Athens. The study results proved the dramatic effect of the high ambient temperatures on indoor environmental quality and energy use in these buildings. The duration of hot spells in non-air conditioned buildings extends by increasing length of the heat wave. In this context, improving the indoor environment quality needs solar and heat protection. Furthermore, the use of solar control devices together with the reflective coating on the roofs could decrease the heat transfer to indoor environment and improve the indoor climate condition.

Nicol (1974) conducted an important study on hot arid climatic regions of Roorkee, India and Baghdad, Iraq. The principal result of his study highlighted that people who habitually live in hot arid climates were adapted to and mostly comfortable at a globe temperature of 32 degrees. He indicated that his results contrast with a study conducted by Hamphreys and Nicol (1970) about the English office workers who were comfortable at globe temperature of 20-25 °C.

More recently, Cena and de Dear (2001) carried out a large field study in Kalgoorlie-Boulder, located in a hot-arid region of Western Australia. The purpose of their study was to highlight the effects of indoor climates on thermal perception and adaptive behaviour of office workers in air conditioned office buildings. The main result of the study was that thermal neutrality in accordance with the ASHRAE sensation scale occurred at 20.3° C in winter and at 23.3 °C in summer. The preferred temperature was 22.2° C for both seasons.

Indraganti (2010) conducted a thermal comfort field survey in summer 2008 on the use of adaptive environmental building controls like windows, doors, curtains and comfort responses in apartment buildings in Hyderabad in India. The study investigated five small to medium sized apartment buildings, having three to six floors. A mixed males and females Sample of 113 subjects in forty-five flats in the five apartment buildings has been investigated. Results indicate that about 60% of the occupants were uncomfortable in summer, furthermore, neutral temperature of 29.2 °C and comfort range of 26.0 °C and 32.5 °C was specified by regression analysis while the outdoor maximum and minimum air temperature were 40.4 °C and 27.3 °C respectively. In addition, occupants adaptively used the physical environmental controls like windows, balcony, doors, external doors and curtains to achieve better comfort in the indoor environment.

Herrara (2011) conducted a field study to investigate thermal comfort of inhabitants of low cost dwellings in two northern Mexican arid climate cities (Chihuahua and

Juarez). The study intended to assess this kind of dwellings and to give recommendation for the new design projects. The study used the adaptive approach of thermal comfort and it complied with ISO 7726 standards. The field survey applied to a total sample of 531 inhabitants of dwellings in both cold and hot seasons; February and July of 2010. The survey was made inside the houses during the day hours. A questionnaire was distributed on the sample and indoor field measurements were recorded for dry bulb temperature, wet bulb temperature, relative humidity, black globe temperature and wind speed. The study found that people consider their houses are in better indoor climate in winter than summer. In winter, 70% and 78% of people in Chihuahua and Juarez respectively said that the condition of their houses are tolerable, while, in Summer, percentage of satisfaction with indoor thermal conditions decreased were 58% and 56% of people in Chihuahua and Juarez respectively. The study recommended some design strategies for the future dwellings such as correct orientation and dimensions of openings, higher width in walls with high thermal mass materials, roof insulation, windows solar protection, and better ventilation and higher interior height.

A study by Al-Ragom (2003) on retrofitting residential buildings in Kuwait (a hot-arid climatic country) strives to rationalize the cost of executing effective retrofitting plans. The study developed 15 retrofitting cases[2] in order to compute the cost of electricity to yield a payback period of 5 years. Each case included a differing impact of adding an efficacious energy system. The study focused on using the external thermal insulation rather than internal insulation in that the latter was argued not to be applicable in Kuwait. The insulation materials that were selected are made from extruded polysterene which is common used in Kuwait for its durability and high resistance to moisture transfer. Cost benefit analysis was computed by employing data on real cost, which was attained from diverse building contractors and consulting firms. The study highlighted that among the 15 cases, the 15th case was the most energy efficient case followed by 5th case.

Kruger, Cruz and Givoni (2010) compared long term recorded indoor temperature in a residential building with high thermal mass located at Sde Boqer, Negev region, Israel (hot-dry conditions) to indoor temperature forecasts of second residential building located at Maraibo, Venezuela (hot-humid conditions) that uses indirect evaporative passive cooling technique. Indoor temperatures were monitored in the first building during the period from January o August 2006 while the temperatures were monitored from February to September 2006 in the second building. Predictive formulas for indoor temperatures were generated using the recorded data from February 10 till April 30 2006 and then the data of the rest of the period were used to

[2] 1) wall (R-10) and roof insulation (R-15) with single clear glasses, 2) wall insulation only (R-10) with single clear glasses, 3) roof insulation only (R-15) with single clear glass, 4) wall (R-10) roof insulation (R-15) with clear double glass, 5) wall (R-10) roof insulation (R-15) with reflective double glass, 6) no insulation with clear double glass, 7) no insulation with reflective double glass, 8) wall insulation only (R-10) with reflective double glass, 9) roof insulation only (R-15) with reflective double glass, 10) wall insulation only with clear double glass, 11) roof insulation only (R-15) with clear double glass, 12) roof insulation only (R-15) with reflective single glass, 13) wall insulation only (R-15) with clear single glass, 14) roof insulation only (R-20) with clear single glass, and 15) wall (R-10) and roof insulation (R-15) with reflective double glass.

validate the formulas. The formulas developed for the indirect evaporative passive cooling system (IEPCS) in Maraibo were used to assess indoor temperature profiles in the building using input climatic data for Sde Boqer. The predictive formulas encompass the related variables of outdoor temperature; it could be adopted for the oudoor temperature conditions and fluctuations in Sde Boqer. Results showed that comparisons of IEPCS between observed thermal behavior under hot humid climate and expected thermal behavior under hot arid climate showed a reliability of the output data in both sites, furthermore, the applicability of the generated formulas in hot arid area. Results also showed that both strategies (IEPCS) and thermal mass are beneficial but it is recommended to use them combined to avoid the high drop of temperature values at nighttime by using IECPS alone.

On the local level, in Egypt, there were also limited published studies on residential buildings in this hot-arid climate. Gado and Osman (2009) evaluated the effectiveness of natural ventilation strategies used in state funded dwellings in New Al-Minya city in Egypt. His work was undertaken in two stages. Stage one was a pilot study that investigated the using of transformations that could affect natural ventilation performance such as installing external horizontal and vertical solar shading devices and, changing the window design. Stage two was a computer simulation study using software of Autodesk-Ecotect to evaluate the natural ventilation performance during the hottest period of the year and the computational fluid dynamics software FloVENT to investigate the internal air movement patterns. The results of the work showed that cross ventilation and night purge ventilation for the case study could only achieve 4.9% reduction in temperature, so that passive cooling was not effective for this case study.

Sheta W. (2011) used building simulation modeling ‘Design Builder’ to investigate the thermal performance of an existing residential building and its relationship with building materials at one of the new communities around Cairo is called El Tagammu’ El Khames. This study aimed mainly to validate design builder simulation software by comparing the indoor and outdoor temperature between the field measurements and simulation work. The main result was that the design of New Cairo buildings didn’t take in consideration the prevailed climate condition.

Attia and De Herde (2009) have investigated different active and passive design strategies such as thermal insulation, efficient glazing systems and solar applications to achieve low Energy performance in Madinat Al Mabu’ssin residential compound in Cairo. The simulation results indicated that the combination of active and passive strategies not only achieved up to 83% total reduction in electric energy demand but also improved the comfort and quality of living.

Attia (2010) investigated the possibility of achieving thermal comfort and reducing energy demand for existing buildings. A case study of chalet in Ain El-Sokhna (a semi arid climate area on the red sea coast in Egypt) was chosen. The red sea area has almost 3300 hours of sunshine per year with high wind speed of 5.0 to 7.1 m/s. The study examined six different active and passive retrofitting strategies to reach zero energy demand in the reference case. The examined strategies were: 1) reducing the heat gain by external skin insulation and installing window shading devices, 2) reducing thermal loads by replacing old appliances by efficient ones, 3) passive cooling by natural ventilation, 4) installing thermal solar system of the thermosyphone for space heating and domestic water, 5) using solar electric of photovoltaic panels, 6) using small scale wind turbine system. The result was that the first strategy achieved the largest energy saving (48%) followed by the thermosyphone solar system strategy (26%). In addition, all the strategies were not feasible except the second and the fourth one.

Michelle S. and Elsayed H. (2006) conducted a field survey and simulation analysis in Cairo and Alexandria to investigate the energy performance of the residential buildings and urban planning and its relationship with climate conditions in both cities. The study aimed at reducing the energy consumption, increasing the building energy efficiency and improving the indoor and outdoor comfort level. The study showed how the passive solutions in design have a significant impact among the other different design elements.

Attia et. al. (2012) developed two simulation models that represent electricity consumption patterns of residential apartments in three different cities in Egypt; Cairo, Alexandria and Asyut. Data about building characteristics and end-use energy patterns were collected by conducting a survey for 1500 apartments in the three Egyptian cities. the study was conducted in three main steps; first step was aimed to reviewing past and recent surveys, second step aimed at surveying the typical building typologies and characteristics, third step was to develop two representative benchmark models for air-conditioned apartments as well as a parametric simulation was conducted for the models using EnegyPlus software program. Walkthrough survey and collecting Utility bills together helped to specify the consumption patterns of the visited apartments. The survey results investigated three main issues. First was the monthly average electricity consumption for two apartment typologies in the three cities that was for apartment typology 1: 22.4 $kWh/m^2/year$ in Alexandria, 26.6 $kWh/m^2/year$ in Cairo and 31 $kWh/m^2/year$ in Asyut and for apartment typology 2: 11 $kWh/m^2/year$ in Alexandria, 14 $kWh/m^2/year$ in Cairo and 18 $kWh/m^2/year$ in Asyut. Typology 1 was higher in consumption than 2 because of its larger exposed surface external walls area that increase heat gain. Second was to analyze the occupancy rates such as occupancy density, occupancy schedules, internal load intensities (lighting intensities and schedules, plug load intensity and schedules and cooking and domestic hot water), mechanical cooling intensities (electric fans and air conditioners). Third was to identify two simulation representative benchmark models based on the internal loads analysis and patterns. The model shows that the air-conditioning dominated the energy usage in residential buildings in the three cities especially during the summer period when the electricity consumption patterns are considerably affected. The study indicated that all the surveyed buildings in the three cities had very poor thermal performance and indoor environmental quality because of poor envelope materials used with non insulated walls with no shading treatments and single glazed openings. the majority of 80% of the apartments was equipped by at least one air-conditioning unit that highly increase the peak electric load, in addition, the apartments were kept closed long time a day that can affect the indoor air quality especially in a city of high air pollution like Cairo. The results of the survey also proved that domestic appliances rate is high among the investigated sample that could be due to increasing personal income which led to increase in energy demand. The study referred that the increase in temperature profile in the last decade in Egypt due to global climate change reflected its negative effect on energy demand and consumption rates energy. The study suggested that the solution of this problem might be to depend more on solar energy and renewable energy technologies for air-conditioning systems. The study indicated that there is an opportunity to reduce energy consumption in residential buildings in Egypt through end-use utilization efficiency by improving building envelopes, operation patterns and using efficient domestic appliances.

Ali and Ahmed (2012) conducted a study that aims at exploring the effect of differing shading devices on indoor thermal performance of residential buildings in the hot arid climate of New Assiut city, Egypt. Their research was conducted in two parts; 1) first section comprised an introduction, a brief analysis of the case study area and explanation of simulation procedures applied, and 2) the application of Thermal Analysis Software to perform simulation-based analysis through the application disparate shading techniques for different orientation. They found whilst the application of vertical fins in Northern, Western and Eastern orientations minimizes indoor temperature by 1.5 °C, the combined shading and overhanging devices reduce indoor temperature by 1.5 °C in Southern orientation.

2.5 CONCLUSION

This chapter presents extensive literature review about thermal comfort definitions, variables and approaches in the built environment.
The last section of this chapter made an effort to pinpoint and review extant works related to indoor thermal comfort in residential buildings in hot-arid climates all over the world. It was evident that studies on this field, to the best of the researcher's knowledge, are meager. The discussion above revealed that out of these works, one study each has been conducted on the following countries: Greece, Kuwait, Mexico, Iraq, Israel and Australia. Further, two studies have concentrated on India. In regards to Egypt, the discussion illuminates seven studies on this research area. Although these seven studies have concentrated on indoor thermal comfort and energy performance in residential buildings, none of these studies focused on examining local material insulation techniques to improve indoor thermal comfort, furthermore, none of them focused on the prototypical buildings for low income class in 6th of October city in Greater Cairo. In addition, none of the studies paid any attention to study thermal comfort in winter season.

CHAPTER THREE

3. FIELD SURVEY, VALIDATION STUDIES AND COMFORT ZONE ANALYSES

1. FIELD SURVEY ANALYSES
2. VALIDATION STUDIES
3. COMFORT ZONE ANALYSIS

3.0 INTRODUCTION

This chapter is partitioned into three main parts; 1) field survey analysis, 2) validating the synthetic simulation weather profile of indoor air temperature in the Integrated Environmental Solutions – Virtual Environment (IES<VE>) software program version 6.5 by comparing the indoor dry bulb temperature between field measurements and simulation predictions in both winter and summer seasons under the hot arid climate conditions of greater Cairo in Egypt, 3) discusses the comfort zone limits for Cairo climate condition in each month for the whole year.

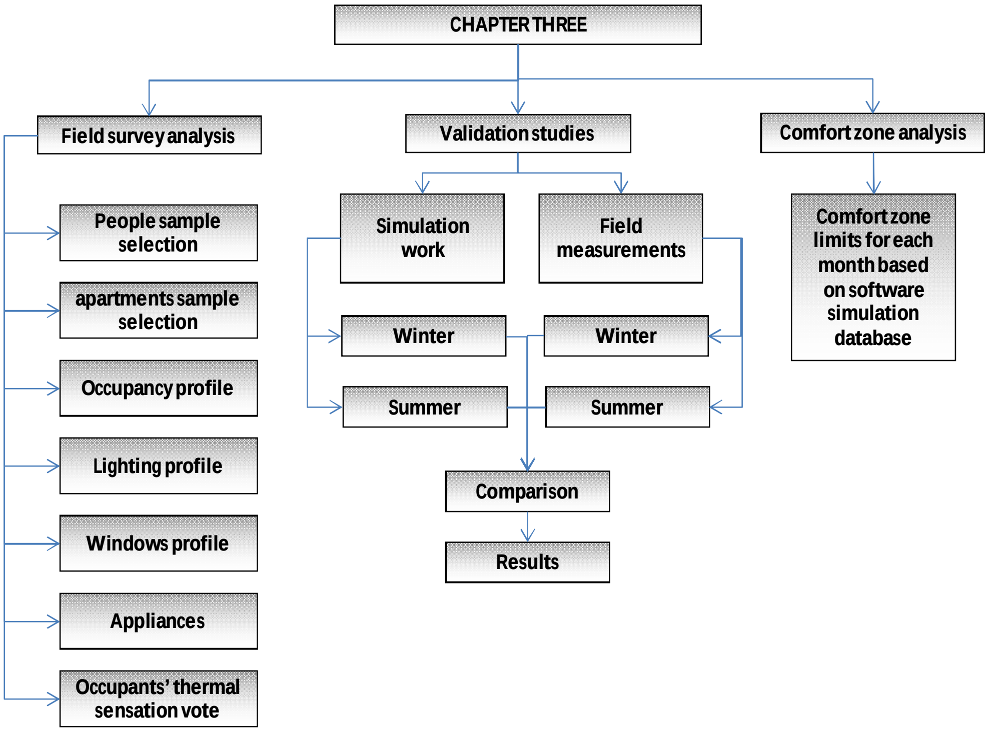

Figure 3.1 Chapter three structure

3.1 FIELD SURVEY ANALYSIS

The field survey was conducted by distributing a semi-structured questionnaire (see appendix 8.5) to a sample of thirty people in summer season and the same thirty people in winter season. Whilst, 7th January, 2013 was chosen to represent winter season, 1st of July, 2013 was chosen to represent summer season. The questionnaire aimed to obtain three main set of data:

1- Data about the internal heat gains. Accordingly, some of the questions focused on occupancy profile, lighting profile and appliances. The obtained data from these questions were coded in IESVE software simulation program to calculate the internal heat gains.
2- Data about windows profile. These data were coded in IESVE software as based behavioral survey scenarios for natural ventilation.
3- Data about thermal sensation of the inhabitants. These data used hypothetically to check either there if there is thermal discomfort in the research case study.

3.1.1 RESPONDENTS SELECTION

The study's respondents were chosen regardless of sex. These respondents live in different apartments in various buildings. The percentage of male respondents was 80% and female, 20%. This explicitly highlights that the percentage of male is higher than female because of the difficulties related to Egyptian culture and security reasons that make women to be afraid engage in a discussion with individuals they are not familiar with.
Additionally, the average occupancy in the chosen apartments was about 4 persons per apartment (2 males and 2 females). This is quite close to the national average apartment occupancy that is equal to 4.19 people per apartment (CAMPAS, 2006).

3.1.2 APARTMENTS SAMPLE SELECTION

The apartments were chosen in different orientations. The orientations were north, south, east and west and their percentages from the chosen sample were 30%, 30%, 20% and 20% respectively (Figure 3.2). The reason behind the disparity between north and south orientations, East and West orientations is that the north was assumed to be the worst orientation in winter season (as it is less exposed to the sunlight) while the south was assumed to be the worst orientation in summer season (as it is the most exposed to sunlight).

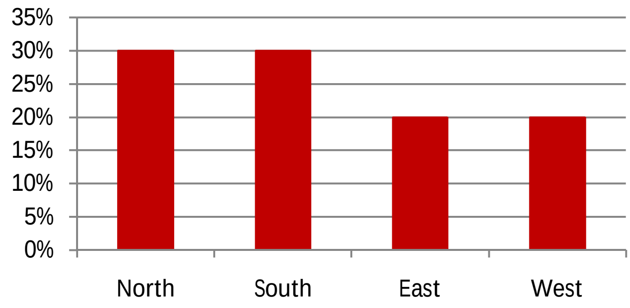

Figure 3.2 percentages apartments' orientation sample

3.1.3 LIVING ROOM OCCUPANCY PROFILE

Since the study at hand focuses on living room thermal performance, respondents were asked about the hours in which they stay in their living rooms. The rationale behind concentrating on living rooms was that they are the most occupied place in the apartment during day and a large part of night. In addition, average occupancy percentages were calculated for each hour during day and night. Figure (3.3) below depicts that the highest percentage of occupancy for the living rooms was from 19:00 to 21:00 probably because at that time people come back from their work and relax, chat with family. On the other hand, the lowest occupancy for the living rooms was from 2:00 to 6:00 as people always are sleeping.

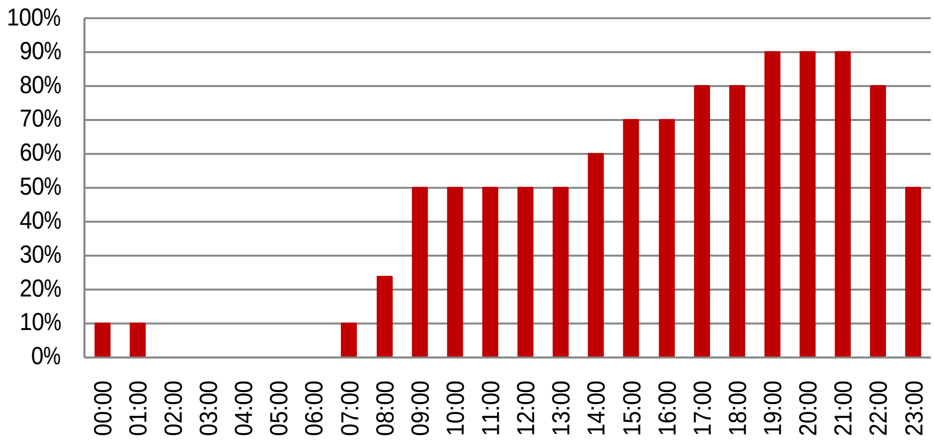

Figure 3.3 Living room occupancy profile

3.1.4 LIVING ROOM LIGHTING PROFILE

Respondents were asked about the hours in which they switch on/off the lights in living rooms. Figure (3.4) below illustrates an average percentages of lighting during day and night. Obviously, the highest period they switch on the light spanned, 20:00 to 22:00 and the lowest period they switch off the light spanned, 2:00 to 18:00 probably because at that time the occupants are either sleeping or working. Another reason would probably be that they do not need the artificial light during the day because of daylight.

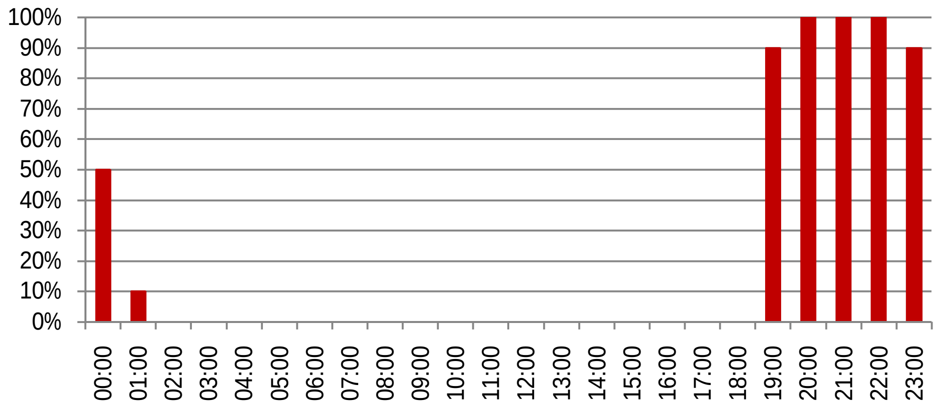

Figure 3.4 Living room lighting profile

3.1.5 EXTERNAL WINDOWS PROFILE

Respondents were asked about the time in which they open and close the external windows in both summer and winter surveys. In winter, the occupants revealed that opening windows is not desirable except just for fresh air intake for short time at morning before they leave to work and short time afternoon after they come back. For simulation analysis reasons, this limited time was approximated to be one hour in the morning (from 8:00 to 9:00) and one hour in the afternoon (from 17:00 to 18:00). On the other hand, in summer, occupants responded various answers. Their answers were categorized into four; 1) the people who open the windows 24 hours, 2) the people who open the windows from 9:00 to 24:00, 3) the people who open the window from 18:00 to 23:00 and 4) the people who open the window from 8:00 to 14:00 (see figure 3.5).

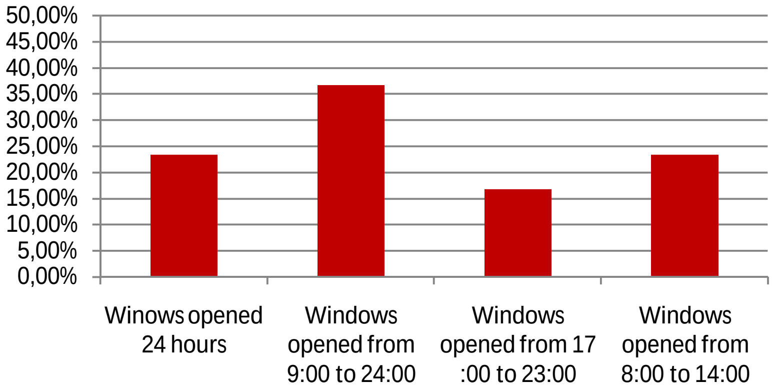

Figure 3.5 External windows behavioral survey profiles

3.1.6 APPLIANCES

The data about appliances were coded into the simulation software program (IESVE) for calculating the internal heat gains inside the apartment. As a consequence, respondents were asked about the appliances that they possessed in their apartments. From questionnaire, all respondents have the basic most needed appliances for

Egyptian family such as refrigerator, washing machine, water heater and television. Additionally, some of them have extra appliances such as a ceiling fan and a computer.

3.1.7 THERMAL SENSATION VOTE

Respondents were asked about their thermal sensation in both winter and summer conditions using ASHRAE thermal sensation scale (See appendix 8.4 – table 7.1). In winter, 13.3% of total respondents felt cold, 63.3% felt cool, 13.3% felt slightly cool and 10% felt neural. In summer, 33.3% felt hot, 40% felt warm, 10% felt slightly warm and 16.7% felt neutral (see figure 3.6). The differences between these percentages happened probably because of many other factors that affect human thermal sensation (see chapter Two).

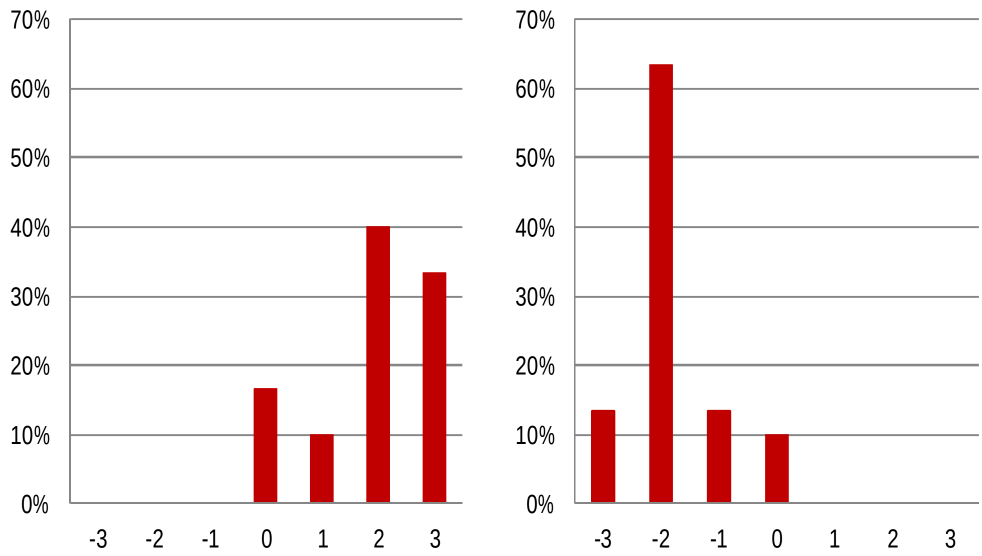

Figure 3.6 people's thermal sensation vote in summer (on the left) and winter (on the right)

3.2 FIELD MEASUREMENTS

According to the U.S. Department of Energy (DOE) there are 393 software tools available for assessing the performance of buildings regarding energy efficiency, renewable energy use and sustainability credentials in buildings. The building performance simulation commercial code IES<VE> (Integrated Environmental Solutions - Virtual Environment) was chosen to simulate the thermal performance of one of the chosen residential buildings. IES<VE> uses the calculation engine of Apache thermal analysis module, which provides either steady-state or dynamic analysis of energy consumption and indoor thermal conditions (University of Cambridge 2013). Furthermore, IES <VE> is considered one of the 20 major building energy simulation programs. Additionally, it includes ApacheSim, a dynamic thermal simulation tool based on first-principles mathematical modeling of building heat transfer processes. More so, it is a validated tool using the ASHRAE Standard 140 and authorized as a Dynamic Model in the CIBSE system of model classification (Crawley et al. 2005; Leng, 2010; Attia, 2009).

The following subsections addresses a comparison between measured globe air temperature and indoor dry bulb temperature, furthermore, validation studies to check the accuracy of the weather profile in the simulation package IES<VE> version 6.5 under the hot-arid climate conditions. The field measurements that were used for this validation studies were conducted inside a living room of one of the apartments in typical floor for a period of one week in January and another week in June. The comparison made between the indoor air temperatures that was measured in the field with its counterpart generated by IES<VE> simulation software for the same living room in the same apartment in three hour intervals. Figure (3.7) shows the model built by IES<VE> for the reference case that has been simulated in the same periods of field measurements.

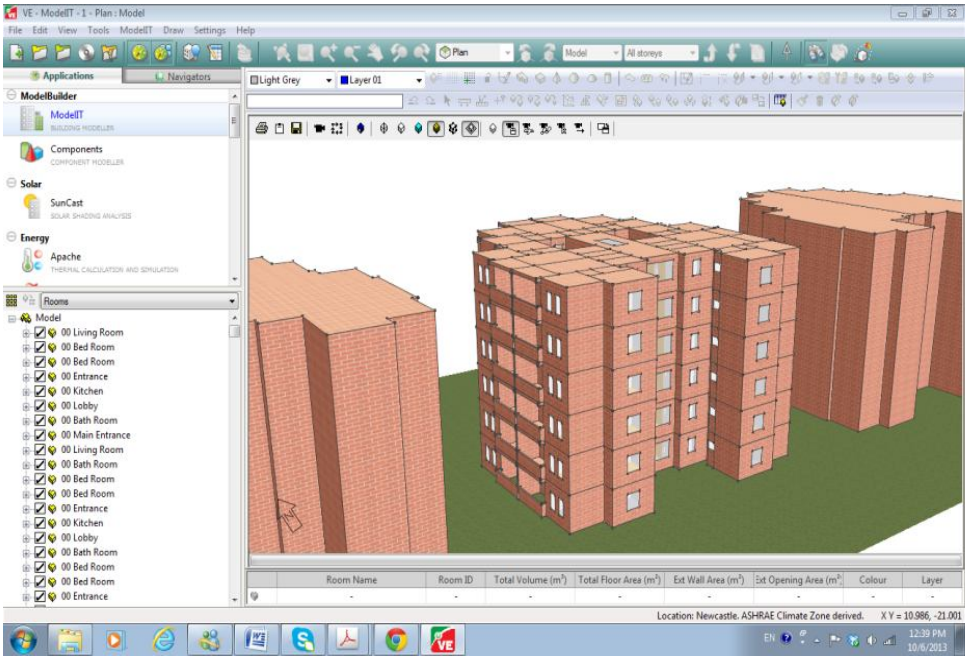

Figure 3.7 case study modeling analysis

3.2.1 MEASURED GLOBE TEMPERATURE (TG) AND AIR TEMPERATURE (TA) COMPARISON

The indoor globe temperature (Tg) and the indoor dry bulb (Ta) were monitored in three hour intervals during the last week of June (table 3.1). This was done to verify the difference between them and to decide about which one will be used in the rest of the research study.

Table 3.1 comparison between measured Ta and measured Tg

date	time	Ta □C	Tg □C	Difference □C
24-Jun	0:00	30	29.9	0.1
	3:00	29.6	29.6	0
	6:00	29.6	29.6	0
	9:00	29.6	29.6	0
	12:00	29.7	29.6	0.1

	15:00	30.2	30.2	0
	18:00	30.7	30.7	0
	21:00	30.5	30.5	0
25-Jun	0:00	30.1	30.1	0
	3:00	29.8	29.7	0.1
	6:00	29.6	29.6	0
	9:00	29.7	29.7	0
	12:00	29.8	29.9	-0.1
	15:00	31.1	31.3	-0.2
	18:00	31.2	31.3	-0.1
	21:00	30.7	30.7	0
26-Jun	0:00	30.4	30.4	0
	3:00	29.8	29.9	-0.1
	6:00	29.6	29.4	0.2
	9:00	29.8	29.7	0.1
	12:00	29.8	29.8	0
	15:00	30.6	30.7	-0.1
	18:00	31.2	31.1	0.1
	21:00	30.5	30.4	0.1
27-Jun	0:00	29.9	30	-0.1
	3:00	29.3	29.2	0.1
	6:00	28.9	28.9	0
	9:00	28.8	28.8	0
	12:00	29.3	29.3	0
	15:00	29.9	29.8	0.1
	18:00	30.3	30.2	0.1
	21:00	29.8	29.8	0
28-Jun	0:00	29.2	29.1	0.1
	3:00	28.6	28.6	0
	6:00	28.5	28.5	0
	9:00	28.6	28.6	0
	12:00	29.3	29.2	0.1
	15:00	30.7	30.7	0
	18:00	30.6	30.5	0.1
	21:00	29.8	29.7	0.1
29-Jun	0:00	29.2	29.1	0.1
	3:00	27.7	27.8	-0.1
	6:00	27.6	27.7	-0.1
	9:00	27.9	28	-0.1
	12:00	28.9	28.8	0.1
	15:00	29.6	29.6	0
	18:00	29.4	29.3	0.1
	21:00	28.9	28.9	0

30-Jun	0:00	28.9	28.9	0
	3:00	28.4	28.3	0.1
	6:00	27.8	27.8	0
	9:00	27.8	27.8	0
	12:00	28.6	28.5	0.1
	15:00	29.4	29.4	0
	18:00	29.9	29.8	0.1
	21:00	29.4	29.4	0
Average %				**0.02%**

From table (3.1), the discrepancies between Ta and Tg is ranged between 0.0 °C and 0.1 °C and the total average difference during the whole week is 0.02%. Accordingly, as the differences are negligible it was considered that air temperature equal to the globe temperature.

From literature, if the air velocity is negligible, then the mean radiant temperature (T_{mrt}) is equal to the globe temperature (T_g) (see equation 2.2 in chapter two). Hence, in the research case study; mean radiant temperature (T_{mrt}), globe temperature (Tg) and air temperature are equal. Moreover, the operative temperature (OT) will be also equal (see section 2.2.1.2 in chapter two). According to this result, the measured and simulated air temperature values are adopted to conduct thermal comfort calculations in this research.

3.2.2 WINTER FIELD MEASUREMENTS

The winter field measurements were conducted in the winter season of 2013 over one week in the first half of January. According to the climatological reports over thirty years from 1976 to 2005, January is the coldest month of the year in Cairo (Egyptian meteorological authority, 2011).

The 63 m^2 dwelling for rent in October 6th city were chosen to carry out the field measurements. Air temperature was measured inside one of the apartment's living rooms. The chosen living room is north oriented. The external air temperature was provided by the meteorological authority in Cairo. The apartment was naturally ventilated without any cooling or heating systems. The external air temperature was obtained from Cairo international airport meteorological station no. 623660.

3.2.3 SUMMER FIELD MEASUREMENTS

The summer field measurements were conducted in the summer season of 2013 during the last week of June. The indoor air temperature was recorded in three hour intervals using Davis weather station.

Field measurements were carried out inside one of the 63 m^2 dwellings for rent in October 6th city. North oriented living room inside one of the apartment was chosen to monitor the indoor air temperature. The chosen apartment was naturally ventilated without any cooling or heating systems. The external air temperature was obtained from Cairo international airport meteorological station no. 623660.

3.3 RESULTS OF WEATHER PROFILE VALIDATION STUDY

This section addresses the results of the validation studies. The first subsection focused on validation of IES<VE> weather profile in regards to the winter season. And the second subsection concentrated on the summer validation.

3.3.1 RESULTS OF WINTER VALIDATION STUDY

The indoor air temperature and humidity was monitored in three hours intervals during one week from 4th of January 2013 until 10th of January 2013. Measurements were carried out inside a living room space of one of the apartments in the first floor level. In addition, all construction details and materials used in the buildings for external envelope, interior partitions, doors and windows were applied to IES<VE> simulation program. Cairo weather data file which was obtained from the meteorological authority was used for the simulation work. The occupation profile, occupant's activities profile, windows profiles and doors profiles were deduced from the questionnaire analysis.

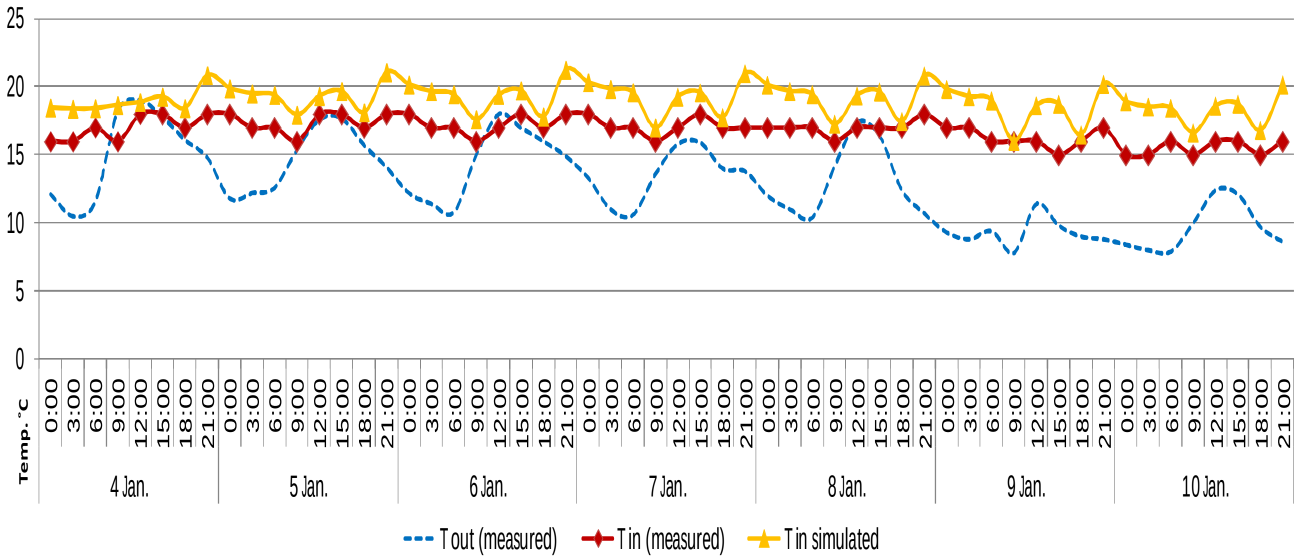

Figure 3.8 comparison between measured air temperature and simulation predictions during one week in January

Figure (3.8) and table (3.2) show a comparison between the measured and simulated indoor air temperature inside the living room of one of the apartments in the first floor and the difference between them and the outdoor air temperature. The comparison made mainly to ensure the accuracy of IES<VE> software program in terms of the weather data profile. The comparison shows that indoor maximum measured air temperature; minimum measured air temperature and average measured air temperature are 18 °C, 15 °C and 16.8 °C respectively during the one week period specified previously. The simulated indoor air temperature in the same living space during the same period of measurements shows that maximum simulated temperature, minimum simulated temperature and average simulated temperature are 19.9 °C, 14.5 °C and 17.8 °C respectively.

Table 3.2 min., max. and average of outdoor, measured indoor and simulated indoor air temperatures during one week in January.

	Max. Temp. (°C)	Min. Temp. (°C)	Av. Temp. (°C)
Outdoors ($T_{a,out}$)	18.2	7.8	12.8
Measured indoor temp.($T_{a,in}$ measured)	18	15	16.8
Simulated indoor temp.($T_{a,in}$ simulated)	19.9	14.5	17.8

Accordingly, the differences between simulated $T_{a,in}$ and measured $T_{a,in}$ in the maximum, minimum, and average air temperature are 1.9 °C, 1.5 °C, 1 °C respectively. So that, the differences between the measured temperature and the simulated doesn't exceed 1.9 °C in general. This result shows that there is a small difference between the field measurements and the simulation work which gives credibility for the IES<VE> software for simulating the thermal performance for this kind of buildings.

Moreover, by comparing the outdoor air temperature ($T_{a,out}$) and the indoor measured $T_{a,in}$ during the one week specified, Table (3.2) is showing that the maximum, minimum and average Outdoor air temperatures are 18.2 C, 7.8 C and 12.8 C respectively. Consequently, the differences between $T_{a,out}$ and $T_{a,in}$ in maximum, minimum, and average are 0.2 °C, 7.2 °C, 4 °C respectively. This shows that the difference between outside and inside air temperature during the peak hours is quite very small while the difference between outside and inside air temperature during the night-time is quite higher indoors than outdoors. This is observed also in figure (3.8) that during the day time from 9:00 to 18:00 the measured temperature inside follows the outside ambient temperature profile especially in the peak hours but during night-time from 18:00 to 9:00 recorded inside temperature is higher than ambient temperature. There are many explanations for that, for example, the building envelop has large heat storage which conserve solar heating at the day but radiates it at night in the indoor environment. Accordingly, this could be appreciated in winter as the people generally feel cold at night according to the questionnaire analysis but it may make the building hotter at summer season at night. There are also other explanations such as the occupancy of the apartment at night-time is higher than the daytime and this was proved also by the questionnaire which distributed to inhabitants. The use of lighting and living equipment inside the apartment such as televisions and kitchen equipment increases in the evening than in daytime. These factors combined lead to a significant increase in indoor temperatures (Sedki, 2013 a, b).

In addition, it is observed in figure (3.8) that both indoors measured and simulated air temperature mostly dipped twice per day at 9:00 and 18:00; the reason behind this decline may refer to the inhabitants' daily habits as they prefer to open the windows once at 9:00 in the morning before leaving and again at 18:00 both for one hour after they come back from work.

However, most of the inhabitants as questionnaire analysis indicates stated that they didn't feel thermally comfortable in their apartments as they felt slightly cold during daytime and general discomfort being colder at night-time. Observations showed that people use adaptive behavior such as wearing heavy clothes at night to acclimatize with the indoor cold environment.

Additionally, the root mean square error (RMSE) was calculated to ensure the accuracy of IES<VE> simulation software program. (RMSE) is commonly used to calculate the differences between values predicted by a model or an estimator and the values that is actually observed (Rob J. 2006). The RMSE of an estimator $\hat{\theta}$ with respect to an estimated parameter θ could be calculated as indicated in equation (3.1).

$$\mathrm{RMSE}(\hat{\theta}) = \sqrt{\mathrm{MSE}(\hat{\theta})} = \sqrt{E((\hat{\theta} - \theta)^2)} \qquad (3.1)$$

In this context, the RMSE between $T_{a,in}$ measured and $T_{a,in}$ simulated during the one week specified was calculated and the result that it is equal to 0.08. As Maamari et al. (2006) suggested the acceptable percentage difference between the building performance simulation result and the field measurement result should not exceed 20%, so that the difference of 8% is acceptable. Furthermore, the fact that the simulated values of the indoor air temperature are quite closer to the measured indoor air temperature at the day time than the night time (see figure 3.8) means that the accuracy of the simulation software is higher at daytime.

3.3.2 RESULTS OF SUMMER VALIDATION STUDY

Measurements were carried out inside a living room of one of the apartments in the first floor level where the indoor air temperature was monitored in three hours intervals during the last week of June 2013.

Construction materials that were used in the buildings' case study such as external and internal walls, doors and windows were all specified and applied to IES<VE> simulation software. Cairo weather data file (air temperature, relative humidity, wind speed and direction, solar radiation and so on) was obtained from the meteorological authority and was used for the simulation process. The occupation profile, occupant's activities profile, windows profiles and doors profiles were obtained from a questionnaire analysis.

Figure (3.9) and table (3.3) includes an assessment comparison between the indoor measured and simulated $T_{a,in}$ inside the living room of one of the apartments in the first floor and the difference between them and the $T_{a,out}$. The comparison seeks basically to guarantee the accuracy of IES<VE> software program in terms of air temperature. The comparison shows that maximum measured $T_{a,in}$, minimum measured $T_{a,in}$ and average measured $T_{a,in}$ are 31.2 °C, 27.6 °C and 29.5 °C respectively during the one week period specified previously. The simulated $T_{a,in}$ in the same living room during the same period of measurements shows that maximum $T_{a,in}$, minimum simulated $T_{a,in}$ and average simulated $T_{a,in}$ are 32.41 °C, 27.2 °C and 29.3 °C respectively.

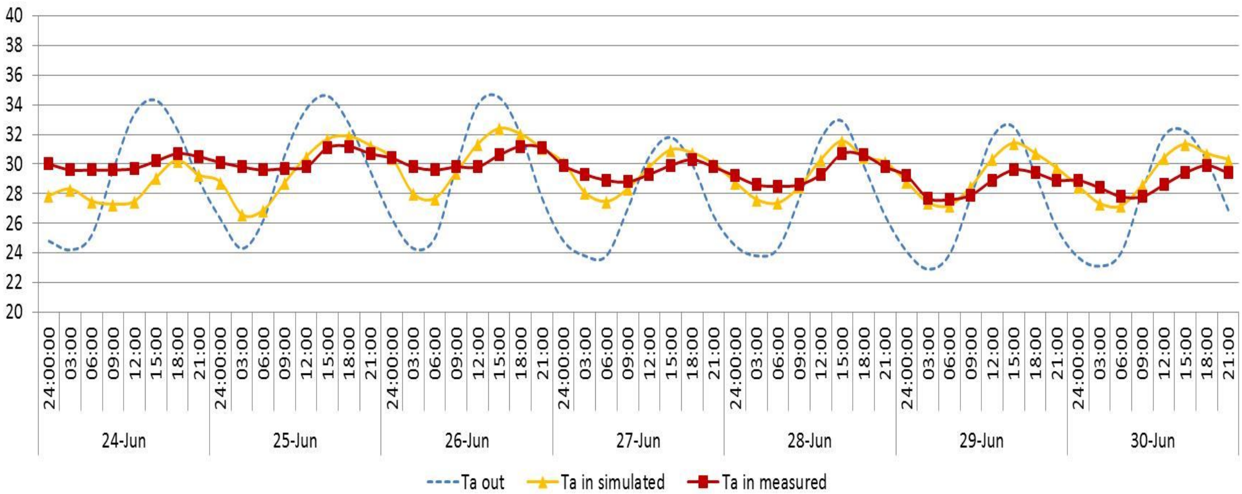

Figure 3.9 comparison between measured air temperature and simulation predictions during one week in June

Accordingly, the differences between simulation and measurements in the max., min., and av. $T_{a,in}$ are 1.2 °C, 0.4 °C, 0.2 °C. So that, the differences between the measured and simulated temperature doesn't exceed 1.2 °C in general. This result shows that the difference is quite small between the field measurements and the simulation work that accordingly gives credibility for the IES<VE> software for simulating the thermal performance of this kind of buildings.

Table 3.3 min., max. and average of Ta,out, measured Ta,in and simulated Ta,in during one week in June

	Max. Temp. (°C)	Min. Temp. (°C)	Av. Temp. (°C)
$T_{a,out}$	34.6	22.9	28.2
Measured $T_{a,in}$	31.2	27.6	29.5
Simulated $T_{a,in}$	32.4	27.2	29.3

Moreover, by comparing $T_{a,out}$ and $T_{a,in}$ during the specified one week, Table (3.3) is showing that the max., min. and av. Outdoor air temperature are 34.6 °C, 22.9 °C and 28.2 °C respectively. Consequently, the differences between the measured $T_{a,in}$ and $T_{a,out}$ in max., min., and av. are 3.4 °C, 4.7 °C, 1.3 °C respectively. Figure (3.9) shows that the difference between Ta,out and $T_{a,in}$ during the peak hours is quite small (3.4 °C in maximum and it becomes even smaller in the last four days of the week) while the difference between $T_{a,out}$ and $T_{a,in}$ during the night-time is quite higher indoors than outdoors. It is observed also in figure (3.9) that during the peak time from 9:00 to 18:00 the outside ambient temperature is higher than the indoor measured temperature especially in the peak hours but during night-time from 18:00 to 9:00 recorded $T_{a,in}$ are higher than $T_{a,out}$.

It may explained that the building envelop has large heat storage which conserve solar heating at the day but radiates it at night in the indoor environment. Accordingly, this could be appreciated in winter season as the people generally feel cold at night according to the questionnaire of the winter study but it is actually make the building overheated at summer season at night causing discomfort thermal sensation. There are also other explanations such as the occupancy of the apartment at night-time is higher than the daytime and this was proved also by the questionnaire that distributed to the inhabitants. The use of lighting and living equipment inside the apartment such as televisions and kitchen equipment increases in the evening than in daytime. These combined factors lead to a significant increase in indoor temperatures.

However, questionnaire analysis indicates that most of the inhabitants didn't feel thermally comfortable in their apartments as they felt hot during daytime and general discomfort being slightly hot at night-time. Observations showed that people use adaptive behavior such as wearing light clothes to acclimatize with the indoor hot environment.

The root mean square error (RMSE) was calculated to ensure the accuracy of IES<VE> simulation software program. (RMSE) is commonly used to calculate the differences between predicted values by a model or an estimator and the values actually observed (Rob J. 2006). The RMSE of an estimator $\hat{\theta}$ with respect to an estimated parameter θ could be calculated from equation (3.1) in the previous section.

In this context, the RMSE between Tin measured and Tin simulated during the one week specified was calculated and the result was equal to 0.06. As Maamari et al. (2006) suggested the acceptable percentage difference between the building performance simulation result and the field measurement result should exceed 20%, so that, the difference of 6% is acceptable (Sedki, 2013 a, b).

3.4 COMFORT ZONE ANALYSIS

This section specifies the comfort zone for the research case study. As the study was conducted in the year 2013 that was not finished till the moment of writing these words, furthermore, it wasn't possible to obtain the climatic data for the whole year of 2013. The obtained climate data were only for January and June 2013 (one month represents winter season and another month represents summer season). Thus, the study used the default climate data from IES<VE> software program that is took the averages of 28 years of climate data for Cairo city. The data of January and June used to validate the 28 years averages data of IES<VE> and to know the percentage of error between them.

3.4.1 WINTER CLIMATE DATA

The obtained three hour intervals climate data for the month of January 2013 used to validate its counterpart of the averages climate data of 28 years in IES<VE> software. Table (3.4) shows the three hour interval values between January 2013 and the average of 28 year values for January in IESVE for Cairo weather profile.

Table 3.4 Cairo climatic data for January 2013 and January averages of 28 years

Date	Time	2013 meteorological data ℃	IESVE 28 years average values ℃
Tue, 01/Jan	0:00	12	11
	3:00	11.8	10.2
	6:00	13.3	9.7
	9:00	18	14.9
	12:00	18.9	16.3
	15:00	17.6	15.5
	18:00	14.8	14.4
	21:00	12.3	13.2
Wed, 02/Jan	0:00	12.0	11
	3:00	11.7	10.4
	6:00	14.4	10.3
	9:00	18.7	15.3
	12:00	19.6	18
	15:00	17.7	17.6
	18:00	15.1	14.4
	21:00	13.7	13.2
Thu, 03/Jan	0:00	12.1	12.1
	3:00	12.0	11.2
	6:00	13.0	12.6
	9:00	16.3	14
	12:00	18.7	15.3
	15:00	17.3	15.6
	18:00	15.7	15.6
	21:00	14.9	14.6
Fri, 04/Jan	0:00	12.0	13.6
	3:00	10.9	14
	6:00	13.8	13
	9:00	18.5	14
	12:00	18.6	14
	15:00	17.2	14.7
	18:00	15.7	14.9
	21:00	13.9	12
Sat, 05/Jan	0:00	12.1	13
	3:00	12.3	13.3
	6:00	13.5	13
	9:00	16.1	14.3
	12:00	17.6	16.6
	15:00	17.0	13.1
	18:00	15.2	12.6
	21:00	13.3	13

Sun, 06/Jan	0:00	11.7	12
	3:00	11.2	12.8
	6:00	12.2	12.4
	9:00	16.0	16
	12:00	17.7	17.1
	15:00	16.7	15
	18:00	15.6	17.1
	21:00	14.0	12.9
Mon, 07/Jan	0:00	11.8	12.7
	3:00	10.9	12
	6:00	11.6	11.8
	9:00	14.3	16
	12:00	15.8	18
	15:00	15.3	17
	18:00	13.9	14.4
	21:00	13.6	12
Tue, 08/Jan	0:00	12.5	11.3
	3:00	10.8	10
	6:00	11.7	10
	9:00	15.3	15
	12:00	17.1	17.7
	15:00	15.1	16.6
	18:00	11.8	14.5
	21:00	11.1	13
Wed, 09/Jan	0:00	10.9	12
	3:00	9.0	10.6
	6:00	8.9	11.6
	9:00	9.0	16
	12:00	10.9	17.1
	15:00	9.5	16.5
	18:00	8.9	14.5
	21:00	9.0	15.8
Thu, 10/Jan	0:00	8.9	11.1
	3:00	8.0	12.6
	6:00	8.6	11.4
	9:00	10.8	19.1
	12:00	12.3	20.9
	15:00	11.3	19.7
	18:00	9.3	17
	21:00	8.5	13.8
Fri, 11/Jan	0:00	8.7	12
	3:00	9.5	10.9
	6:00	11.3	11.5
	9:00	14.3	15.6

	12:00	15.5	15
	15:00	14.3	14.7
	18:00	13.1	12.6
	21:00	12.1	11.7
Sat, 12/Jan	0:00	10.1	11.2
	3:00	11.5	11.4
	6:00	13.0	11
	9:00	16.7	13
	12:00	18.2	17.2
	15:00	16.2	16.6
	18:00	13.7	14.8
	21:00	12.8	13.7
Sun, 13/Jan	0:00	11.9	12.3
	3:00	12.5	10.8
	6:00	14.3	12
	9:00	18.0	17.1
	12:00	18.8	17.8
	15:00	17.2	17.3
	18:00	14.8	14.2
	21:00	13.3	11.8
Mon, 14/Jan	0:00	11.5	10
	3:00	11.4	10.5
	6:00	13.2	10.6
	9:00	17.0	14.9
	12:00	18.8	16.4
	15:00	17.1	15.4
	18:00	13.9	13
	21:00	11.9	13
Tue, 15/Jan	0:00	10.8	12
	3:00	8.9	10.6
	6:00	11.8	11.4
	9:00	17.8	15.6
	12:00	19.3	17
	15:00	17.5	14.8
	18:00	13.3	12.3
	21:00	10.2	11.6
Wed, 16/Jan	0:00	9.2	11
	3:00	8.5	9.6
	6:00	11.5	10.5
	9:00	16.4	15
	12:00	19.3	15.4
	15:00	18.8	14.6
	18:00	16.0	11.6
	21:00	13.3	10.6

Thu, 17 / Jan	0:00	10.1	9.8
	3:00	13.1	9.1
	6:00	15.1	9.6
	9:00	19.0	13.8
	12:00	20.5	14.8
	15:00	18.5	13.3
	18:00	15.7	11.7
	21:00	14.5	9.6
Fri, 18 / Jan	0:00	13.9	8.8
	3:00	11.9	9.4
	6:00	12.9	9.3
	9:00	17.6	12
	12:00	19.1	14.9
	15:00	18.1	14
	18:00	16.1	13.8
	21:00	14.0	13.2
Sat, 19 / Jan	0:00	12.1	11.8
	3:00	11.1	10.3
	6:00	13.8	10.8
	9:00	18.5	15.3
	12:00	20.1	17
	15:00	18.6	16.2
	18:00	15.0	13.8
	21:00	13.1	11
Sun, 20 / Jan	0:00	12.3	8.5
	3:00	13.3	7
	6:00	16.7	8.5
	9:00	21.1	14.8
	12:00	22.1	18
	15:00	19.9	16.6
	18:00	15.8	13.3
	21:00	13.9	11.4
Mon, 21 / Jan	0:00	12.3	9.1
	3:00	12.3	8.2
	6:00	16.8	9.6
	9:00	23.3	16
	12:00	26.9	17.7
	15:00	24.8	16.9
	18:00	21.9	13.9
	21:00	18.4	12.1
Tue, 22 / Jan	0:00	15.0	10.6
	3:00	19.1	9
	6:00	20.2	7.8
	9:00	22.9	16

	12:00	23.5	18.6
	15:00	20.5	17
	18:00	17.0	13.9
	21:00	16.5	12.2
Wed, 23/Jan	0:00	16.7	11
	3:00	13.5	9.6
	6:00	15.2	11.2
	9:00	18.3	17.4
	12:00	19.2	19
	15:00	18.2	14
	18:00	16.1	15.8
	21:00	13.8	14.4
Thu, 24/Jan	0:00	12.7	12.4
	3:00	12.3	11
	6:00	14.3	11.5
	9:00	19.5	15
	12:00	20.9	18.3
	15:00	19.6	18
	18:00	17.6	16.2
	21:00	16.6	14.5
Fri, 25/Jan	0:00	15.4	14.1
	3:00	18.5	12.4
	6:00	18.7	12.9
	9:00	20.1	16.7
	12:00	21.1	18.8
	15:00	19.7	18
	18:00	17.2	14
	21:00	17.3	13
Sat, 26/Jan	0:00	17.0	12.6
	3:00	14.3	12.2
	6:00	16.5	12.6
	9:00	19.5	16.2
	12:00	21.3	17.6
	15:00	20.3	18
	18:00	17.1	14.8
	21:00	14.9	13.5
Sun, 27/Jan	0:00	13.9	12.1
	3:00	13.3	10.5
	6:00	13.7	14.2
	9:00	17.0	18.1
	12:00	18.0	20.2
	15:00	17.0	19
	18:00	15.5	15.5
	21:00	15.3	13.8

Mon, 28/Jan	0:00	14.4	12.7
	3:00	10.9	11.1
	6:00	13.0	12.2
	9:00	16.6	17.1
	12:00	16.2	18.7
	15:00	14.8	18.7
	18:00	12.5	16
	21:00	12.3	13.5
Tue, 29/Jan	0:00	12.0	12.2
	3:00	9.4	12
	6:00	11.1	10.8
	9:00	15.9	16.9
	12:00	18.3	19.2
	15:00	17.2	18.6
	18:00	15.3	15.2
	21:00	13.0	13.2
Wed, 30/Jan	0:00	10.9	11.6
	3:00	11.9	10.2
	6:00	13.7	11.8
	9:00	16.3	18.2
	12:00	17.1	20
	15:00	16.6	20
	18:00	14.5	16.1
	21:00	13.5	15.2
Thu, 31/Jan	0:00	12.9	16
	3:00	10.9	16
	6:00	11.5	15.6
	9:00	14.3	19.4
	12:00	15.7	22.5
	15:00	14.7	23
	18:00	13.3	20.9
	21:00	12.4	18.2
average $T_{a,out}$		**14.9**	**13.9**

Using equation (2.8) in chapter two in section (2.3.2), the neutral temperature (T_n) of the month of January for the meteorological data and for the IESVE 28 years data will be 22.4 °C and 22.1 °C respectively. Consequently the comfort range (T_n +/- 2.5 °C) will be between 19.9 °C and 24.9°C and between 19.6 °C and 24.6 °C respectively.

From the above comparison, it is noticeable that the discrepancies in T_n between the meteorological data and the 28 years averages of IESVE data for Cairo weather profile in winter conditions are small and the differences are negligible. Accordingly, the 28 years weather data file of IESVE software database could be used for simulation process in the case study of this research.

For double check the above result of validation of the data in table (3.4), the statistical paired t-test was conducted between the two set of data of the month of June. Paired t-test (John, 2006; Fisher, 1987; David, 1997) generally is being conducted in statistics between two samples of the same units to check its hypothesis. The t value from the equation:

$$t = \frac{Xd}{SD/\sqrt{n-1}} \qquad (3.2)$$

Where X_d is the mean difference (equal to the total number of differences divided by the number of differences), SD is the standard deviation and n is the number of differences.
By applying the previous equation, it is found that t value is equal to 1.3. By reviewing the rejection region table for the right tail test (where we go to the □ row because in this case we have number of differences greater than 29), for the level of confidence of 0.95 and the rejection region α is equal to 0.05. Consequently, as t is equal to 1.3, so it does not fall in the rejection region. Accordingly, there is no significant difference between the two set of values.

3.4.2 SUMMER CLIMATE DATA

The obtained three hour intervals climate data for the month of June 2013 used to validate its counterpart of the averages climate data of 28 years in IES<VE> software. Table (3.5) shows the three hour interval values between January 2013 and the average of 28 year values for January in IESVE for Cairo weather profile.

Table 3.5 Cairo climatic data for January 2013 and June averages of 28 years

Date	Time	2013 meterological data	IESVE 28 years average values
Sat, 01/June	0:00	26.0	27.8
	3:00	23	25.1
	6:00	26.4	24.7
	9:00	32.4	30
	12:00	35.6	32
	15:00	35.8	29
	18:00	30	25
	21:00	25.3	22
Sun, 02/June	0:00	25.4	19
	3:00	27	19
	6:00	35.2	20.5
	9:00	40.9	26
	12:00	44.7	28
	15:00	42	30
	18:00	36.9	26
	21:00	35	22
Mon, 03/June	0:00	23.9	19

	3:00	24.7	18
	6:00	24.6	21
	9:00	28.9	24
	12:00	32.2	27
	15:00	31.5	29
	18:00	27.2	26
	21:00	23.6	21
Tus, 04/June	0:00	28	18
	3:00	20.5	18
	6:00	22.4	20
	9:00	26.3	23
	12:00	30.4	27
	15:00	31.1	29
	18:00	26.9	26
	21:00	25.7	21
Wed, 05/June	0:00	21.4	18
	3:00	21	17
	6:00	22.1	18.7
	9:00	26.9	23
	12:00	30.7	27
	15:00	31.1	28.4
	18:00	27.6	25
	21:00	22.9	21
Thu, 06/June	0:00	21.8	19
	3:00	22.2	17
	6:00	24.8	19
	9:00	27.8	25.4
	12:00	28.8	30
	15:00	27.5	31
	18:00	25.3	27
	21:00	25.3	23
Fri, 07/June	0:00	22.9	20
	3:00	24.6	18
	6:00	24.9	20
	9:00	31.1	26
	12:00	34.1	31
	15:00	33.2	33
	18:00	30.7	29
	21:00	27.4	25.3
Sat, 08/June	0:00	25.9	21
	3:00	26.3	19
	6:00	30.5	19.9
	9:00	37.2	25
	12:00	40.2	29.7

	15:00	41.6	32
	18:00	33.6	28
	21:00	28.6	23
Sun, 09/June	0:00	25.8	20
	3:00	23.2	19
	6:00	24.6	20
	9:00	28	26
	12:00	30.8	31
	15:00	30.3	32.6
	18:00	27.4	30
	21:00	24.9	25
Mon, 10/June	0:00	23.5	22
	3:00	21.6	19
	6:00	22.9	20
	9:00	28	26
	12:00	31.3	32
	15:00	31.3	34
	18:00	28.4	30
	21:00	24.4	25
Tus, 11/June	0:00	23	21
	3:00	20.8	20
	6:00	23.4	20
	9:00	28.9	27
	12:00	33.7	34
	15:00	34.3	36
	18:00	31.9	32
	21:00	29.6	27
Wed, 12/June	0:00	22.2	23
	3:00	25.8	20
	6:00	25.6	20
	9:00	28.8	26
	12:00	32.9	34
	15:00	32.6	37
	18:00	27.3	34.2
	21:00	24	27
Thu, 13/June	0:00	27.4	23
	3:00	20.9	21
	6:00	23.1	22
	9:00	27	29
	12:00	28.7	34
	15:00	29.8	35
	18:00	27	33
	21:00	23.3	28
Fri, 14/June	0:00	22	23

	3:00	20.8	22
	6:00	22.6	22
	9:00	26.6	27
	12:00	29.3	32
	15:00	29.6	33
	18:00	26.7	32
	21:00	24	27
Sat, 15/June	0:00	21.9	23
	3:00	20.8	21
	6:00	22.2	21
	9:00	26.4	28
	12:00	28.2	33
	15:00	29.2	34
	18:00	26.5	32
	21:00	23.7	26
Sun, 16/June	0:00	22	23
	3:00	21.4	21
	6:00	22.8	24
	9:00	26.6	28
	12:00	28.7	33
	15:00	29	35
	18:00	26	32
	21:00	23.4	28
Mon, 17/June	0:00	21.9	24
	3:00	22.1	22
	6:00	24.2	22
	9:00	27.5	30
	12:00	31.2	35
	15:00	31.8	37.2
	18:00	29.3	34.5
	21:00	25.8	30.4
Tus, 18/June	0:00	22	26.2
	3:00	22.5	22
	6:00	23.1	23.3
	9:00	30.4	29
	12:00	33.8	34
	15:00	34.5	37
	18:00	32	33.4
	21:00	27.6	28
Wed, 19/June	0:00	24	24
	3:00	23.9	22
	6:00	24.7	23
	9:00	31.2	29
	12:00	34.5	33

	15:00	34.3	35
	18:00	31.9	30
	21:00	28.4	25
Thu, 20/June	0:00	26.1	22
	3:00	23.2	19
	6:00	29.6	21
	9:00	33.5	26
	12:00	36.5	31
	15:00	36	32
	18:00	33.4	30
	21:00	28.8	25
Fri, 21/June	0:00	25.1	23
	3:00	28.4	22
	6:00	29	24
	9:00	34	30
	12:00	35.3	35
	15:00	34.2	35
	18:00	30.4	32
	21:00	27.7	28
Sat, 22/June	0:00	26.2	25
	3:00	24.2	24
	6:00	27	26
	9:00	31	32
	12:00	35.2	36.2
	15:00	34.7	38
	18:00	31.6	35
	21:00	27.6	29
Sun, 23/June	0:00	25.4	26
	3:00	24.2	28
	6:00	25.4	33
	9:00	32	34
	12:00	35.1	39
	15:00	34.6	38
	18:00	30.9	33
	21:00	26.8	29
Mon, 24/June	0:00	25.1	25
	3:00	23.6	22
	6:00	26	22
	9:00	31.4	28
	12:00	34.4	33
	15:00	34.3	34
	18:00	31.2	29
	21:00	27.8	25
Tus, 25/June	0:00	25.5	22

	3:00	23.8	20
	6:00	27.6	22
	9:00	32.2	26
	12:00	34.4	31
	15:00	34.7	31.6
	18:00	31.7	28
	21:00	28.4	24
Wed, 26/June	0:00	25.2	21
	3:00	23.8	20
	6:00	25.7	22
	9:00	31.9	25.5
	12:00	35	30
	15:00	34.2	31
	18:00	30.9	28
	21:00	26	24
Thu, 27/June	0:00	25.2	21
	3:00	23.1	21
	6:00	24.2	21
	9:00	28.5	26
	12:00	31.6	31
	15:00	32	33
	18:00	29.1	30
	21:00	25.1	25
Fri, 28/June	0:00	24.1	22
	3:00	23.7	22
	6:00	24.7	23
	9:00	29.3	27
	12:00	33	32
	15:00	32.8	34
	18:00	28.4	31
	21:00	25.6	26
Sat, 29/June	0:00	23.4	23
	3:00	22.6	21.9
	6:00	24.6	23
	9:00	29.4	30
	12:00	33	35
	15:00	32.2	36
	18:00	27.8	32
	21:00	24.6	27.1
Sun, 30/June	0:00	23.3	24
	3:00	23	23.3
	6:00	24.6	23
	9:00	29.9	30
	12:00	32.8	37

	15:00	32	38
	18:00	29.3	32
	21:00	25.7	28.7
Average Temp.		**28.1**	**26.7**

Using equation (2.8) in chapter two, the neutral temperature (T_n) of the month of January for the meteorological data and for the IESVE 28 years data will be 26.5 °C and 26.1 °C respectively. Consequently the comfort range (T_n +/- 2.5 °C) will be between 24 °C and 29 °C and between 23.6 °C and 28.6 °C respectively.
From the above comparison, it is noticeable that the discrepancies in T_n between the meteorological data and the 28 years averages of IESVE data for Cairo weather profile in Summer conditions are small and the differences are negligible. Accordingly, the 28 years weather data file of IESVE software database could be used for simulation process in the case study of this research.

For double check the above result of validation of the data in table (3.5), the statistical paired t-test was conducted between the two set of data of the month of June. Paired t-test (John, 2006; Fisher, 1987; David, 1997) generally is being conducted in statistics between two samples of the same units to check its hypothesis. The t value was obtained from the equation (3.2) in the previous section.

By applying the equation, it is found that t value is equal to 1.3. By reviewing the rejection region table (see appendix 7.6) for the right tail test (where we go to the □ row because in this case we have number of differences greater than 29), for the level of confidence of 0.95 and the rejection region α is equal to 0.05. Consequently, as t is equal to 1.3, so it does not fall in the rejection region. That means that we fail to reject the null hypothesis and there is no significant difference between the two sets of data.

3.4.3 COMFORT ZONE CALCULATIONS

This section comprises the he neutral temperature and accordingly the comfort zone calculations for each month using the climate data available in Cairo weather profile in IES<VE> database. The neutral temperature was calculated according to equation (2.8) in chapter two, section (2.3.2). The neutrality temperature (T_n) has been used to calculate the comfort zone for human body considering (T_n – 2.5) °C and (T_n + 2.5) °C as the acceptability of 90% of neutrality temperature (ASHRAE, 2003) (table 3.6).

Table 3.6 Neutrality temperature and comfort zone for each month

Month	Min.	Max.	Average Ta □C	Tn □C	Comfort range	
					from (°C)	to (°C)
Jan	7	23	14.0	22.1	19.6	24.6
Feb	8	26	14.5	22.3	19.8	24.8
Mar	9	28.9	16.6	22.9	20.4	25.4
Apr	10	39	21.6	24.5	22.0	27.0
May	13	41.3	24.7	25.5	23.0	28.0
Jun	16.7	40	26.7	26.1	23.6	28.6

Jul	17	37	27.9	26.5	24.0	29.0
Aug	21	38	27.9	26.5	24.0	29.0
Sep	18.4	37	26.5	26.0	23.5	28.5
Oct	16	34.2	23.8	25.2	22.7	27.7
Nov	8.5	28.2	19.0	23.7	21.2	26.2
Dec	7	25	14.9	22.4	19.9	24.9

The comfort range values were used to specify the comfort zone on the psycrometric chart of ASHRAE standards. Figure (3.10) shows how the comfort zone is shifting from the peak cold in January to the peak hot in July and August. As people in free running buildings can adapt themselves for higher and lower temperatures than out of the comfort zone limits (Baker and Standeven in Givoni, 1998), so that, the extreme limits of comfort; from 19.6 (the lowest level of comfort in January) to 29 (the highest level of comfort in July and August) according to the calculations made in table (3.6) were considered a fixed limits of comfort in each month for the whole year in this research.

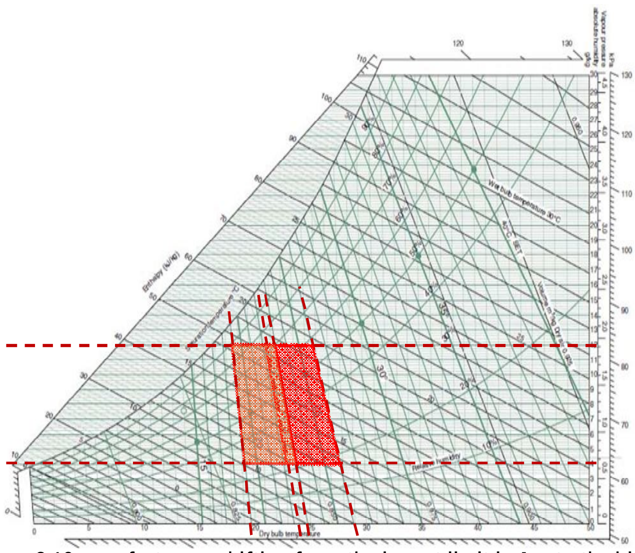

Figure 3.10 comfort zone shifting from the lowest limit in Jan to the highest limit in Jul. and Aug

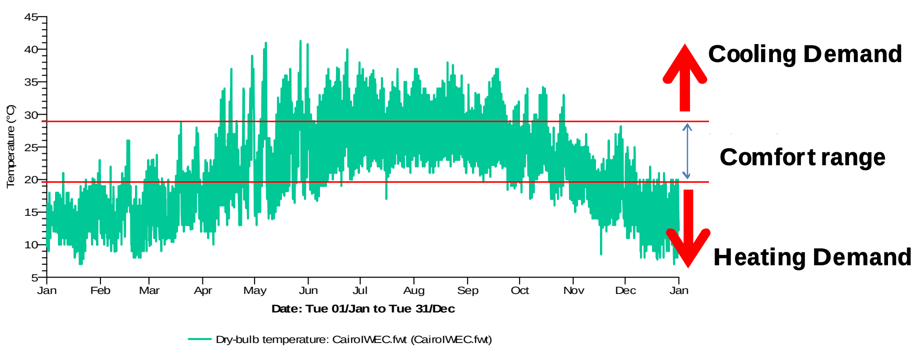

Figure 3.11 adaptive comfort range used in this research

3.5 CONCLUSION

This chapter discussed a set of validation studies that was needed to accomplish this research. The chapter proved that the case study was approximately isothermal condition wherein indoor dry bulb temperature, indoor globe temperature, mean radiant temperature and operative temperature were equal. Furthermore, the field measurements were conducted to check the IES<VE> accuracy for indoor air temperature predictions in both winter and summer seasons of Cairo's hot-arid climate. In this context, the indoor air temperature was recorded inside a living room of one of the apartments in typical floor during one week in January and another week in June. The measurements output data were compared with the simulation predictions for the same period. The results proved the credibility of IES<VE> version 6.5 for predicting indoor air temperature during the selected weeks specified previously. The last section of this chapter comprises comfort zone calculations for each month over the whole year based on the IES<VE> Cairo weather profile. Accordingly, the lowest limit of 19.6 °C in January and the highest limit of 29 °C in July and August were considered for further calculations in this research as. Based on the comfort zone limits, the next chapter will investigate the natural ventilation as a behavioral solution that can improve the indoor thermal comfort in the case study.

CHAPTER FOUR

4. BEHAVIOURAL STRATEGIES

1. NATURAL VENTILATION
2. EFFECT OF NATURAL VENTILATION DIFFERENT SCENARIOS ON RESEARCH CASE STUDY
3. IMPACT OF ORIENTATION ON INDOOR THERMAL COMFORT FOR A LIVING ROOM IN TYPICAL FLOOR
4. COMPARISON BETWEEN TYPICAL AND UPPER FLOOR
5. CONCLUSION

4.0 INTRODUCTION

This chapter identifies the interrelationship between natural ventilation and thermal comfort in hot arid climates; furthermore, it discusses the effectiveness of natural ventilation different scenarios on indoor thermal comfort of the research case study. The examined scenarios were compared to the base case and were categorized into two main groups. First group includes the based behavioral survey scenarios that were deduced from the questionnaire analysis in winter and summer seasons and second group includes the scenarios that were suggested to improve thermal comfort in summer season. Each scenario was applied on the reference case and then was simulated using IES<VE> simulation software. The effect of natural ventilation was investigated for each month in winter (represented by the months that have zero cooling demand), summer (represented by the months that have zero heating demand) and spring and autumn months (represented by the months where both cooling and heating are needed). The impact of orientation was investigated for the best scenarios that gave the best effect on indoor thermal comfort. The difference between the typical and the upper floor was discussed in the last section of this chapter (see figure 4.1 below for chapter four structure).

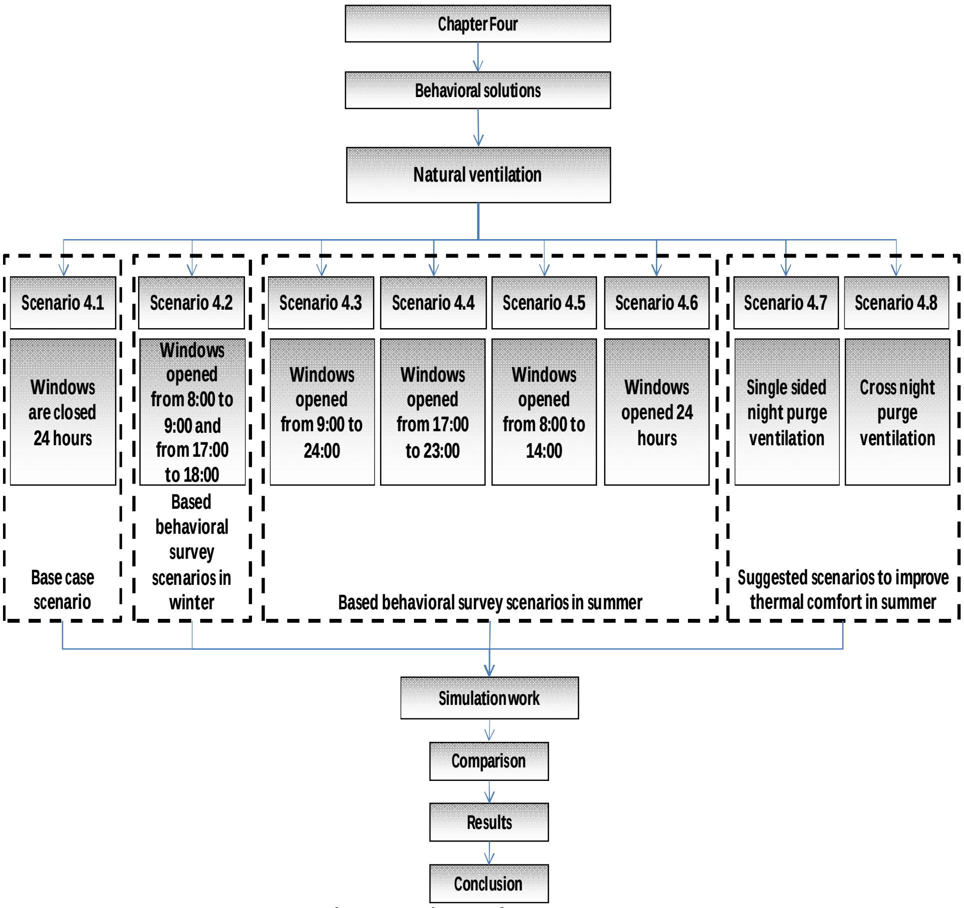

Figure 4.1 chapter four structure

4.1 NATURAL VENTILATION

Wind is considered a very important design factor for architects (McCarthy, 1999) as well as air velocity is one of the most significant factors that affect thermal comfort. Naturally ventilated buildings, uses the adaptive approach of thermal comfort by specifying acceptable operative temperature ranges for naturally conditioned spaces (ASHRAE, 2010) Thus, natural ventilation design frameworks got to be more practical and was recognized by international standards as an approach to enhance sustainability, energy efficiency and comfortable environment in buildings.

The airflow throughout a building depends on the area and resistances of the openings and the dissimilarity in air pressure between different areas (CIBSE guide A, 2006). This pressure variation (Figure 4.2) probably happen because of wind (wind-driven natural ventilation) or variation in temperature between indoor and outdoor that causes differences in air density (stack effect) or the use of fans to create a pressure dissimilarity in a mechanical way (Roaf, 2001).

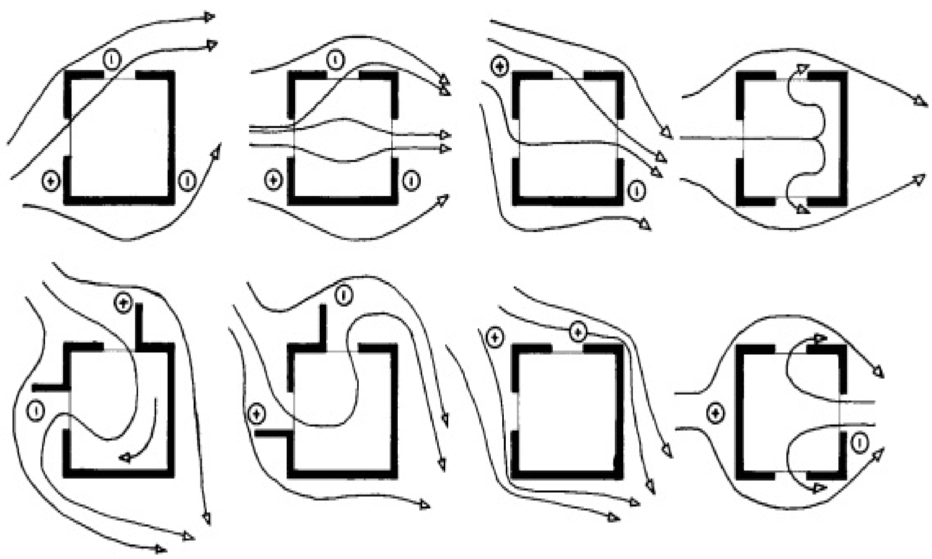

Figure 4.2 positive and negative wind pressure around different building configurations (Roaf, 2001)

The airflow from openings could happen through building envelope or purposely installed openings by one of the following techniques:

- Single-Sided Ventilation (Figure 4.3): Limited to zones close to the openings.
- Cross-Ventilation (Figure 4.3): Two or more openings on opposite walls and normally it cover a larger zone than the single-sided openings.
- Stack Ventilation: Buoyancy-driven that makes the air flows larger.
- Wind catchers: Wind and buoyancy driven - effective in warm and moderate climates.
- Solar-Induced Ventilation: using the sun to heat building elements to increase buoyancy - more effective in warm climates.

In hot dry climates, natural ventilation is considered one of the most important passive cooling strategies. It is based on the idea that when the air velocity increases around the human body, then the rate of heat dissipation by evaporation and convection will be significantly accelerated (Asimakopolous and Santamouris, 1996). Accordingly, indoor thermal comfort can be improved by natural ventilation throughout two different ways (Givoni 1998; 1994; McMullan and Seeley, 2007). First one is to raise the indoor air velocity by opening the windows letting the air cross inside the spaces and then increasing the cooling effect indoors.

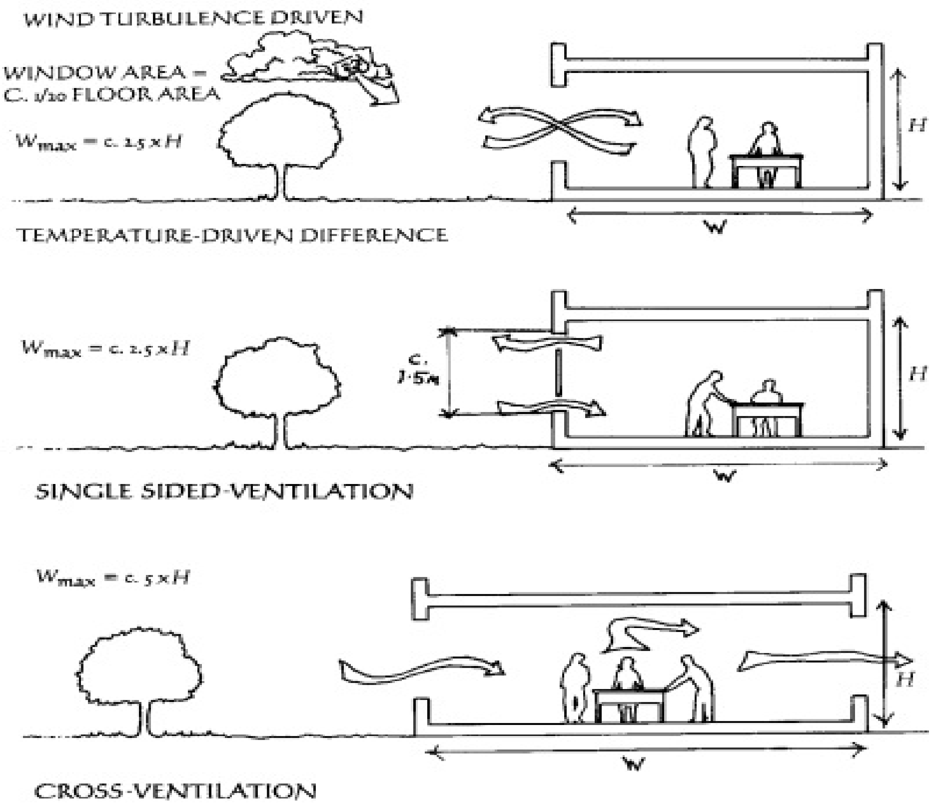

Figure 4.3 single sided and cross ventilation (Roaf, 2001)

The second way is called “nocturnal ventilative cooling” that can be indirectly happen by ventilating the spaces at night time to flush out of heat from the building during night and this, consequently, can cool the internal mass of the building and consequently can reduce the indoor temperature rise in the successive day (Krishan et. al., 2001).

However, the second way of nocturnal ventilative cooling (or as it is called in other literature “night purge ventilation”) is more advisable in hot-dry climate regions because opening the windows during the day can significantly increase the indoor temperature and consequently increases discomfort while during night can diminish the heat that was gained during the day time (Givoni 1994).

(Givoni, 1998) indicated that, in hot dry climates, nocturnal ventilative cooling is beneficial when diurnal temperature ranges between 32 °C and 36 °C and nocturnal temperature drop down until 20 °C, this process becomes more efficient with high thermal mass buildings. However, in case of the extreme hot diurnal temperature that exceeds 36 C, nocturnal ventilative cooling is not effective even with high thermal mass buildings.

Asimakopolous and Santamouris (1996) stated that an appropriate nocturnal ventilative rate for a building with high thermal mass and all windows closed during the day time can attain 35% to 45% diminution in indoor temperature.

Gado and Osman (2009) conducted a study on the state funded dwellings in New Al-Minya city in Egypt to examine the efficiency of natural ventilation strategies for this kind of buildings. The study was conducted in two phases. First phase was a pilot study that discussed the impact of the use of transformations, like reshape the window and installing vertical and horizontal shading devices, on natural ventilation. The second phase examined the natural ventilation effectiveness during the hottest period of the year using Autodesk-Ecotect simulation software program, as well as, it investigated the air movement using computational fluid dynamics software FloVENT. The main finding of the study was that the cross ventilation of nocturnal ventilative cooling is not effective for the case study because it achieved only 4.9% reduction in temperature.

Gado (2000), in his M.Sc. Thesis, examined the effectiveness of the passive design strategies in various climatic regions in Egypt. One of the prototypical governmental walk-up housing stocks was used as a case study. Parametric analyses were conducted for the proposed passive strategies to examine its effect on thermal comfort and energy efficiency for these projects. The results were concluded that **the utilize of external insulation for external walls with light colors on external surfaces and wide-ranging shading devices give the best results in terms of thermal comfort and energy efficiency all over Egyptian climate conditions**. The study recommended applying such strategies in the first design phase.

El-Hefnawi (2000) conducted a computer simulation parametric analysis for a case study of a typical youth housing dwelling in El-Obour city in the eastern desert of Cairo. The aim of his study was to examine different strategies to ameliorate the thermal performance of these buildings using in summer season. The tested strategies are different building materials, wall thicknesses, shading devices and night purge ventilation. **The study recommended using high thermal mass with external wall insulation;** reducing window area to be at maximum 40% of the space area; using reflective glass for the windows with thickness of 6 mm; fixing external shading devices for both west and south orientations and **using night purge ventilation.**

4.2 EFFECT OF NATURAL VENTILATION DIFFERENT SCENARIOS ON RESEARCH CASE STUDY

Based on the above literature, **natural ventilation as one of important strategies to improve thermal comfort was adopted in this research** to be examined on the case study of 6th of October city in Greater Cairo. The research used IESVE software simulation program to examine the effect natural ventilation different scenarios on indoor thermal comfort. The examined scenarios (Figure 4.4) were categorized into three main groups. The first group includes only the base case scenario. The second group includes the based behavioral survey scenarios that were deduced from questionnaire analysis in winter and summer seasons. The third group includes the hypothetical suggested scenarios to improve the situation in summer season. Each scenario is explained more in details below:

- Scenario 4.1 (base case): windows were closed 24 hours.
- Scenario 4.2: windows were opened from 8:00 to 9:00 at morning and from 17:00 to 18:00 afternoon – internal doors were opened continuously.
- Scenario 4.3: windows were opened from 9:00 to 24:00 – internal doors were opened continuously.
- Scenario 4.4: windows were opened from 17:00 to 23:00 – internal doors were opened continuously.
- Scenario 4.5: windows were opened from 8:00 to 14:00 – internal doors were opened continuously.
- Scenario 4.6: windows were opened 24 hours - internal doors were opened continuously.
- Scenario 4.7: single sided night purge ventilation; all windows were opened during night time (from sunrise to sunset) - internal doors were closed continuously.
- Scenario 4.8: cross night purge ventilation; all the windows were opened during night time (from sunrise to sunset) - internal doors were opened.

The effect of each the above mentioned scenarios is explained in details in the following sections.

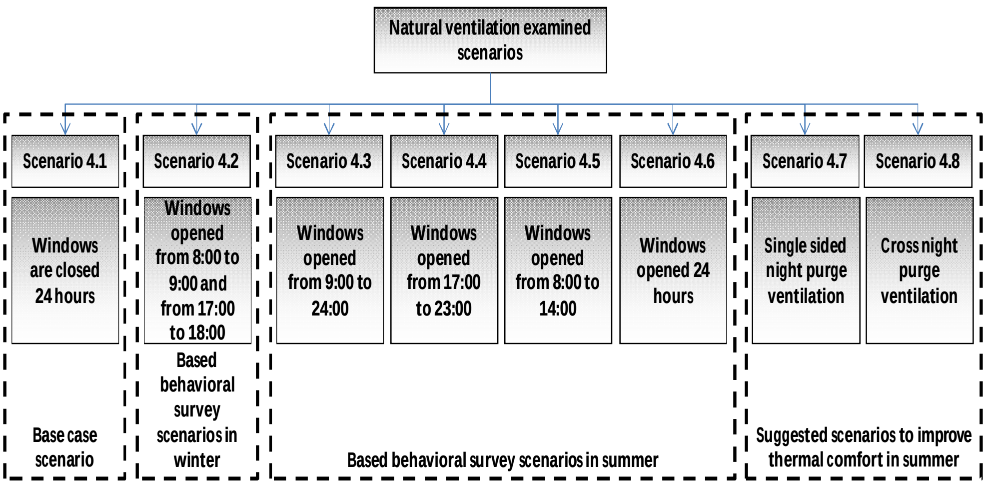

Figure 4.4 natural ventilation examined scenarios

4.2.1 EFFECT OF NATURAL VENTILATION DIFFERENT SCENARIOS ON THERMAL COMFORT FOR A LIVING ROOM IN TYPICAL FLOOR FACING SOUTH

The southern apartments of the typical floor were simulated for the whole year according to the above mentioned scenarios for natural ventilation. The following graphs show in percentages the number of hours whereby heating is needed, the number of hours whereby cooling is needed and the number of hours that are within comfort range wherein neither heating nor cooling. These were specified according to the comfort zone analysis explained in chapter four that showed the extreme limits of comfort and adaptive comfort for this case study are ranged between 19.6 °C and 29 °C. These were considered as fixed limits of comfort zone for the whole year.

Figures 4.6 to 4.21 illustrate the thermal performance of a living room in typical floor facing south during the whole year. In consequence, each figure represents one month and introduces a comparison among natural ventilation scenarios that considered to be compared in this month according to the season. Moreover, the year was divided into three main groups; winter months (where cooling demand is approximating zero percent from total hours), summer months (where heating demand is approximating zero percent from total hours) and spring-autumn months (where both heating and cooling are needed)

Accordingly, the winter season was represented by the month of January, February, March, November and December since it was observed that in these months the cooling demand is approximating 0.0% from the total hours of the whole month. The summer season was represented by the month of June, July, August and September because in these months the heating demand is approximating 0.0% from the total hours of the whole month. The spring-autumn seasons were represented by the month of April, May, and October. Although, these months are considered the most thermally comfortable months in Cairo climate, they have small percentages from total hours are of both cooling and heating demand according to comfort zone analysis.

In the winter months; January, February, March, November and December (Figure 4.6, 4.7, 4.8, 4.9 and 4.10 respectively), the comparison was made between the base case scenario (scenario 4.1) and the based behavioral survey scenario that is derived from questionnaire analysis (scenario 4.2) (see figure 4.5 below). Scenario 4.2 is the most likelihood to happen in winter as deduced from the questionnaire analysis; this is because the inhabitants prefer opening the external windows only for fresh air intake for little time at morning after they wake up and little time afternoon after they come back from work (this little time was approximated to be one hour for simulation purposes).

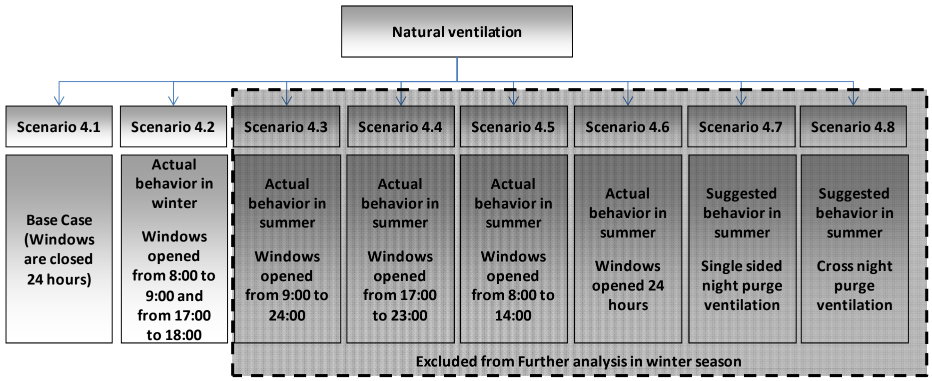

Figure 4.5 compared scenarios of natural ventilation in winter season

In January (Figure 4.6), this is one of the peak heating dominated months in Cairo in all presented scenarios. Scenario 4.1; the base case scenario (windows are closed 24 hours) and scenario 4.2; the based behavioral survey scenario (windows are opened from 8:00 to 9:00 and from 17:00 to 18:00) achieved equal percentages of 1.7% from the total hours are within the comfort range and 98.3% from the total hours are of heating demand. **Based on this comparison, there is no any significant impact on thermal comfort between the base case scenario and the based behavioral survey scenario during the month of January for the reference case under Cairo climate condition.**

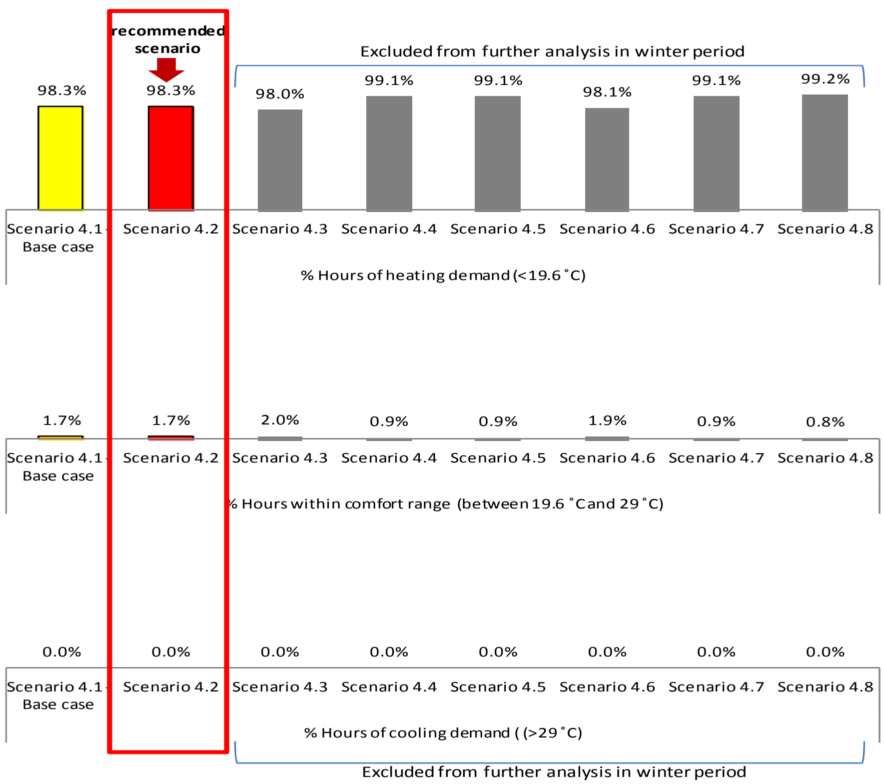

Figure 4.6 Effect of natural ventilation different scenarios on southern living room in typical floor during the month of January

In February (Figure 4.7), this is one of the peak heating dominated months in Cairo in all presented scenarios. scenario 4.1 (the base case scenario) and scenario 4.2 (the based behavioral survey scenario) achieved 11.5% and 10.9% respectively from the total hours are within the comfort range and 88.5% and 89.1% respectively from the total hours are of heating demand.

On the basis of this comparison, scenario 4.1 achieved slightly higher percentage of comfort than scenario 4.2 because opening the windows one hour at morning and one hour afternoon can brings cold air from outdoors to indoors. However, scenario 4.2 is preferable to improve indoor air quality.

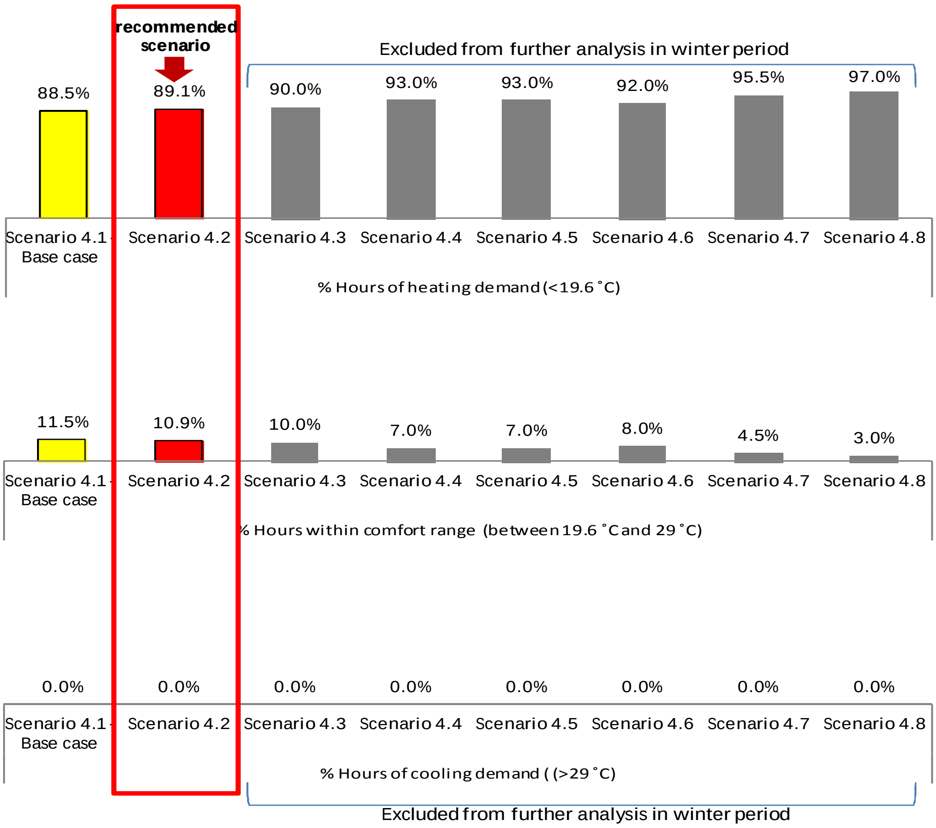

Figure 4.7 Effect of natural ventilation different scenarios on southern living room in typical floor during the month of February

In March (Figure 4.8), this is one of the months of heating demand in Cairo in all presented scenarios. scenario 4.1; The base case scenario (windows are closed 24 hours) and scenario 4.2; the based behavioral survey scenario (windows are opened from 8:00 to 9:00 and from 17:00 to 18:00) that is deduced from questionnaire analysis achieved 48.4% and 44.4% respectively from the total hours are within the comfort range and 51.6% and 55.6% respectively from the total hours are of heating demand. **In view of this comparison, scenario 4.1 achieved slightly higher percentage of comfort than scenario 4.2 because opening the windows one hour at morning and one hour afternoon can brings cold air from outdoors to indoors. However, scenario 5.2 is preferable for fresh air intake that improves indoor air quality.**

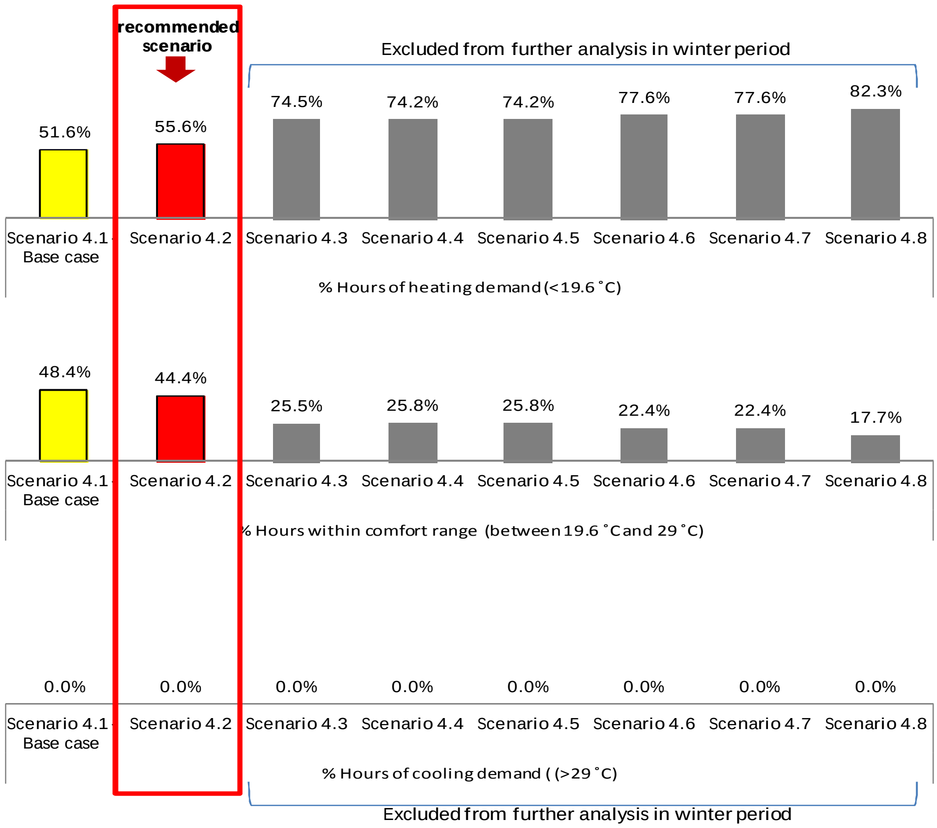

Figure 4.8 Effect of natural ventilation different scenarios on southern living room in typical floor during the month of March

In November (Figure 4.9), this is one of the months of heating demand in Cairo in all presented scenarios. scenario 4.1 (the base case scenario) and scenario 4.2 (the based behavioral survey scenario) achieved 93.5% and 92.2% respectively from the total hours are within the comfort range and 6.5% and 7.8% respectively from the total hours are of heating demand. **In view of the said comparison, scenario 4.2 reduces indoor thermal because opening the window for two hours per day brings cold air indoors. However, scenario 4.2 is preferable because closing windows for 24 hours in scenario 4.1 can negatively affect indoor air quality.**

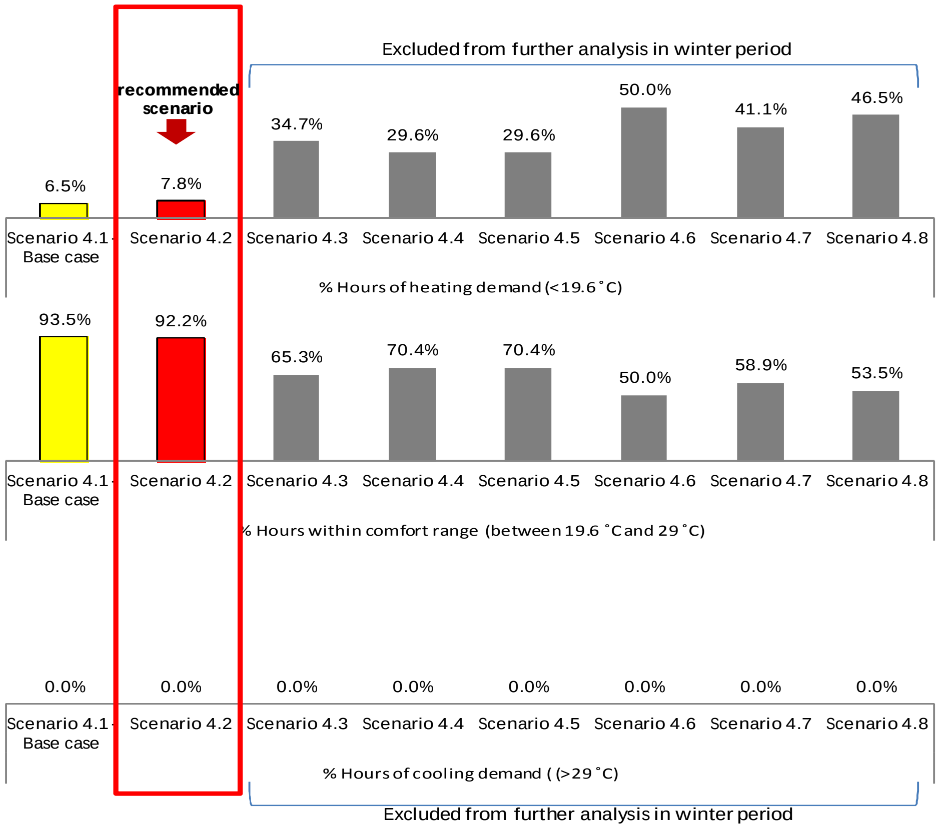

Figure 4.9 Effect of natural ventilation different scenarios on southern living room in typical floor during the month of November

In December (Figure 4.10), this is one of the peak heating dominated months in Cairo in all presented scenarios. scenario 4.1; The base case scenario (windows are closed 24 hours) and scenario 4.2; the based behavioral survey scenario (windows are opened from 8:00 to 9:00 and from 17:00 to 18:00) achieved 20.7% and 21.1% respectively from the total hours are within the comfort range and 79.3% and 78.9% respectively from the total hours are of heating demand. **Based on this comparison, on the opposite of the previous winter months, scenario 4.2 slightly increased indoor thermal comfort.**

From the above investigations for the whole period of winter months (the period of zero cooling demand in January, February, March, November and December) (Figure 4.11), it was observed that the base case scenario (scenario 4.1) where windows were closed 24 hours achieved higher percentage (35.2%) from total hours within comfort range while when open the windows one hour at morning and one hour at evening (scenario 4.2), it reduced the comfort by 1.3% to become 34.1% from total hours within comfort range. As a consequent, **even though natural ventilation is undesirable in winter season as it reduces the indoor thermal comfort, It is important for indoor air quality and fresh air intake. So that, scenario 4.2 is preferable to be followed in winter season.**

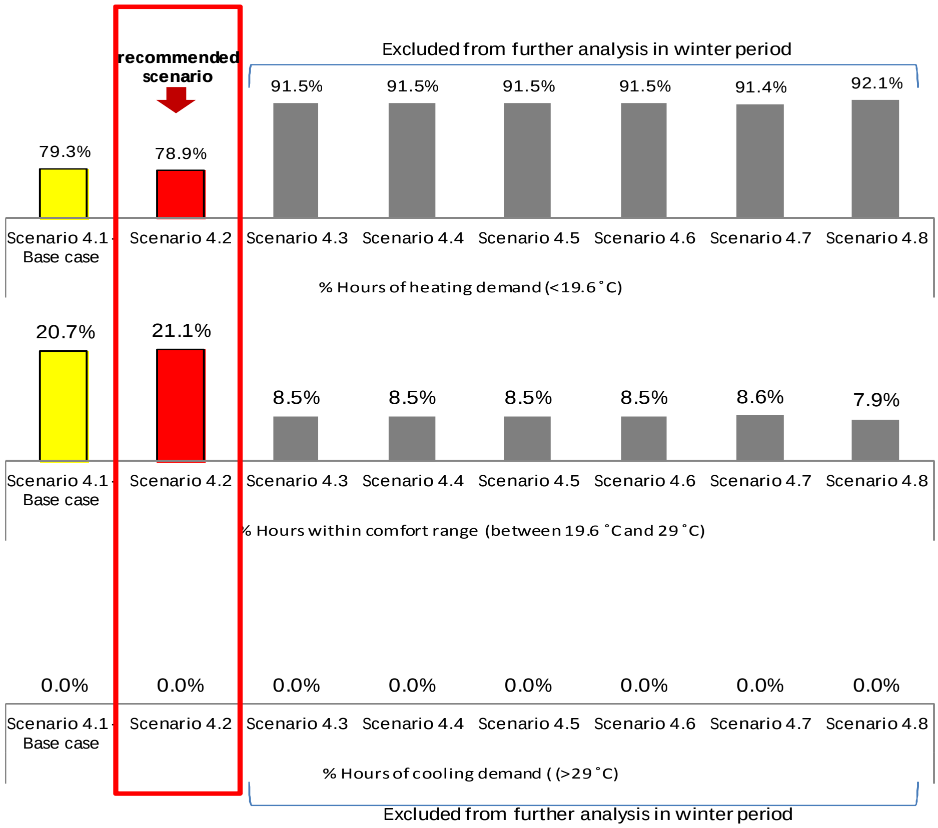

Figure 4.10 Effect of natural ventilation different scenarios on southern living room in typical floor during the month of December

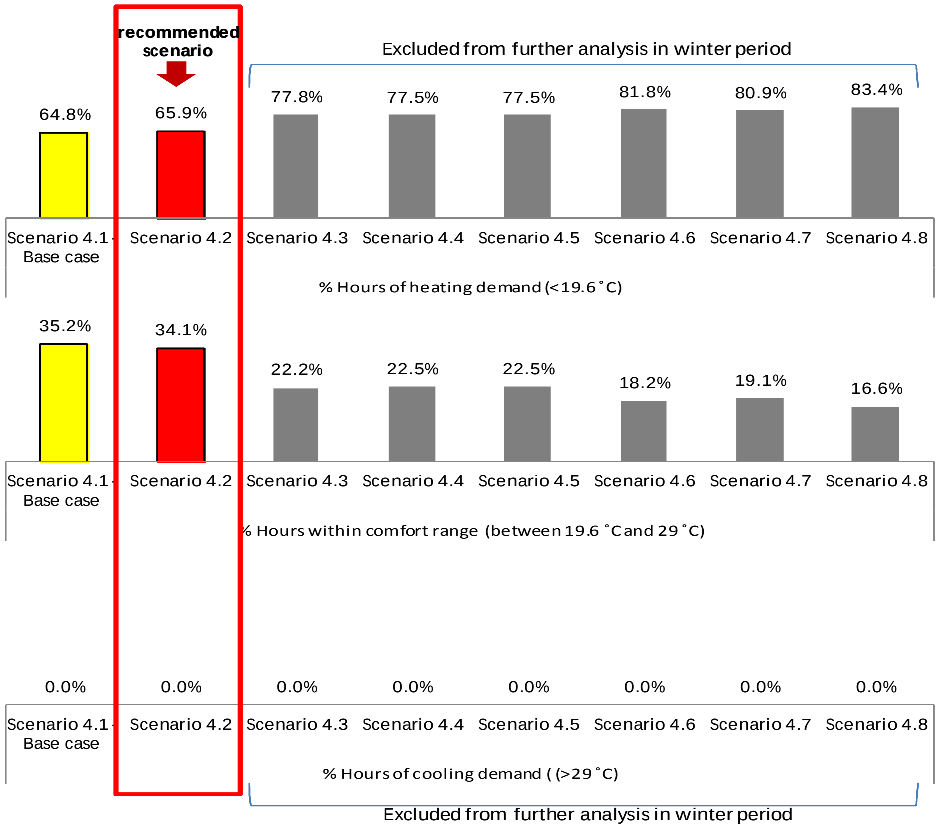

Figure 4.11 Effect of natural ventilation different scenarios on southern living room in typical floor during the whole winter month's period

In the summer months; June, July, August and September (Figures 12, 13, 14 and 15) the comparison was made among the base case scenario (scenario 4.1), the based behavioral survey scenarios that is derived from questionnaire analysis (scenario 4.3, scenario 4.4, scenario 4.5 and scenario 4.6) and the hypothetical suggested scenarios (scenario 4.7 and scenario 4.8) (Figure 4.12).

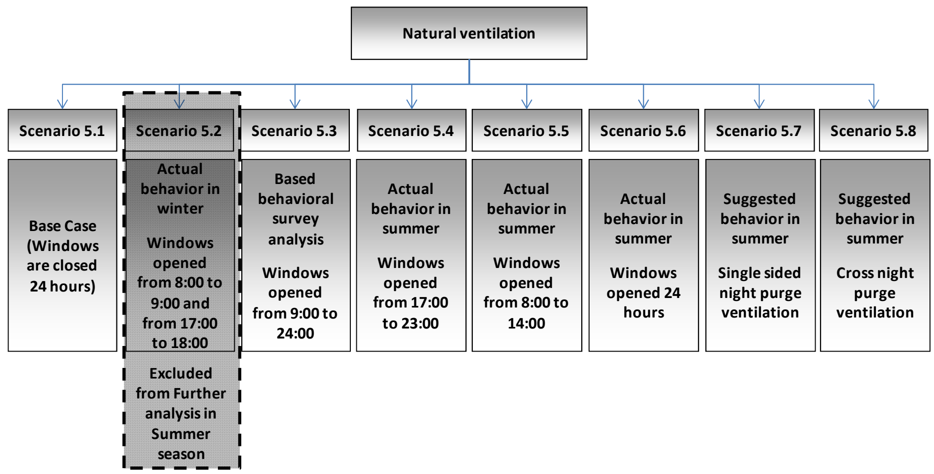

Figure 4.**12** compared scenarios of natural ventilation in summer season

In June (figure 4.13), this is one of the months of cooling demand in Cairo in all presented scenarios. **the base case scenario (scenario 4.1) and The based behavioral survey scenarios**; scenario 4.3 (Windows opened from 9:00 to 24:00), scenario 4.4 (Windows opened from 17:00 to 23:00), scenario 4.5 (Windows opened from 8:00 to 14:00) and scenario 4.6 (Windows opened 24 hours) achieved 39.0%, 54.7%, 58.9%, 58.9% and 63.1% respectively from the total hours are within the comfort range and 61.0%, 45.3%, 41.1%, 41.1% and 35.6% respectively from the total hours of cooling demand. These analyses show that by following the best actual behavioral scenario, people could achieve 63.1% within comfort range if they open the windows 24 hours.

The hypothetical suggested scenarios to improve thermal comfort; scenario 4.7 (single sided night purge ventilation) and scenario 4.8 (cross night purge ventilation) achieved 71.7% and 75.3% from total hours within comfort range and 28.2% and 23.6% respectively from total hours are of cooling demand.

Based on the above comparison, people should follow scenario 4.8 of cross night purge ventilation as it achieved the highest percentage of total hours (75.3%) within comfort range and the lowest percentage from total hours (23.6%) of cooling demand.

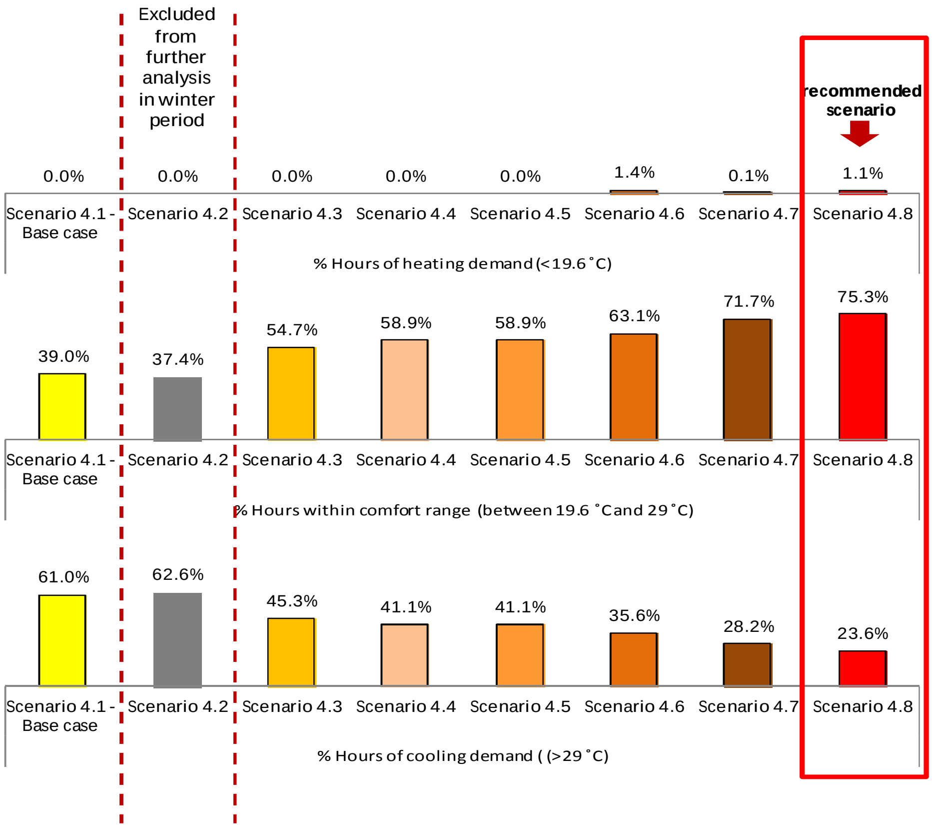

Figure 4.13 Effect of natural ventilation different scenarios on southern living room in typical floor during the month of June

In July (figure 4.14), this is one of the peak cooling dominated month in Cairo in all presented scenarios**. the base case scenario (scenario 4.1) and the based behavioral survey scenarios** that is deduced from questionnaire analysis; scenario 4.3 (Windows opened from 9:00 to 24:00), scenario 4.4 (Windows opened from 17:00 to 23:00), scenario 4.5 (Windows opened from 8:00 to 14:00) and scenario 4.6 (Windows opened 24 hours) achieved 8.7%, 38.7%, 35.5%, 35.5% and 56.2% respectively from the total hours are within the comfort range and 91.3%, 61.3%, 64.5%, 64.5% and 43.8% respectively from the total hours of cooling demand. These findings show that by following the best actual behavioral scenario, people could only achieve 56.2% comfort if they open the windows 24 hours.

The hypothetical suggested scenarios to improve thermal comfort; scenario 4.7 (single sided night purge ventilation) and scenario 4.8 (cross night purge ventilation) achieved 54.7% and 61.4% respectively from total hours within comfort range and 45.3% and 38.6% respectively from total hours are of cooling demand.

Based on the above comparison, people should follow the scenario of cross night purge ventilation as it achieved the highest percentage of total hours (61.4%) within comfort range and the lowest percentage of total hours (38.6%) of cooling demand.

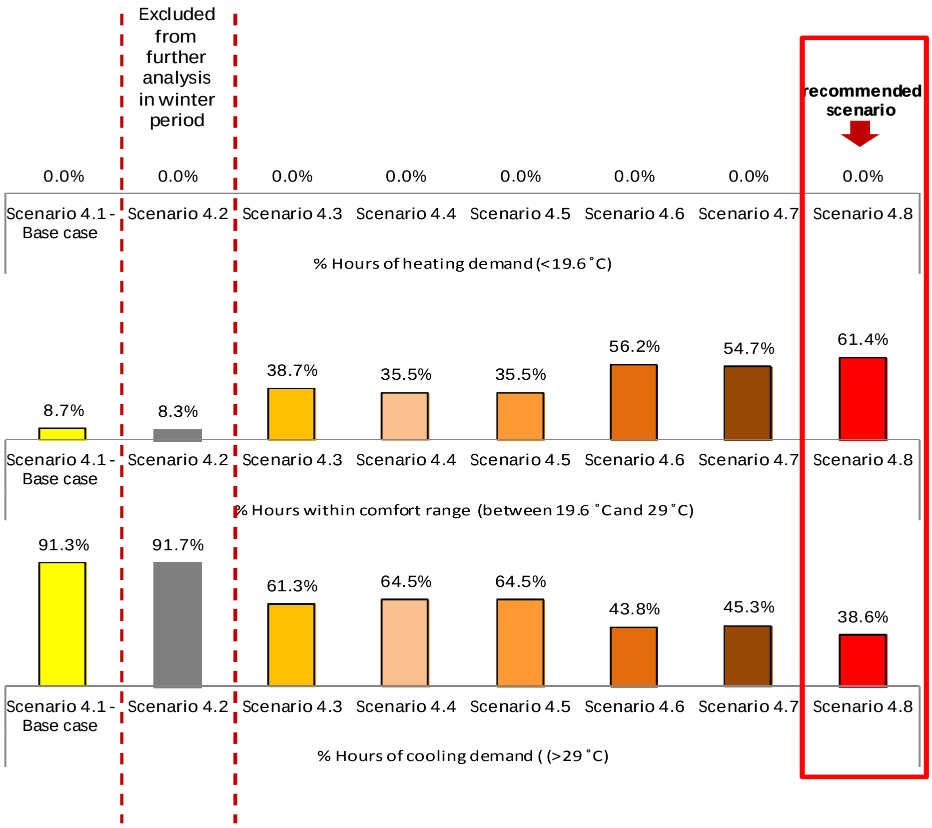

Figure 4.14 Effect of natural ventilation different scenarios on southern living room in typical floor during the month of July

In August (figure 4.15), this is also one of the peak cooling dominated month in Cairo in all presented scenarios. **the base case scenario (scenario 4.1) and The based behavioral survey scenarios**; scenario 4.3 (Windows opened from 9:00 to 24:00), scenario 4.4 (Windows opened from 17:00 to 23:00), scenario 4.5 (Windows opened from 8:00 to 14:00) and scenario 4.6 (Windows opened 24 hours) achieved 5.5%, 38.3%, 35.6%, 35.6% and 58.7% respectively from the total hours are within the comfort range and 94.5%, 61.7%, 64.4%, 64.4% and 41.3% respectively from the total hours of cooling demand. These analyses show that by following the best actual behavioral scenario, people could only achieve 58.7% within comfort range if they open the windows 24 hours.

The hypothetical suggested scenarios to improve thermal comfort; scenario 4.7 (single sided night purge ventilation) and scenario 4.8 (cross night purge ventilation) achieved 55.8% and 62.1% from total hours within comfort range and 44.2% and 37.9% respectively from total hours are of cooling demand.

In view of the above comparison, people should follow the scenario of cross night purge ventilation as it achieved the highest percentage of total hours (62.1 %) within comfort range and the lowest percentage of total hours (37.9%) of cooling demand.

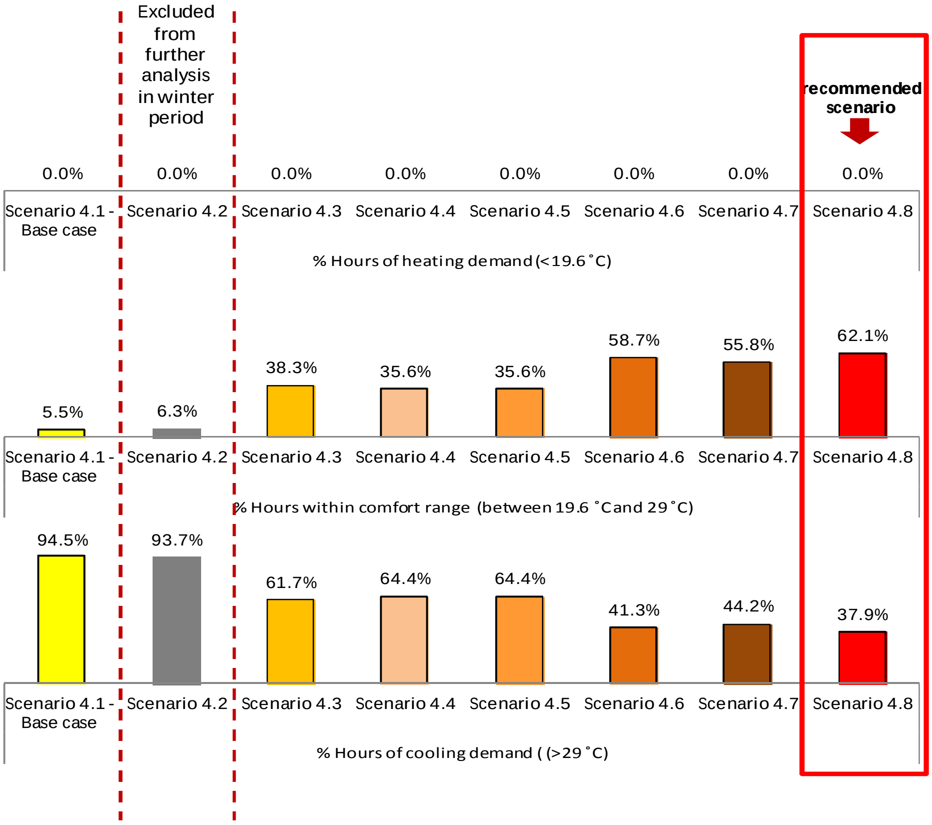

Figure 4.15 Effect of natural ventilation different scenarios on southern living room in typical floor during the month of August

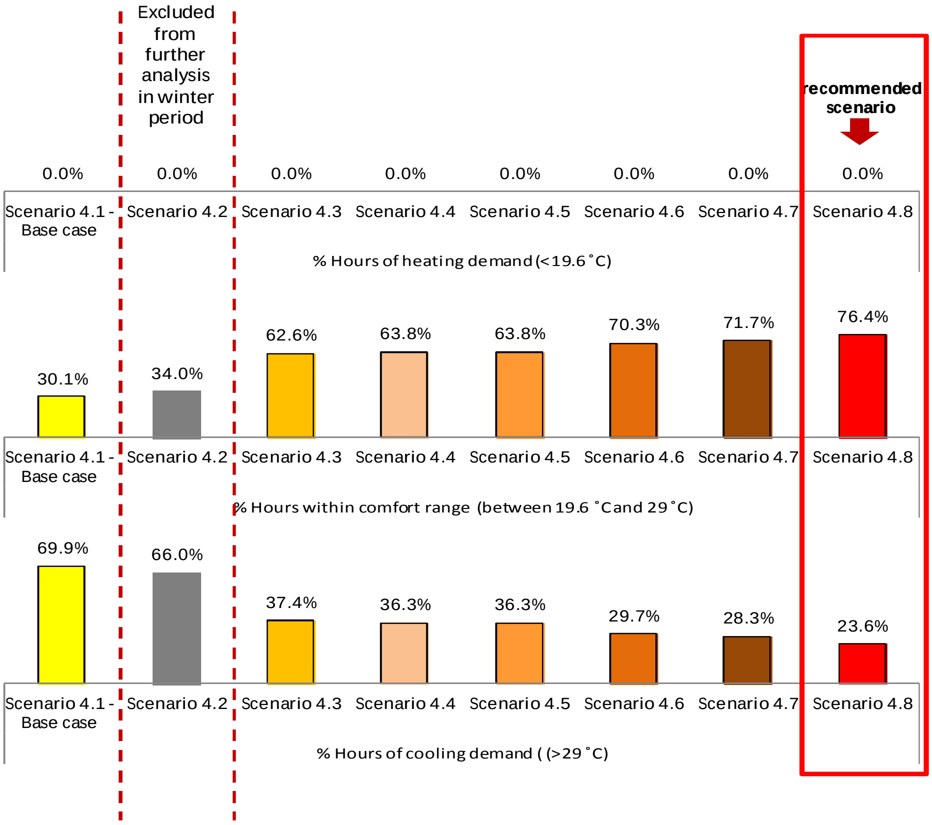

Figure 4.16 Effect of natural ventilation different scenarios on southern living room in typical floor during the month of September

In September (figure 4.16), this is one of the months of cooling demand in Cairo in all presented scenarios. **the base case scenario (scenario 4.1) and The based behavioral survey scenarios** that is derived from questionnaire analysis; scenario 4.3 (Windows opened from 9:00 to 24:00), scenario 4.4 (Windows opened from 17:00 to 23:00), scenario 4.5 (Windows opened from 8:00 to 14:00) and scenario 4.6 (Windows opened 24 hours) achieved 30.1%, 62.6%, 63.8%, 63.8% and 70.3% respectively from the total hours are within the comfort range and 69.9%, 37.4%, 36.3%, 36.3% and 29.7% respectively from the total hours of cooling demand. These analyses show that by following the best actual behavioral scenario, people could achieve 70.3% within comfort range if they open the windows 24 hours.

The hypothetical suggested scenarios to improve thermal comfort; scenario 4.7 (single sided night purge ventilation) and scenario 4.8 (cross night purge ventilation) achieved 71.7% and 76.4% from total hours within comfort range and 28.3% and 23.6% respectively from total hours are of cooling demand.

On basis of the above comparison, people should follow the scenario of cross night purge ventilation as it achieved the highest percentage of total hours (76.4 %) within comfort range and the lowest percentage from total hours (23.6%) are of cooling demand.

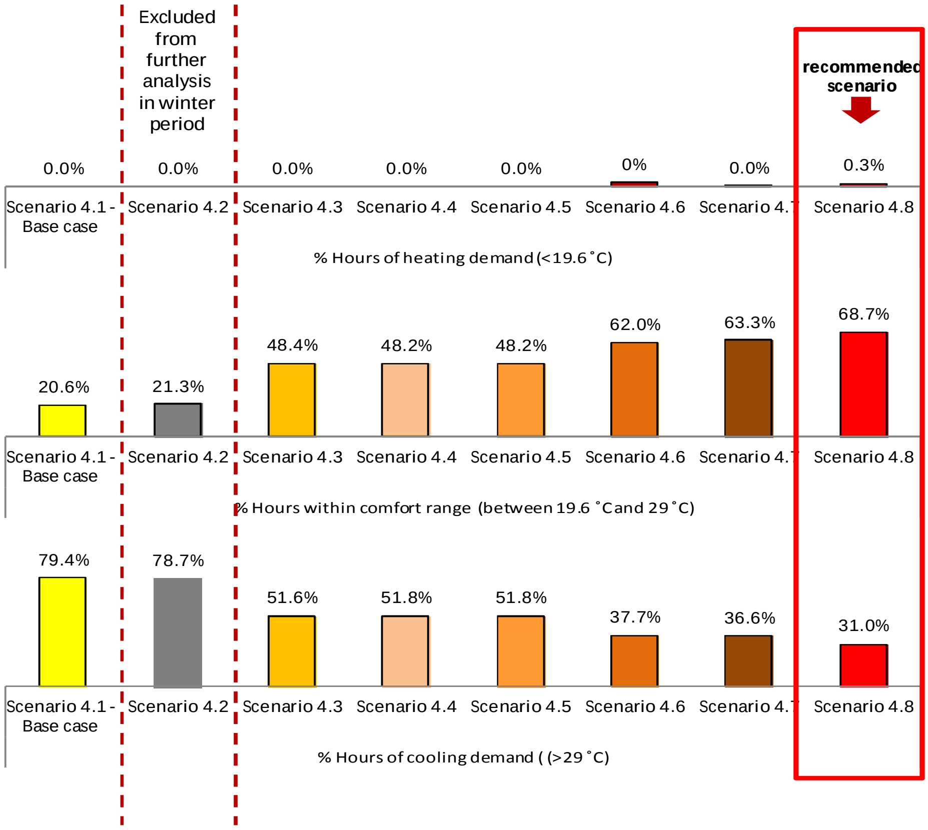

Figure 4.17 Effect of natural ventilation different scenarios on southern living room in typical floor during the whole summer month's period

From the above investigations for **the whole period of summer months** (the period of almost zero heating demands in June, July, August and September) (Figure 4.17**), it was proved that cross night purge ventilation is the best scenario for the summer months**. This scenario achieved 68.7% from total hours within comfort range improving the situation by 48.1% from total hours higher than the base case scenario. Although the percentage is different, this result corroborates the findings of Givoni (1998), Asimakopolous and Santamouris (1996) and El-Hefnawi (2000) in the fact that the nocturnal ventilative cooling is one of the most effective strategies to improve thermal comfort in hot arid climates in summer season.

In the spring-autumn months; April, May and October (Figures 4.18, 4.19 and 4.20 respectively), the comparison was made among all the presented eight scenarios of natural ventilation as these months have both heating and cooling demand.

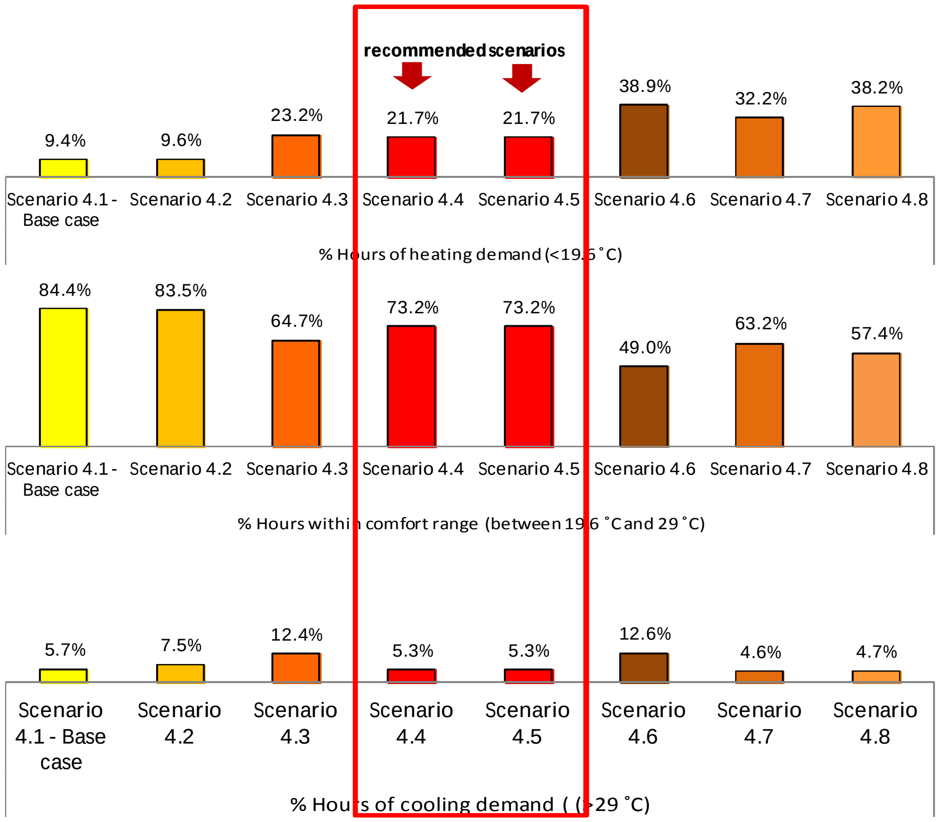

Figure 4.18 Effect of natural ventilation different scenarios on southern living room in typical floor during the month of April

In April (figure 4.18), this is normally one of the months of high percentage of hours within comfort range and low percentages of both cooling and heating demand in Cairo in all presented scenarios. **the base case scenario and the based behavioral survey scenarios**; scenario 4.1 (windows closed 24 hours), scenario 4.2 (windows opened from 8:00 to 9:00 and from 17:00 to 18:00), scenario 4.3 (Windows opened from 9:00 to 24:00), scenario 4.4 (Windows opened from 17:00 to 23:00), scenario 4.5 (Windows opened from 8:00 to 14:00) and scenario 4.6 (Windows opened 24 hours) achieved 9.4%, 9.6%, 23.2%, 21.7%, 21.7% and 38.9% respectively from the total hours are of heating demand, and 84.4%, 83.5%, 64.7%, 73.2%, 73.2% and 49.0% are within the comfort range, and 5.7%, 7.5%, 12.4%, 5.3%, 5.3% and 12.6% respectively from the total hours are of cooling demand.

The hypothetical scenarios that were suggested to improve thermal comfort in summer; scenario 4.7 (single sided night purge ventilation) and scenario 4.8 (cross night purge ventilation) achieved 32.2% and 38.2% from total hours are of heating demand, and 63.2% and 57.4% from total hours are within comfort range, and 4.6% and 4.7% respectively from total hours are of cooling demand.

In view of the said comparison, the base case scenario (scenario 4.1) achieved the highest percentage of hours within comfort range (84.4%) but it is not recommended because it affects negatively the indoor air quality. So that, it is recommended that people should follow scenario 4.2 (windows are opened from 8:00 to 9:00 and from 17:00 to 18:00) as it gives the second highest percentage of comfort (83.5%).

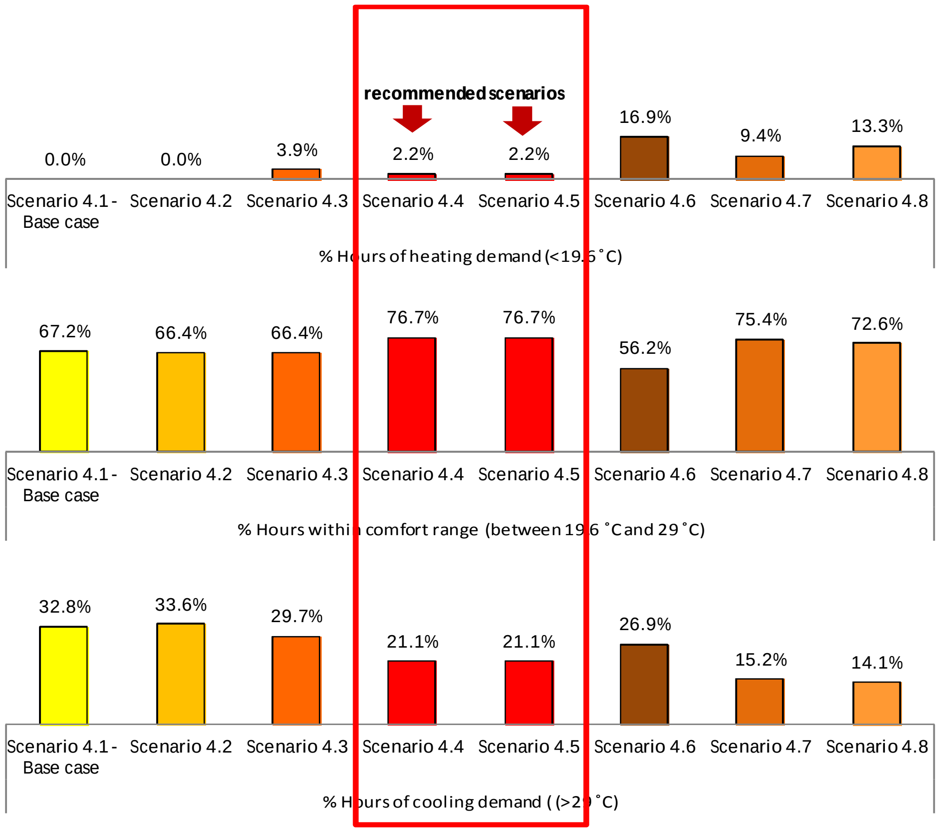

Figure 4.19 Effect of natural ventilation different scenarios on southern living room in typical floor during the month of May

In May (figure 4.19), this is normally one of the months of high percentage of hours within comfort range and low percentages of both cooling and heating demand in Cairo in all presented scenarios. **the base case scenario and the based behavioral survey scenarios** that is derived from questionnaire analysis; scenario 4.1 (windows closed 24 hours), scenario 4.2 (windows opened from 8:00 to 9:00 and from 17:00 to 18:00), scenario 4.3 (Windows opened from 9:00 to 24:00), scenario 4.4 (Windows opened from 17:00 to 23:00), scenario 4.5 (Windows opened from 8:00 to 14:00) and scenario 4.6 (Windows opened 24 hours) achieved 0.0%, 0.0%, 3.9%, 2.2%, 2.2% and 16.9% respectively from the total hours are of heating demand, and 67.2%, 66.4%, 66.4%, 76.7%, 76.7% and 56.2% are within the comfort range, and 32.8%, 33.6%, 29.7%, 21.1%, 21.1% and 26.9% respectively from the total hours are of cooling demand.

The hypothetical scenarios that were suggested to improve thermal comfort in summer; scenario 4.7 (single sided night purge ventilation) and scenario 4.8 (cross night purge ventilation) achieved 9.4% and 13.3% from total hours are of heating demand, and 75.4% and 72.6% from total hours are within comfort range, and 15.2% and 14.1% respectively from total hours are of cooling demand.

On basis of the above comparison, the occupants should follow scenario 4.4 (Windows opened from 17:00 to 23:00) or scenario 4.5 (Windows opened from 8:00 to 14:00) as they achieved equally the highest percentage of hours within comfort range (76.7%).

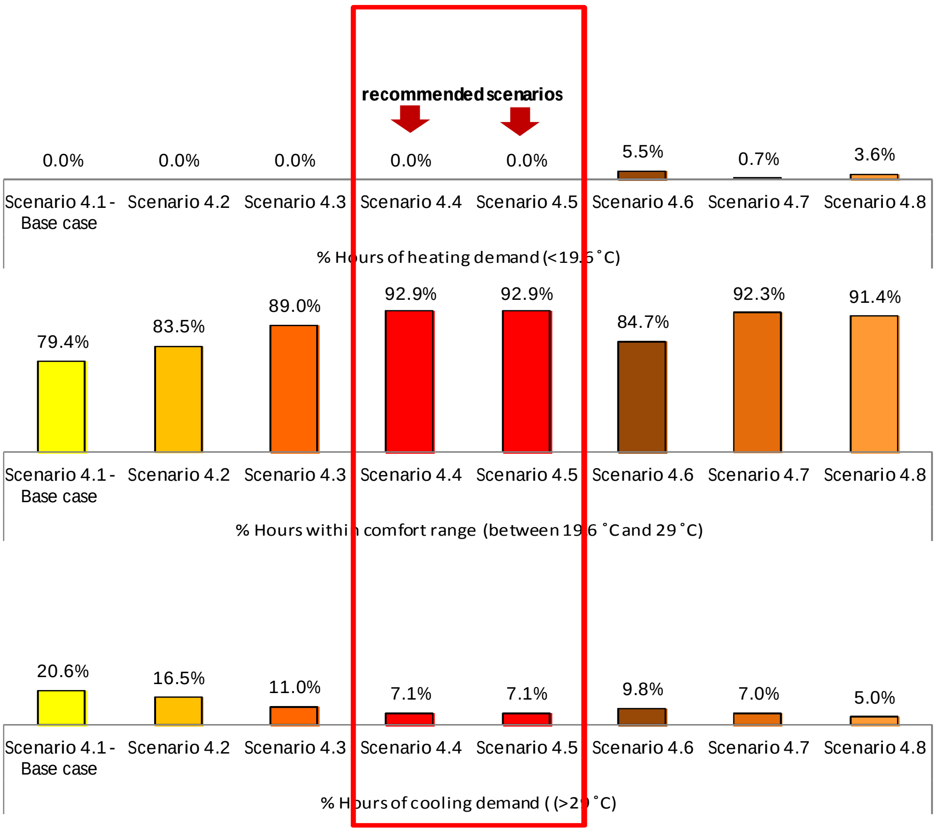

Figure 4.20 Effect of natural ventilation different scenarios on southern living room in typical floor during the month of October

In October (figure 4.20), this is normally one of the months of high percentage of hours within comfort range and low percentages of both cooling and heating demand in Cairo in all presented scenarios. **the base case scenario and the based behavioral survey scenarios** that is derived from questionnaire analysis; scenario 4.1 (windows closed 24 hours), scenario 4.2 (windows opened from 8:00 to 9:00 and from 17:00 to 18:00), scenario 4.3 (Windows opened from 9:00 to 24:00), scenario 4.4

(Windows opened from 17:00 to 23:00), scenario 4.5 (Windows opened from 8:00 to 14:00) and scenario 4.6 (Windows opened 24 hours) achieved 0.0%, 0.0%, 0.0%, 0.0%, 0.0%, and 4.5% respectively from the total hours are of heating demand, and 79.4%, 83.5%, 89.0%, 92.9%, 92.9% and 84.7% are within the comfort range, and 20.6%, 16.5%, 11.0%, 7.1%, 7.1% and 9.8% respectively from the total hours are of cooling demand.

The hypothetical scenarios that were suggested to improve thermal comfort in summer; scenario 4.7 (single sided night purge ventilation) and scenario 4.8 (cross night purge ventilation) achieved 0.7% and 3.6% from total hours are of heating demand, and 92.3% and 91.4% from total hours are within comfort range, and 7.0% and 4.0% respectively from total hours are of cooling demand.

Based on the above comparison, the occupants should follow scenario 4.4 (Windows opened from 17:00 to 23:00) or scenario 4.5 (Windows opened from 8:00 to 14:00) as they achieved equally the highest percentage of hours within comfort range (92.9%).

In generally, from the above analyses for the whole period of the spring- autumn months (April, May and October) (Figure 4.21), **the occupants should follow scenario 4.4 (Windows opened from 17:00 to 23:00) or scenario 4.5 (Windows opened from 8:00 to 14:00) because these scenarios have achieved equally the highest percentages from total hours within comfort range (81.0%) improving the situation by 4.1% comparing to the base case scenario.**

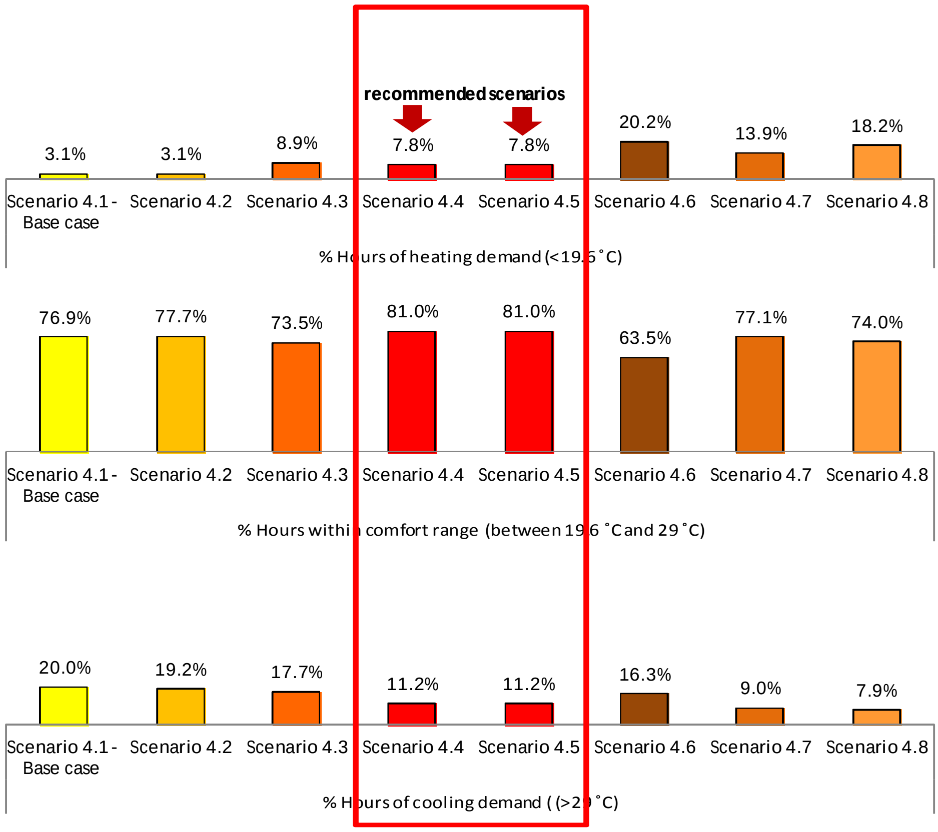

Figure 4.21 Effect of natural ventilation different scenarios on southern living room in typical floor during the whole period of spring-autumn

4.3 IMPACT OF ORIENTATION ON INDOOR THERMAL COMFORT FOR A LIVING ROOM IN TYPICAL FLOOR

This section addresses a cross analysis to investigate the effect of orientation whilst using the best scenarios of natural ventilation in winter, summer and spring-autumn periods. Based on the previous analysis in section 4.2.1, scenarios 4.2, 4.8, 4.4 were chosen to be compared in the different orientations in winter, summer and spring-autumn periods respectively. The results of this comparison are explained in the following subsections.

4.3.1 IMPACT OF ORIENTATION IN WINTER PERIOD

Scenario 4.2 (windows opened from 8:00 to 9:00 and from 17:00 to 18:00) of natural ventilation was compared among the different orientations; North, West, East and South during the winter months (January, February, March, November and December).

In January (Figure 4.22): Northern, Western, Eastern, Southern orientations achieved 0.3%, 1.5%, 1.5% and 1.7% respectively from total hours are within comfort range and 99.7%, 98.5%, 98.5% and 98.3% respectively from total hours are of heating demand.

According to above comparison, the highest effect of comfort was in the southern orientation and the lowest was in the northern orientation. This result is quite reasonable and consistent with the fact that the southern orientation is the most exposed to the sunlight during the day time in the mostly sunny winters of Egypt. However, the differences among all orientation weren't much high. Accordingly, **the orientation has no significant impact on indoor thermal comfort for the reference case during January.**

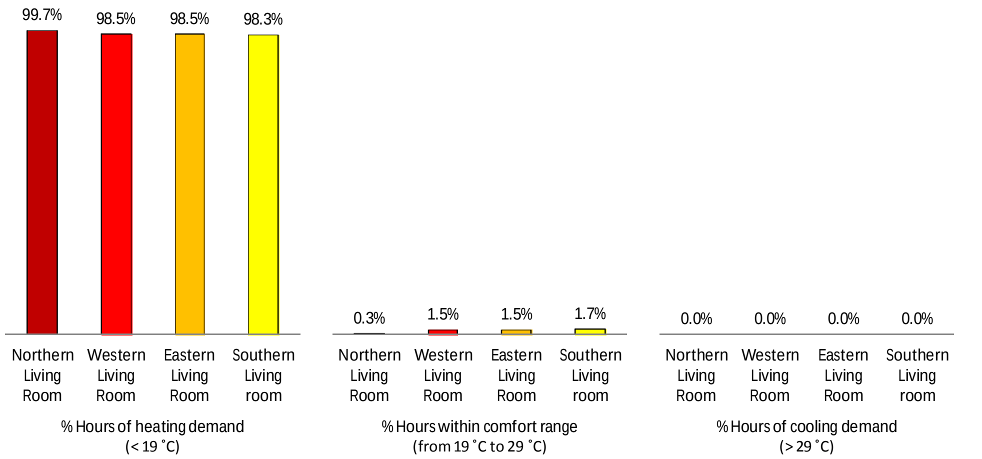

Figure 4.22 Impact of orientation on indoor thermal comfort using the best scenario of natural ventilation during the month of January

In February (Figure 4.23): Northern, Western, Eastern, Southern orientations achieved 5.5%, 8.3%, 8.5% and 10.9% respectively from total hours are within comfort range and 94.5%, 91.7%, 91.5% and 89.1% respectively from total hours are of heating demand.

In view of the said comparison, the highest effect of comfort was in the southern orientation and the lowest was in the northern orientation. This result is evenhanded and corroborates the fact that the southern orientation is the most exposed to the sunlight during the day time during the sunny winter of Egypt. However, the differences among all orientations weren't significantly high. Therefore, **the orientation has no considerable impact on indoor thermal comfort for the reference case during February.**

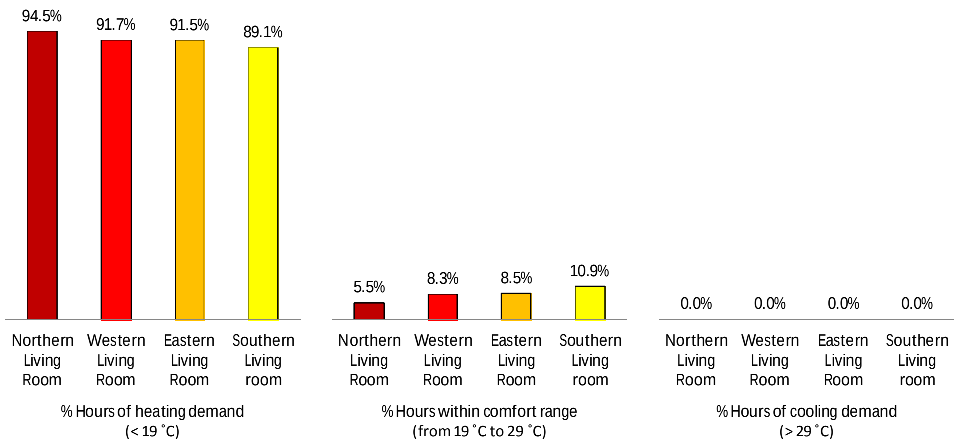

Figure 4.23 Impact of orientation on indoor thermal comfort using the best scenario of natural ventilation during the month of February

In March (Figure 4.24): Northern, Western, Eastern, Southern orientations achieved 32.3%, 38.0%, 37.0% and 44.4% respectively from total hours are within comfort range and 67.7%, 62.0%, 63.0% and 55.6% respectively from total hours are of heating demand.

Based on the above comparison, the highest impact of comfort was in the southern orientation and the lowest was in the northern orientation with difference between them of 12.1% from total hours of comfort range. This result is quite logical as the southern orientation is the most exposed to the sunlight during the day time in the mostly sunny winters of Egypt. Accordingly, **the orientation somehow affects the indoor thermal comfort of the reference case during March.**

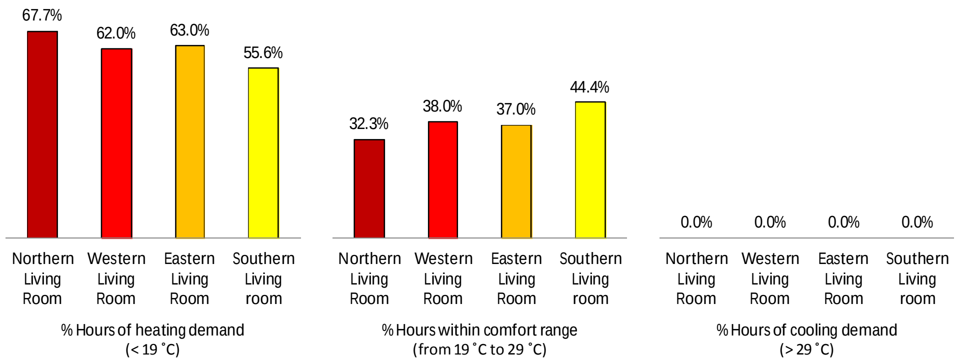

Figure 4.24 Impact of orientation on indoor thermal comfort using the best scenario of natural ventilation during the month of March

In November (Figure 4.25): Northern, Western, Eastern, Southern orientations achieved 84.2%, 85.7%, 85.7% and 92.2% respectively from total hours are within comfort range and 15.8%, 14.3%, 14.3% and 7.8% respectively from total hours are of heating demand.

Based on the above comparison, the highest result of comfort was in the southern orientation and the lowest was in the northern orientation with difference between them of 12.0% from total hours of comfort range. This result is quite reasonable and consistent with the fact that the southern orientation is the most exposed to the sunlight during the day time in the mostly sunny winters of Egypt. In view of that, **the orientation in some way affects the indoor thermal comfort of the reference case during the month of November.**

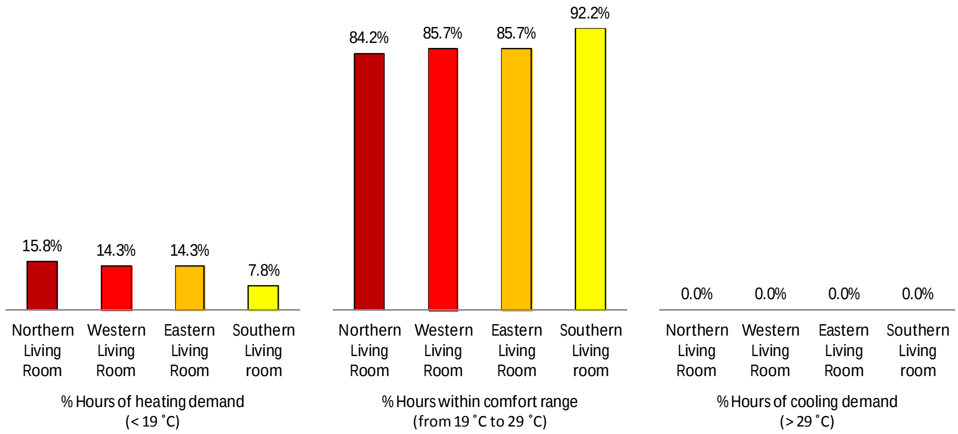

Figure 4.25 Impact of orientation on indoor thermal comfort using the best scenario of natural ventilation during the month of November

In December (Figure 4.26): Northern, Western, Eastern, Southern orientations achieved 14.0%, 14.8%, 15.1% and 21.1% respectively from total hours are within comfort range and 86.0%, 85.2%, 84.9% and 78.9% respectively from total hours are of heating demand.

On the basis of the above comparison, the highest effect of comfort was in the southern orientation and the lowest was in the Northern orientation with difference between them of 7.1% from total hours of comfort range. This result is quite realistic and consistent with the fact that the southern orientation is the most exposed to the sunlight during the day time in the mostly sunny winters of Egypt. As a result, **the orientation to some extent affects the indoor thermal comfort of the reference case during the month of December.**

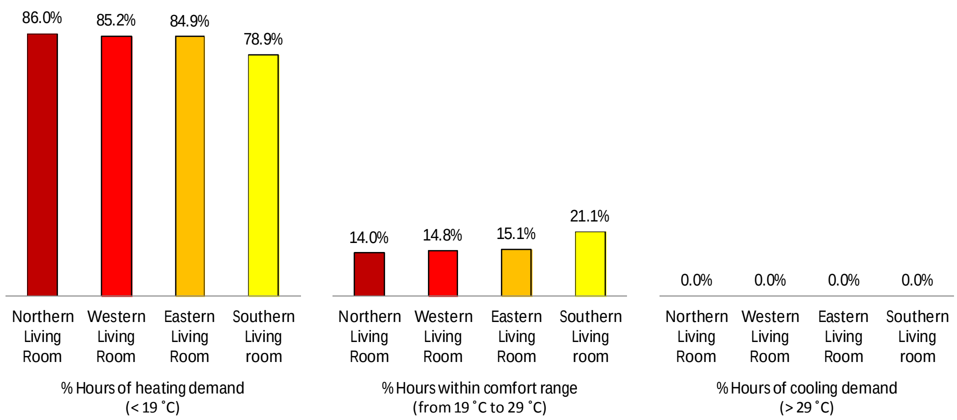

Figure 4.26 Impact of orientation on indoor thermal comfort using the best scenario of natural ventilation during the month of December

For the whole period of winter season (Figure 4.27): Northern, Western, Eastern, Southern orientations achieved 27.3%, 29.7%, 29.6% and 34.1% respectively from total hours are within comfort range and 72.7%, 70.3%, 70.4% and 65.9% respectively from total hours are of heating demand.

Based on the above comparison, the highest effect of comfort was in the southern orientation and the lowest was in the Northern orientation with difference between them of 6.8% from total hours of comfort range. This result is quite reasonable and consistent with the fact that the southern orientation is the most exposed to the sunlight during the day time in the mostly sunny winters of Egypt.

According to the above analysis, **whilst the orientation has no significant impact among Northern, Western and Eastern orientations, to some extent affects indoor thermal comfort in the Southern orientation during the winter period (Sedki, 2013, c).**

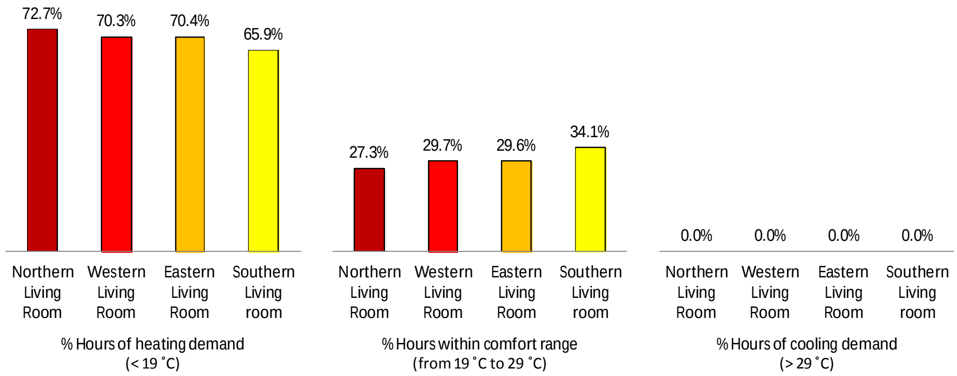

Figure 4.27 Impact of orientation on indoor thermal comfort using the best scenario of natural ventilation during the whole period of winter months

4.3.2 IMPACT OF ORIENTATION IN SUMMER PERIOD

Scenario 4.8 (cross night purge ventilation), as it was proved that is the best scenario in summer season, was compared among the different orientations; North, West, East and South during the summer months (June, July, August and September).

In June (Figure 4.28): Northern, Western, Eastern, Southern orientations achieved 74.6%, 74.7%, 72.2% and 75.3% respectively from total hours are within comfort range and 23.2%, 24.7%, 24.2% and 23.6% respectively from total hours are of cooling demand.

In view of the said comparison, the highest effect of comfort was in the southern orientation and the lowest was in the Eastern orientation. This is inconsistent with the assertion that the Northern orientation in Egypt is the most comfortable in summer as it is less exposed to sunlight. This happened probably because of the slight effect of heating demand; that is if added to the comfort hours, the Northern orientation would achieve the highest percentage of comfort. This observable fact is reinforced by the result that the Northern orientation achieved the lowest percentage of cooling demand. In generally, **the differences between the four orientations are very small thus confirming the insignificant impact of orientation on thermal comfort during the month of June.**

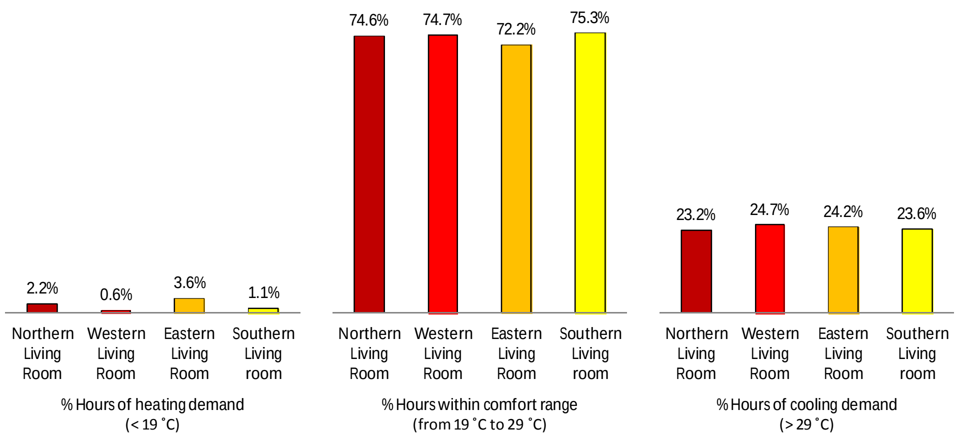

Figure 4.28 Impact of orientation on indoor thermal comfort using the best scenario of natural ventilation during the month of June

In July (Figure 4.29): Northern, Western, Eastern, Southern orientations achieved 62.2%, 60.8%, 61.7% and 61.4% respectively from total hours are within comfort range and 37.8%, 39.2%, 38.3% and 38.6% respectively from total hours are of cooling demand.

In view of the said comparison, the highest effect of comfort was in the Northern orientation and the lowest was in the Western orientation. This is consistent with the claim that the Northern orientation in Egypt is the most comfortable in summer but is contradicting with the claim that the Southern orientation is most uncomfortable. In generally, **the differences between the four orientations are very tiny thus confirming the not worth mentioning impact of orientation on thermal comfort during the month of July.**

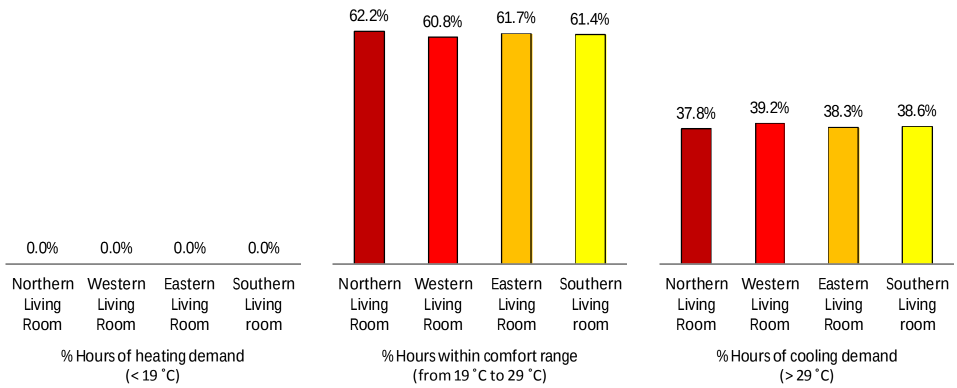

Figure 4.29 Impact of orientation on indoor thermal comfort using the best scenario of natural ventilation during the month of July

In August (Figure 4.30): Northern, Western, Eastern, Southern orientations achieved 64.4%, 62.2%, 62.4% and 62.1% respectively from total hours are within comfort range and 35.6%, 37.8%, 37.6% and 37.9% respectively from total hours are of cooling demand.

On basis of the above comparison, the highest effect of comfort was in the Northern orientation and the lowest was in the Sothern orientation. This is consistent with the claim that the Northern orientation in Egypt is the most comfortable in summer. In generally, **the differences between the four orientations are very miniature thus confirming the immaterial impact of orientation on thermal comfort during the month of August.**

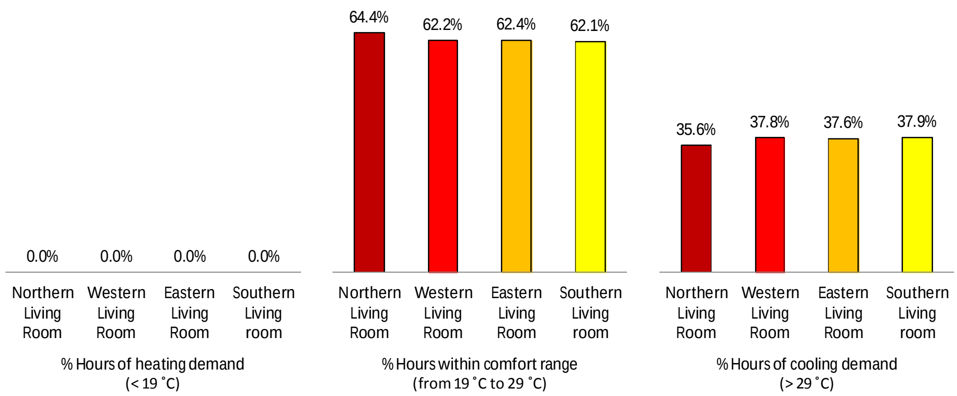

Figure 4.30 Impact of orientation on indoor thermal comfort using the best scenario of natural ventilation during the month of August

In September (Figure 4.31): Northern, Western, Eastern, Southern orientations achieved 84.4%, 76.3%, 79.4% and 76.4% respectively from total hours are within comfort range and 15.6%, 23.8%, 20.6% and 23.6% respectively from total hours are of cooling demand.

In the view of the above comparison, whilst the highest effect of comfort was in the Northern orientation, the lowest was in the Western orientation. This is in line with the claim that the Northern orientation in Egypt is the most comfortable in summer but is contradicting with the claim that the Southern orientation is most uncomfortable. In generally, **the differences between the four orientations are small thus confirming the inconsequential impact of orientation on thermal comfort during the month of September.**

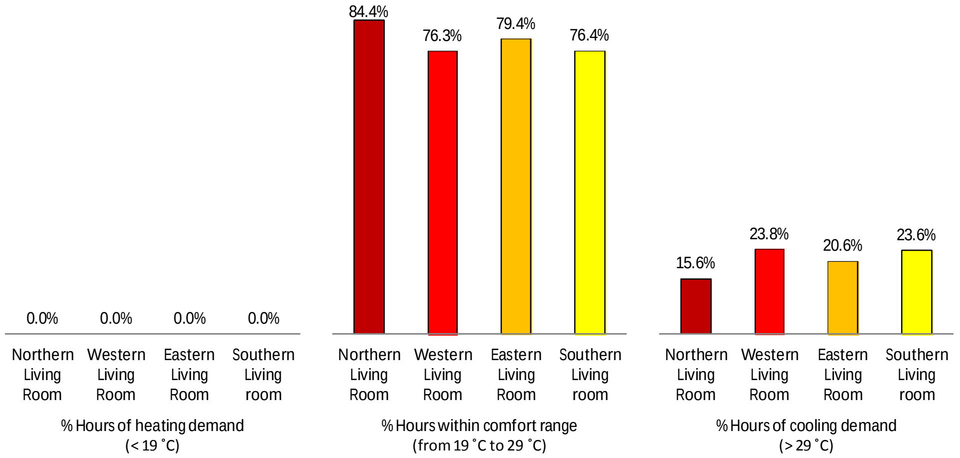

Figure 4.31 Impact of orientation on indoor thermal comfort using the best scenario of natural ventilation during the month of September

For the whole period of summer season (Figure 4.32): Northern, Western, Eastern, Southern orientations achieved 71.3%, 68.4%, 68.8% and 68.7% respectively from total hours are within comfort range and 28.2%, 31.5%, 30.3% and 31.0% respectively from total hours are of heating demand.

On the basis of the above comparison, the highest effect of comfort was in the Northern orientation and the lowest was in the Southern orientation with difference between them of 2.6% from total hours of comfort range. This result is corroborating with the prevailed claim that whilst the Northern orientation is the most comfortable in summer in Egyptian climate because it is the least exposed for the sunlight and it is facing the wind direction that is north-west most of the year in Egypt, the Southern orientation is the most exposed to the sunlight and opposite to the wind direction most of the year. **Generally, as the differences are small, the above comparison proves that there is no noteworthy impact of orientation on indoor thermal comfort during the summer period. (Sedki, 2013d)**

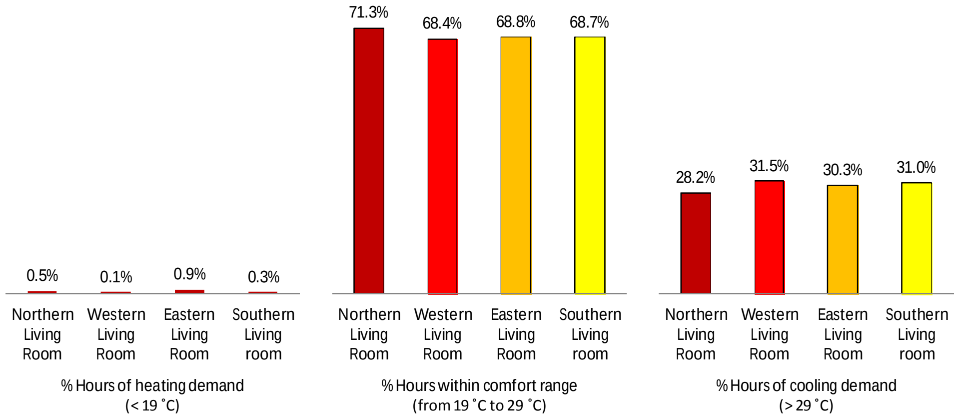

Figure 4.32 Impact of orientation on indoor thermal comfort using the best scenario of natural ventilation during the whole period of summer months

4.3.3 IMPACT OF ORIENTATION IN SPRING- AUTUMN PERIOD

Scenario 4.4 and scenario 4.5 of natural ventilation were proved together that they are the best scenarios in spring-autumn seasons. Thus, this section compares scenario 4.4 among the different orientations; North, West, East and South during the spring-autumn months (April, May and October).

In April (Figure 4.33): Northern, western, eastern, southern orientations achieved 23.5%, 23.5%, 23.6% and 21.7% respectively from total hours are of heating demand, 71.3%, 71.1%, 71.1% and 73.2% respectively from total hours are within comfort range and 5.3%, 5.4%, 5.3% and 5.1% respectively from total hours are of cooling demand.

Based on the above comparison, whilst the highest effect of comfort was in the southern orientation, the lowest was equally in the western and the eastern orientations. Furthermore, in April, the heating demand is significantly higher than the cooling demand; the southern orientation is the most comfortable because its exposition to solar radiation for longer time that reduces the heating demands hours. Noticeably, **the differences among the four orientations are very small thus confirming the not worth mentioning impact of orientation on thermal comfort during the month of April.**

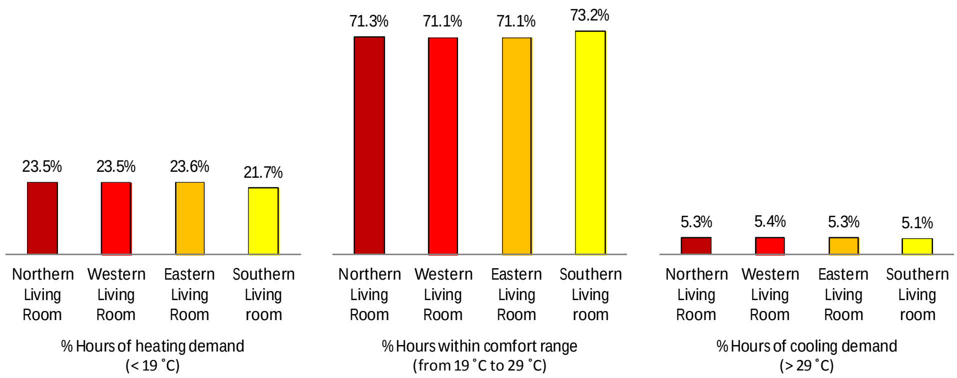

Figure 4.33 Impact of orientation on indoor thermal comfort using the best scenario of natural ventilation during the month of April

In May (Figure 4.34): Northern, western, eastern, southern orientations achieved 3.4%, 2.2%, 3.8% and 2.2% respectively from total hours are of heating demand, 75.9%, 77%, 75.7% and 76.7% respectively from total hours are within comfort range and 20.7%, 20.8%, 20.6% and 21.1% respectively from total hours are of cooling demand.

In view of the above comparison, whilst the highest effect of comfort was in the western orientation, the lowest was in the eastern orientations. Observably, **the differences among the four orientations are very small thus confirming the immaterial impact of orientation on thermal comfort during the month of April.**

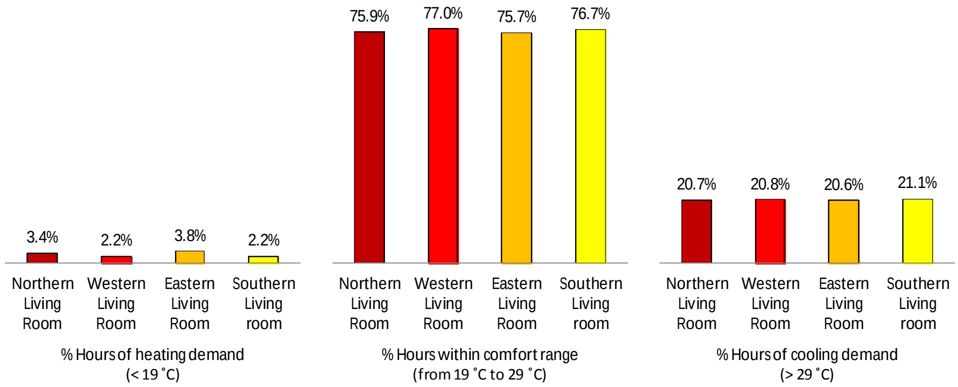

Figure 4.34 Impact of orientation on indoor thermal comfort using the best scenario of natural ventilation during the month of May

In October (Figure 4.35): this is the most comfortable month in all orientations. Northern, western, eastern, southern orientations achieved 97.3%, 94.8%, 95.7% and 92.9% respectively from total hours are within comfort range and 2.7%, 5.2%, 4.2% and 7.1% respectively from total hours are of cooling demand.

On basis of the above comparison, whilst the highest effect of comfort was in the northern orientation, the lowest in the southern orientation. this finding confirm that the northern orientation is the most comfortable during the months of cooling demand because it is less exposed to solar heat gain during daytime. Obviously, **the differences among the four orientations are very little thus confirming the insignificant impact of orientation on thermal comfort during the month of October.**

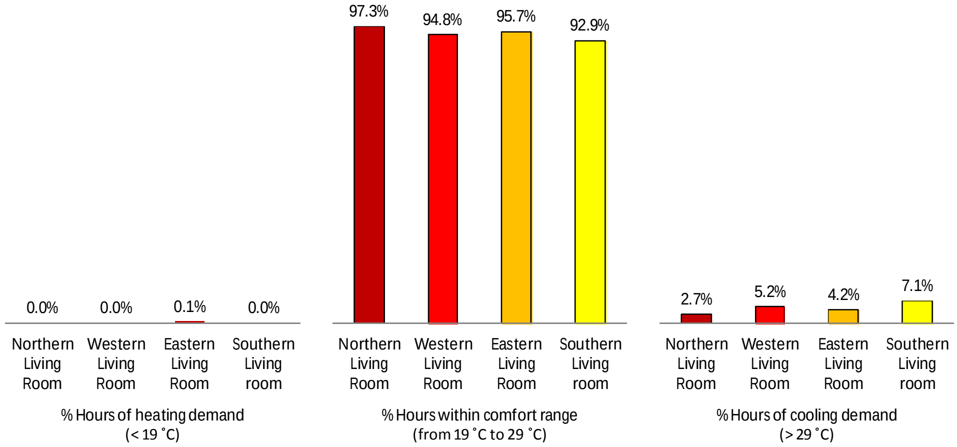

Figure 4.35 Impact of orientation on indoor thermal comfort using the best scenario of natural ventilation during the month of October

For the whole period of spring-autumn seasons (Figure 4.36): Northern, Western, Eastern, Southern orientations achieved 8.8%, 8.4%, 9.0% and 7.8% respectively from total hours are of heating demand, 81.6%, 81.1%, 80.9% and 81.0% respectively from total hours are within comfort range and 9.6%, 10.8%, 10.1% and 11.2% respectively from total hours are of heating demand.

Based on the above comparison, the highest effect of comfort was in the northern orientation and the lowest was in the eastern orientation with difference between them of 0.7% from total hours of comfort range. Accordingly, **the differences are very small, thus confirms the not worth mentioning impact of orientation on indoor thermal comfort during the spring-autumn period.**

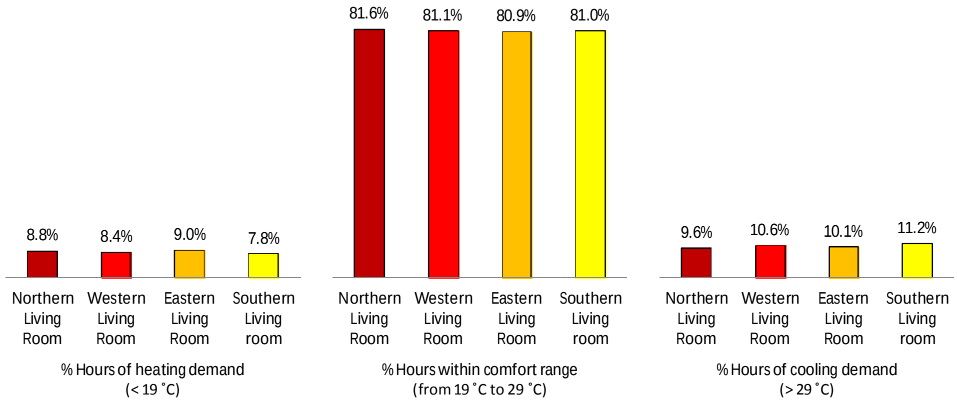

Figure 4.36 Impact of orientation on indoor thermal comfort using the best scenario of natural ventilation during the whole period of spring and autumn months

4.4 COMPARISON BETWEEN TYPICAL AND UPPER FLOOR

This section presents a comparison between a living room facing south in the typical floor and its counterpart in the upper floor. The south orientation was chosen as it is the most exposed to the solar heat gain; in addition, it is the one that was chosen in previous analysis to specify the best scenario of natural ventilation for winter, summer and spring-autumn periods. Furthermore, the effect of orientation mostly has no significant impact on indoor thermal comfort as it was investigated in the previous section.

4.5 COMPARISON BETWEEN TYPICAL AND UPPER FLOOR FOR A LIVING ROOM FACING SOUTH IN WINTER PERIOD

Scenario 4.2 (windows opened from 8:00 to 9:00 and from 17:00 to 18:00), as the preferred scenario of natural ventilation in winter, was compared between the typical and the upper floor for a living room facing south during the winter months (January, February, March, November and December).

In January (Figure 4.37): the typical and the upper floor achieved equal percentage of 98.3% from total hours are of heating demand and equal percentage of 98.3% from total hours is within comfort range. Accordingly, there is no any change in indoor thermal comfort between the typical and upper floor for living room facing south during the month of January.

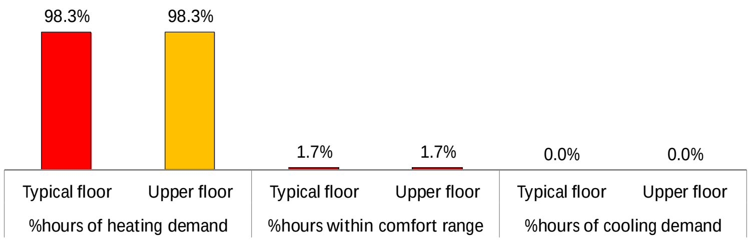

Figure 4.37 Comparison between typical and upper floor during the month of January

In February (Figure 4.38): the typical and the upper floor achieved 89.1% and 89.6% respectively from total hours are of heating demand and 10.9% and 10.4% from total hours are within comfort range.

On the basis of the above comparison, the typical floor achieved a slightly higher percentage of total hours within comfort range. This difference is very small that is only 0.5% from total hours. This happened probably because of the larger exposed area of the upper floor to the cold air during night. As a result, there is no significant difference in indoor thermal comfort between the typical and upper floor for living room facing south during the month of February.

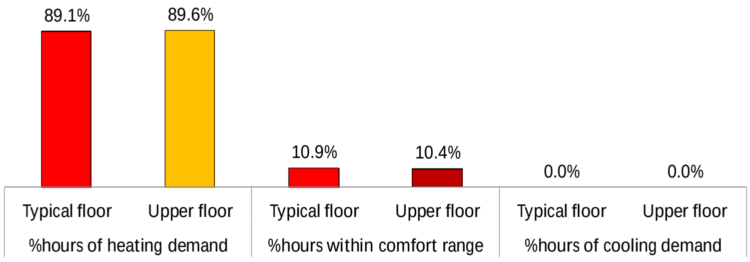

Figure 4.38 Comparison between typical and upper floor during the month of February

In March (Figure 4.39): the typical and the upper floor achieved 55.6% and 56.5% respectively from total hours are of heating demand and 44.4% and 43.5% from total hours are within comfort range.

In view of the above comparison, the typical floor achieved a slightly higher percentage of total hours within comfort range. This difference is relatively small that doesn’t exceed 0.9% from total hours. This might happened because of the larger exposed area of the upper floor to the cold air during night. However, this finding shows that there is inconsequential difference in indoor thermal comfort between the typical and upper floor for living room facing south during the month of March.

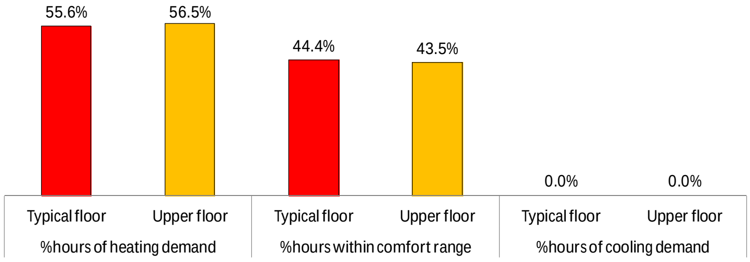

Figure 4.39 Comparison between typical and upper floor during the month of March

In November (Figure 4.40): the typical and the upper floor achieved 7.8% and 7.4% respectively from total hours are of heating demand and 92.2% and 92.6% from total hours are within comfort range.

On the basis of the above comparison, the upper floor achieved a slightly higher percentage of total hours within comfort range. This difference is quite very small that is equal to 0.4% from total hours. This happened probably because of the larger exposed area of the upper floor to the sunlight during daytime. However, this finding shows that there is no significant difference in indoor thermal comfort between the typical and upper floor for living room facing south during the month of November.

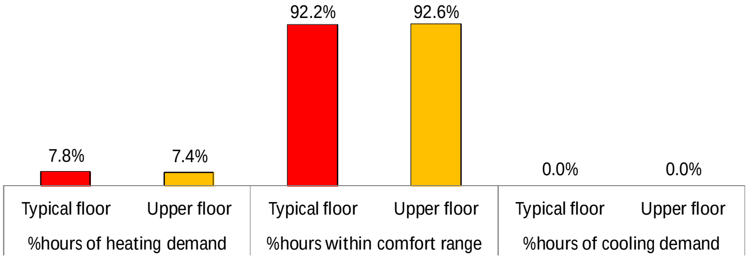

Figure 4.40 Comparison between typical and upper floor during the month of November

In December (Figure 4.41): the typical and the upper floor achieved 78.9% and 79.7% respectively from total hours are of heating demand and 21.1% and 20.3% from total hours are within comfort range.

On the basis of the above comparison, the typical floor achieved a slightly higher percentage of total hours within comfort range. This difference is relatively small that doesn't exceed 0.8% from total hours. This happened probably because of the larger exposed area of the upper floor to the cold air during the long night of December. Obviously, this finding shows that there is not worth mentioning difference in indoor thermal comfort between the typical and upper floor for living room facing south during the month of December.

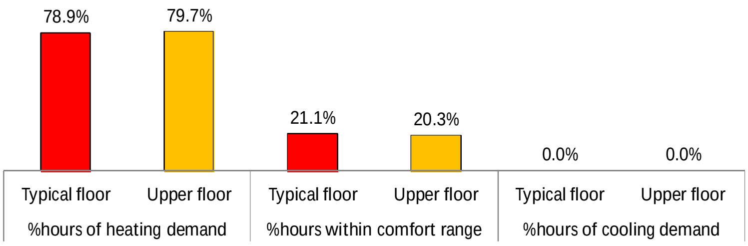

Figure 4.41 Comparison between typical and upper floor during the month of December

For the whole period of winter months (Figure 4.42): the typical and the upper floor achieved 65.9% and 66.2% respectively from total hours are of heating demand and 34.1% and 33.8% from total hours are within comfort range.

Based on the above comparison, the typical floor achieved a slightly higher percentage of total hours within comfort range. This difference is very small that equal to 0.3% from total hours. This happened probably because of the larger exposed area of the upper floor to the cold air during night. Accordingly, there is not worth mentioning difference in indoor thermal comfort between the typical and upper floor for living room facing south during the winter period.

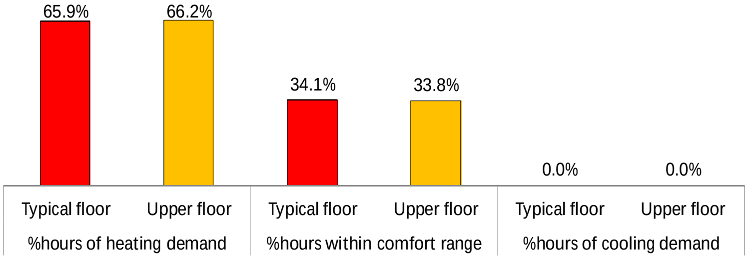

Figure 4.42 Comparison between typical and upper floor during the whole period of winter months

4.6 COMPARISON BETWEEN TYPICAL AND UPPER FLOOR FOR A LIVING ROOM FACING SOUTH IN SUMMER PERIOD

Scenario 4.8 (cross night purge ventilation – windows opened from sunset to sunrise), as proved that is the best scenario of natural ventilation in summer, was compared between the typical and the upper floor for a living room facing south during the summer months (June, July, August and September).

In June (Figure 4.43): the typical and the upper floor achieved 23.6% and 23.1% respectively from total hours are of cooling demand and 75.3% and 75.7% respectively from total hours are within comfort range.

In view of the above comparison, the upper floor achieved higher percentage of total hours within comfort range. However, the difference is very small that is equal to 0.2% from total hours. Hence, this finding indicates that there immaterial difference in indoor thermal comfort between the typical and upper floor for living room facing south during the month of June.

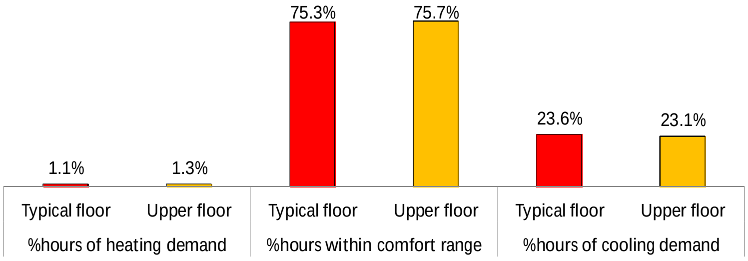

Figure 4.43 Comparison between typical and upper floor during the month of June

In July (Figure 4.44): the typical and the upper floor achieved 38.6% and 38.8% respectively from total hours are of cooling demand and 61.4% and 61.2% respectively from total hours are within comfort range.

In view of the above comparison, the typical floor achieved slightly higher percentage of total hours within comfort range. Obviously, the difference is very small that is equal to 0.2% from total hours. Apparently, this result confirms that there is no significant difference in indoor thermal comfort between the typical and upper floor for a living room facing south during the month of July.

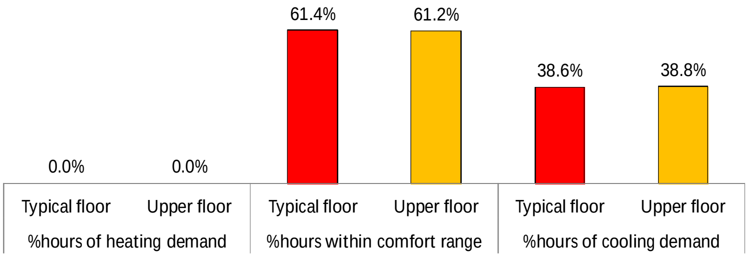

Figure 4.44 Comparison between typical and upper floor during the month of July

In August (Figure 4.45): the typical and the upper floor achieved 37.9% and 38.0% respectively from total hours are of cooling demand and 62.1% and 62.0% respectively from total hours are within comfort range.

According to the above comparison, the typical floor achieved slightly higher percentage of total hours within comfort range. However, the difference is very small that is equal to 0.1% from total hours. Clearly, this result confirms that there is no significant difference in indoor thermal comfort between the typical and upper floor for a living room facing south during the month of August.

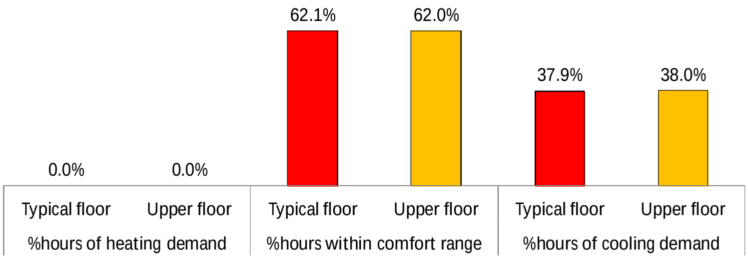

Figure 4.45 Comparison between typical and upper floor during the month of August

In September (Figure 4.46): the typical and the upper floor achieved 23.6% and 23.1% respectively from total hours are of cooling demand and 76.4% and 76.9% respectively from total hours are within comfort range.

According to the above comparison, the upper floor achieved faintly higher percentage of total hours within comfort range. However, the difference is very small that is equal to 0.3% from total hours. Clearly, this result confirms that there is no noteworthy difference in indoor thermal comfort between the typical and upper floor for a living room facing south during the month of September.

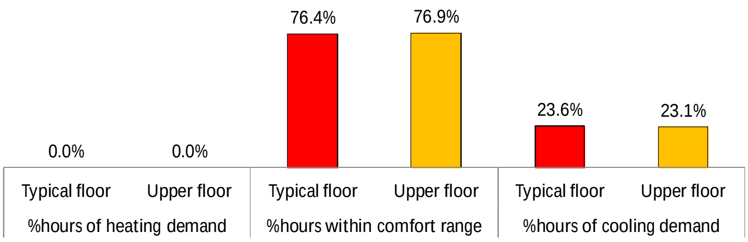

Figure 4.46 Comparison between typical and upper floor during the month of September

For the whole period of summer months (Figure 4.47): the typical and the upper floor achieved 31.0% and 30.9% respectively from total hours are of heating demand and 68.7% and 68.8% from total hours are within comfort range.

On the basis of the above comparison, the typical floor achieved a very slight higher percentage of total hours within comfort range. This difference is equal to 0.1% from total hours. So that, this result confirms there is not worth mentioning difference in indoor thermal comfort between the typical and upper floor for living room facing south during the winter period.

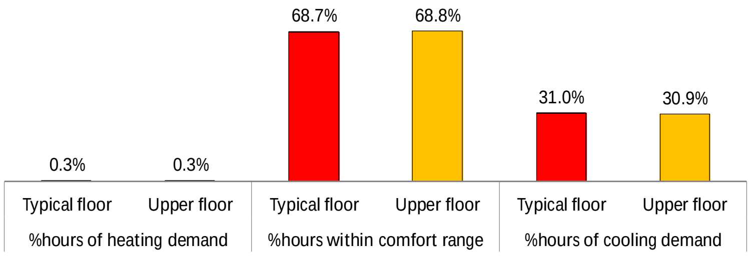

Figure 4.47 Comparison between typical and upper floor during the whole period of summer months

4.7 COMPARISON BETWEEN TYPICAL AND UPPER FLOOR FOR A LIVING ROOM FACING SOUTH IN SPRING-AUTUMN PERIOD

Scenarios 4.4 (Windows opened from 17:00 to 23:00) and scenario 4.5 (Windows opened from 8:00 to 14:00) were proved that they are equally the best scenarios of natural ventilation in spring-autumn period. So that, scenario 4.4 was compared between the typical and the upper floor for a living room facing south during the spring-autumn months (April, May and October).

In April (Figure 4.48): the typical and the upper floor achieved 21.7% and 21.3% respectively from total hours are of heating demand and 76.4% and 76.9% respectively from total hours are within comfort range and 5.1% and 5.3% respectively from total hours are of cooling demand.

According to the above comparison, **the upper floor achieved barely higher percentage of total hours within comfort range**. Clearly, the difference is very small that is equal to 0.3% from total hours. Accordingly, this result indicates that there is no noteworthy difference in indoor thermal comfort between the typical and upper floor for a living room facing south during the month of April.

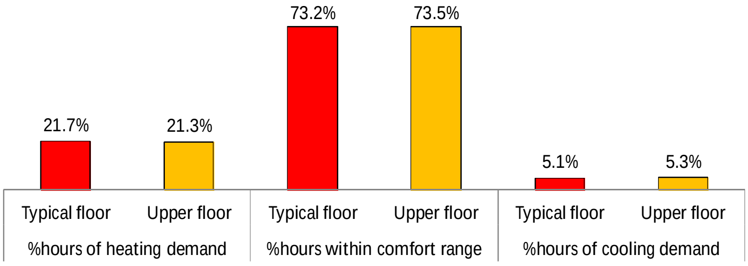

Figure 4.48 Comparison between typical and upper floor during the month of April

In May (Figure 4.49): the typical and the upper floor achieved 2.2% and 2.7% respectively from total hours are of heating demand and 76.7% and 76.3% respectively from total hours are within comfort range and 21.1% and 21.0% respectively from total hours are of cooling demand.

Based on the above comparison**, the typical floor achieved slightly higher percentage of total hours within comfort range.** Yet, the difference is very minute that is equal to 0.4% from total hours. Accordingly, this result indicates that there is no major difference in indoor thermal comfort between the typical and upper floor for a living room facing south during the month of May.

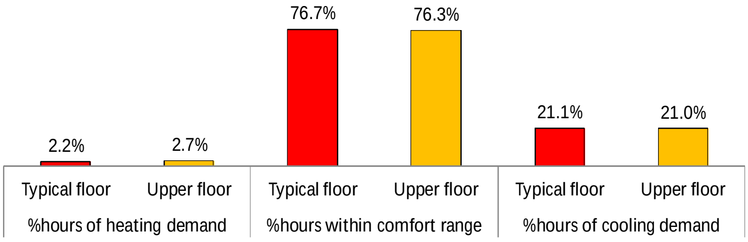

Figure 4.49 Comparison between typical and upper floor during the month of May

In October (Figure 4.50): the typical and the upper floor achieved an equal percentage of 0.0% from total hours are of heating demand and an equal percentage of 92.9% from total hours are within comfort range and an equal percentage of 7.1% from total hours are of cooling demand.

Based on the above comparison, **the typical and upper floors achieve the same percentages from total hours within comfort range**. Accordingly, there is no any difference in indoor thermal comfort between the typical and upper floor for a living room facing south during the month of October.

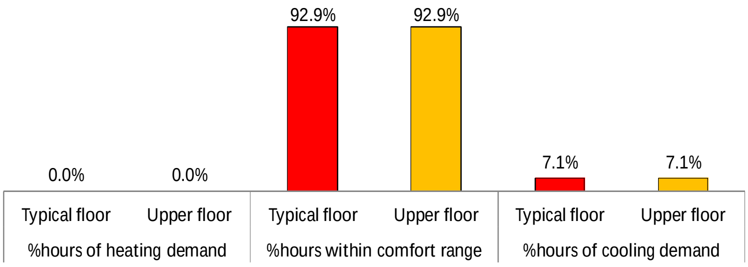

Figure 4.50 Comparison between typical and upper floor during the month of October

For the whole period of spring-autumn months (Figure 4.51): the typical and the upper floor achieved an equal percentage of 7.8% from total hours are of heating demand and an equal percentage of 81.0% from total hours are within comfort range and an equal percentage of 11.2% from total hours are of cooling demand. In view of the said comparison, **there is no any difference in indoor thermal comfort between the typical and upper floor for a living room facing south during spring-autumn period.**

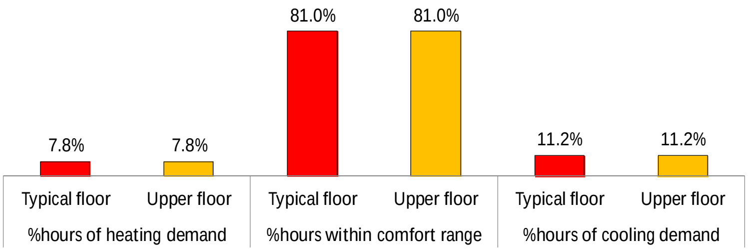

Figure 4.51 Comparison between typical and upper floor during the whole period of spring-autumn months

4.8 CONCLUSION

This chapter examined the effectiveness of different scenarios of natural ventilation on indoor thermal comfort for the case study. The scenarios were categorized into three; **the base case scenario, the based behavioral survey scenarios that was obtained from questionnaire analysis and the hypothetical suggested scenarios to improve the situation in summer**. The findings divulged that the best scenario in winter season was the base case scenario, but the based behavioral survey scenario in winter was recommended for the fresh air intake. This is because the indoor air quality would be negatively affected if the windows were closed for 24 hours in the base case scenario. In regards to the findings of summer season, the recommended scenario was the cross night purge ventilation as it gives the highest percentage of total hours within comfort range. Further, in relation to the spring-autumn period, the based behavioral survey scenarios 4.4 (windows opened from 17:00 to 23:00) and 4.5 (windows opened from 8:00 to 14:00) were recommended because they achieved the highest comfort.

The chapter discussed the impact of orientation on indoor thermal comfort, the results illuminated that the orientation has no significant effect on indoor thermal comfort in winter, summer and spring-autumn seasons. Furthermore, the investigations between typical and upper floor highlighted that there is no significant difference between them in terms of thermal comfort. The following chapter will address the effect of the combination of best scenarios of natural ventilation with insulation retrofitting technique to improve thermal comfort.

CHAPTER FIVE

5. TECHNICAL INTERVENTIONS

1. INTRODUCTION
2. BACKGROUND
3. HEAT TRANSFER MECHANISM THROUGH BUILDING ENVELOP
4. OVERVIEW ON INSULATION AND THERMAL MASS
5. INSULATING MATERIALS CHARACTERISTIC PROPERTIES
6. CRITERIA OF SELECTING A SUITABLE INSULAT
7. CASE STUDY TECHNICAL DETAILS BEFORE AND AFTER INTERVENTIONS
8. SIMULATION RESULTS FOR A LIVING ROOM FACING SOUTH
9. IMPACT OF ORIENTATION
10. DIFFERENCIES WITH UPPER FLOOR
11. CONCLUSION

5.0 INTRODUCTION

This chapter examines the effectiveness of the combination of natural ventilation and insulation retrofitting technique to improve indoor thermal comfort. Thus, the chapter tests the combination between the best scenario of natural ventilation according to the previously investigated scenarios in chapter Four and insulation technique and shows their effect on indoor thermal comfort comparing to the base case (see figure 5.1 for chapter 5 structure).

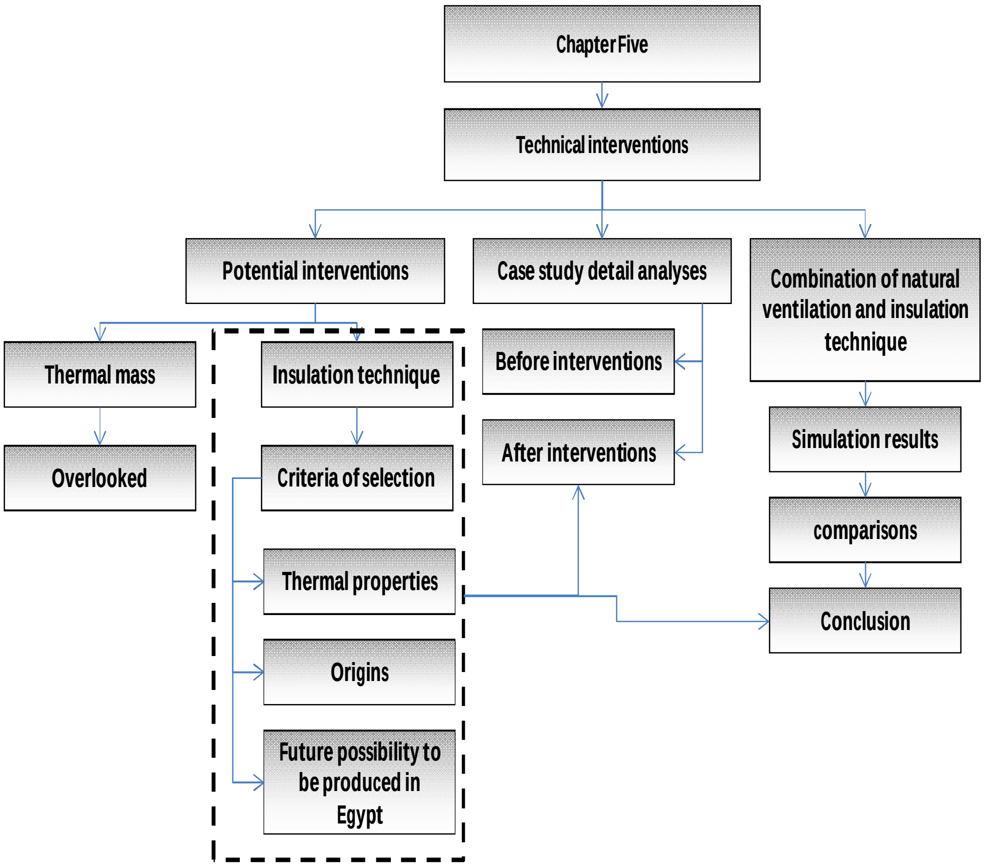

Figure 5.16 Chapter Five structure

5.1 BACKGROUND

It was not until the 1940s, after the growth of paper industry in the United States, insulation paper-based cellulose (originally manufactured as a sound deadener) was utilized as an effective dense building insulation material. However, the recent fiber technology applications had not been used in early cellulose insulation production. Later, after the World War II, the fiber glass became increasingly more popular than cellulose insulation. In 1970s, after the energy crisis, the demand on building insulation increased consequently and new materials were entered the market (Richard, 2000). In 1965, the regulation for building insulation and standards started to be issued to be applied on dwellings only in order to maintain minimum level for health and safety within buildings. These regulation were expanded later to include all buildings and, simultaneously, maintaining other aspects like conservation of fuel and power at a national level (Waters, 2003).

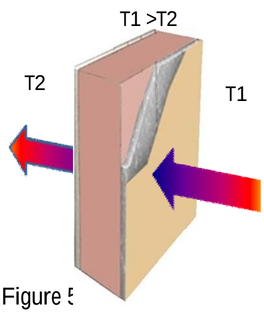

Figure 5
through a wall

5.2 HEAT TRANSFER MECHANISM THROUGH BUILDING ENVELOP

Technical interventions in this research focuses on building's envelop as it is considered the crossing point between the indoor and outdoor environment. In addition, Building's envelop acts as a thermal barrier and hence it is responsible significantly about regulating internal temperatures leading to a specific amount of energy have to be used to keep the building thermally comfortable indoors (Straube, 2005). Accordingly, minimizing heat transfer throughout the building envelope (figure 6.2) is essential for dipping the required energy for heating and/or cooling for indoor spaces. Whilst, the building envelope is able to reduce the required energy for heating in cold climates; it is able to reduce the amount of energy required for cooling in hot climates (Okba, 2005; H.a.B.N.R. - ECP 306, 2005).

Building gains sensible heat[3] (or lose sensible heat from) to the surrounding environment through three basic mechanisms (figure 5.3):

- Conduction: is the transfer of heat through a material by direct contact.
- Convection: is the transfer of heat through the movement of a liquid or gas with a change in their heat content.
- Radiation: is the transfer of heat by electromagnetic waves that travel though space. When these waves fall on a surface, they transfer the heat to this surface.

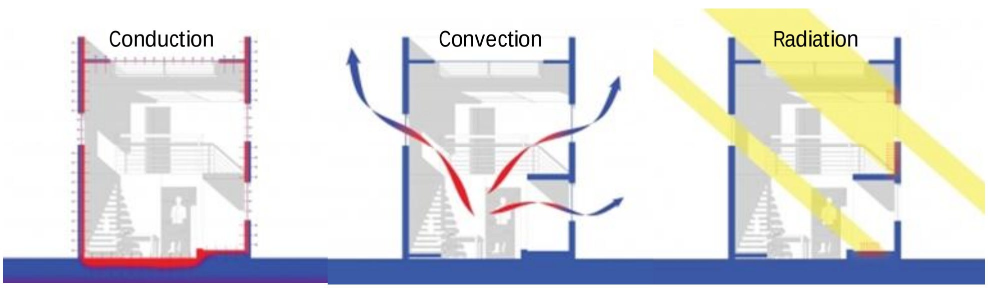

Figure 5.18 Heat transfer mechanisms (Autodesk sustainability workshop ,at: http://sustainabilityworkshop.autodesk.com/buildings/heat-energy-flows-buildings)

[3] Heat flows is two types; sensible heat and latent heat. Sensible heat flow results in a change in temperature. Latent heat flow results in a change in moisture content (often humidity of the air). Total heat flow is the sum of sensible and latent heat flows.

There are various technical interventions could be carried out in building envelop to protect the indoor environment from outdoors heat swings. Thermal insulation and thermal mass is one of the most common techniques to retard heat flow through the building envelop and consequently protect internal environment from heat swings (Thomas, 2006; Straube, 2006). The next subsection discusses role of using thermal mass and thermal insulation techniques in achieving indoor thermal comfort for the case study.

5.3 OVERVIEW ON INSULATION AND THERMAL MASS

Ventilation, insulation and thermal Mass are considered the most important **passive design principle keys for sustainable buildings**.

There are materials that are described as dense and heavy or massive such as earth, masonry, concrete and water that can absorb and store a large amount of heat over time. Because of this capacity they act as a heat source (warming their surroundings as they release the stored heat slowly again after their surroundings get colder) or as a heat sinks (drawing heat from and cooling their surroundings). Thus, they could be used as a heating source to warm up their surroundings or to cool them down (Thomas, 2006; Roaf, 2001).

Buildings in climates with large diurnal (day-night) temperature swings, like the high-elevation Southwest, offer a classic example of the time-lag effect of thermal mass. High thermal mass walls absorb intense daytime heat, keeping temperatures comfortable inside. During the cold night, the walls pour out their accumulated heat, keeping the inside warm. By morning the walls, if they are designed correctly, can again absorb the daytime heat.[4]

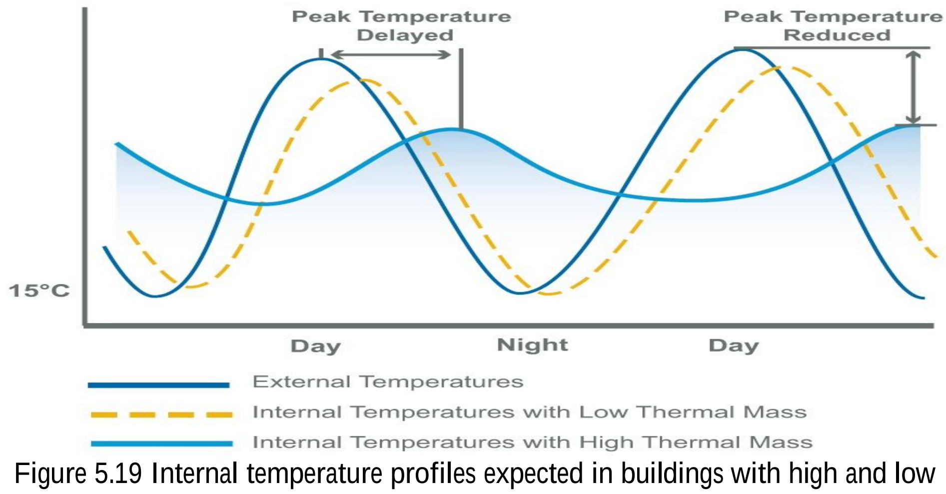

Figure 5.19 Internal temperature profiles expected in buildings with high and low levels of thermal mass[5]

[4] Available at (http://www.buildinggreen.com/auth/article.cfm/2007/10/30/Thermal-Mass-What-It-Is-and-When-It-Improves-Comfort/), accessed on 01/02/2014

[5] Available at (http://www.new4old.eu/guidelines/D3_Part2_H2.html), accessed on 01/02/2014

The mud brick high thermal mass walls were early used in Egypt by Hassan Fathy (see figure 5.4 below) to avoid solar radiation from piercing into the interior spaces. The large temperature diurnal range makes thermal mass outfit for the climate (Fathy, 1986). However, **Thermal mass is not a substitute for insulation,** but because Hassan Fathy used such thick walls, the heat does not reach the inner surface of the wall, when the temperature drops at night, the cool breezes can then draw the heat out into the night sky.

Additionally, **A high mass well insulated building is less likely to overheat in summer than a low mass one** because materials with high thermal mass have long time lag and moderating effects to temperature swings.(Ogoli, 2003; Roaf, 2001). Moreover, Roaf, (2001) indicated that natural ventilation and insulation must be considered together to improve thermal comfort of the indoor spaces.

From literature in chapter two and chapter four (section 4.1), Gado (2000) indicated that **the use of external insulation for external walls with light colors on external surfaces** and wide-ranging shading devices **give the best results in terms of thermal comfort and energy efficiency all over Egyptian climate** conditions. In addition, El-Hefnawi (2000) **recommended using high thermal mass with external wall insulation**. Further, (Givoni, 1998) indicated that nocturnal ventilative cooling becomes more efficient with high thermal mass buildings in hot-dry climates. Moreover, Attia (2010) indicated that the **retrofitting strategy of the use of external insulation and installing window shading devices together can achieved the largest energy saving and thermal comfort** for the investigated case study in Ain El-Sokhna in Egypt.

Figure 5.20 one of Hassan Fathy's high thermal mass mud brick buildings at New Gourna, Egypt

In the context of this study, **the application of thermal mass was overlooked in that it will require constructing a new external wall which needs a specific skeleton structure** to build upon. In addition, carrying out that task is costly. In consequence, **the research in hand focused on the application of insulation as the readily available and easier technique** to examine whether its application can ameliorate the indoor thermal comfort or otherwise. Further, it was proved in chapter Four that natural ventilation can assist in improving thermal comfort, **the study combined the recommended scenarios of natural ventilation in winter, summer and spring-autumn (see section 4.2.1) with the external insulation technique.**

The following sections provide an overview of the most important characteristic properties that influence insulation materials performance and its classification according to their origins with a special concern for the ecologic materials that have natural organic origins.

5.4 INSULATING MATERIALS CHARACTERISTIC PROPERTIES

The most important characteristics that influence insulant's performance are thermal conductivity, thermal resistance, transmittance, specific heat capacity and density.

Thermal conductivity (k or λ) is defined as the amount of heat transfer per unit of thickness for a given temperature differences (Thomas, 2006). Technically, it is a measure of the rate of heat conduction through 1 m3 of a material with a 1°C temperature difference across the two opposite faces. The lower conductivity value leads to more efficiency for the insulation material (Smith, 2004).

The high thermal conductivity for specific material causes a higher rate of heat flow through it than the low thermal conductivity. Hence, materials of high thermal conductivity are commonly used as a heat sink and **materials of low thermal conductivity are used as thermal insulation. Further, the low thermal conductivity for an insulation material leads to less heat flow through it and better performance to protect the building from outside heat swings.** Thermal conductivity is measured by W/mk. According to DIN 4108 (2001), materials with thermal conductivity in the range 0.030 to 0.050 W/mk can classified as good insulants, whilst, materials with conductivity <0.030 W/mk can be regarded as very good.

Thermal resistance (R) is a value that indicates how much the material can resist the heat flow. For a specific thickness of a material (d) the relationship between R and thermal conductivity K in the following equation:

$$R = d/\lambda \ (m^2K/W) \quad (5.1)$$

The total thermal resistance of a wall that includes different material layers is:

$$R\ (total) = R_1 + R_2 + R_3 + \ldots\ldots\ldots + R_n \quad (5.2)$$

Thermal transmittance (U-Value) is the reciprocal of the thermal resistance:

$$U = 1/R \ (W/m^2K) \quad (5.3)$$

The U-Value specifies the quantity of the heat exchange per second between a surface of 1 m2 and the surrounding air during constant heating with a temperature difference of 1 K between the surface and the air**. Generally, lower the U-value of an element of a building's fabric, the more slowly heat is able to transmit through it, and so the better it performs as an insulator, consequently,** the less energy is required to maintain comfortable conditions inside the building.

Specific heat capacity (C): It describes the specific ability of a material to absorb heat according to its mass. Thus, it is the quantity of heat (Q) required to raise the temperature of a material mass (m) by 1 K (temperature difference ΔT)

$$C = Q / m \Delta T \text{ (J/kgK)} \qquad (5.4)$$

Density: It refers to is a quantitative expression that explains the amount of mass contained per unit volume (kg/m^3). Commonly, the most preferable density range for an insulation material is between 20 and 100 kg/m^3. at density value less than 20 kg/m^3, the heat transmittance by radiation increases and at density value higher than 100 kg/m^3, the heat transmittance by conduction increases (Pfundstein, 2007).

5.5 CRITERIA OF SELECTING A SUITABLE INSULAT

There are a wide variety of insulation products available on the market. Studying technically the pros and cons of all different materials to be able to compare them together is beyond the scope of this research. However, the criteria of selecting a specific insulation material for the in hand research project is depending upon three main key issues that should be considered;

- Thermal conductivity;
- The ecological aspect of this material (materials derived from organic or recycled sources and which do not use high levels of energy during production) and;
- Availability to be produced in Egypt in Future.
- Availability to find in a cheaper cost.

According to Smith (2004) there are three main categories of insulation materials:

- Inorganic, mineral based (come in two forms, fiber or cellular structure);
- Organic synthetic, derived from oil and;
- Natural organic, derived from animals and plants.

The mineral based insulation materials produced in two forms; fiber (such as Rock wool and Glass wool) and cellular structures (such as Cellular glass and vermiculite). In addition, the organic synthetic insulation materials limited to cellular structures such as EPS (expanded polystyrene: rigid flame retardant cellular), XPS (extrude polystyrene: closed cell insulant water and vapour tight), RIP (polyisocyanurate: Cellular plastic foam) and phenolic (rigid cellular foam). Further, natural organic insulants derived from plants and animals (such as cellulose, sheep’s wool, straw and hemp).

This research project focuses on the application of natural organic materials to improve thermal comfort and energy efficiency in the case study buildings for the following reasons:

1. Natural insulation materials do not underperform when compared to manmade synthetic insulation. Further, they are renewable and sustainable materials which meet key sustainability criteria.

2. The CO2 footprint from natural insulation is considerably less than other forms of insulation materials. Furthermore, many natural insulation materials such as hemp or wood fiber not only reduce CO2 in buildings, but also may suck up CO2 while being harvested. Indeed, it has been demonstrated at least 13kg of CO2 is absorbed when producing one cubic meter of Thermo Hemp natural insulation.

3. The specific heat capacity for a large number of natural fiber insulation materials exceeds 2000 J/Kg.K, while, for mineral wool is only 800 J/Kg.K and for plastic insulations is 1400 J/Kg.K. when taking into account the high density of the majority of natural insulation materials, then, the thermal mass of natural insulants such as wood fiber, cellulose and hemp is higher than other forms of insulants with the same R- value.

4. There is a future possibility to produce natural insulants in Egypt as it has a large amount of agricultural waste (El-Shimi, 2005). As a consequent, this availability of raw materials on site can give an economical sense in terms of reducing the cost of insulants if they are locally-manufactured. The government can resort to Public-Private Partnership (PPP) to task the existing private construction firms to use agricultural residues to manufacture natural-based insulation materials. In so doing, the government can also give tax incentives to these manufacturing companies in order to encourage them to engage in the production of these insulation materials.

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Table 5.1 classification of available insulation materials

	material	thickness (mm)	Density (Kg/m3)	Thermal conductivity (W/mK)	R (m2K/W)	U-Value	Environmental characteristics
Plants origin	Insulating mat from jute fiber	2 - 5 - 10	100	0.05	0.4 - 1 - 2	2.5 - 1 - 0.5	reusable
	Insulating panels of linen fiber	variable from 2 to 10	30 - 60	0.04	0.5 to 2.5	2 to 0.4	biodegradable
	Insulating pannels of Mais fiber	**variale from 20 to 60**	**20 - 40**	**0.036**	**0.55 to 1.7**	**1.82 to 0.58**	**recyclable**
	Insulating panels of march reeds	20 and 50	190	0.056	0.36 and 0.89	2.77 - 1.12	biodegradable - recyclable
	Insulating panels of coconut fibers	variable from 10 to 40	85/125	0.043	0.23 to 0.93	4.34 to 1.07	biodegradable - recyclable

	Insulating panels of compressed wood fiber	variable (from 40 to 200)	50	0.038	1.05 to 5.3	0.95 to 0.18	biodegradable - recycled - preconsumed
	Insulating panels of mineralized wood wool	variable (from 25 to 50)	400	0.075	0.33 to 0.67	3.03 to 1.49	biodegradable - recyclable
	Insulating panels of kenaf and cannabis fibers	30	30-50	0.037	0.81	1.23	recyclable
	Insulating panels of cannabis fibers	45 - 80 - 100	30-37	0.042	1.07 - 1.9 - 2.8	0.93 - 0.53 - 0.36	recyclable
	Insulation panels of blond cork	variable (from 10 to 50)	85/125	0.04	0.25 to 1.25	4 to 0.8	biodegradable - recyclable
	Insulation panels of cellulose fibers	flakes in bulk packs	-	0.39			ricycled
Animals origin	insulation mat of sheep's wool	variable (from 3 to 24)	17.9	0.037	0.08 to 0.65	12.5 to 1.5	biodegradable - recyclable
	insulating mat made of natural animals feathers	40 - 80 - 110	25 - 35	0.04	1 - 2 - 2.75	1- 0.5 - 0.36	biodegradable - recyclable
mineral origin	Insulating panels of expanded glass granulate	plates 40 to 180/panels 40 to 140	120	0.04	1 to 4.5/ 1 to 3.5	1 to 0.22/ 1 to 0.29	ricycled - postconsumed
	Insulating panels of fiberglass	variable (from 40 to 80)	-	0.032	1.25 to 2.5	0.8 to 0.4	-
	Insulating pannels of cellular glass	variable (from 13 to 40)	170	0.048	0.27 to 0.83	3.7 to 1.2	-
	Insulating material of granulated expanded clay	in bulks	380	0.09			-
	natural lime cement	in bulks	400	0.085			-
	Rock wool fiber	100	40 to 180	0.037	2.7	0.37	-
	Expanded perlite	grains from 1 to 5 mm	100	0.042/.053			recyclable
	Pumice	sand and grit	500 - 600	0.1			recyclable
	Grains of recycled glass	Grains with variable diameter	350-2000	0.098 - 0.8			ricycled - postconsumed
	Insulation material of exfoliated vermiculite	grains	2.6	0.049 - 0.072			recyclable

Legend | Preferred materials | Chosen material | Excluded materials

Since previous studies have proved that stalks of maize are considered the second highest agricultural residues in Egypt (El-Shimi, 2005; El-Mashad, 2003), maize was selected as an insulation material for the case study. Although table (5.2) below shows that the by-product of wheat constitutes the largest proportion of total wastes of agricultural products in Egypt, its application to this study was overlooked in the sense that there is no evidence - to the best of the researcher's knowledge - that it is produced as an insulation materials for buildings yet.

Table 5.2 Agricultural residues in Egypt (Hamdy, 1998)

Crop	Total wastes (1000 ton)
Wheat	5998
Maize	**3814**
Sugar Cane	3634
Rice, Paddy	2724
Tomatoes	1441
Seed Cotton	835
Broad Beans, Dry	467
Sugar Beets	440
Potatoes	380

From the above literature about available insulation materials and agricultural residues in Egypt, it is now obvious that choosing the maize fiber panels to be realistically employed on the research case study is reasonable. In this context, this insulation material will be utilized in the retrofitting process in order to improve the thermal behaviour of the building envelop in terms of reducing its overall thermal conductivity and U-value. Accordingly, this may lead to achieving the research goal of enhancing indoor thermal comfort. Moreover, applying the mentioned material in a large scale in this project could confer the chance to produce it in Egypt in a cheaper price exploiting the large amount of agricultural wastes that are available on site. The following section will analyze the status-quo of the case study building fabric to better understand the thermal behaviour and the quality of building envelop material layers, more so, it illustrates, within architectural details, the critical thermal points that will be discussed further after applying insulation retrofitting strategy.

5.6 CASE STUDY TECHNICAL DETAILS BEFORE AND AFTER INTERVENTIONS

The case study is represented by one of the prototypical buildings that are spread on the site (see case study description in chapter one). This section explains in details the building envelope in terms of thermal behavior before and adding the insulation technique used in this research. As it is mentioned previously in chapter one, the case study is composed of six floor building. Further, each floor includes six apartments consists of one living, two bedrooms, one kitchen and one bathroom for each. Figures (5.6), (5.7) and (5.8) show the typical floor plan and the cross sections that consequently show the critical thermal points of the building envelop that will be presented before and after the interventions.

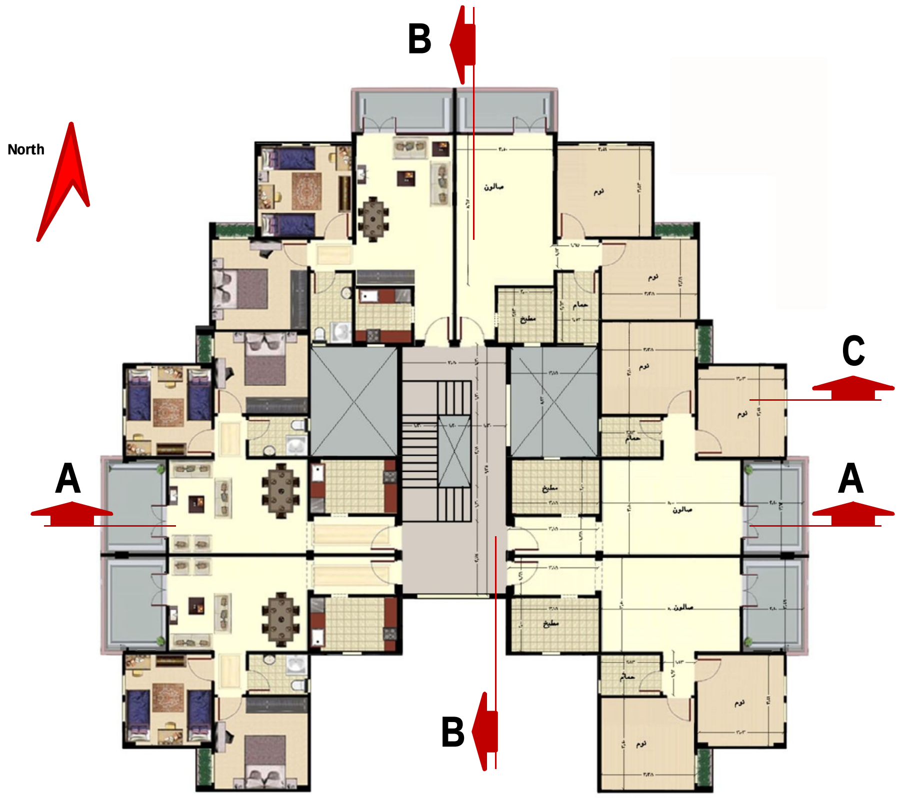

Figure 5.6 case study's typical floor plan

Figure 5.7 case study's typical floor plan with external insulation

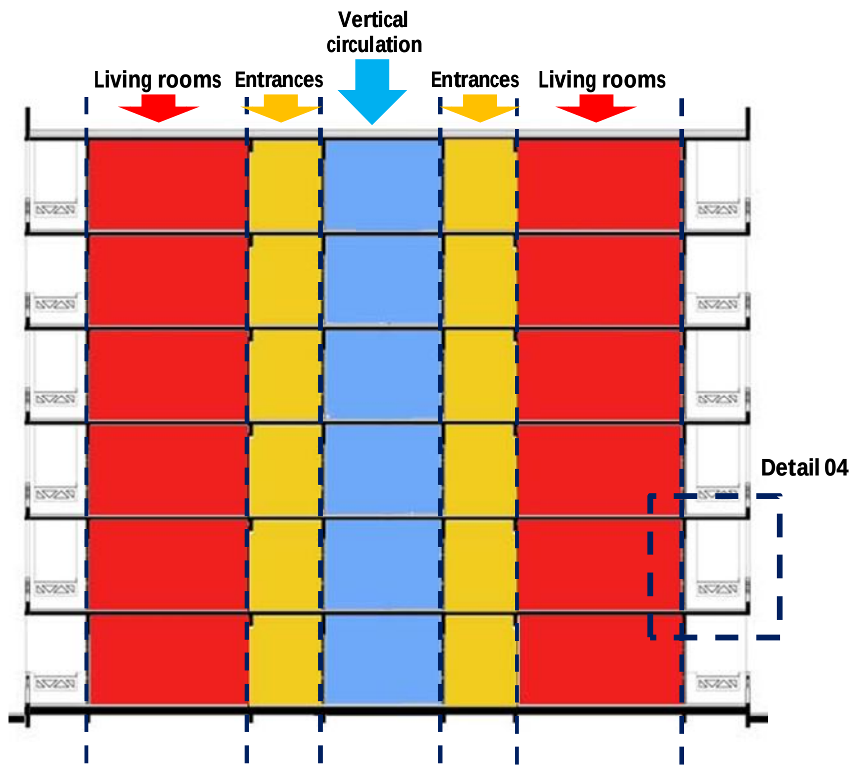

Figure 5.21 Section A-A

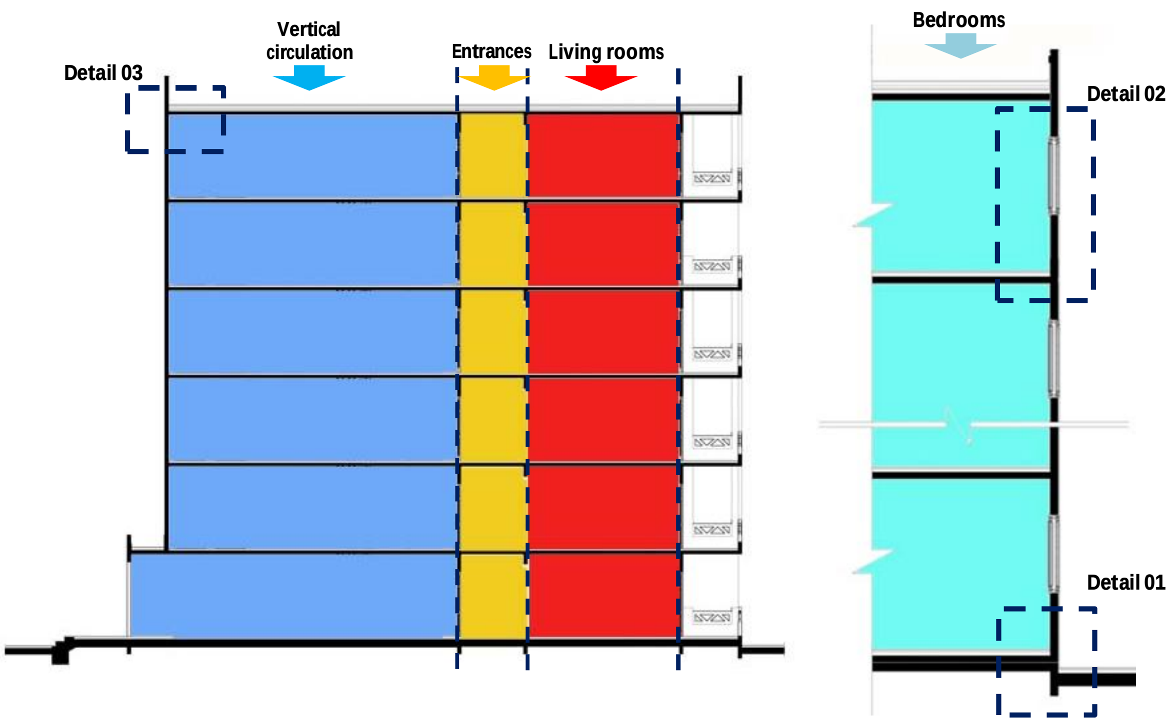

Figure 5.22 Section B-B (on the right) and wall section C (on the left)

5.6.1 BEFORE INTERVENTIONS (STATUS-QUO)

The following details (figures 5.10, 5.11, 5.12, 5.13, 5.14 and 5.15) show the critical points in the building envelop before adding insulation material (status-quo).

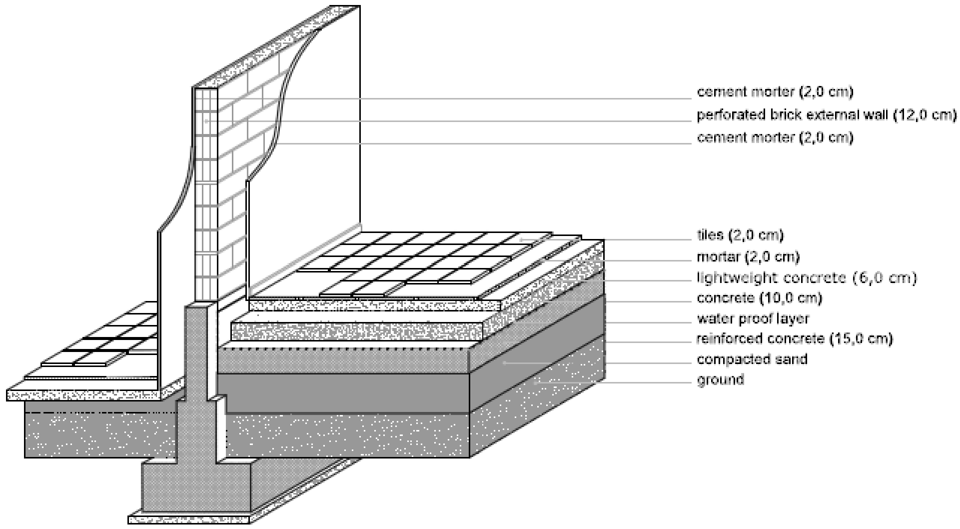

Figure 5.23 Detail 01 - wall ground connection

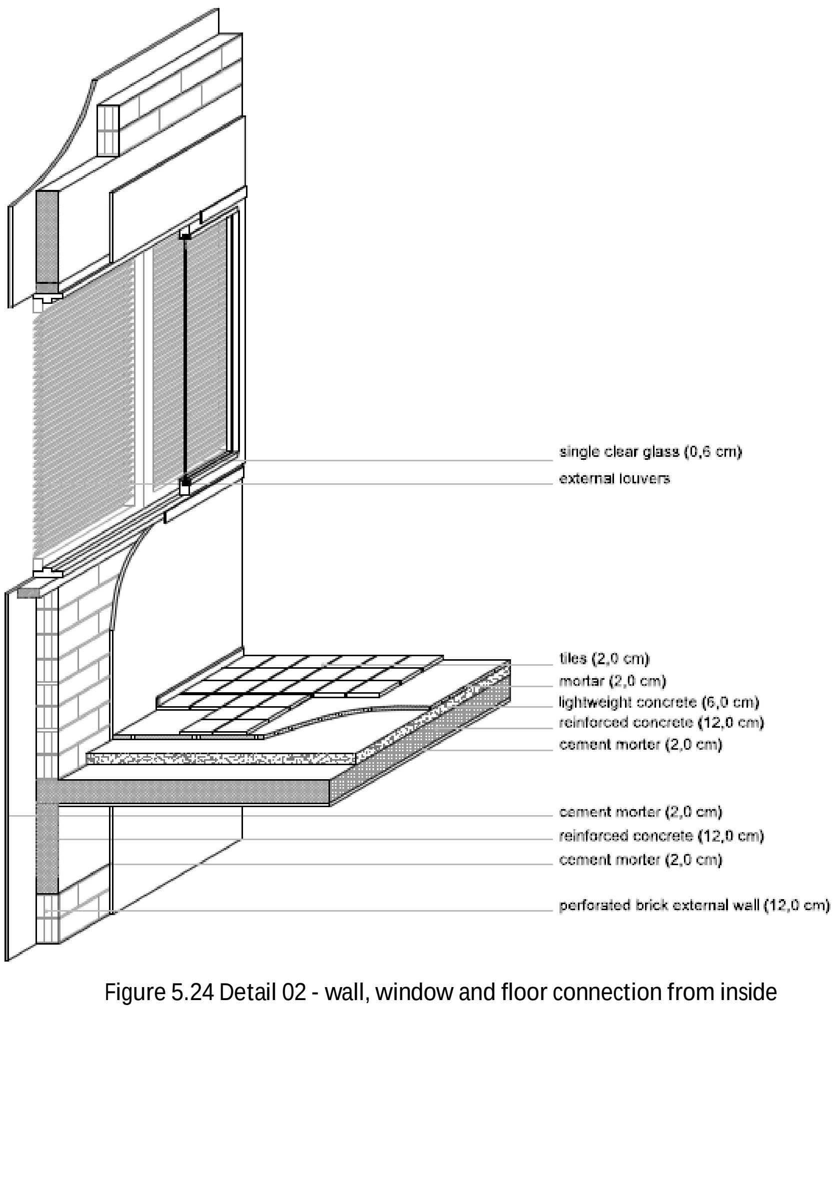

Figure 5.24 Detail 02 - wall, window and floor connection from inside

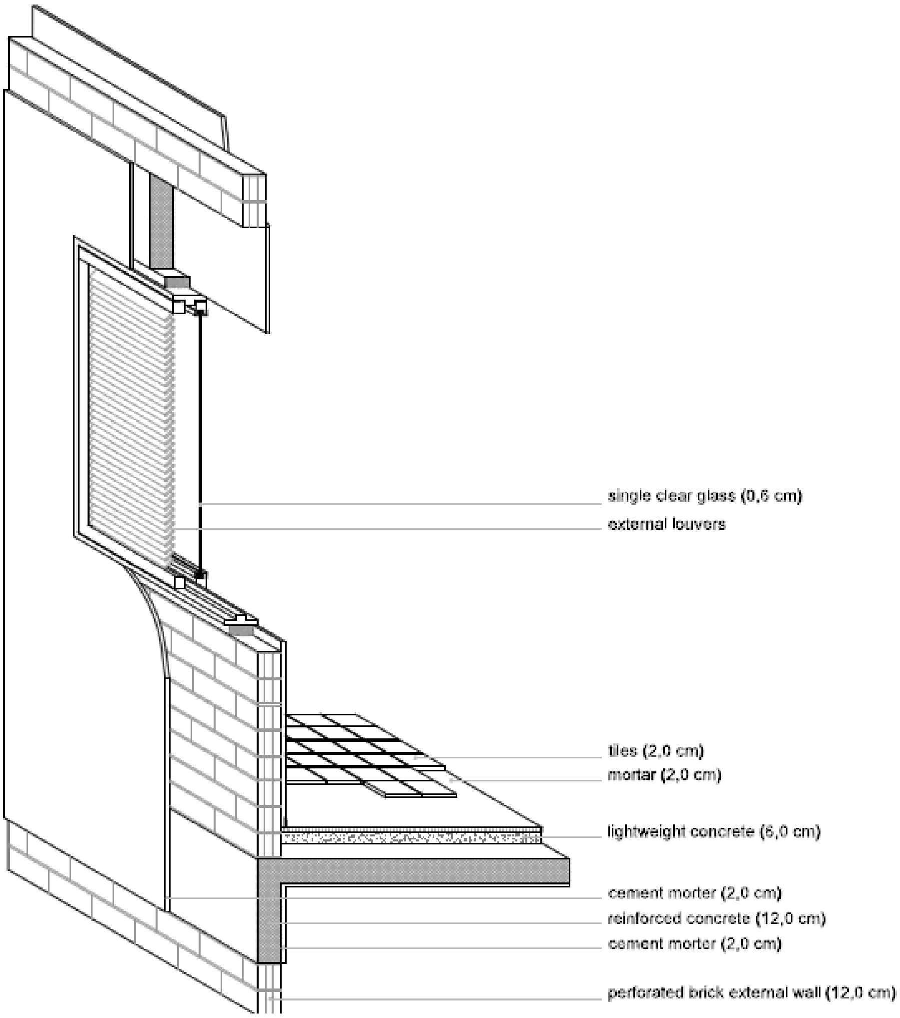

Figure 5.12 Detail 02 - wall, window and floor connection from outside

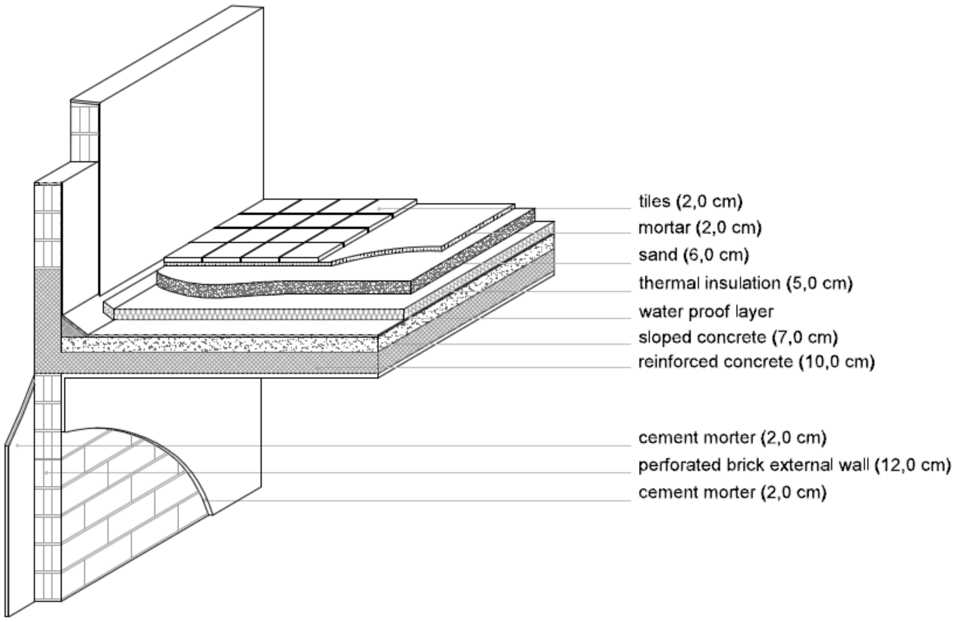

Figure 5.13 Detail 03 - roof wall connection from inside

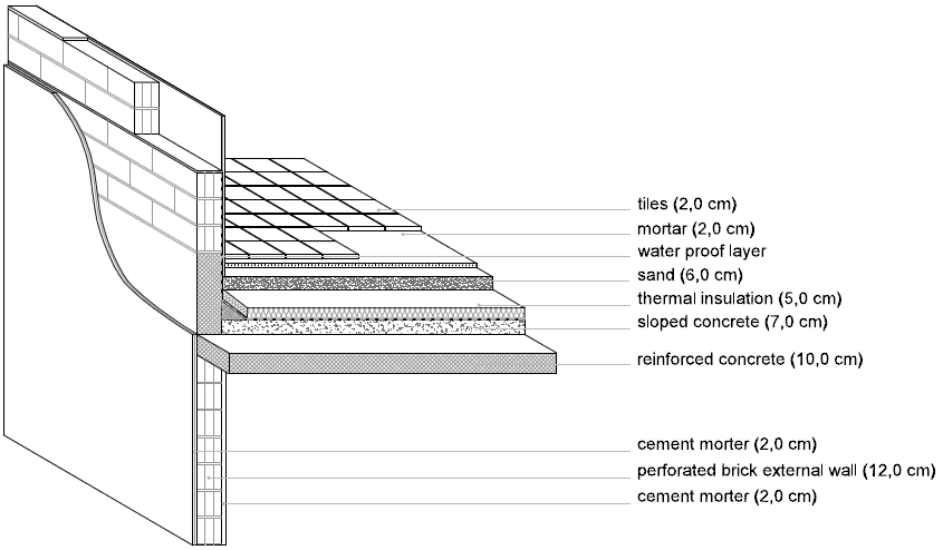

Figure 5.14 Detail 03 - roof wall connection from outside

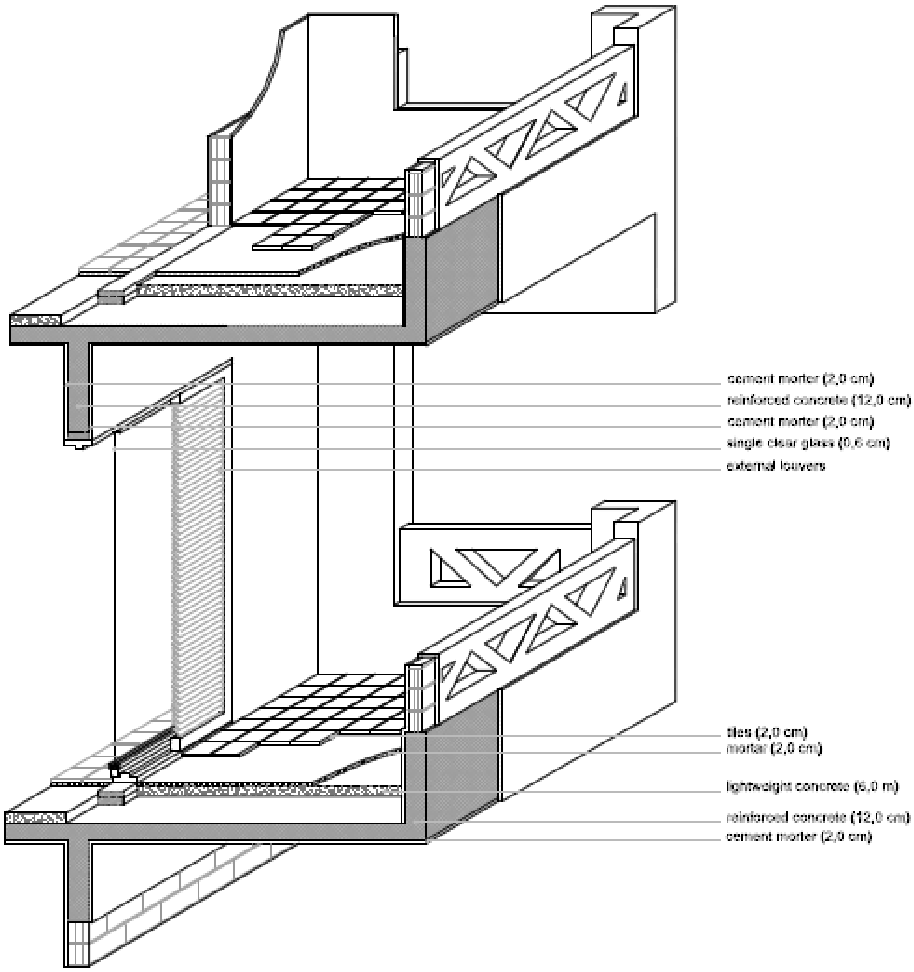

Figure 5.15 Detail 04 - balcony detail

Tables (5.3) and (5.4) and shows the thermal properties for the external wall and roof layers, furthermore, figures (5.16), (5.17) and (5.18) shows the predicted thermal behavior of the wall and roof during the lowest recorded outdoor temperature in winter and the highest recorded outdoor temperature in summer. According to IES<VE> data base for Cairo weather profile (the hourly average temperatures during 28 years), the lowest recorded average temperature was 7 °C, average external relative humidity was 87 at 7th of January at 02:00 O'clock and the highest average recorded temperature was 41.3 °C, average external relative humidity was 14 at 27th of May at 13:00 O'clock. Noticeably, The graphs shows the poor thermal performance of the building envelope towards the outdoor climate conditions.

Table 5.3 Thermal properties of external wall layers

No.	Thickness (mm)	Materials (from indoors to outdoors)	λ (W/mK)	R (m²K/W)	U- value (W/m²K)
		Thermal contact resistance		0.130	7.7
1	2	Plaster paint	0.25	0.008	125
2	20	cement render	1.40	0.014	71.4
3	120	Clay brick	0.60	0.182	5.5
4	20	cement render	1.40	0.014	71.4
5	2	Plaster paint	0.25	0.008	125
		Thermal contact resistance		0.040	25
Total	**164**	**Whole component**		**0.396**	**2.53**

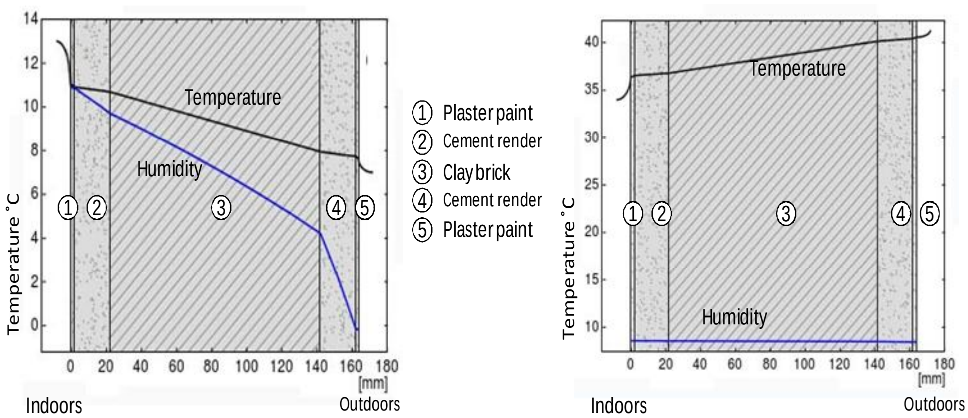

Figure 5.16 Thermal behaviour of the external wall during the lowest recorded temperature (on the left) and the highest recorded temperature (on the right)

Table 5.4 Thermal properties for roof layers

No.	Thickness (mm)	Materials(from indoors to outdoors)	λ(W/mK)	R (m^2K/W)	U value (W/m^2K)
		Thermal contact resistance		0.130	7.7
1	2	Plaster paint	0.25	0.008	125
2	20	cement mortar	1.40	0.014	71.4
3	100	Reinforced concrete	2.50	0.040	25
4	70	Sloped concrete	1.30	0.054	18.5
5	2	Water proof			
6		Insulation panels of maize fiber	0.036	1.7	0.58
7	60	sand	2.00	0.030	33.3
8	2	Cement mortar	1.40	0.008	125
9	20	tiles	1.20	0.017	58.8
		Thermal contact resistance		0.040	25
Total	**164**	**Whole component**		**2.041**	**0.49**

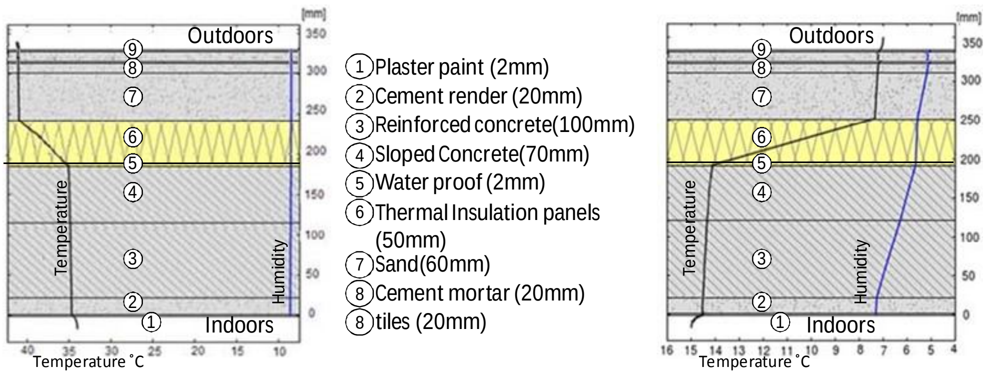

Figure 5.17 Thermal behaviour of the roof during the lowest recorded temperature (on the left) and the highest recorded temperature (on the right)

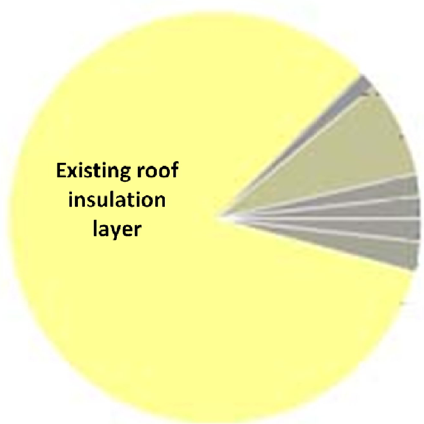

Figure 5.18 contribution of insulation material layer in the roof to overall thermal protection

5.6.2 AFTER INTERVENTIONS

The following details (figures 5.19, 5.20, 5.21, 5.22, 5.23 and 5.24) shows the critical points in the building envelop after adding the insulation material. Furthermore, figure (5.25) and (5.26) shows the predicted thermal performance of the wall after adding external insulation and the contribution of insulation to overall thermal protection.

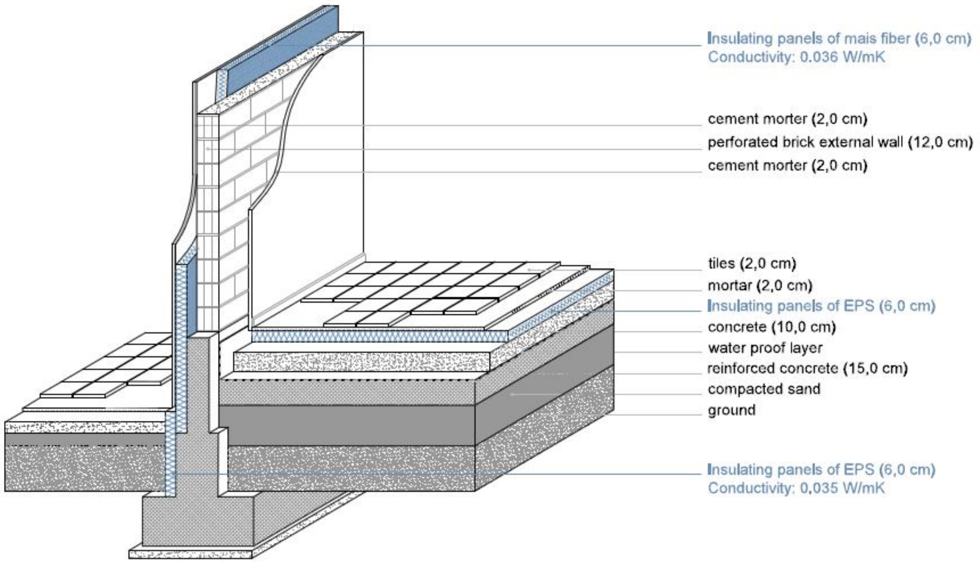

Figure 5.19 Detail 01 - wall groung connection after intervention

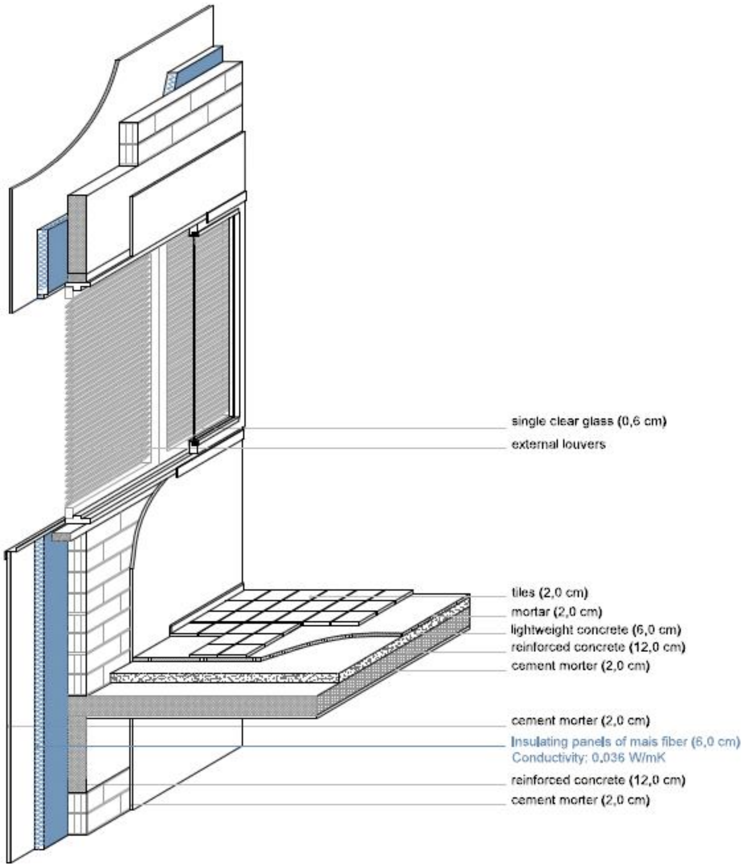

Figure 5.20 Detail 02 - wall, window and floor connection after intervention from inside

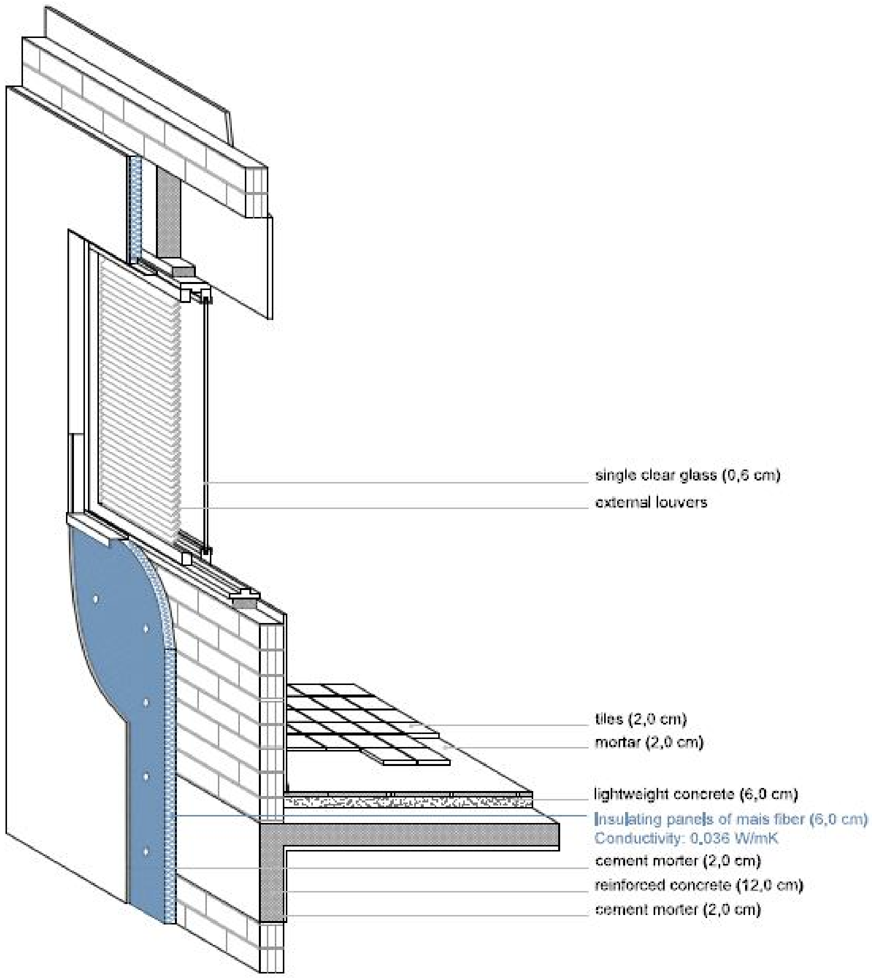

Figure 5.21 Detail 02 - wall, window and floor connection after intervention from outside

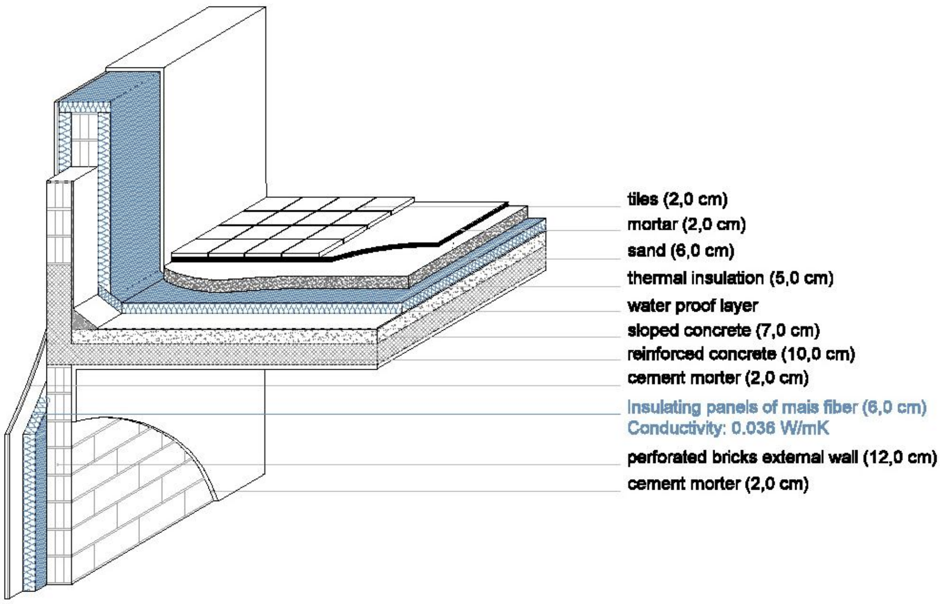

Figure 5.22 Detail 03 - wall roof connection after intervention from inside

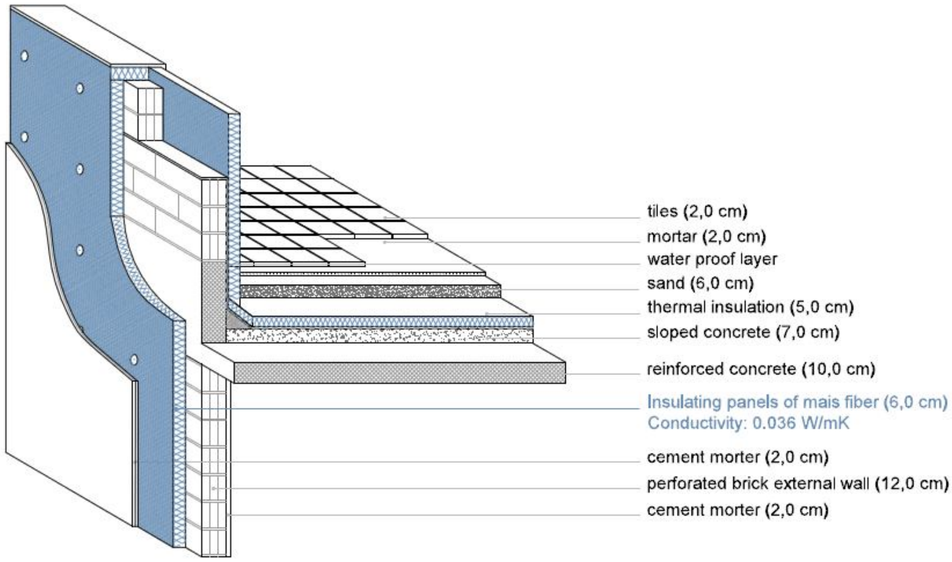

Figure 5.23 Detail 03 - wall roof connection after intervention from outside

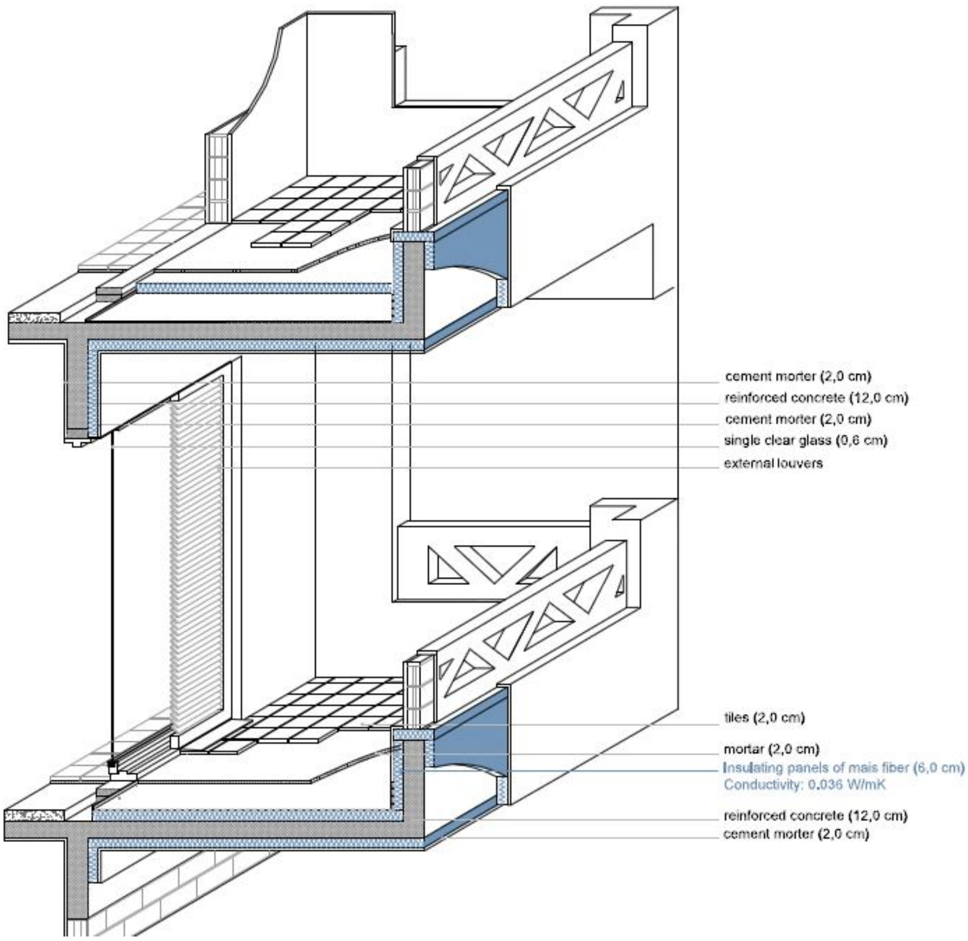

Figure 5.24 Detail 04 - balcony detail after intervention

Table 5.5 The external wall layer properties after adding insulation of maize fiber

No.	Thickness (mm)	Materials(from indoors to outdoors)	λ(W/mK)	R (m^2K/W)	U value (W/m^2K)
		Thermal contact resistance		0.130	7.7
1	2	Plaster paint	0.25	0.008	125
2	20	cement render	1.40	0.014	71.4
3	120	Clay brick	0.60	0.182	5.5
4	20	cement render	1.40	0.014	71.4
5	2	Plaster paint	0.25	0.008	125
6		Insulation panels of maize fiber	0.036	1.7	0.58
7	20	cement render	1.40	0.014	71.4
8	2	Plaster paint	0.25	0.008	125
		Thermal contact resistance		0.040	25
Total	**164**	**Whole component**		**2.12**	**0.47**

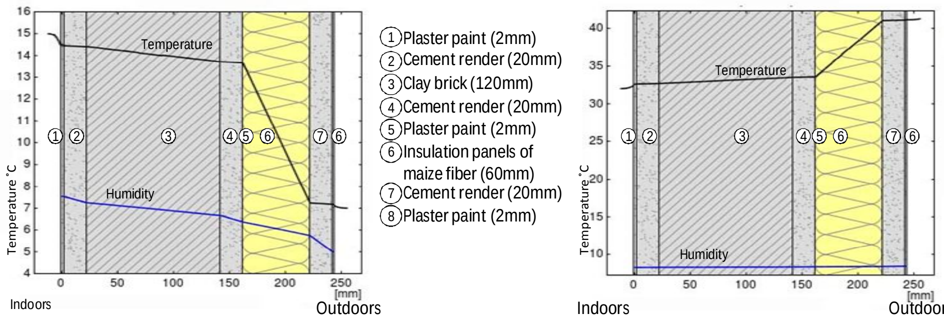

Figure 5.25 Thermal behaviour of the insulated external wall during the lowest recorded temperature (on the left) and the highest recorded temperature (on the right)

Figure 5.26 Contribution of Insulation material layer to overall thermal protection

5.7 SIMULATION RESULTS FOR A LIVING ROOM FACING SOUTH

This section comprises the results of the simulation that was conducted to examine the effectiveness of insulation retrofitting technique on the case study during winter, summer and spring-autumn periods. In consequence, the comparison made in each period among four scenarios; the base case scenario (4.1), the base case after adding insulation (scenario 5.1), natural ventilation recommended scenario (scenarios 4.2, 4.8 or 4.4 according to the period (see chapter four) and the combination of the recommended scenario of natural ventilation and insulation retrofitting technique (scenario 5.2).

5.7.1 WINTER PERIOD

In the winter months; January, February, March, November and December (Figures 5.27, 5.28, 5.29, 5.30 and 5.31 respectively), the comparison was made among the **base case scenario** (scenario 4.1 where windows closed 24 hours without applying insulation (see chapter 4)), **scenario 6.1** (windows closed 24 hours after applying external insulation of maize fiber), **Scenario 5.2** (windows opened from 8:00 to 9:00 and from 17:00 to 18:00 without applying external insulation – see chapter 4) and **scenario 6.2** (windows opened from 8:00 to 9:00 and from 17:00 to 18:00 after applying external insulation).

In January (Figure 5.27), this is one of the peak heating dominated months in Cairo in all presented scenarios. Scenario 5.1, scenario 6.1, scenario 5.2 and scenario 6.2 achieved 1.7%, 4.4%, 1.7% and 2.0% from total hours are within comfort range and 98.3%, 95.6%, 98.3% and 98.0% from total hours are of heating demand. **Based on this comparison, there is no significant difference between scenario 5.2 (the recommended natural ventilation scenario in winter) and scenario 6.2 (the combination of natural ventilation and external insulation technique). Accordingly, this combination is not effective during the month of January for the reference case under the climate condition of Cairo.**

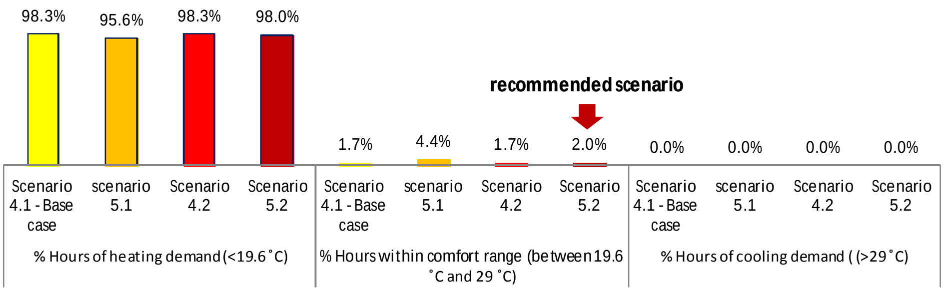

Figure 5.27 comparison among different scenarios of natural ventilation and insulation strategies for a living room facing south during the month of January

In February (Figure 5.28), this is one of the peak heating dominated months in Cairo in all presented scenarios. Scenario 5.1(base case scenario – windows closed 24 hours without applying external insulation), scenario 6.1 (base case with external insulation), scenario 5.2(windows were opened from 8:00 to 9:00 and from 17:00 to 18:00 without applying external insulation) and scenario 6.2 (combination of scenario 5.2 of natural ventilation and external insulation) achieved 11.5%, 26.3%, 10.9% and 13.4% from total hours are within comfort range and 88.5%, 73.7%, 89.1% and 86.6% from total hours are of heating demand. **Based on this comparison, there is a slight difference between scenario 5.2 (the recommended natural ventilation scenario in winter) and scenario 6.2 (the combination of natural ventilation and external insulation technique). Accordingly, this combination is not effective during the month of February for the reference case under the climate condition of Cairo.**

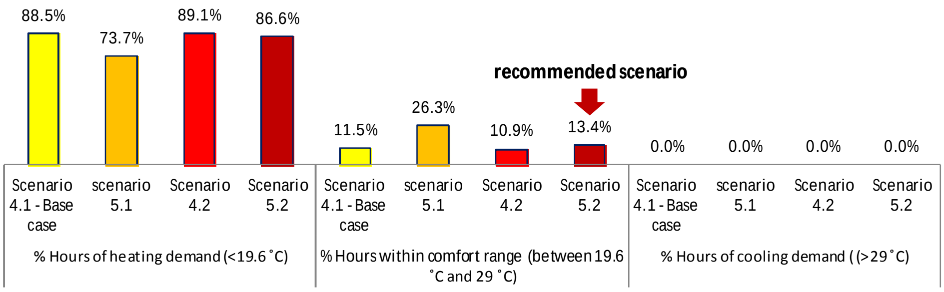

Figure 5.28 comparison among different scenarios of natural ventilation and insulation strategies for a living room facing south during the month of February

In March (Figure 5.29), this is one of the heating demand months in Cairo in all presented scenarios. Scenario 5.1(base case scenario – windows closed 24 hours without applying external insulation), scenario 6.1 (base case with external insulation), scenario 5.2(windows were opened from 8:00 to 9:00 and from 17:00 to 18:00 without applying external insulation) and scenario 6.2 (combination of scenario 5.2 of natural ventilation and external insulation) achieved 48.4%, 71.9%, 44.4% and 56.5% from total hours are within comfort range and 51.6%, 28.1%, 55.6% and 43.5% from total hours are of heating demand. **Based on this comparison, the combination between the recommended scenario of natural ventilation in winter and external insulation is recommended as it achieved the second highest percentage of indoor thermal comfort, however, scenario 6.1 achieved the highest range of comfort but it is not preferable because of indoor air quality reasons.**

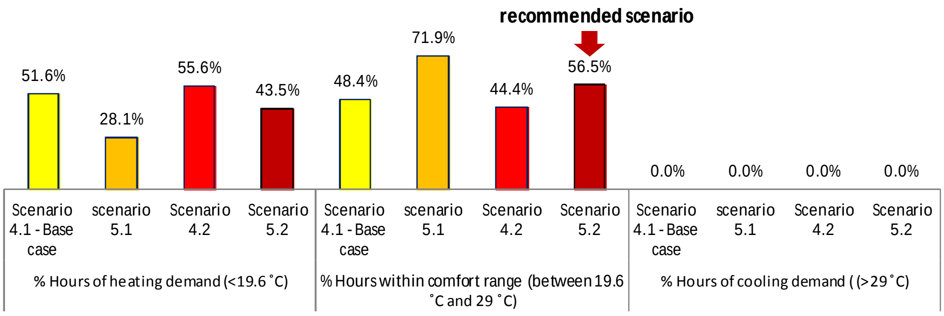

Figure 5.29 comparison among different scenarios of natural ventilation and insulation strategies for a living room facing south during the month of March

In November (Figure 5.30), this is one of the most thermally comfortable months in Cairo in all presented scenarios. Scenario 5.1(base case scenario – windows closed 24 hours without applying external insulation), scenario 6.1 (base case with external insulation), scenario 5.2 (windows were opened from 8:00 to 9:00 and from 17:00 to 18:00 without applying external insulation) and scenario 6.2 (combination of scenario

5.2 of natural ventilation and external insulation) achieved 93.5%, 100.0%, 92.2% and 98.6% from total hours are within comfort range and 6.5%, 0.0%, 7.8% and 1.4% from total hours are of heating demand. **Based on this comparison, the combination between the recommended scenario of natural ventilation in winter and external insulation is recommended as it achieved the second highest percentage of indoor thermal comfort, however, scenario 6.1 achieved the highest range of comfort but it is not preferable because of indoor air quality reasons.**

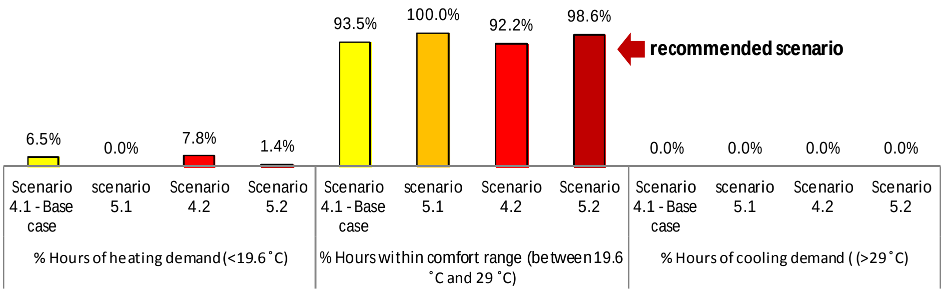

Figure 5.30 comparison among different scenarios of natural ventilation and insulation strategies for a living room facing south during the month of November

In December (Figure 5.31), this is one of the heating demand months in Cairo in all presented scenarios. Scenario 5.1(base case scenario – windows closed 24 hours without applying external insulation), scenario 6.1 (base case with external insulation), scenario 5.2(windows were opened from 8:00 to 9:00 and from 17:00 to 18:00 without applying external insulation) and scenario 6.2 (combination of scenario 5.2 of natural ventilation and external insulation) achieved 20.7%, 35.8%, 21.1% and 26.9% from total hours are within comfort range and 79.3%, 64.2%, 78.9% and 73.1%from total hours are of heating demand. **Based on this comparison, thermal comfort was slightly improved in scenario 6.2 that is combining the external insulation with the preferred scenario of natural ventilation in winter. However, scenario 6.2 achieved the second highest percentage of indoor thermal comfort, it is recommended more than scenario 6.1 (the highest percentage of comfort) because of indoor air quality reasons.**

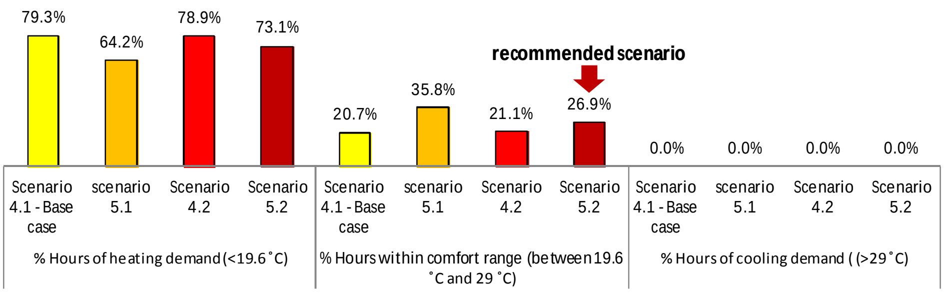

Figure 5.31 comparison among different scenarios of natural ventilation and insulation strategies for a living room facing south during the month of December

From the above investigations for the whole period of winter months (the period of zero cooling demand in January, February, March, November and December) (Figure 5.32), the combination of the recommended scenario of natural ventilation in winter and the application of external insulation on the case study (scenario 6.2) makes **improvement in indoor thermal comfort by only 4.4% from the base case and by 5.5% from natural ventilation only** (scenario 5.2) during all the total period of winter season. **Consequently, the application of external insulation on this research is not much effective in winter season.**

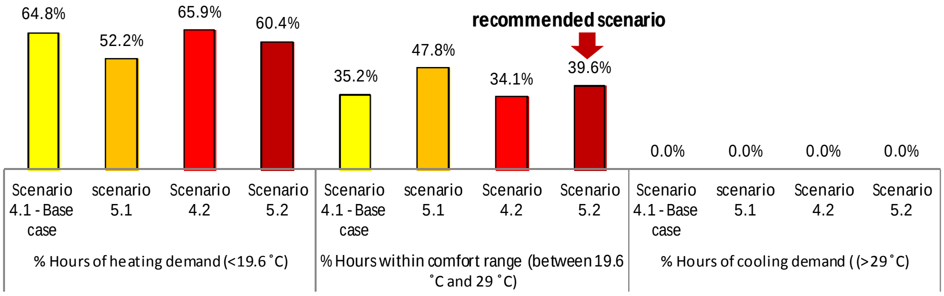

Figure 5.32 comparison among different scenarios of natural ventilation and insulation strategies for a living room facing south during the whole winter period

5.7.2 SUMMER PERIOD

In the summer months; June, July, August and September (Figures 5.33, 5.34, 5.35 and 5.36) the comparison was made among the **base case scenario** (scenario 5.1 where windows closed 24 hours without applying insulation (see chapter 4)), **scenario 6.1** (windows closed 24 hours after applying external insulation of maize fiber), **Scenario 5.8** (cross night purge ventilation scenario without applying external insulation – see chapter 4) and **scenario 6.2** (cross night purge ventilation scenario after applying external insulation).

In June (figure 5.33), this is one of the months of cooling demand in Cairo in all presented scenarios. **Scenario 5.1**(base case scenario – windows closed 24 hours without applying external insulation), **scenario 6.1** (base case with external insulation), **scenario 5.8** (cross night purge ventilation without applying external insulation) and **scenario 6.2** (combination of scenario 5.8 of natural ventilation and external insulation) achieved 39.0%, 17.2%, 75.3% and 87.8% from total hours are within comfort range and 61.0%, 82.8%, 23.6% and 10.8%from total hours are of cooling demand. **Based on this comparison, thermal comfort was significantly improved by 48.8% comparing to the base case when combining the external insulation with the recommended scenario of natural ventilation in summer (scenario 6.2). in addition, applying external insulation made an improvement in comfort by 12.5% than natural ventilation only during the month of June.**

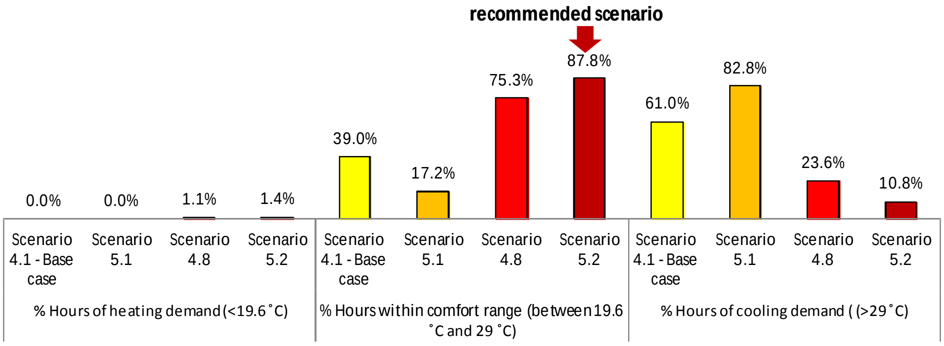

Figure 5.33 comparison among different scenarios of natural ventilation and insulation strategies for a living room facing south during the month of June

In July (figure 5.34), this is one of the peak months of cooling demand in Cairo in all presented scenarios. **Scenario 5.1**(base case scenario – windows closed 24 hours without applying external insulation), **scenario 6.1** (base case with external insulation), **scenario 5.8** (cross night purge ventilation without applying external insulation) and **scenario 6.2** (combination of scenario 5.8 of natural ventilation and external insulation) achieved 8.7%, 0.0%, 61.4% and 71.5% from total hours are within comfort range and 91.3%, 100.0%, 38.6% and 28.5%from total hours are of cooling demand. **Based on this comparison, thermal comfort was significantly improved by 61.8% comparing to the base case when combining the external insulation with the recommended scenario of natural ventilation in summer. in addition, applying external insulation made an improvement in comfort by 10.1% than natural ventilation only during the month of July.**

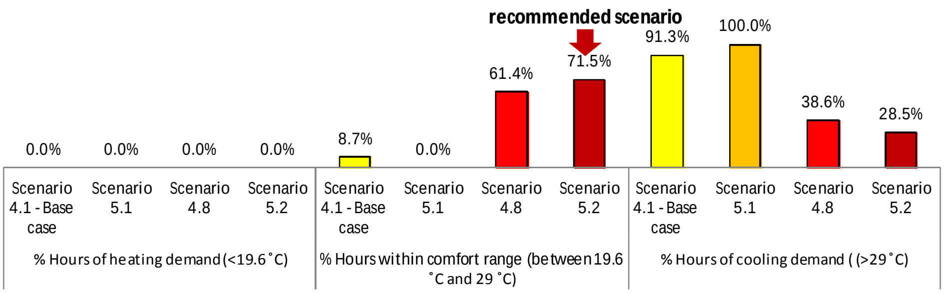

Figure 5.34 comparison among different scenarios of natural ventilation and insulation strategies for a living room facing south during the month of July

In August (figure 5.35), this is one of the peak months of cooling demand in Cairo in all presented scenarios. **Scenario 5.1**(base case scenario – windows closed 24 hours without applying external insulation), **scenario 6.1** (base case with external insulation), **scenario 5.8** (cross night purge ventilation without applying external insulation) and **scenario 6.2** (combination of scenario 5.8 of natural ventilation and external insulation) achieved 5.5%, 0.0%, 62.1% and 71.1% from total hours are within comfort range and 94.5%, 100.0%, 37.9% and 28.9%from total hours are of cooling demand. **Based on this comparison, thermal comfort was significantly improved by 64.6% comparing to the base case when combining the external insulation with the recommended scenario of natural ventilation in summer. Furthermore, applying external insulation made an improvement in comfort by 9.0% than natural ventilation only during the month of July.**

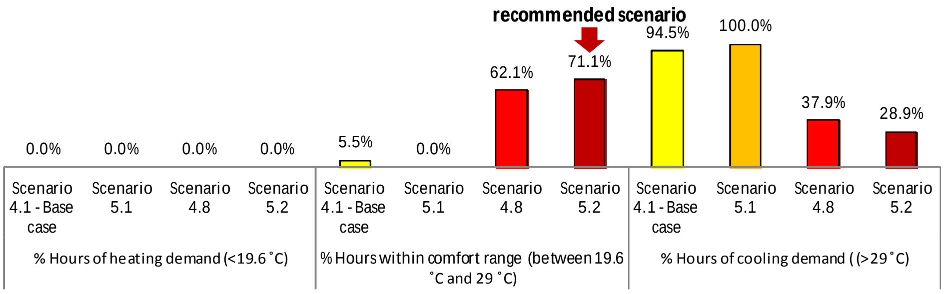

Figure 5.35 comparison among different scenarios of natural ventilation and insulation strategies for a living room facing south during the month of August

In September (figure 5.36), this is one of the cooling demand months in Cairo in all presented scenarios. **Scenario 5.1**(base case scenario – windows closed 24 hours without applying external insulation), **scenario 6.1** (base case with external insulation), **scenario 5.8** (cross night purge ventilation without applying external insulation) and **scenario 6.2** (combination of scenario 5.8 of natural ventilation and external insulation) achieved 30.1%, 1.8%, 76.4% and 85.8% from total hours are within comfort range and 69.9%, 98.2%, 23.6% and 14.2% from total hours are of cooling demand. **Based on this comparison, thermal comfort was significantly improved by 65.7% comparing to the base case when combining the external insulation with the recommended scenario of natural ventilation in summer. Furthermore, applying external insulation made an improvement in comfort by 9.4% than natural ventilation only during the month of July.**

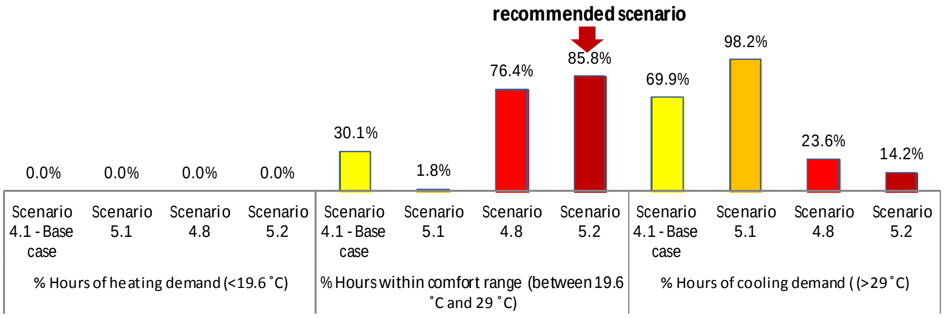

Figure 5.36 comparison among different scenarios of natural ventilation and insulation strategies for a living room facing south during the month of September

From the above investigations for the whole period of summer months (the period of zero heating demand in June, July, August, and September) (Figure 5.37), the combination of the recommended scenario of natural ventilation in summer with the application of external insulation on the case study (scenario 6.2) made an **improvement in indoor thermal comfort by 58.3% from the base case during all the total period of summer season. Further, the application of external insulation made a slight improvement of 10.2% in indoor thermal comfort during the whole summer period.**

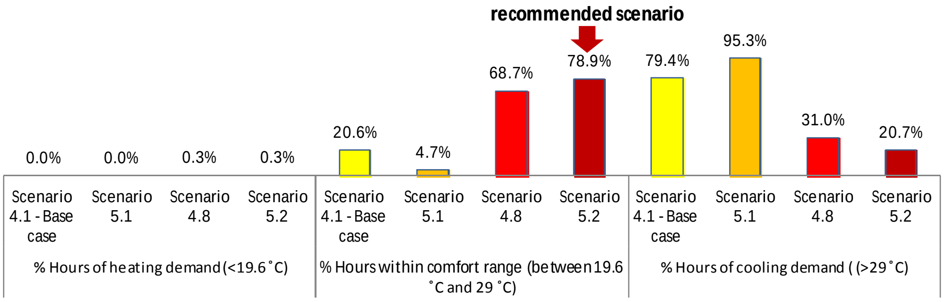

Figure 5.37 comparison among different scenarios of natural ventilation and insulation strategies for a living room facing south during the whole summer period

5.7.3 SPRING-AUTUMN PERIOD

In the spring-autumn months; April, May and October (Figures 5.38, 5.39 and 5.40), the comparison was made among the **base case scenario** (scenario 5.1 where windows closed 24 hours without applying insulation (see chapter 4)), **scenario 6.1** (windows closed 24 hours with the application of external insulation of maize fiber), **Scenario 5.4** (windows opened from 17:00 to 23:00 – see chapter 4) and **scenario 6.2** (the combination of scenario 5.4 of natural ventilation with external insulation).

In April (figure 5.38), this is generally one of the thermally comfortable months in Cairo. **Scenario 5.1**(base case scenario – windows closed 24 hours without applying external insulation), **scenario 6.1** (windows closed 24 hours with the application of external insulation of maize fiber), **Scenario 5.4** (windows opened from 17:00 to 23:00) and **scenario 6.2** (the combination of scenario 5.4 of natural ventilation with external insulation) achieved 82.9%, 94.4%, 71.1% and 74.2% from total hours are within comfort range, 5.7%, 5.4%, 5.3% and 4.9% from total hours are of heating demand and 11.4%, 0.1%, 23.6% and 21.0% from total hours are of cooling demand. **Based on this comparison, thermal comfort was decreased by 6.7% when combining the external insulation with the recommended scenario of natural ventilation in scenario 6.2 comparing to the base case. However, applying external insulation made a slight improvement in comfort by 3.1% than natural ventilation only during the month of April.**

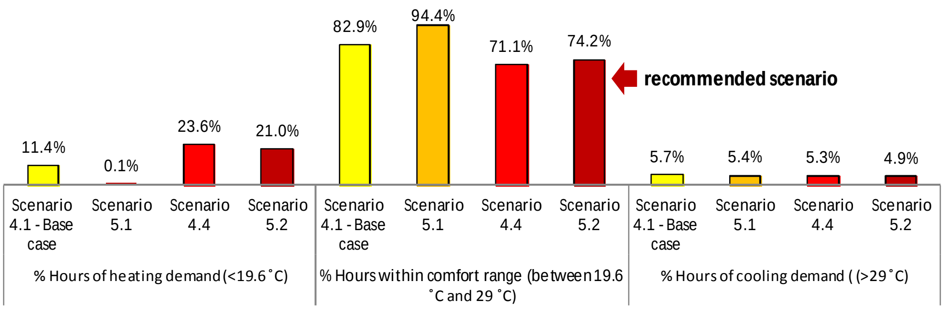

Figure 5.38 comparison among different scenarios of natural ventilation and insulation strategies for a living room facing south during the month of April

In May (figure 5.39), this is generally one of the thermally comfortable months in Cairo. **Scenario 5.1**(base case scenario – windows closed 24 hours without applying external insulation), **scenario 6.1** (windows closed 24 hours with the application of external insulation of maize fiber), **Scenario 5.4** (windows opened from 17:00 to 23:00) and **scenario 6.2** (the combination of scenario 5.4 of natural ventilation with external insulation) achieved 67.2%, 57.5%, 76.7% and 80.0% respectively from total hours are within comfort range, 0.0%, 0.0%, 2.2% and 2.2% respectively from total hours are of heating demand and 32.8%, 42.5%, 21.1% and 17.9% from total hours are of cooling demand. **Based on this comparison, thermal comfort was improved by 12.8% when combining the external insulation with the recommended scenario of natural ventilation in scenario 6.2 comparing to the base case. Furthermore, applying external insulation made a slight improvement in comfort by 3.3% than natural ventilation only during the month of May.**

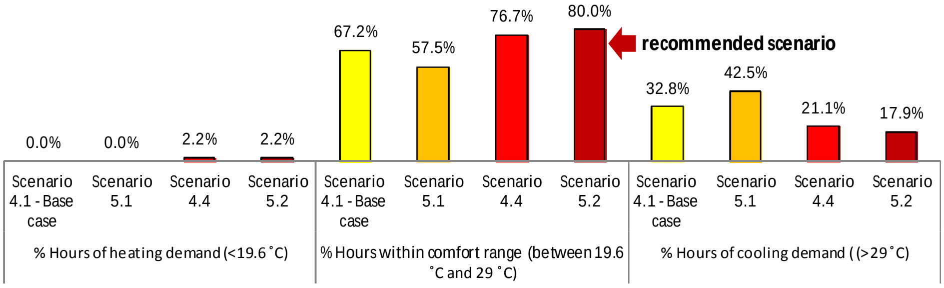

Figure 5.39 comparison among different scenarios of natural ventilation and insulation strategies for a living room facing south during the month of May

In October (figure 5.40), this is generally one of the thermally comfortable months in Cairo. **Scenario 5.1**(base case scenario – windows closed 24 hours without applying external insulation), **scenario 6.1** (windows closed 24 hours with the application of external insulation of maize fiber), **Scenario 5.4** (windows opened from 17:00 to 23:00) and **scenario 6.2** (the combination of scenario 5.4 of natural ventilation with external insulation) achieved 79.4%, 50.0%, 92.9% and 93.4% respectively from total hours are within comfort range, an equal percentage of 0.0% from total hours are of heating demand and 20.6%, 50.0%, 7.1% and 6.6% from total hours are of cooling demand. **Based on this comparison, thermal comfort was improved by 14.0% when combining the external insulation with the recommended scenario of natural ventilation in scenario 6.2 comparing to the base case. Furthermore, applying external insulation made an insignificant improvement in comfort by 0.5% than natural ventilation only during the month of October.**

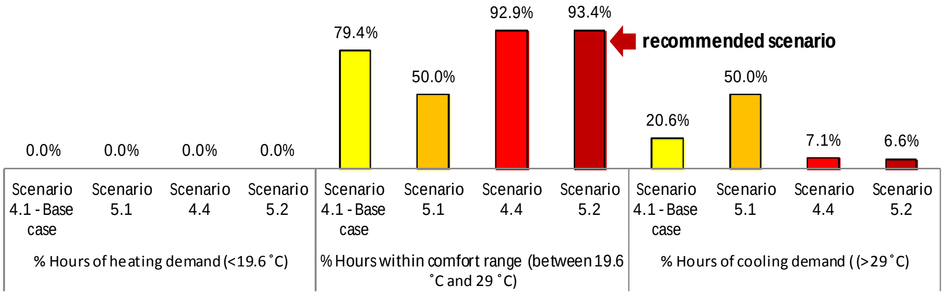

Figure 5.40 comparison among different scenarios of natural ventilation and insulation strategies for a living room facing south during the month of October

From the above investigations, for the whole period of spring-autumn months (April, May and October) (Figure 5.41), the combination of the recommended scenario of natural ventilation in spring-autumn period with the application of external insulation on the case study (scenario 6.2) made an **improvement in indoor thermal comfort by only 6.0% from the base case** during all the total period of spring-autumn seasons. **Further, the application of external insulation made an insignificant improvement of 1.9% in indoor thermal comfort during the whole mentioned period. As a result, the mentioned combination strategy is not effective in spring-autumn period.**

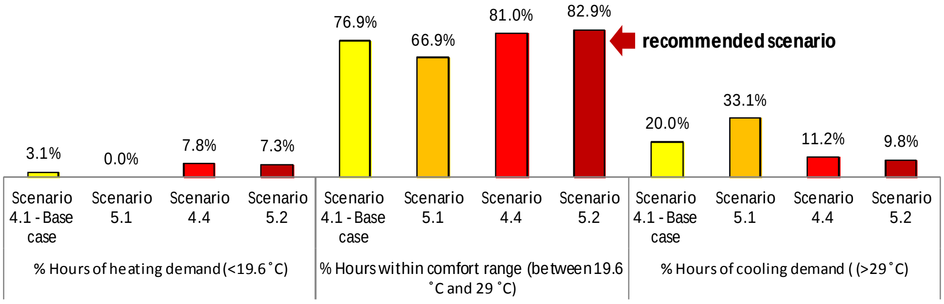

Figure 5.41 comparison among different scenarios of natural ventilation and insulation strategies for a living room facing south during the whole spring-autumn period

5.8 IMPACT OF ORIENTATION

This section comprises a cross analysis to compare Scenario 5.2 (the combination of the recommended scenario of natural ventilation in each season with the application of external insulation) among the different orientations; North, West, East and South during winter, summer, and spring-autumn periods.

5.8.1 WINTER PERIOD

During the total period of winter months (January, February, March, November and December), when applying scenario 5.2 (the combination of scenario 5.2 of natural ventilation and external insulation of maize fiber) on the orientations of North, West, East and South, it achieved 32.5%, 35.7%, 35.5%, 39.6% respectively from total hours within comfort range (see figure 5.42 below). Accordingly, the highest percentage of comfort was in Southern orientation and the lowest was in Northern orientation. This happened probably because the South orientation is more exposed to the sun light during the day and less exposed to cold wind in winter, unlike to the North orientation. **As a result, the orientation has a slight effect on indoor thermal comfort when applying scenario 6.2 in winter period.**

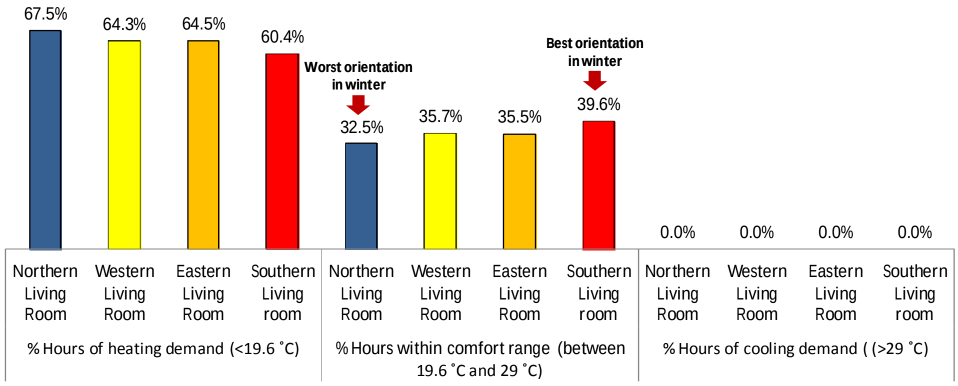

Figure 5.42 Impact of orientation on indoor thermal comfort when combining natural ventilation and insulation strategies during the whole winter period

5.8.2 SUMMER PERIOD

During the total period of summer months (June, July, August, and September), when applying scenario 6.2 (the combination of scenario 5.8 of natural ventilation and external insulation of maize fiber) on the orientations of North, West, East and South, it achieved 80.2%, 76.9%, 76.4%, 78.9% respectively from total hours within comfort range (see figure 5.43 below). Accordingly, the highest percentage of comfort was in Northern orientation and the lowest was in Eastern orientation. This result is reasonable as the North orientation is less exposed to the sun light during the day in summer than other orientations. Furthermore, the north orientation have more chance for the cross ventilation when open the windows at night. However, the differences between the four orientations were very small. **As a result, the orientation has no significant effect on indoor thermal comfort when applying scenario 6.2 in summer period.**

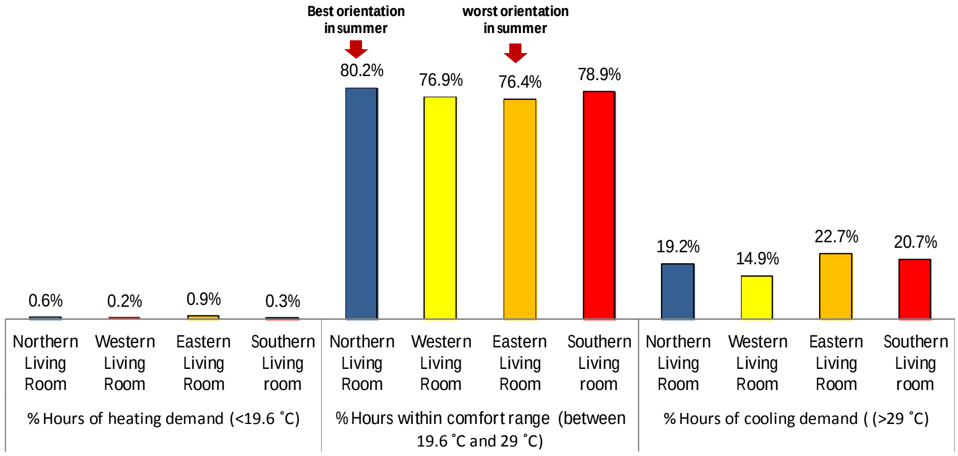

Figure 5.43 Impact of orientation on indoor thermal comfort when combining natural ventilation and insulation strategies during the whole summer period

5.8.3 SPRING-AUTUMN PERIOD

During the total period of spring-autumn months (April, May, and October), when applying scenario 6.2 (the combination of scenario 5.4 of natural ventilation and external insulation of maize fiber) on the orientations of North, West, East and South, it achieved 84.0%, 83.3%, 82.8%, 82.9% respectively from total hours within comfort range (see figure 5.44 below). Accordingly, the highest percentage of comfort was in Northern orientation and the lowest was in Eastern orientation. However, the differences between the four orientations were very small and negligible. **As a result, the orientation has no significant effect on indoor thermal comfort when applying scenario 6.2 in spring-autumn period.**

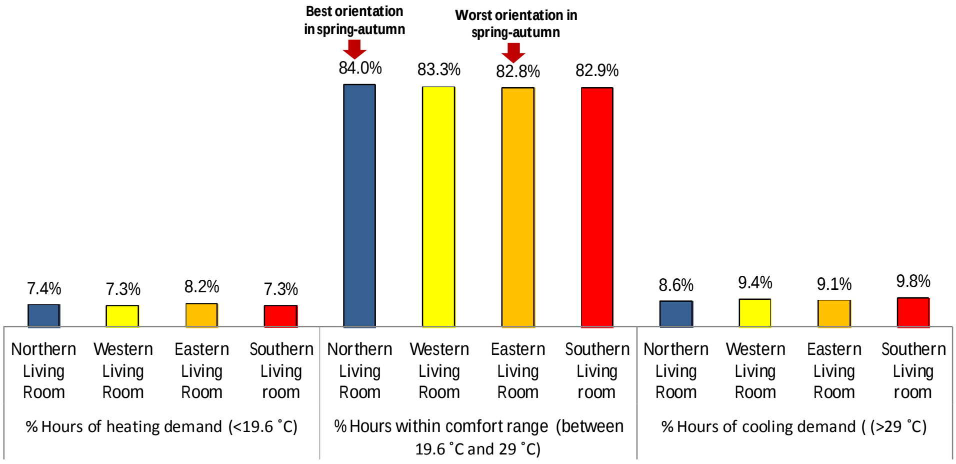

Figure 5.44 Impact of orientation on indoor thermal comfort when combining natural ventilation and insulation strategies during the whole spring-autumn period

5.9 DIFFERENCIES WITH UPPER FLOOR

This section encompasses a cross analysis to compare Scenario 6.2 (the combination of the recommended scenario of natural ventilation in each season with the application of external insulation) between typical and upper floor during winter, summer, and spring-autumn periods.

5.9.1 WINTER PERIOD

During the total period of winter months (January, February, March, November and December), when comparing scenario 6.2 (the combination of scenario 5.2 of natural ventilation and external insulation of maize fiber) between typical and upper floor (see figure 5.45 below), it is noticeable that the difference in percentage of hours within comfort range is equal to 1.5% in typical floor higher than the upper floor. **As a result, there is no much difference between typical and upper floor during winter.**

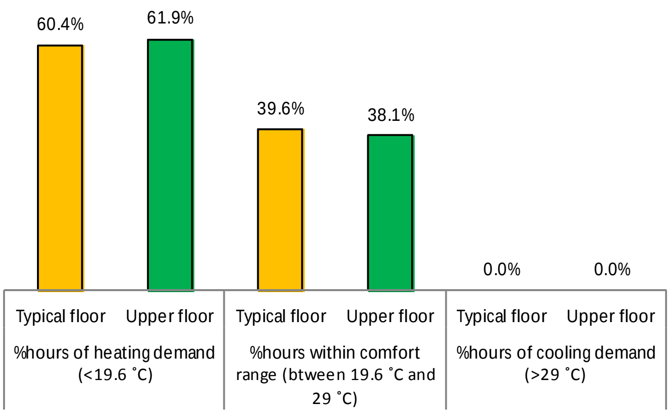

Figure 5.45 comparison between typical and upper floor when combining natural ventilation and insulation strategies during the whole winter period

5.9.2 SUMMER PERIOD

During the total period of summer months (June, July, August and September), when comparing scenario 6.2 (the combination of scenario 5.2 of natural ventilation and external insulation of maize fiber) between typical and upper floor (see figure 5.46 below), it is evident that the difference in percentage of hours within comfort range is equal to 0.8% in typical floor higher than the upper floor. **As a result, there is no significant difference between typical and upper floor during summer.**

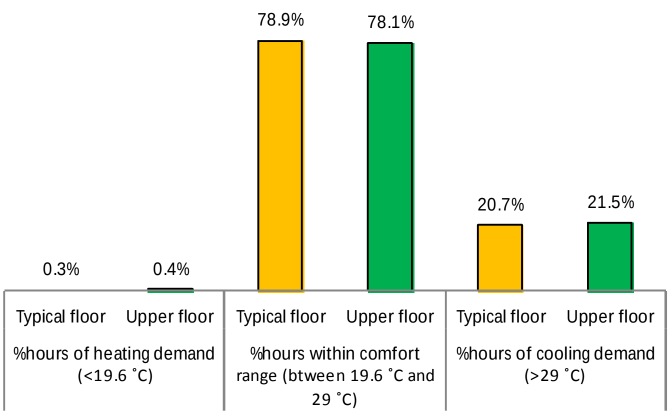

Figure 5.46 comparison between typical and upper floor when combining natural ventilation and insulation strategies during the whole summer period

5.9.3 SPRING-AUTUMN PERIOD

During the total period of summer months (June, July, August and September), when comparing scenario 6.2 (the combination of scenario 5.2 of natural ventilation and external insulation of maize fiber) between typical and upper floor (see figure 5.47 below), it is obvious that the difference in percentage of hours within comfort range is equal to 0.8% in typical floor higher than the upper floor. **As a result, there is no significant difference between typical and upper floor during spring-autumn period.**

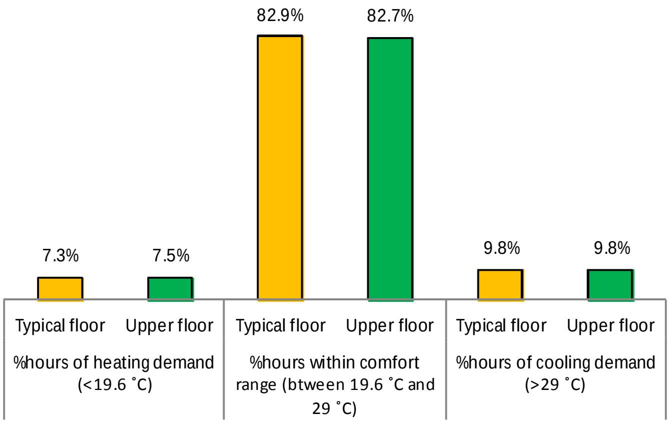

Figure 5.47 comparison between typical and upper floor when combining natural ventilation and insulation strategies during the whole spring-autumn period

5.10 CONCLUSION

This chapter examined the effectiveness of the combination of natural ventilation strategy and external insulation retrofitting technique (scenario 5.2). Accordingly, the recommended scenarios of natural ventilation for each period of the year (winter, summer and spring-autumn) were combined with the application of external insulation on the case study. The findings revealed **that this combination is not effective in winter period as it has** made an **improvement by 4.4% from the base case and by 5.5% from natural ventilation only** (scenario 4.2). In addition**, the mentioned combination strategy was significantly effective in summer period** as it has improved **indoor thermal comfort by 58.3% from the base case** and **by 10.2% comparing to scenario 4.2 of natural ventilation only.** Further**, the mentioned strategy was not much effective during spring-autumn period** as it made an **improvement in indoor thermal comfort by only 6.0% from the base case** and by **1.9% comparing to scenario 5.2** (natural ventilation only).

The chapter discussed the impact of orientation whilst applying the above mentioned strategy. The results illuminated **that the orientation has no significant effect on indoor thermal comfort** in winter, summer and spring-autumn seasons. Furthermore, **the investigations between typical and upper floor highlighted that there is no significant difference between them in terms of thermal comfort.** The following chapter will address the conclusion remarks for the study and recommendations that should be followed while dealing with these types of dwellings behaviorally and technically, in addition, the future research will be discussed regarding this aspect.

CHAPTER SIX

6. CONCLUSIONS, RECOMMENDATIONS AND FURTHER WORK

6.0 INTRODUCTION

The research introduction and research methodology were introduced in chapter one. Chapter two presented a literature review on thermal comfort definitions, variables, approaches and overview on thermal comfort in residential building in hot-arid climates particularly Egypt. Chapter three comprised a field survey, validation studies and comfort zone analysis for the research case study. A simulation process was conducted in Chapter four to evaluate the natural ventilation based behavioural survey scenarios as well as the hypothetical suggested scenarios to improve the situation especially in summer season. Eventually, Chapter five encompassed the combination of natural ventilation recommended scenarios and insulation retrofitting technique that was suggested to enhance the poorly adapted building envelop with the prevailed climate. In this chapter, a conclusion and recommendation for the whole research work are presented. It also presents the contributions of the study, overview on research prepositions and finally highlights areas for future research.

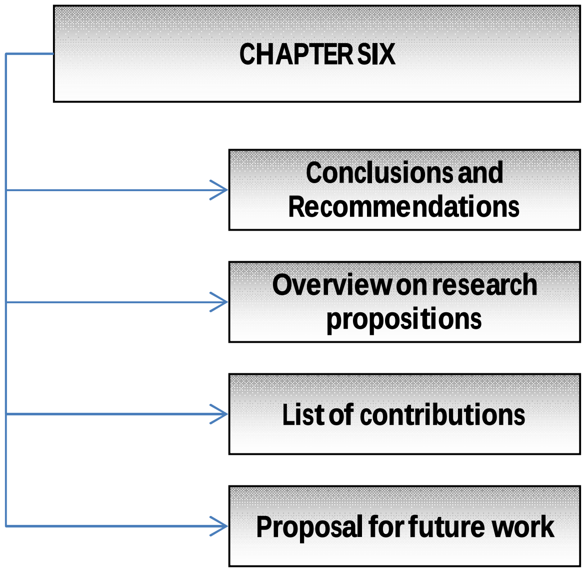

Figure 6.1 Chapter six structure

6.1 CONCLUSIONS AND RECOMMENDATIONS

The problem of thermal comfort in the prototypical social housing building stocks in the hot arid climate of Egypt has been identified in this research. The buildings were poorly adapted to the climate condition in terms of design strategies and building materials. As a result, this created comfort problems for the occupants in both winter and summer seasons. None of the previous literature tried to combine natural ventilation behavioral strategies with insulation retrofitting techniques to solve thermal comfort problems in the prototypical housing stocks in Egypt, further, none of them tried to evaluate this combination in winter season. This gap of knowledge was approached in this research. In this context, **the in hand study was conducted to examine the combination of natural ventilation behavioral strategies and insulation technique in order to fulfill the main goal of improving thermal comfort through a possible solution without using any mechanical cooling or heating systems.**

To accomplish the previously mentioned aim of this research, the study was conducted in three main phases:

1- Qualitatively and quantitatively evaluating the status-quo of the case study buildings through observation, field survey and field measurements.
2- Quantifying possible behavioural strategies for natural ventilation that can ameliorate the situation especially in summer.
3- Enhancing the building envelope thermal performance through insulation retrofitting technique made of available ecologic material that possibly can be found on site.

Observations, field survey and field measurements revealed that there is a comfort problem in both summer and winter seasons in the chosen case study. Accordingly, the study examined behavioural and technical strategies that can be concluded as following:

6.1.1 ENHANCING NATURAL VENTILATION THROUGH BEHAVIOURAL STRATEGIES (ZERO COST SOLUTIONS)

A case study research strategy was employed in the study as a springboard to examine the effectiveness of different scenarios of natural ventilation on indoor thermal comfort. The scenarios were categorized into three; the base case scenario, the based behavioral survey scenarios that was obtained from questionnaire analysis and the hypothetical suggested scenarios to improve the situation in summer. **The results illuminated that the hypothetical suggested scenario of cross night purge ventilation revealed a considerable improvement in indoor thermal comfort in summer period, more so, whilst natural ventilation scenarios had a modest improvement in thermal comfort in spring-autumn periods, it had a negative effect in winter period.** The recommended scenarios of natural ventilation in each period are concluded below:

- Although the best scenario **in winter season** was the base case scenario, the based behavioural survey scenario in winter was recommended for the fresh air intake. This is because the indoor air quality would be negatively affected if the windows were closed for twenty-four hours in the base case scenario**. In terms of the findings of summer** season, the recommended scenario was the cross night purge ventilation as it offers the highest percentage of total hours within comfort range. Moreover, **in respect of the spring-autumn period**, the based behavioral survey scenarios 4.4 (windows opened from 17:00 to 23:00) and 4.5 (windows opened from 8:00 to 14:00) were recommended in that they achieved the highest comfort.
- Further, the study evaluated the effect of orientation on indoor thermal comfort through the application of the recommended scenarios in winter, summer and spring-autumn periods. Accordingly**, the results showed that the orientation has no significant effect on indoor thermal comfort for the aforementioned periods.**
- More so, the examination between typical and upper floor revealed **that there is no significant difference between them in regards to thermal comfort.** The following chapter will address the effect of the combination of best scenarios of natural ventilation with insulation retrofitting technique to improve thermal comfort.

6.1.2 ENHANCING INDOOR THERMAL COMFORT THROUGH THE COMBINATION OF BUILDING ENVELOP INSULATION RETROFITTING TECHNIQUE AND NATURAL VENTILATION

The effectiveness of the combination of natural ventilation strategy and external insulation retrofitting technique was examined. In other words, the recommended scenarios of natural ventilation for each period of the year (winter, summer and spring-autumn) were combined with the application of external insulation on the case study. The findings revealed that:

- **In winter,** (see section 5.6.1, scenario 5.2) **this combination was found not to be effective in winter period as the thermal comfort increased by only 4.4%** as compared to the base case and by 5.5% as against the natural ventilation only (scenario 4.2 – see chapter 4).

- **In summer**, the mentioned combination strategy **was significantly effective in summer period as it has improved indoor thermal comfort by 58.3%** as compared to the base case and by 10.2% comparing to scenario 4.2 of the natural ventilation only.

- **In spring-autumn**, the combined strategy **was relatively not effective during spring-autumn period as it made an improvement in indoor thermal comfort by only 6.0%** as against the base case and by 1.9% comparing to scenario 5.2 (natural ventilation only).

According to the above conclusion, whilst the combined strategy was highly effective to improving thermal comfort in summer, it had a small effect in both winter and spring-autumn periods. However, this result is beneficial in Egyptian climatic condition because summer in Egypt is more severe than winter. Based on the researcher's personal observation, people tend to adapt themselves easily to the prevailing winter condition in Egypt, but they find it difficult to do so in summer season.

The study further assessed **the effect of orientation on indoor thermal comfort** via the utilisation of the combination of natural ventilation strategy and external insulation retrofitting technique in winter, summer and spring-autumn periods. The observable fact illuminated that the orientation has no significant effect on indoor thermal comfort in winter, summer and spring-autumn seasons. Additionally, the comparison between typical and upper floor confirmed that there is no significant difference between them in terms of thermal comfort.

6.2 OVERVIEW OF THE RESEARCH PROPOSITIONS

The table below presents an overview of the study's hypotheses:

Table 6.1 overview on research hypotheses

Hypothesis	Confirmation		
	In Winter	In Summer	In Spring-Autumn
Behavioural strategies of natural ventilation control have a significant impact in reducing cooling demand in residential building stocks within hot arid context.	Not confirmed	Confirmed	Confirmed to a very small extent
Using external insulation in residential buildings will reduce heating and cooling demand in buildings.	Confirmed to a very small extent	Confirmed to a small extent	Confirmed to a very small extent
The combination of natural ventilation behavioural strategies and insulation retrofitting technique can significantly improve indoor thermal comfort.	Confirmed to a very small extent	Confirmed	Confirmed to a very small extent

6.3 LIST OF CONTRIBUTIONS

Many contributions were added to the body of knowledge by this research in this field of study as following:

- The research introduced a methodology to identify, qualitatively and quantitatively, the thermal performance, in both winter and summer seasons, in the governmental public housing in 6th of October city in greater Cairo, Egypt.

- The study evaluated the effectiveness of the based behavioural as well as the hypothetical suggested strategies of natural ventilation through field survey and conducted simulation process to enhance thermal comfort in residential building stocks in Egypt.

- The study evaluated the effectiveness of the combination of natural ventilation behavioural control and external insulation retrofitting technique to enhance indoor thermal comfort in social housing stocks in Greater Cairo.

- The study checked the validity of the simulation tool of Integrated Environmental Solutions – Vertual Environment (IES<VE>) software program in terms of weather profile under the hot arid climate condition of Egypt.

6.4 PROPOSAL FOR FURTHER WORK

The future research in this field is drawn in the following points:

- A case study qualitative as well as quantitative research method was employed in this study, focusing on social housing building stocks in Cairo, Egypt. The findings revealed important issues, which to a certain extent, apply to this kind of buildings in the hot arid climate of Egypt. Further studies in other bioclimatic zones of Egypt, rather than Cairo, are needed.

- This study can be replicated in different areas of hot arid climates across the world by applying the same methodological framework in order to compare the findings as the increase in the number of comparative studies would substantially contribute to develop further understanding on the broader enhancement of building adaptation and retrofitting strategies in hot-arid climate regions.

- Furthermore, as the strategies proposed in this study was not effective in winter season, additional studies should be conducted to suggest and examine other retrofitting strategies aiming to solve the heating demand problems in winter season (such as solar green house effect and solar heating techniques).

- maximizing the cross ventilation through changing window size of the internal spaces (such as kitchens and bathrooms), more so, Buoyancy-driven ventilation for the case study through stair well and internal courts should be investigated in future research.

- Further studies needed to focus on the case study building fabric in order to raise its thermal performance in terms of insulation materials and thermal mass.

- Cost and benefit analyses studies are required for better evaluation for the suggested strategies.

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APPENDICES

8. APPENDICES

1. AIR TEMPERATURE SCALES AND DIFINITIONS
2. HUMIDITY MEASUREMENT TOOLS
3. HEAT BALANCE EQUATION
4. PMV
5. QUESTIONNAIRE
6. T-PAIRED TEST
7. RELATED PUBLISHED WORK

APPENDICES

8.1 AIR TEMPERATURE MEASUREMENT AND SCALES

There are many scales to measure temperature but it is usually measured by the most three famous scales Celsius (C), Fahrenheit (F) and Kelvin (K). The Celsius scale is based on water freezing and boiling points taken as 0°C and 100°C respectively (Szokolay, 2008). 0 degrees Celsius is equal to 32 degrees Fahrenheit while 0 degrees Kelvin is approximately equal to -273 degrees Celcius and -460 degrees Fahrenheit. Kelvin is called also the standard international unit and 0 Kelvin is called the absolute zero as it is the coldest temperature possible, and is the point at which all molecular motion stops (Quinn, 1983; Vlachopoulos, 2002). Air temperature is measured by thermometer.

8.2 HUMIDITY MEASUREMENT TOOLS

Humidity is measured by revolving a psychrometer (Figure 7.1) which contains two thermometers; wet bulb and dry bulb one. The wet bulb thermometer has its bulb wrapped in wet gauze to keep it moist. Then, the cooling effect is obtained by revolving the psychrometer freely in the air or exposing it for a source of air like a fan to reach the maximum evaporation. Then, the wet bulb temperature (WBT) and the dry bulb one (DBT) can be obtained from the two thermometers. The difference between wet and dry bulb readings is called the wet-bulb depression and it is considered as the humidity value. When the air is saturated, then there is no cooling effect or evaporation rate from the wet bulb thermometer and, in this case, wet bulb will be equal to dry bulb temperature (Szokolay, 2008).

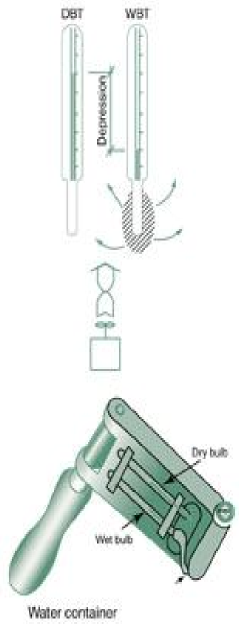


Figure 7.1 Revolving a psychrometer

8.3 HEAT BALANCE EQUATION

Thermal comfort is based on the body's heat balance which was expressed by Gagge (1936) as:

$M \pm R \pm C - E = \Delta S$ (W) (1)

Or if we consider the conduction the equation could be rewritten as:

$M \pm R \pm Cv \pm Cd - E = \Delta S$ (W) (2)

Where:

ΔS = Heat balance / change in heat stored

M = Metabolic rate that contributes to heat gain

Cd = Conductance that is considered to be zero in application and is typically not used

Cv = Convection and,

R = radiation that can be positive or negative (adding to or subtracting from metabolic heat gain), depending on environmental temperature vs. the body

E = Evaporation that is always negative (subtracting from metabolic heat gain), reducing body temperature

8.4 PMV

In the experiments of PMV, the subjects were exposed to different thermal environments while worn the same clothes and practiced the same activities. The participants then were asked about their thermal sensation using ASHRAE seven-point thermal sensation scale which range from (-3) for cold environment to (+3) for hot environment and (0) in the middle for neutral Environment. The subsequent equation from this study became known as “Predicted Mean Vote” (PMV) index and it described the thermal comfort for a certain environment and certain level of activity as an imbalance between the heat flow from the and the desired heat flow for an idealistic comfort level (Fanger 1970; Djongyang et al. 2010). the PMV generated the “Predicted Percentage of Dissatisfied” (PPD) with specific relationship between them as shown in figure (7.2).

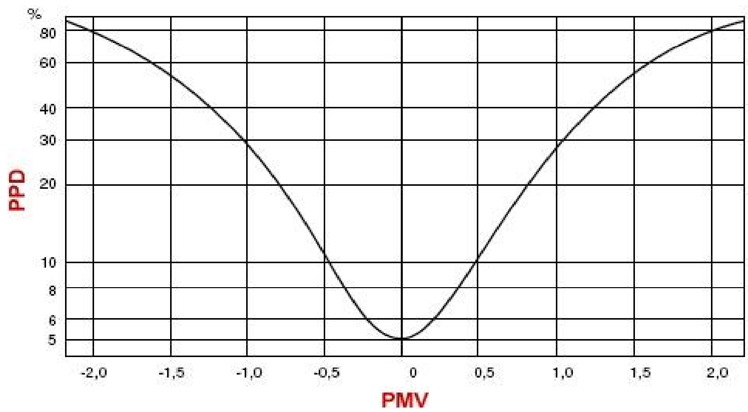


Figure 7.2 PMV and PPD interrelationship

The PMV index predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale:

Table 7.1 ASHRAE thermal sensation scale

Value	Thermal Sensation
+3	hot
+2	warm
+1	slightly warm
0	neutral
-1	slightly cool
-2	cool
-3	cold

Mathematically, the PMV is expressed by the following equation:

PMV = 3.155 (0.303$e^{-0.114M}$ + 0.028) l

Where M = metabolic rate

L = thermal load defined as the difference between the internal heat production and the heat loss to the actual environment for a person hypothetically kept at comfort values of skin temperature and evaporative heat loss by sweating at the actual activity level.

$$L\ (\text{Kcal}\ /\text{m}^2\text{hr}) = \frac{M}{A_{Du}}(1-) - 0.35\left[43 - 0.061\frac{M}{A_{Du}}(1-) - P_a\right] - 0.42\left[\frac{M}{A_{Du}}(1-) - 50\right] - 0.0023\frac{M}{A_{Du}}(44 - P_a) - 0.0014\frac{M}{A_{Du}}(34 - t_a) - 3.4\,.\,10^{-8} f_{cl}\left[(t_{cl}+273)^4 - (t_{cl}+273)^4\right] - f_{cl}h_c(t_{cl} - t_a)$$

$$t_{cl} = 35.7 - 0.032\frac{M}{A_{Du}}(1-) - 0.18\,I_{cl}\left[3.4\,.\,10^{-8} f_{cl}[(t_{cl}+273)^4 - (t_{cl}+273)^4] + f_{cl}h_c(t_{cl}-t_a)\right]$$

$$h_c = \begin{cases} 2.05\,(t_{cl}-t_a)^{0.25} & For\ 20.5\,(t_{cl}-t_a)^{0.25} > 10.4\sqrt{v} \\ 10\sqrt{v} & For\ 20.5\,(t_{cl}-t_a)^{0.25} < 10.4\sqrt{v} \end{cases}$$

Where:

t_{cl} = average surface temperature of clothed body, °F
f_{cl} = ratio of surface area of the clothed body to the surface area of the nude body.
A_{Du} = DuBois area (the surface area of the nude body (m2).
h_c = convection heat transfer coefficient, Btu/h ft2°F
t_a = air temperature, °F
I_{cl} = total thermal resistence from the skin to the outer surface of the closed body.
□ = external mechanical efficiency
P_a = vapour pressure in ambient air

The PMV equation considers the combined influence of the four environmental variables, activity level and clothing insulation on thermal comfort (Fanger, 1970; Yao Li et al., 2009).

One of the famous models that depend on heat balance approach is the so called two-node model (figure). This model treats with the body as two isothermal parts as heat transfers first from human body core to skin and then from skin to the surrounding environment. This model was developed by John B. Pierce Foundation at Yale University in 1970s (Gagge et. al., 1970). in 1977 and another similar two-node model developed at Kansas State University (KSU two-node model) that can predicts thermal sensation (TSV) differently for warm and cold environment (Azer and Hsu, 1977).

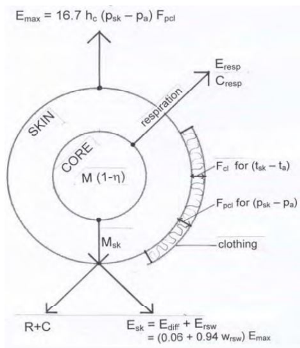


Figure 7.3 the two node model

The most recent version of the Pierce two-node model argues the notion of effective temperature (ET*) that defined as the dry bulb temperature of a uniform enclosure at relative humidity of 50%. Standard effective temperature (SET*) was derived from ET* and it was discussed by Gagge (1986) that it is the ET* in a standardised conditions by making the subjects wear standard clothing in a given activity in the real environment. SET* became the basis of ASHRAE standard 55-1992 (thermal environmental conditions for human occupancy) as it is more appropriate for the general everyday work environment.

8.5 QUESTIONNAIRE

Questionnaire	Researcher: Ali Sedki Yassin	Date: ....
Outdoor Climate Condition (to be filled in by the researcher): ………………………… Season (Summer – Winter): .... Outside air temperature: .... Relative Humidity: .... Sky:		
Occupant's name:	Gender: ▯ Male ▯ Female	Age: ....

1- For how many years you live here?

2- Number of family: Males: .... Females: ....

3- Number of Occupants who are existing in home during day and night:

Hour		Number of Occupants	The room where they are existing (Living room – Bedroom – Kitchen - .....)
From	To		

4- In which time do you switch on the light? Which room?

From	To	Room (Livingroom – Bedroom - ....)

5- Clothes that Occupant wear at home(put a sign on clothes that you usually wear)

▯ Short, long-sleeve shirt
▯ Short, short-sleeve T-shirt
▯ Trousers, short-sleeve T-shirt
▯ Trousers, long-sleeve shirt
▯ Trousers, short-sleeve shirt plus sweater
▯ Trousers, long-sleeve shirt plus sweater
▯ Trousers, long-sleeve shirt plus Jacket
▯ whole dress (Gelbab)
▯ Others (please specify): …………………

Clothes colors:
▯ Dark colors
▯ Light colors
▯ medium dark or mix colors

6- Occupant's everyday activity:

Activity	From	To	Room
Sleeping			
Seated quite			
Seated light activity			
Standing relaxing			
Light activity standing			

Medium activity standing			
High activity			
Cocking			
Others (please specify):			

7- How many appliances (T.Vs, Fans, Computers, Refrigerators, washing machines ... etc) you have at home?

Appliance	How many?

8- How do you open the windows during the day and night?

Room	From (opening time)	To(closing time)	Opening condition
Living room window			◯glass only ▯Blinds only ▯Both
Bedroom (1) window			◯glass only ▯Blinds only ▯Both
Bedroom (2) window			◯glass only ▯Blinds only ▯Both
Kitchen window			◯glass only ▯Blinds only ▯Both
Bathroom window			◯glass only ▯Blinds only ▯Both

9- How do you feel inside your apartment?

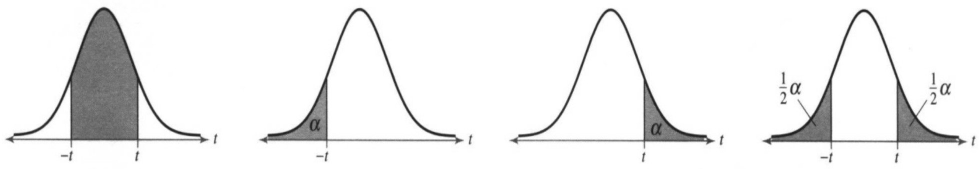
▯ Hot
▯ Warm
▯ Slightly warm
▯ Neutral
▯ Slightly cool
▯ Cool
▯ Cold

10- In which room do you feel more comfortable at your apartment?

11- Apartment orientation (to be filled in by researcher):

8.6 T-PAIRED TEST

Table 5—*t*-Distribution



c-confidence interval | Left-tailed test | Right-tailed test | Two-tailed test

d.f.	Level of confidence, *c*	0.50	0.80	0.90	0.95	0.98	0.99
	One tail, α	0.25	0.10	0.05	0.025	0.01	0.005
	Two tails, α	0.50	0.20	0.10	0.05	0.02	0.01
1		1.000	3.078	6.314	12.706	31.821	63.657
2		.816	1.886	2.920	4.303	6.965	9.925
3		.765	1.638	2.353	3.182	4.541	5.841
4		.741	1.533	2.132	2.776	3.747	4.604
5		.727	1.476	2.015	2.571	3.365	4.032
6		.718	1.440	1.943	2.447	3.143	3.707
7		.711	1.415	1.895	2.365	2.998	3.499
8		.706	1.397	1.860	2.306	2.896	3.355
9		.703	1.383	1.833	2.262	2.821	3.250
10		.700	1.372	1.812	2.228	2.764	3.169
11		.697	1.363	1.796	2.201	2.718	3.106
12		.695	1.356	1.782	2.179	2.681	3.055
13		.694	1.350	1.771	2.160	2.650	3.012
14		.692	1.345	1.761	2.145	2.624	2.977
15		.691	1.341	1.753	2.131	2.602	2.947
16		.690	1.337	1.746	2.120	2.583	2.921
17		.689	1.333	1.740	2.110	2.567	2.898
18		.688	1.330	1.734	2.101	2.552	2.878
19		.688	1.328	1.729	2.093	2.539	2.861
20		.687	1.325	1.725	2.086	2.528	2.845
21		.686	1.323	1.721	2.080	2.518	2.831
22		.686	1.321	1.717	2.074	2.508	2.819
23		.685	1.319	1.714	2.069	2.500	2.807
24		.685	1.318	1.711	2.064	2.492	2.797
25		.684	1.316	1.708	2.060	2.485	2.787
26		.684	1.315	1.706	2.056	2.479	2.779
27		.684	1.314	1.703	2.052	2.473	2.771
28		.683	1.313	1.701	2.048	2.467	2.763
29		.683	1.311	1.699	2.045	2.462	2.756
∞		.674	1.282	1.645	1.960	2.326	2.576

8.7 RELATED PUBLISHED WORK

Journal Papers:

- Sedki A., Hamza N., Zaffagnini T. (2013). Effect of Orientation on Indoor Thermal Neutrality in Hot Arid Climates - Case study: residential building in Greater Cairo. *Int. journal of Engineering and Technology (ijet)* (issn: 1793-8244), pp. 712 - 716.

- Sedki A., Hamza N., Zaffagnini T. (2013). Effect of Orientation on Indoor Thermal Neutrality in Summer Season in Hot Arid Climates. *The Journal of Macrotrends in Applied Science*, paris, france.

Conference Papers:

- Sedki A., Hamza N., Zaffagnini T. (2013). Field Measurements to Validate Simulated Indoor Air Temperature Predictions: A case study of a residential building in a hot arid climate. *IBPSA Egypt, 1st Conference about Building Simulation Contributions in Built Environment in Egypt*, Cairo, Egypt, June 2013, pp. 338 – 347.

- Sedki A., Hamza N., Zaffagnini T. (2013). Indoor Summer Field Measurements to Validate Simulated Air Temperature Predictions in a Hot-Arid Climate Region. *SB13 Dubai International Conference*, Dubai, UAE.