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WELSH SCHOOL OF ARCHITECTURE
Centre of Research in the Built Environment

The Thermal Analysis of Traditional Adobe Dwellings in Riyadh City, Saudi Arabia

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BY

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Dedicated to:

The Soul of My late father Talal

for his love, support and encouragement in the years of my life.

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Abstract

Global warming is being introduced into our ecosystem as one of the most dangerous instabilities. As a result, the choices we make in the way we use energy in our homes and their relationship to global warming is becoming increasingly crucial. Energy used in Riyadh homes is responsible for about 88% of the total electrical consumption of the city. Saudi Arabia also suffers from environmental problems due to pollutants that are produced by electricity consumption in Saudi Arabia, mostly generated by the use of gas. This is a major contributor to global warming and, therefore, improved energy efficiency is a key element of necessary changes.

The purpose of the research presented here was to determine if there was any potential in the adaptive re-use of traditional adobe dwellings in Riyadh City to reduce overall energy use. As these buildings were originally designed to adapt to the climate without using additional or auxiliary energy not already present on their site, they may be able to meet the thermal comfort requirements of modern occupants at only a fraction of the energy cost of modern western-style buildings currently popular in Riyadh. Thus, the work involves an analysis of the thermal performance of these dwellings to develop an understanding of exactly how well they are adapted and to measure how they perform.

This study reviews traditional building characteristics of Saudi in general and Riyadh traditional buildings in particular, and also of modern building. In addition, field measurements were conducted to assess the actual thermal performance of traditional adobe dwellings in Riyadh City, Saudi Arabia.

A range of computer programs have been used throughout this investigation to predict the best passive cooling strategies that can be used in hot weather. These models were then used to determine the design parameters to which the different passive systems were most sensitive.

The findings of this work showed that, using only passive cooling strategies, it is possible to reduce average internal temperatures in these buildings by 4-6°C, and peak temperatures by as much as 12°C. This required the careful control of ventilation at all times, making use of night-cooling and the conditioning of daytime air using evaporative systems within the courtyard. Parametric analysis showed that the spaces were most sensitive to internal gains and ventilation effects, and relatively insensitive to solar and orientation effects. Interestingly, there was some sensitivity to surface colour, suggesting that the whitewashing of exposed surfaces is beneficial if they can be kept sufficiently.

Finally, recommendations have been produced from the analysis to inform the restoration and refurbishment process.

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CHAPTER ONE

INTRODUCTION

1.1 Introduction

"Architecture which was really architecture preceded from the ground and ... somehow the terrain, the native industrial conditions, the nature of materials, and the purpose of the building[1-1]*."*

Over the last 60 years in Saudi Arabia, towns and villages have developed significantly due to the strong economic growth resulting from the discovery of oil. This development was paralleled by rapid population growth occurring in all regions of the country. The Riyadh area was one of these regions. As a result, in the nineteen eighties, Riyadh saw enormous growth and became one of the most developed regions in Saudi Arabia. (Figures 1-1 and 1-2) show the urban growth of Riyadh from 1972 to 1995.

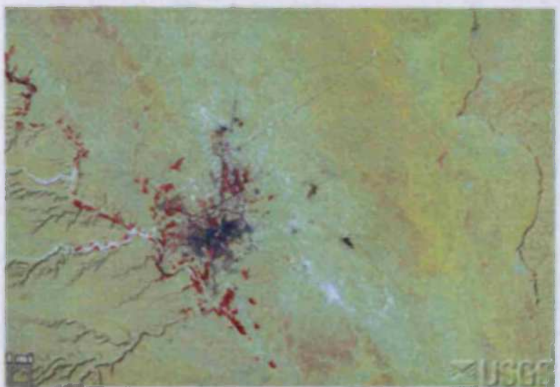


Figure (1-1) Riyadh 1972. Source: USGS [1-2].

Figure (1-2) Riyadh in 1995. Source: USGS [1-2].

The need to provide new buildings in Riyadh region in the early twentieth century was largely satisfied by the production of local people. Riyadh's traditional architecture had developed over centuries in response to the needs of its people and their physical environment. The architectural style was based on the demands of life in this hot and dry region. The construction of the buildings was mainly dependent on simple construction methods provided by local builders and the availability of local materials from the surrounding area. There were no imposed building regulations, thus traditional buildings were a reflection of the culture of society and were highly adapted to the predominant climatic conditions, reflecting local understanding of the harshness of the environment. Buildings were sited with respect for the solar conditions, with the ability to shade each other and with every endeavour was made to utilize wind movement effectively for cooling, using techniques such as central court yards, wind catchers and *Mushrabiyah* (external wooden shading devices). The result of these techniques was a building style that relied on natural energy sources to provide an acceptable level of comfort to the indoor environment.

An example of the techniques used in traditional building was the wall. The thermal mass of traditional materials which were used in wall construction (mainly clay) also played a very important role in absorbing additional heat and therefore reducing overheating in the hot and arid climate of the area.

Following oil production in 1960, and the subsequent massive population growth, many new housing projects were built to meet the need, generating large-scale urban development. New building and urban regulation systems that had been followed in most developing countries were then introduced. Foreign designers provided a source of new and interesting concepts of building design which, overt time, have proved inadequate for the people's needs and for local conditions [1-3].

The direct application of foreign (Western) architectural design forms and guidelines have resulted in the current trend of modern buildings in Riyadh, which display a distinct lack of understanding of the local climate and even less consideration for the use of local building materials or domestic skills and traditions. Despite their high construction, running and maintenance costs, these buildings cannot provide comfortable indoor conditions without the use of auxiliary mechanical cooling systems. Neglect in the use of natural resources in these modern designs results in high energy consumption. In recent years people have suffered from the high cost of energy needed in their home to provide necessary conditions of comfort throughout the year. Consequently, the inhabitants of these houses are constantly trying to modify the poor quality of their thermal comfort by different means (see Figure 1-3). Once these building are occupied, their inhabitants begin by refurbishing the inside and outside building facades and adding more air conditioning units in a search for comfort.


Aluminium sheets


Hung mats


Concert block


Adding A/C


Steel sheets


Wood board

Figure (1-3) Houses modified by inhabitants as a result of poor thermal quality. Photo by author.

The cost of electricity bills paid by consumers has increased dramatically, especially during peak times. In 1994 the electricity price doubled compared with 1975 [1-4], as a result of increasing demand from the number of new buildings and inefficiencies in the utilisation of electrical energy. The total energy generated in the central region of the country during the last decade has doubled, with more than 50% of this used for air conditioning of buildings during summer [1-4].

Due to this high consumption of energy, the Ministry of Industry and Electricity (MIE) has realised that serious consideration must be given to energy conservation and increased efficiencies where significant savings could be achieved through simple rationalisation.

Without such consideration, consumption of fossil fuels will reach unsustainable levels, and will also result in increased air pollution which is linked to the greenhouse effect and ozone depletion [1-5]. There is, therefore, a significant responsibility for both authorities and design architects, who plan and manage the living environments of people, to take into account ways of reducing the demand for energy in buildings and to provide a better quality environment by producing building designs with a greater respect for local climate considerations.

1.2 Statement of the Problem

1.2.1 Global Scale

According to accepted theories [1-6], the relationship between global warming and methods of using energy in homes is becoming increasingly interconnected and crucial. Energy used in the heating and cooling of homes is accepted as a major contributor to 'Global Warming' and therefore, improved energy efficiency is a key element to necessary changes. Awareness of the increased need to conserve energy became of worldwide interest during the oil crises in the nineteen seventies and subsequently as the polluting effects of fossil fuels were better understood [1-7].

Until the 19th century when people started using fossil fuels in large quantities, there was no significant human intervention on the Earth's climate [1-8]. With the industrial revolution and the need of western societies for more energy, provided by many fossil fuels, the climate balance has been markedly altered. The burning of large amounts of fossil fuels produced a huge amount of carbon dioxide in the Earth's atmosphere. While carbon dioxide allows solar radiation (short-wave radiation) to reach the Earth's surface, it does not allow thermal radiation (long-wave radiation) to be released from the Earth's surface and emitted into space. Therefore, by increasing carbon dioxide concentration in the atmosphere, more long-wave radiation is trapped in the atmosphere, making air temperatures rise (the greenhouse effect) [1-9].

It is estimated that global warming of the planet through the use of fossil fuels in the 20th century is 0.8°C [1-8]. Although this may not seem to be particularly high, as Godrej says:

> "*When we are ill with a fever, our body temperature changes from being 'normal' at around 36.7°C to fever pitch at 37°C. This tiny increase of 0.3°C switches us from feeling well to feeling sick. This sensitivity of the human body to temperature changes is one way of appreciating the phenomenon of climate change (powered as it is by global warming) which has taken up permanent residence in the world's headlines*".

Today people are increasingly concerned about the problem of global warming. Governments and the United Nations are being forced to take action. As a result, the United Nations has started investigating the problem by organising research and conferences to decide how to reverse the phenomenon. One of the main outcomes has been a decision that the amount of carbon dioxide generated by human activities and entering the atmosphere should be reduced.

Starting with the 1972 conference in Stockholm, continuing with the Rio Declaration in 1992 and ending with the Kyoto Protocol in 1997, governments all around the world are constrained to take some action to prevent global warming. According to the Kyoto Protocol, countries have to ensure that their own carbon dioxide emissions are reduced by 20% in 2010 from 1990 levels.

Agenda 21 was established within the Rio Declaration in 1992, concerned mainly with energy consumption in buildings and human settlements. It referred to architects, engineers and the decision makers who deal with the design of buildings and cities [(1-10)]. According to Agenda 21, building energy consumption should be reduced and energy generated by fossil fuels in the building sector should be replaced as far as possible with renewable energy sources (solar energy, wind energy, biomass, geothermal energy).

1.2.2 The Saudi Perspective

In 2004 Saudi Arabia approved the Kyoto Protocol treaty on climate change, and global warming has already begun to be noticed in the area [(1-11)]. The weather has started changing in the Kingdom and in neighbouring countries during recent decades, especially in summer months where the concentration of pollutants has increased significantly. This leads to an increasing rainfall in some parts of the peninsula. It is predicted that climate change over the next three decades will cause more extreme heat waves in summer in countries on the Persian Gulf and the Red Sea coast [(1-12)]. Also, people's awareness of environmental issues has increased and the government has a responsibility to protect its citizens from environmental hazards.

The government adopted the Basic Law setting for the country and the obligations of the government to the people of Saudi Arabia. Article 32 of the Basic Law states that:

> *"The state works for the preservation, protection, and improvement of the environment, and for the prevention of pollution"*[(1-13)].

The Public Environmental Law of the government generates a general regulatory structure for the development and enforcement of environmental rules and regulations, and assigns general responsibility for this to the Presidency of Meteorology and Environmental Protection (PME). Among the responsibilities of the PME are:

- Conducting environmental studies;
- Documenting and publishing the results of any environmental studies;

- Preparing, issuing and reviewing relevant environmental standards;
- Ensuring compliance with relevant environmental standards;

Saudi Arabia's energy consumption has been growing significantly during the last decade, as illustrated in Figure (1-4).

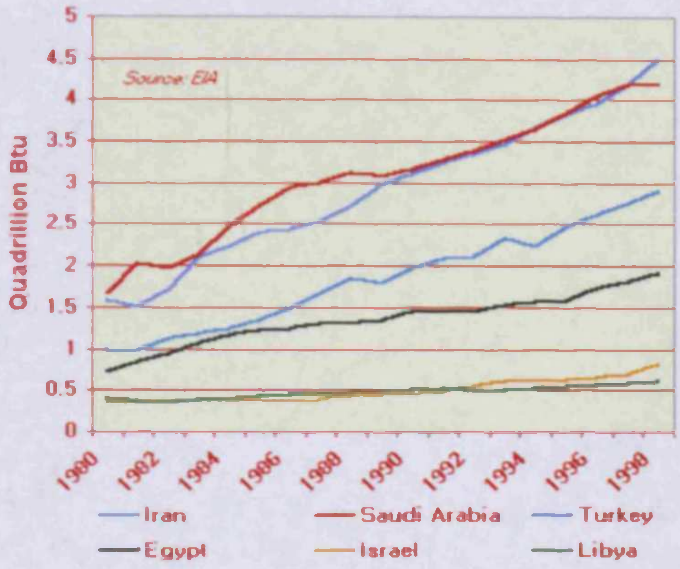


Figure (1-4) Total energy consumption in Saudi and its neighbour countries. Source: EIA [1-12].

According to the report of the International Energy Agency (IEA) about Saudi Arabia's electric power-generating capacity, the country's rapidly growing population and rapid development places increasing demand on electric utilities, as power demand grows by 4.5% or more each year [1-12]. Saudi Arabia's Industry and Electricity Ministry estimates the country will need up to 77,000 gigawatts (GW) of total power generating capacity (compared to 26,600 GW currently, of which about 65% is gas-fired) at a cost of more than $117 billion by the year 2023 [1-12].

In the meantime, new industrial projects have been delayed and brownouts have occurred due to insufficient power supplies, especially during the summer peak cooling demand season [1-14]. Owing to the fact that buildings play a very important role in terms of energy consumption in Saudi Arabia, in 1999 the government started encouraging consumers to turn off their air conditioning when away from home to reduce the huge amount of energy which is wasted. Air conditioning is an important factor which accounts for as much as 70% of energy use in the Kingdom's buildings [1-12]. This can be seen clearly in Figure (1-5), where the electrical energy consumption is shown compared to the air temperature in Riyadh city on 13 August 2001, a working day (Monday). It is obvious from the graph that, when the air temperature rises, the peak loads happen and when the air temperature falls, the electric load follows its downward curve. This clearly demonstrates that air conditioning is a major electrical load in the area.

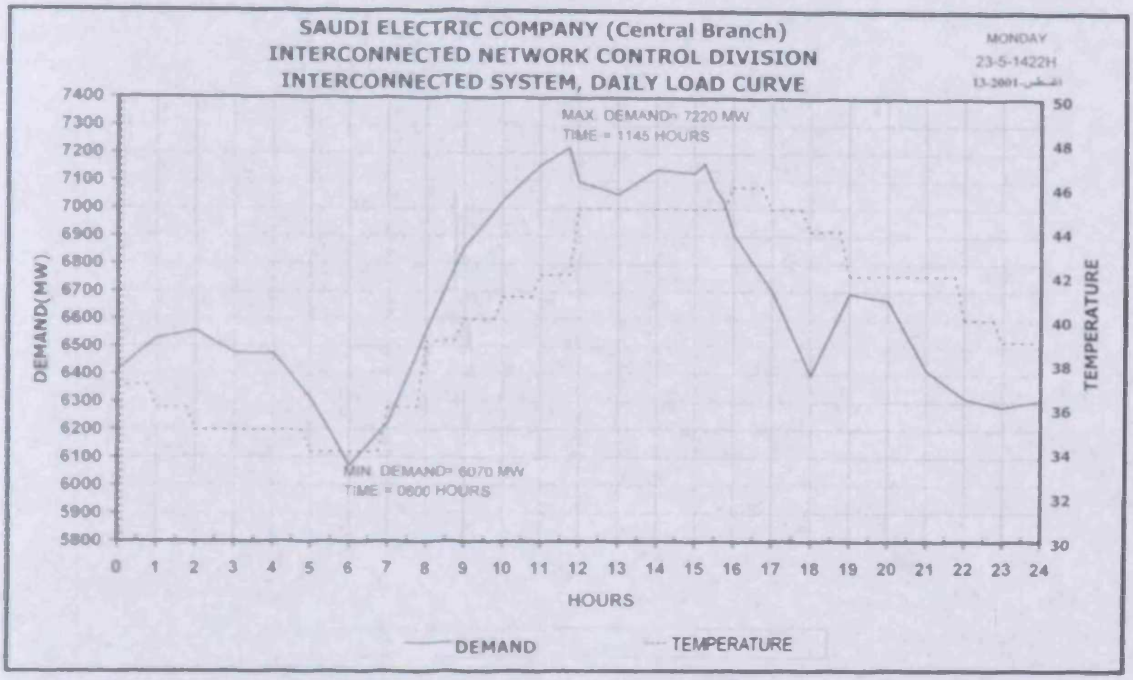


Figure (1-5) Electrical load curve for 13-8-2001. Source: SCECO [1-4].

Most of the energy that is consumed in buildings in Saudi Arabia is electricity. In the instance of Riyadh city, the building sector accounts for more than 88% of the total electrical consumption of the city, as seen in Figure (1-6).

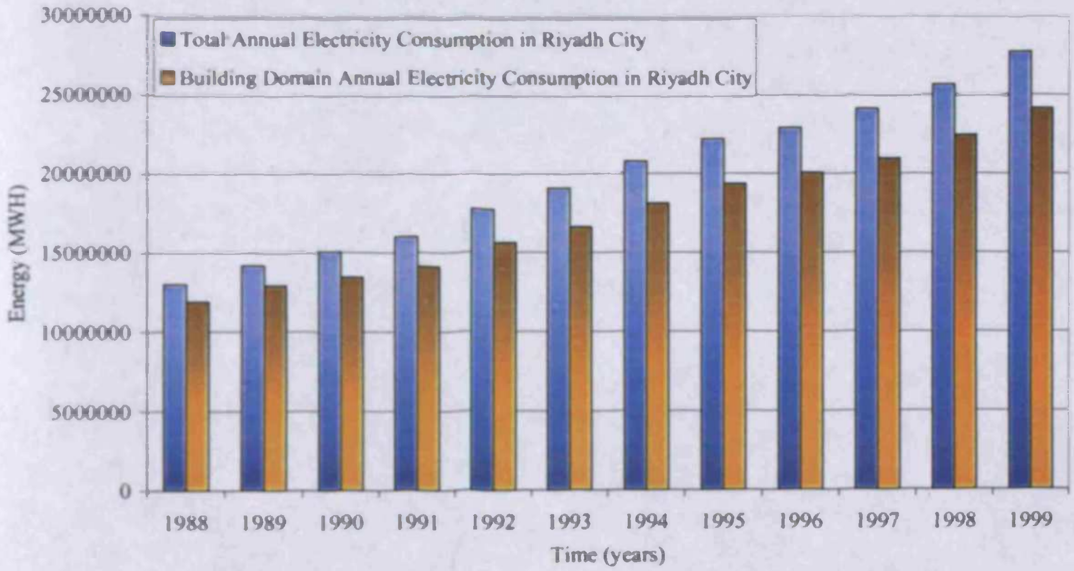


Figure (1-6) Electrical energy consumption in Riyadh City, by author using SCECO report [1-4].

Apart from the problem of demand in respect of energy, Saudi Arabia also suffers from environmental problems due to pollutants that are produced by this huge energy consumption, as electric energy in Saudi Arabia is largely generated by the use of gas [1-11]. In the last 20 years, a huge amount of carbon dioxide has been produced in the area. Carbon emissions have risen from 48.8 million metric tons of carbon emitted to 74.8 million metric tons (see Figure 1-7) [1-12]. This, as was mentioned at the beginning of the section, can lead to local climate change (increase of temperature and rainfall) and other undesirable consequences such as a threat to the health of inhabitants and the ecosystem [1-8].

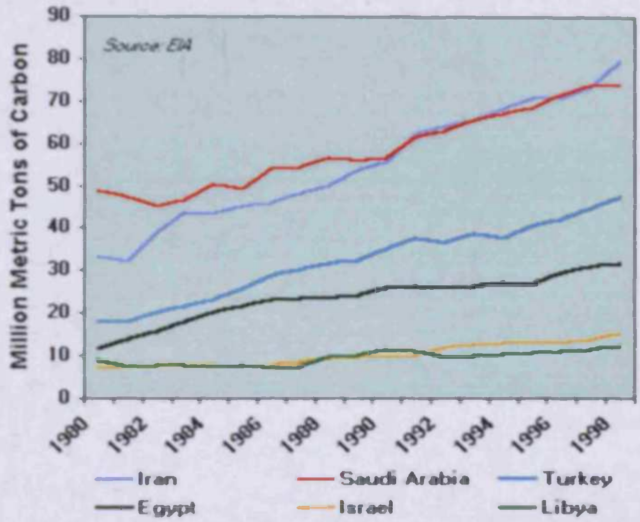


Figure (1-7) Energy related carbon dioxide emissions. Source: Penny Energy [1-12].

However, it seems that energy conservation in Riyadh city and other parts of the country needs to be urgently taken into consideration by the authorities and people because a large part of the energy that is consumed in the country is wasted in the building sector. If this does not happen, generations to come may have a vast problem to deal with. Thus, energy conservation has become an important target for the Saudi government and is supported by the Deputy Minister for Electricity Affairs, Al-Tuwaijri, who believes that:

> *"The demand is very high during summer, mainly due to air conditioning consumption, lack of thermal insulation usage in all buildings, as well as the implementation of proper energy conservation methods and the appropriate techniques for load management. Energy conservation became an important target for the KSA because it is believed that a great potential of energy saving can be achieved"* [1-14].

1.3 Adaptive Re-Use

There are dwellings in many areas of Saudi Arabia, including Riyadh City, that were constructed many years ago using traditional adobe-brick techniques. Whilst some of these are still used, the majority are unoccupied and falling into disrepair. However, as shown in Figure (1-8) they make up a significant portion of central Riyadh City. It is argued here that these buildings are much better adapted to local climatic conditions and, as a result, can provide a relatively comfortable internal living environment without the need for high levels of additional energy for cooling. Thus, if these buildings can be effectively adapted for modern use, they represent a significant opportunity to provide large numbers of low-cost, energy-efficient housing.

Figure (1-8) Adobe houses in Riyadh city. Source: Archnet [1-15].

Obviously there are social and cultural issues regarding the suitability of this type of housing with modern lifestyles. However, given the wide diversity of people and cultures now present in the modern metropolis of Riyadh City, it is assumed here that there are many people, families and marketers innovative enough to adapt these buildings into functional communities as they once were. However, for this to happen, the economic benefits and regulatory incentives have to be sufficiently attractive.

Thus, the very first question to be answered is whether these dwellings will actually be more energy efficient. If used correctly, will the residents be able to achieve acceptable levels of comfort without resorting to the kinds of energy-intensive retrofit technologies required of modern buildings?

1.4 Hypothesis

The fundamental hypothesis on which this work is based is that ***these traditional buildings are in fact well adapted to local climatic conditions and can provide acceptable thermal comfort conditions with only minor modifications and without requiring the retrofit of a modern air conditioning system.***

1.5 The Aims and Objectives of the Study

This work therefore attempts to analyse the thermal performance of traditional dwellings in the hot, arid region of Riyadh City, Saudi Arabia. The aim is therefore to ***analyse the thermal performance of traditional adobe buildings to develop an understanding of exactly how well these buildings are adapted to local conditions and to quantify how they perform thermally. It will also investigate techniques by which their performance can be improved.***

The study will attempt to achieve this through an understanding of the climatic conditions of the area and the thermal performance of different kinds of traditional building design in Saudi regions, with particular concern for the user's thermal comfort. To fulfil the main aim of this study, the following objectives have been drawn:

- To study the climate of Saudi regions and to investigate and analyse the climate data of Riyadh for the whole year.
- To review the literature on traditional buildings design in Saudi regions in general and Riyadh in particular.
- Conduct field measurements of thermal performance in traditional buildings in selected rooms to help to understand how they perform.
- Use computer simulation to predict the thermal performance of traditional houses.
- To investigate the thermal impact of applying different passive strategies to the internal condition of traditional houses.

1.6 Research Scope and Limitation

There are many aspects to the problem of Saudi Arabia houses, particularly in Riyadh. Among these are economic aspects, energy consumption, environmental consideration, socio-cultural needs. Each aspect is very important as a link in the sequence of building development. Despite being interrelated in many dimensional complexities, these aspects cannot be handled all together in a piece of research such as this. Therefore, the scope of the research problem has to be well defined. Thus, dealing with the housing problem in terms of energy consumption (thermal performance) in a simplified manner, as if it were one general problem, could hinder a proper understanding. Consequently, this research has mainly concentrated on the means of analysing the thermal performance of a range of existing traditional houses in Riyadh City. Riyadh has been selected as the main area of investigation of this research due to the fact that Saudi Arabia is divided into five regions; each region has its own traditional style of buildings and different methods of construction. In addition, local builders use different skills and materials to provide shelter to people's houses. This study will briefly survey the traditional types of dwellings over the country as a whole (tents, reed construction, stone buildings and adobe buildings), as well as modern buildings in general. It will then focus on the traditional building of the Riyadh region as a case study. Furthermore, Riyadh, as the capital city of Saudi, was selected as the main domain for research investigation because it is the largest Saudi city in terms of population and area, and is therefore severely affected by the energy consumption problem. It was estimated that the city population would exceed 10 million in 2025 (compared to five million in 2003) [1-3]. As a result of a rapidly expanding population, many public and private houses have been developed within the city and in new urban settlements in its suburbs to cover the high demand for housing in Riyadh.

Finally, the fact that the researcher has lived and work in Riyadh for a long time increases his knowledge of and familiarity with Riyadh's historical and current patterns of housing and urban development. This knowledge and familiarity was utilised in facilitating access to the various sources of information. As a result of these conditions, it was considered that Riyadh would be a suitable field for investigation of the issues addressed in this study.

1.7 Research Methodology

The research methodology chosen to fulfil the main aim of this study comprises five different stages:

- **Examine the characteristics of climatic regions in Saudi Arabia, with special reference to the immediate Riyadh region.**
  The analysis of the climatic context for all Saudi regions is essential as it will provide an understanding of the differences in climatic characteristics, as well as other factors such as topography and location, that have influenced the design of traditional buildings. Additional, it will examine how traditional designers built and dealt with these influences. In achieving this, the study will use different tools for analysing and quantifying climatic performance, beginning with simple classification tools (Mahoney's Table diagram) and proceeding to modern tools (Bioclimatic analysis as used in the Weather Tool software),

to provide a general indication of the basic recommendations for designing buildings according to the climatic data available.

- **To review the literature on traditional building design in Saudi Arabia as a whole and Riyadh in particular.**
  In Saudi Arabia each region developed a very characteristic traditional architecture better suited to the climate, geography, topography and local building materials. Through an understanding of the variation in methods of design and construction used in traditional houses in each region, it is possible to explore the effect of climate on building performance and to investigate how traditional architecture managed to adapt to the hot and arid climate of the area. This will also include a review of the literature in the field of traditional building types, as well as modern construction and the problems resulting from rapid development. The study will then focus on Riyadh's traditional building type and methods of construction.

- **Field Measurements of Thermal Performance in Traditional Buildings.**
  In order to assess the thermal performance of traditional building, field experiments and measurements of selected traditional buildings in Riyadh City will be carried out. The field measurements are intended to assist in the calibration of computer models used in the thermal simulations and predictive modelling, enabling predicted results to be directly compared with measured data. The collected measurements from the case studies can provide a significant practical situation of the performance of case studies houses [1-16].

- **Conduct a series of computer simulations of the example buildings.**
  This stage involves the generation of comprehensive computer models of the measured buildings. The aim is to compare measured data with the results of computational simulations in order to gain a better understanding of the models themselves and greater confidence in the applicability of these models to the real situation. Further to this aim, the results of three different thermal analysis tools will be compared, not just a single tool. Obviously the results of the simulations will not be directly comparable to the measured data, for reasons that are discussed in depth later in the thesis, however the informal comparison and investigation of differences will greatly inform subsequent simulation processes.

- **Investigate the thermal impact of the application of different passive strategies in traditional houses.**
  Once a set of comprehensive computer models of the measured buildings have been generated and confidence has been established in their output, the next stage is to use these models to predict the potential effects of a range of different design strategies aimed at improving occupant thermal comfort.

1.8 Justification for the Research

When looking at research into the approaches to the housing design problems in Saudi Arabia in particular and in Arab-Muslim cities in general, only a small number of studies take into consideration building performance and environmental design issues. Several writers have highlighted the problems of culture and climate. However, most of these researchers discuss the problem from either a social, cultural or urban pattern point of view and mainly investigate the problem of house privacy. Numerous writers, such as Mousali (1977) [1-17] Daghistani (1985) [1-18] Akbar (1980) [1-19] Talib (1984) [1-20] and many others, have investigated these cultural and climatic problems in the context of Saudi Arabia and other Arab countries. They investigate how the principles of the traditional built environment of Arab-Muslim cities were influenced by the introduction of imported modern technology.

In the Saudi Arabian context, some other researchers have attempted to assess governmental policies for producing formal low-cost housing in new development areas or, like Al-Gabbani (1996) [1-21] and Al-Hemaidi (1996) [1-22], to measure the satisfaction of house users. Others have tried to determine whether inherited social and religious principles could be used to control the housing process, as they may have been controlling the transformation process in formal and informal housing in the past throughout Saudi traditional housing. Religious and inherited social principles have been documented by several writers such as Akbar [1-23], and Al-Hathloul [1-24]. An example of these books is: *Crisis in the Built Environment the Case of Muslim City* by Akbar (1998) and *The Arab-Muslim City: Influence of Islamic Role on Producing Urban Environmental* written in Arabic language by Al-Hathloul (1994).

Many others are limited only to the documentation or monitoring of different traditional housing elements, focusing on issues of standardization, aesthetic decoration and their conditions, or on the evaluation of the user's attempts at transformation, without searching in any depth the environmental performance of the dwelling or the environmental impact of the building process or its operation. Such research was published by Al-Hussayen in 2002, his study aimed at documenting *Ar Rawshan* (wooden screen placed on window) as the most important element of traditional house facades in Al-Madinah City. His study concluded that the significance of designing *Ar Rawshan* is an aesthetic uniqueness of ornamented and engraved units [1-25]. It also investigates the techniques used to construct the *Ar Rawshan* as well as its light controlling characteristics when viewed from different angles. Another example was published by Eben Saleh in 2001, who aimed to investigate the decoration of space and façade of Riyadh traditional buildings [1-26].

Most of the research in this domain is oriented towards social, political and economic approaches, with very few developed from an energy performance or environmental viewpoint. Thus climatic performance in these above mentioned studies, and in fact some others, was not considered an issue to be improved or assessed. Therefore, studies on the topic of environmental housing design in Saudi are very few in number. Indeed, there is a lack of research dealing with purely environmental aspects of the building and design processes. In particular, there are very few examples of research into the relationship between housing and c limate, which might provide valuable data for the development of regionally appropriate building technology design.

However, it is worth mentioning that the following section will focus on research that has been found investigating the thermal performance of modern and traditional buildings and on the studies that were carried out in the hot and arid climate of Riyadh, in particular, and the work made similar to these types of buildings.

One of the earliest studies that has been done in Riyadh City was carried out by the Egyptian architect Hassan Fathy between 1973 and 1975 [1-27]. He designed two prototypes for a single residential unit after studying traditional adobe houses in the Dirr'iyah area in Riyadh City. The documents, which include a survey of a typical existing house in the village, carefully show how each of the rooms relates to an interior courtyard. One of these prototypes was actually built, as seen in Figures (1-9, 1-10, 1-11), but because the government was against the prototype it was not widely applied and fell into disrepair. Thus, complete information was not available and it is very difficult to take the study result of that prototype. (Hassan Fathy's prototype proposal is explained further in Appendix A of Chapter One).

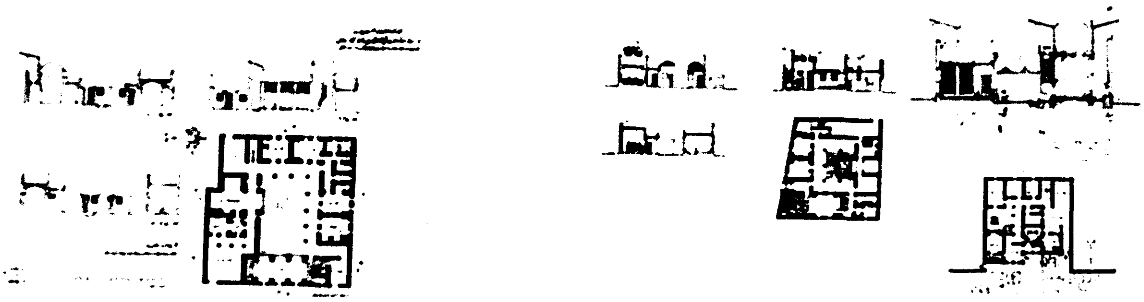


Figure (1-9) The prototype of Dirr'yah houses designed by Hassan Fathy. Source: Archnet [1-15].

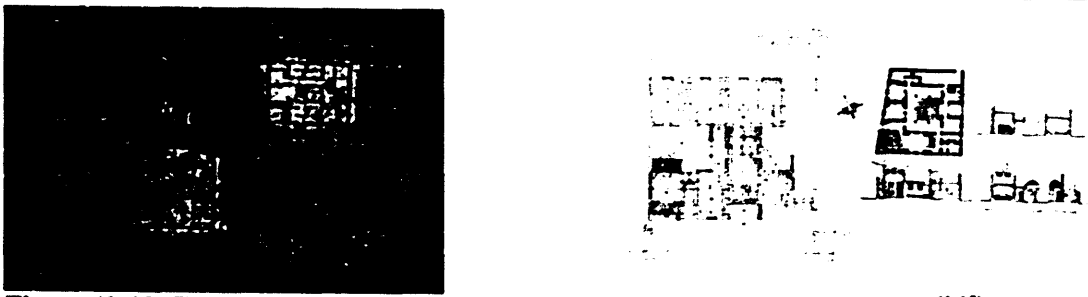


Figure (1-10) Hassan Fathy designed in the Dirr'yah area. Source: Archnet [1-15].

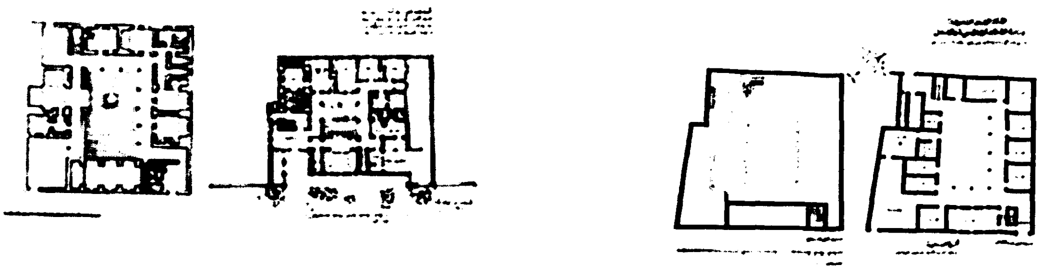


Figure (1-11) Hassan Fathy's prototype houses in Dirr'yah. Source: Archnet [1-15].

In addition, Hassan Fathy [1-28] conducted an experiment in Cairo (1964) to assess the cost and local availability of a number of rooms being built using different materials. Of these rooms, one was built completely of adobe brick with 50 cm thick walls and a roof in the shape of a combined dome and vault. The other was built of 10 cm thick prefabricated concrete panels for both the walls and the roof. Plans and sections of these buildings are given in Figure (1-12).

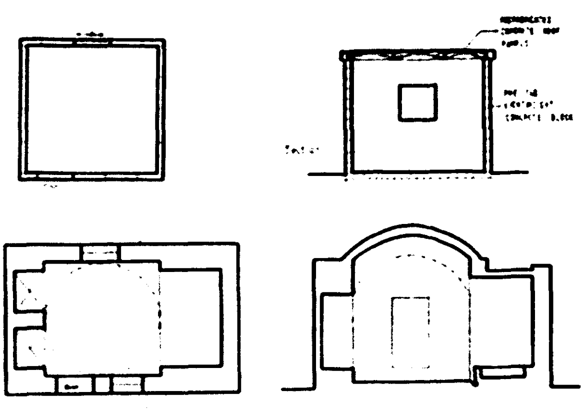


Figure (1-12) The two different models used in the (BRC) research. Source: Hassan Fathy [1-28].

According to Hassan Fathy, the problem with this research is that the experiment was not evaluated during the important period of the year (salient dates of the equinoxes and summer and winter solstices) which may have provided more complete information [1-28]. However, it is very difficult to take the result of this experiment as an example model to be applied in different weather such as that of Riyadh, which is quite different from that of semi moderate Cairo. Even if the experiments were made for the whole year, the results of the buildings' performance would not be very similar to the results made in a hot and arid climate. Also, the method of adobe house construction that was used in the roof was different: the roof in Fathy's experiment was constructed as a dome, while in Riyadh houses roofs are mostly flat.

However in 1981 Mofti conducted a survey by questionnaire to determine the knowledge held by middle income families in Riyadh, Saudi Arabia of traditional and modern houses, regarding the factors of culture, economics, climate and technologies. His questionnaires used for its measure a scale from 0 to 10, with 0 representing the lower value and 10 the higher value (Mofti's questionnaire is explained further in Appendix A). The final outcome of the questionnaire showed that respondents preferred the traditional to the modern houses, with the traditional house graded at a higher value at 8.32 in suitability to the above mentioned factors and modern houses at 4.12, as can be seen in Table (1-1) [(1-29)].

It should be mentioned here that in Mofti's field study work there were two questions (Q7 and Q11) with particularly important connotations for this study. In question seven, respondents were asked to evaluate how effectively the house types (traditional and modern) coped with the following: temperature, solar radiation, light and glare, wind, sand storm and low humidity. In question eleven, respondents were asked to evaluate how suitable was the cooling of traditional and modern houses in terms of comfort, materials, temperature, humidity and maintenance expense. The answer in Figure (1-13) reveals that traditional houses received the highest rating of 8.18, followed by the modern buildings at 4.05 in terms of effectively utilising the natural climate, while the traditional houses received the highest rating of 8.08 followed by the modern at 4.05 in terms of comfort, materials, temperature, humidity and maintenance expense. The answers for both questions indicate that, in spite of people's constant selection of traditional housing rather than modern buildings in respect of different type factors, they are searching for traditional building techniques which are regularly better than modern housing in meeting cultural, economic and climatic demands, as can be seen in Figure (1-14). In general, the results of this research offer a good indication that traditional building in Riyadh certainly required further exploration and that it is important to carry out the investigation of such traditional housings, as energy is important, particularly where energy-conscious design is concerned nowadays.

Table (1-1) Summary of Mofti's questioners results by author.

Question		Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}	Q_{12}	Ave.
Means	**Traditional**	**7.66**	**8.55**	**8.22**	**8.12**	**7.33**	**8.02**	**8.18**	**8.58**	**8.26**	**5.74**	**8.08**	**8.32**	**7..92**
	Modern	**4.46**	**1.14**	**4. 50**	**4.20**	**5.35**	**5.26**	**4.05**	**3.68**	**3..55**	**7.78**	**4.05**	**4.12**	**4.60**
Standard Deviation	Traditional	1.47	1.09	1.35	1.32	1.60	1.59	1.78	1.11	2.14	1.34	1.49	1.33	1.47
	Modern	1.85	1.74	1.81	1.53	2.23	1.72	1.40	1.38	1.93	1.50	1.60	1..54	1.69
Percentage of 7 or >	Traditional	86.00	94.00	90.00	90.00	62.50	86.00	95.00	92.40	34.00	90.30	86.90	92.00	83.26
	Modern	12.00	14.00	18.00	10.00	21.00	20.00	4.00	2.80	80.00	7.00	10.40	6.50	17.14

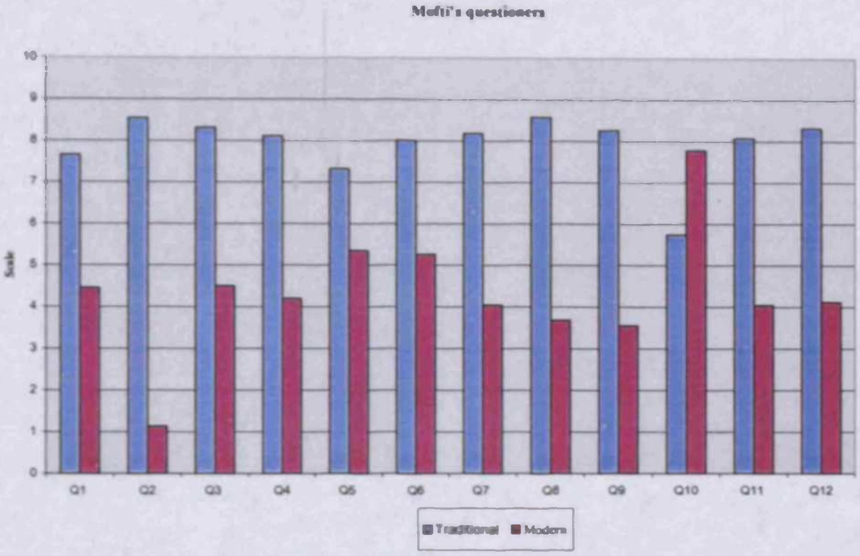


Figure (1-13) Summary Mofti's questioners by author.

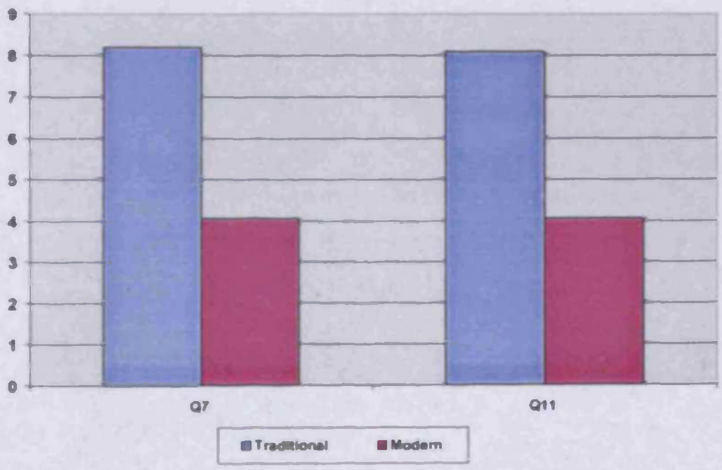


Figure (1-14) Mofti's Q7 and Q11for both traditional and modern houses by author.

Another study has also shown the importance of traditional buildings, but from the urban design point of view, carried by Al-Hemaidi W. in 2001. He has highlighted the sources and evidence of social and climatic problems created by the imported urban forms and planning regulations, focusing on some particular aspects of the urban pattern. The aim of his study is to identify and analyse the types of built environment in Riyadh, and to discuss the cultural conflicts resulting from the use of imported planning prinoiples and regulations. Al-Hemaidi's study showed that most of the imported urban design and spatial organization have been rejected by the residents because of their physical and behavioural implications. However, among the results of Al-Hemaidi's works, there was especially significant connotation for this study. His results showed that the traditional built environment of the city of Riyadh was planned and designed according to the cultural and social values of its people and was appropriate to the climatic conditions of the region. This traditional built environment provides a natural solution to the harsh climatic problems of the region [1-30].

In terms of technical research related to the climatic performance of buildings, or improved and sought after in the building elements, there were three studies searching in this domain in general and not specifically focused on thermal performance. The *first* one was conducted in 1987 by Al-Megren [1-31]. His study was focused only on the application of wind tower on modern buildings in hot arid areas. The *second* was carried out in 1995 by Al-Hemiddi [1-32]. He conducted an experiment to investigate the applicability of three passive cooling systems in a full size concrete room. The *third* is the most up to date research done in this field, carried out by Al-Bakri [1-33] in 1997. It investigated the means of natural ventilation in the triangular opening windows and the courtyard of adobe houses.

However, all of the above mentioned studies have not experimented with the thermal performance of traditional buildings, therefore their measurements cannot be used because of the difference in the type of building design and construction methods or the materials' properties and because they focus on a particular design element of houses, such as triangular opening windows, while most Riyadh traditional buildings are constructed within a rectangular opening design.

With respect to all research referred to, it is clear that additional research is needed to improve, or at least test, the environmental performance of such dwellings built in Saudi Arabia and to reduce their environmental impact at both a local and global level. This is due to the fact that the method of evaluating a house's thermal performance for buildings in research is common practice in the west but is hardly practised in architectural research in Saudi. This gap is partly due to irrelevant existing building codes, which almost completely neglect the climatic design aspects of buildings. Recently there has been increased awareness of this gap accompanied by attempts to overcome it through both personal and academic efforts to establish a background of climatic factors. However, a lack of design tools restrain the accomplishment of any appreciative progress and practical application in this domain is very limited. Thus, it is still difficult to accurately assess the climatic performance of buildings, their elements and alternatives, as well as their efficiency considering indoor climatic conditions. If available, they would help in evaluating the use of many elements, especially traditional ones with their relatively successful, experienced performance.

Consequently, detailed technical research is needed to help architects, designers and decision makers in the Saudi Arabian government to complete new developments in an environmental and sustainable way. Research that can give thermal design analysis, climatic analysis and strategic guidelines to test and evaluate the modification of passive systems to be used by local architects in helping them provide climatic responsive local architecture. Therefore, there is a need to evaluate the existing traditional building designed and observe the possibilities of improvement using passive means. As architects play a role in solving these problems, research in this domain is needed not only to fulfil the human need, but also to protect the natural environment from both the threats of global warming and environmental pollution.

In summary, the importance of this research comes from several theoretical and practical grounds:

- The study attempts to fill gaps in the research which have resulted from a general lack of concern for the environmental aspects of the built environment in Saudi Arabia;
- This work attempts to deal with gaps in practice and research emerging from the investigation of the same research problem as previous researchers, but on a different scale and using different methods;
- The result of this study will help to develop the architectural practice in understanding the thermal behaviour of such a traditional building. It is again a reminder for all architects, engineers, project managers, consultants and other professionals involved in energy efficiency improvements to realized the importance of home energy use in our environment;
- The study will assist in developing a strategy that may be used for energy efficiency improvements in housing development in this field. Overall, it will help to make a small, but significant, contribution to the well-being of the global environment: living in a healthier environment; saving energy;

- The findings of this study will not only help us in our aim to improve energy efficiency in our homes and increase standards and performance of the traditional building thermal performance properties, but also develop the potential for future improvements and energy savings in Saudi. The following are a series of points that summarise why it is new and different from those previously mentioned:
  - The use of different passive strategies in the different studies in this region will be evaluated.
  - The impact of some proposed passive measures on the thermal performance of the building and on human thermal comfort will be investigated.
  - Looking for the best modification that can reduce the impact of outdoor climate condition in order to provide an adequate thermal knowledge of traditional building.
  - The actual climatic data will be used in the thermal simulation computer program to predict the thermal performance of traditional houses.
  - It will include the thermal characteristics (conductivity, heat capacity etc) of traditional materials (adobe brick, adobe roof) which will be investigated for use in prediction.
  - Conduct field measurements of thermal performance in traditional buildings in the central region in selected rooms to help to understand how they perform.
  - Using three different computer simulation programs (Ecotect, HTB2, and EnergyPlus) will give the results more validity and confidence.
  - To review the traditional houses in all Saudi regions and how they perform and adapt to each local climate.

1.9 Research Structure

The study will be broken down into discrete sections, denoted by the following chapters:

- **Chapter One** - introduces the topic and defines the problem. It sets out the aims and objectives as well as the scope and limitations of the study. It then goes on to describe the research methodology employed to achieve the study's aims and objectives.

- **Chapter Two** - presents a brief description of the geographic location and climatic characteristics of the different regions of Saudi Arabia. It also gives detailed information about the climate of Riyadh city and provides the necessary data analysis used to determine the appropriate passive responses used by Riyadh houses in the case study. Data on the Riyadh region is illustrated in more detail and analysed using both traditional design tools and a weather analysis computer program.

- **Chapter Three** - discusses the theoretical background and reviews the literature in the field of human thermal comfort. This chapter looks at environmental and human factors affecting thermal comfort and describes a range of thermal comfort indices used to quantify comfort.

- **Chapter Four** - provides a brief explanation of Saudi's traditional houses in each region and explains the methods and techniques of construction. It gives background information about the effect of climatic and environmental conditions on the design of architectural styles in different regions.

- **Chapter Five** - provides a background of the pattern of urban development in Riyadh and details the traditional adobe houses used as case studies in this thesis. It investigates the methods and construction skills used to cope with the hot arid climate and provides an explanation of the problems resulting from rapid economic change. It also reviews and evaluates traditional and modern building design.

- **Chapter Six** - describes the fieldwork which was undertaken in Riyadh city, including the site selection, and presents the measurement data of the thermal performance of existing traditional adobe houses which were used as the criteria on which the thermal modelling in Chapter Seven would be based.

- **Chapter Seven** - describes the range of computer simulation tools that were used to test the thermal performance of traditional adobe houses. It also outlines the techniques used to generate models for each of the tools and how the results will be used as a confidence check to fine-tune the models for use in Chapter Nine.

- **Chapter Eight** - outlines the different passive and semi-active strategies which will be simulated and tested for their effects on thermal comfort within the case study houses in Riyadh. The assumed operation and potential effect of each strategy will be discussed as well as the modelling approach.

- **Chapter Nine** – will describe the techniques and the methods used to compare analysis results of the simulation tools with measurement data described in Chapter Six. It will describe the analysis process within the each of the tools used to simulate and evaluate the different strategies described in Chapter Eight. The results of each analysis will be compared and discussed in detail.

- **Chapter Ten** - outlines recommendations of the most effective combination of the passive design principles discussed in Chapter 8 and 9, discussing their potential effect on the overall performance of the case study buildings.

- **Chapter Eleven** - will include the summary and conclusion drawn from this study. This is followed by recommendations for future research in this field.

CHAPTER TWO

GEOGRAPHICAL LOCATION AND CLIMATE

2.1 Introduction

Climate is one of the most important factor influencing buildings and human behaviour [2-1]. Therefore, it should be taken into account when planning or designing houses. In Saudi the different climate types in each region impose different requirements on buildings, and therefore their architecture design and the methods to improve thermal comfort. As a result there are variations in the treatment of traditional buildings from one region to the other to provide a better response to the existing climate. This chapter aims to create a foundation for following discussions about climatic conditions and environment effects on buildings in Saudi Arabia. This will develop towards an understanding of the differences between the main climatic characteristics in each region as well as other factors such as topography and location, and if the difference in climate influence is either greater or lesser in the design of traditional buildings. There are two main parts to this chapter. First is a brief description of the geographic location and characteristics of the climate in Saudi Arabia regions. Secondly, the climate data of the Riyadh region is illustrated in more detail as a selected case study of this work.

2.2 Geographical Location of Saudi Arabia

The Kingdom of Saudi Arabia located in the middle of Africa and Asia, which are separated by the Red Sea and the Arabian Gulf as seen in Figure (2-1). The Middle Eastern country of Saudi Arabia lies on the Arabian Peninsula at a latitude of between 16 and 30 degrees north.

On the west it is bordered by the Red Sea and on the east by the Arabian Gulf. To the south there are borders with Yemen and the Sultanate of Oman. To the east lie the United Arab Emirates, Qatar and the Kingdom of Bahrain. In the north Saudi Arabia has borders with Kuwait, Iraq and Jordan.

The Kingdom itself covers about 2,250,000 square kilometres (868,730 square miles) and it is one the largest countries in the Middle East, Saudi borders are shown in Figure (2-2).

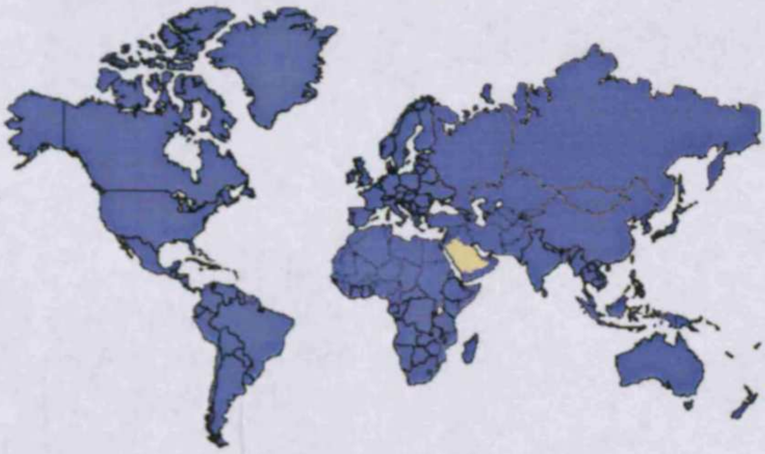


Figure (2-1) Saudi Arabia location in the world map. Source: SESRTCIC [(2-2)].

Figure (2-2) Saudi Arabia borders and location in the Middle East map. Source: Saudi embassy [(2-3)].

2.3 Climate Characteristics of Saudi Arabia

Climate is defined as "*an integration in time of the physical state of the atmospheric environment, characteristic of a certain geographical location*" [(2-4)]. In order to design any kind of building, it is necessary to study the external factors which may affect its function and the comfort of those who use it. Of these external factors, climate is one of the most influential, and the short explanation which follows describes the Saudi Arabian climate.

Saudi Arabia is categorized as a hot arid zone because of its closeness to the equator. As a result of its location, it receives more direct solar radiation than anywhere else on earth [(2-5)]. Because of its varied topographical nature and the influence of a subtropical high pressure system, the climate of Saudi Arabia varies from one region to another. Saudi Arabia has a desert climate characterized by extreme heat during the day, and an abrupt drop in temperature at night.

The climate is generally hot in summer and cold in winter, with rain falling most often in winter. During the summer months on the Red Sea and Arabian Gulf coasts, it tends to be hot and humid. The winter months are much cooler with light rain. Further inland and in the north it is very hot and dry during the summer and dust storms are also frequent, while the winters are very cold. However, in the south west, the mountains ensure a more moderate climate, though the winters are cold. Figure (2-3) shows the climate zone of Saudi Arabia.

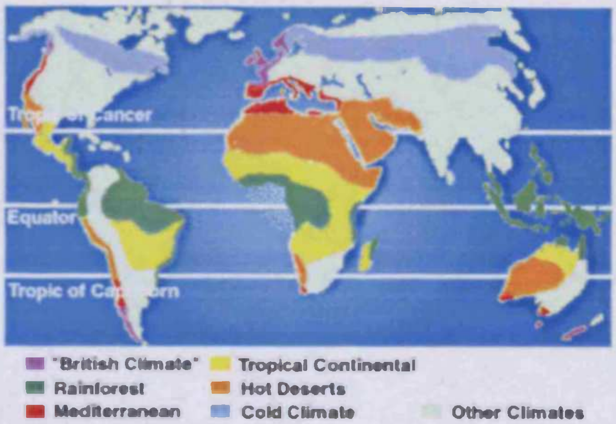


Figure (2-3) Saudi Arabia classified as a hot arid country. Source: the UK environmental change network [2-6].

2.4 Saudi Regions

Saudi Arabia comprises almost four-fifths of the Arabian Peninsula and, geographically, is divided into five major regions as shown in Figure (2-4). This country covers a vast area (868,730 square miles) and is composed of high mountains, deep valleys, extensive coastal areas, and large deserts. These varied physical and geographical barriers have given rise to four distinct climatic regions, each of which has its own climate, traditions, and architectural heritage [2-7].

According to Talib [2-8] (1984) these five major regions of Saudi Arabian could be divided by geographical location into the following four climatic regions. The first region, which includes the central region and the desert of Al-Nufud, Al-Dahna Al-Rub Al-Khali is hot and dry, with ineffective precipitation. The second region, which includes the Red Sea coast on the west side is hot and humid with light but ineffective precipitation. The third region, the eastern region on the gulf coast, is composite with light and ineffective precipitation. The fourth region, which includes the upland from 1200-1800 meters in the west, also has light but ineffective precipitation. Figure (2-3) shows each region and their cities.

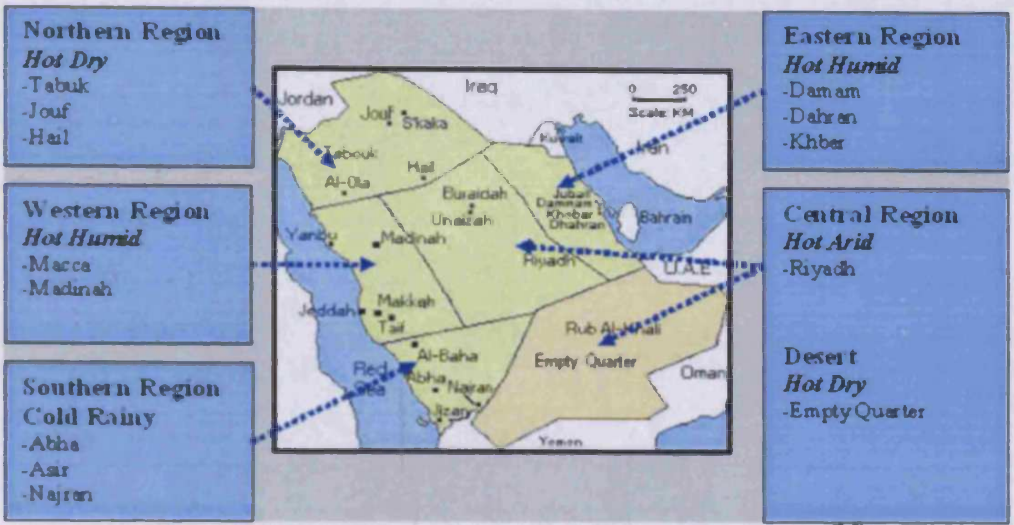


Figure (2-4) The regions of Saudi Arabia. Source: Gerbino [2-9].

2.4.1 Regions Climate

Saudi Arabia, one of the hottest and most arid countries in the world, is located within the same desert belt as the Sahara [2-10], and the climate is a major influence on the design of Arabian houses in all five regions. As traditional housing has evolved to meet local and environmental needs, the relationship between the climate and the design of traditional houses can be illustrated by describing each region's climate. This section concentrates on the specific climates in each region of Saudi Arabia. This is the first step to understanding the relation between climate and traditional building design. Figure (2-5) shows the climate zone of Saudi Arabia.

Figure (2-5) Climate zone map of Saudi Arabia. Source: Talib [2-8].

2.4.1.1 Western Region

The Western Region, or Hijaz, contains the two holy cities of Mecca and Medina, and also the city of Jeddah. This region is situated on the coast of the Red Sea. It contains a mountain chain (with peaks rising to 3,000 meters), running south to north, decreasing gradually in elevation as it moves northward, and the coastal plain bordering the Red Sea [2-7].

The west cost of the country along the Red Sea is extremely humid throughout the year. Humidity ranges from 75% to 80%. The Western Region's average daily maximum temperature is about 42°C during the summer months of May, June, July and August and the average daily minimum temperatures are relatively mild about 15°C during the months of December and January [2-8].

2.4.1.2 Eastern Region

Al-Ahsa, or the Eastern Region, is on the coast of the Arabian Gulf, and its largest cities are Damman and Dhahran, which contains the Kingdom's massive petroleum resources. The world's largest petroleum port is located in the north of Dhahran [2-7].

Eastern Region is comparable in climate to the Central Region, though with higher humidity. This humidity is caused by the fact that the region abuts the very hot Al-Dahna desert to the west and is also very close to the Arabian Gulf and the average daily maximum temperature range between 35°C to 42°C during May to October and 40°C and approximately 29°C to 31°C during November to April. Average relative humidity throughout the year is above 41% and the annul average rainfall 79mm during November to April [2-8].

2.4.1.3 Southern Region

The Southwestern Region is also known as Asir, also the name of its largest city. It is the relatively fertile area of coastal mountains in the extreme southwest (near Yemen). Mountain peaks rise to 3,000 meters and there is ample rainfall to support natural vegetation and cultivation [2-7].

In the Southern Region the average daily maximum temperature range is from 24°C to 28°C during July and August and the average daily minimum temperature range is from 10°C to12°C. The maximum recorded of the relative humidity is 80% around the rainfall period in August and the lower relative humidity 40% during November to February. The total rain fall record is 30 cm in the month of August [2-8].

2.4.1.4 Northern Region

The largest city in the Northern Region, which is also known as Tabouk itself. It lies in the north west of the Kingdom. It is stretches north to Jordan, south to Omluj, east to Taima and Markaz, and west to the Red Sea (2-7).

As the city of Tabouk is 700 meters above sea level, it has a moderate climate with temperature tending to drop in winter, reaching minus 7 °C in some cases. The average annual temperature is 22 °C to 46 °C in July and August (2-7).

2.4.1.5 Central Region Geography and Climate

2.4.1.5.1 Geography

The climate parameters of the Riyadh mainly depend on its geographic location and topography. Riyadh lies on the great limestone plateau of Najd in the centre of the Arabian Peninsula, at a height of approximately 600 meters above mean sea level. It is located at latitude 24° 38' North and longitude 46° 43' East as can be seen in Figure (2-4).

2.4.1.5.2 Climate

In general, Riyadh's climate is dry and hot in summer with average daily temperatures often ranging from 40°C to 44°C in July. Humidity ranges between 10 and 13%. In winter, it is cold with temperatures falling to about 14°C. Some winter temperatures have been recorded at lower than -2°C. However, it should be noted here that the data analysis of Riyadh based on the available weather data which has been collected from the Meteorological and Environmental Protection Administration (MEPA), and Presidency of Meteorology and Environment (Riyadh International Airport). Establishing an understanding of the climatic features of this region is one of the major aims of this chapter. The components of Riyadh region will be explained in the next following sections.

2.4.1.5.3 Deserts

Riyadh city is surrounding by three deserts that stretch from the north to the south of the country. The largest of these is named Al-Rub Al-Khali, an area known as the Empty Quarter, Figure (2-6) shows the sand sea of this desert. It is the world's largest sand sea in the world covering almost (600,000 square kilometres) and extends to 1,200 by 500 kilometres in the southeast. The other two deserts comprise a 400 mile strip to the east (2-12). Figures (2-6), and (2-7) show the huge amount of sea sands dunes, which are surrounding Riyadh City taken by NASA (2-13).

Figure (2-6) The three desert surrounding Riyadh. Source: NASA (2-13).

Figure (2-7) The sea sand of empty quarter. Source: NASA (2-14).

The Al-Dahna desert covers an area of 40,789 square kilometres, and the Al-Nufud desert covers about 64,630 square kilometres and extends at its longest about 342 kilometres from east to west. From the north to the south it extends 572 kilometres, and about 128 kilometres to the east. Figure (2-10) shows the map of the surrounding desert.

2.4.1.5.4 Air Temperature

The climate data shows that the temperature in the Central region reaches 50°C in summer by day with a drop of about 20°C at night. The high daytime temperature is due to the surrounding deserts and the lack of clouds or rivers resulting in considerable solar radiation. Relative humidity may fall to less than 9% during daytime in summer. Figure (2-8) shows that the monthly maximum, mean and minimum dry bulb temperature (DBT) reaches 48°C in the summer, while in winter it reaches 0°C for the year 2000, where the hottest months are May, June, July, August and September. The coldest period is during the months of December, January and February. It also shows the temperate period in the months of March, April, October, and November.

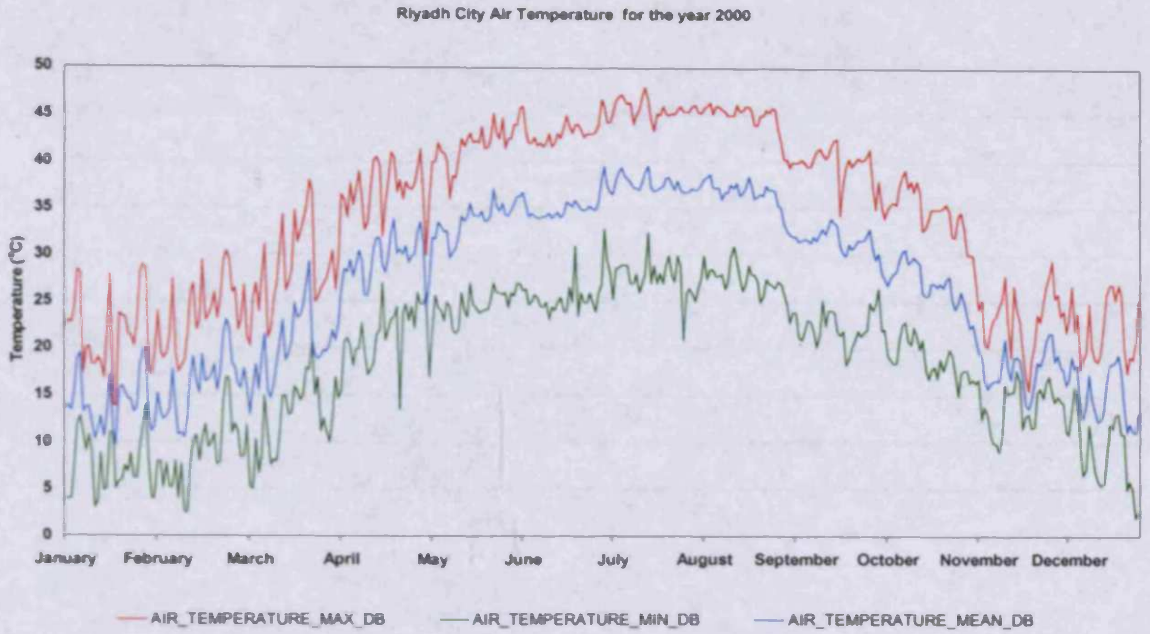


Figure (2-8) Riyadh Air Temperature for year 2000, by the author using the weather data of Presidency of meteorology and environment [2-15].

2.4.1.5.5 Wind

In this region the wind direction is normally from the north during summer, with severe gales throughout the year. However, when normal conditions prevail in winter, the prevailing wind blows from the south. These northerly and southerly winds reach speeds of between 1 to 3.6 m/s. The changeability in both speeds and direction is a natural but unstable source of ventilation. Sand storms, dust, and rain, which are also driven to the Central region by the force of this unruly wind. Figure (2-9) shows the Riyadh annual average wind speed for the years 1984- 2000 by using the weather data of MEPA [2-16].

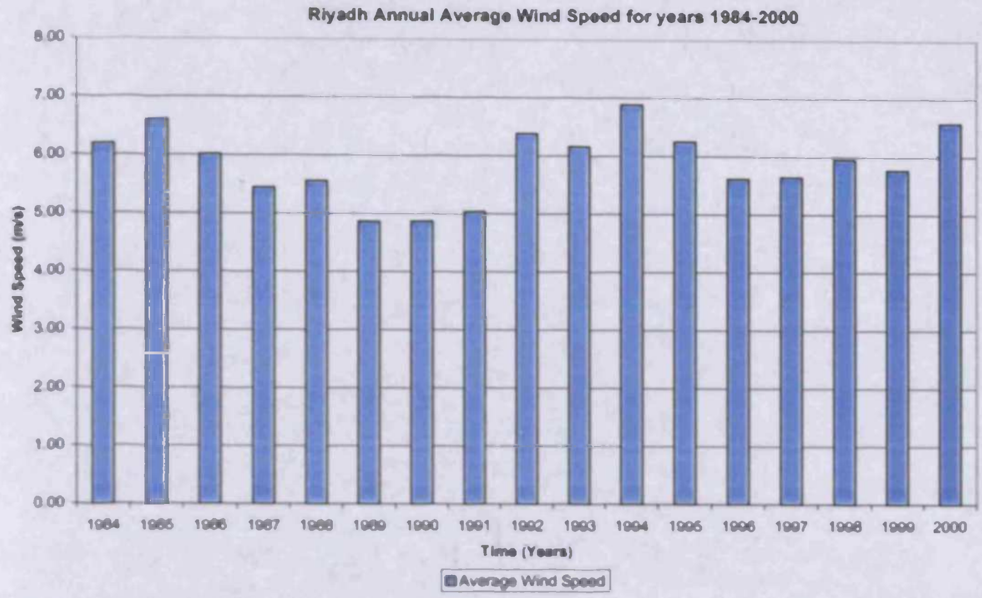


Figure (2-9) Riyadh annual average wind speed for year 1984-2000, by the author using the weather data of MEPA [(2-16)].

2.4.1.5.6 Dust

Because of the presence of the three deserts, and the fact that the prevailing winds are either from north or south in origin, there is a high possibility of sand and dust storms. Wind-driven dust is derived from the Al-Nufud desert when the prevailing wind is from the north, whilst the Al-Rub Al-Khali desert provides a burden of dust for the south wind to carry. Figure (2-10) shows the occurrence of dust to the city.

It is has been argued that the regional climate is becoming more extreme with every passing year. Yet there appears to be evidence which underlines the occurrence of blowing and drifting dust in of a total of 106 hazy days recorded in a year.

Figure (2-10) The dust storm occur to the Riyadh City. Source: Water Atlas of Saudi Arabia [(2-12)].

In general, strong variable winds associated with storms blow during the winter months of December to February, with the strongest usually recorded in February. During the months of March through May, these persistent strong winds decrease in frequency. However, very strong wind continues to occur in the vicinities of localized thunderstorms.

In the summer time during the months June to September, the direction of the wind is north to northwest. By the mid of summer, frequent strong north winds called '*Shamal*' occur at a speed of 100 kilometres per hour have been recorded. During these *Shamals*, blowing dust can greatly reduce visibility. These winds, however, decrease by the end of July. Figures (2-11) and (2-12) show the image of a dust storm taken by NASA over Saudi.

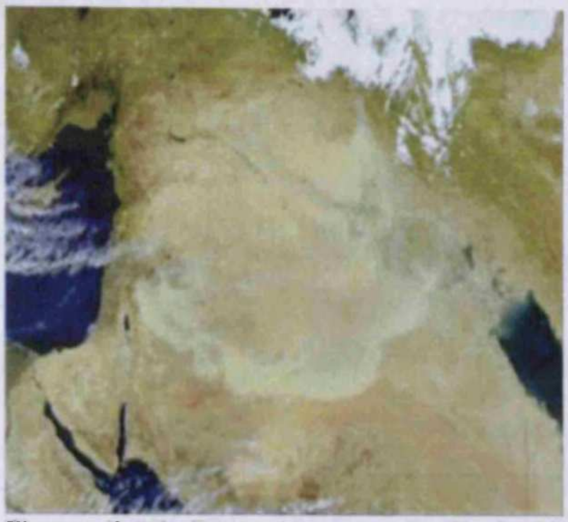


Figure (2-11) Dust storm on Saudi Arabia. Source: NASA (2-17).

Figure (2-12) Dust storm on the Red Sea Saudi Arabia. Source: NASA (2-13).

2.4.1.5.7 Rainfall

Rainfall in most of the areas of Saudi Arabia is scarce and irregular. The difference in rainfall rate between years is high and long periods may pass without rain. When rainfall does occur it is very local and sometimes takes the form of violent storms of short duration. The intensity of the rainfall during such storms is far in excess of the capacity of the land to absorb it. Figure (2-13) shows the rainfall for year 2000.

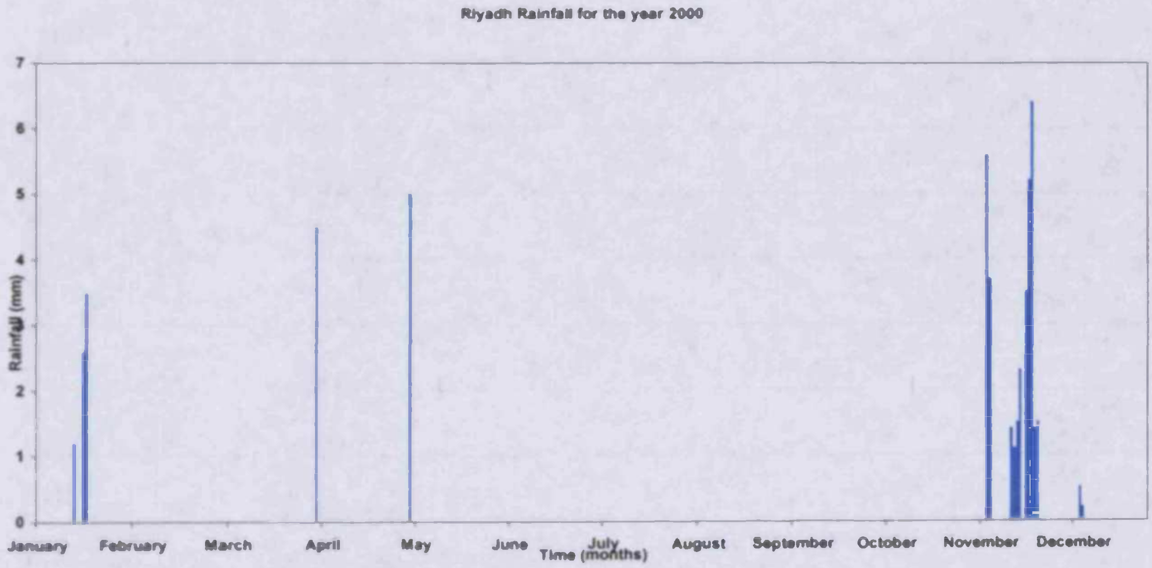


Figure (2-13) Riyadh rain fall for year 2000, by the author using the weather data of Presidency of meteorology and environment (2-15).

It is clear from the above paragraphs that the amount of rainfall in the central region is very low. Apart from that, the vegetation is very scarce in this area of Saudi Arabia. All these factors add up to a significant lowering of air humidity, as described in the next paragraph.

2.4.1.5.8 Relative Humidity

Relative humidity displays variations within Riyadh. During the three months of summer (June, July and August) the relative humidity is very low, with a mean monthly average of around 23 % whilst December and January are the months of maximum relative humidity (53%). Monthly relative data for the thirty-five year period 1964-2000 are shown in Figure (2-14), while Figure (2-15) shows the relative humidity for the year 2000.

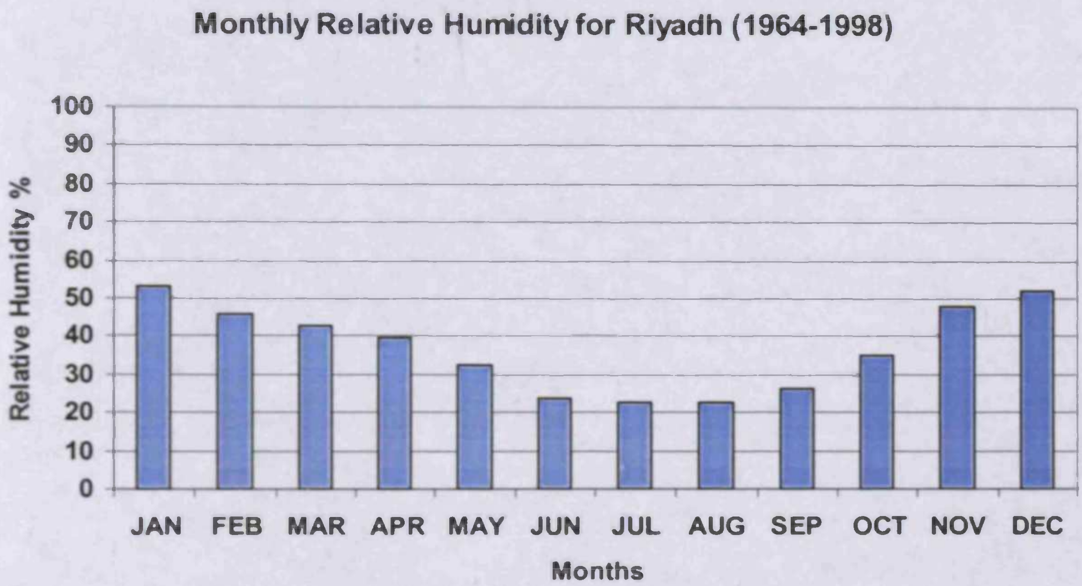


Figure (2-14) Monthly relative humidity for Riyadh 1964-1998, by the author using the weather data of Presidency of meteorology and environment [2-15].

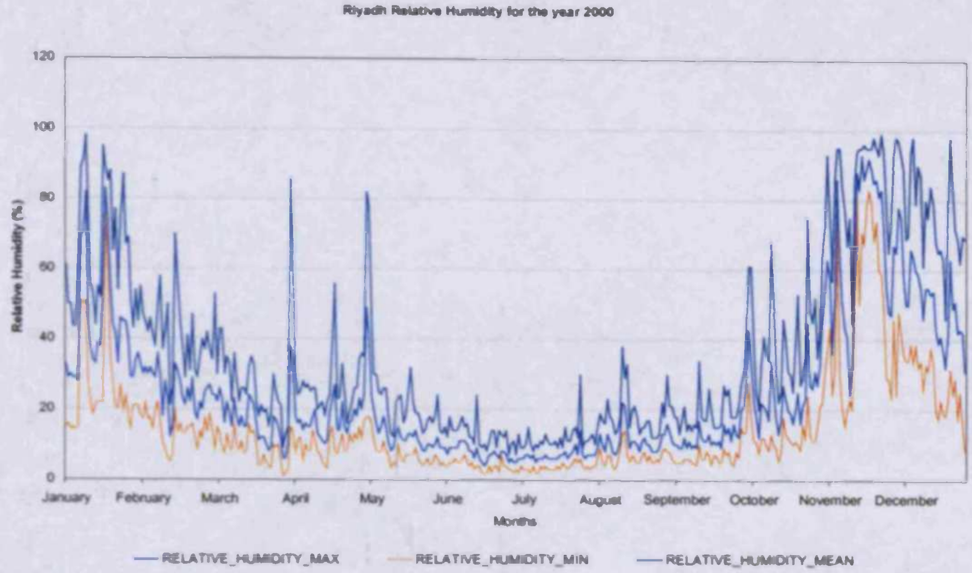


Figure (2-15) Riyadh Monthly Relative Humidity for year 1984-2000, by the author using the weather data of Presidency of meteorology and environment [(2-15)].

2.4.1.5.9 Sunshine

Sunshine duration is expressed in hours of sunshine and provides information on the length of the day and on cloudy periods when the intensity of solar radiation decreases below a certain level. Figure (2-16) shows a sixteen year record of mean monthly sunshine hours per day in Riyadh city. The sunshine hours were highest in June (10.66) and lowest in December (7.14) with an annual average of 8.78 hours per day.

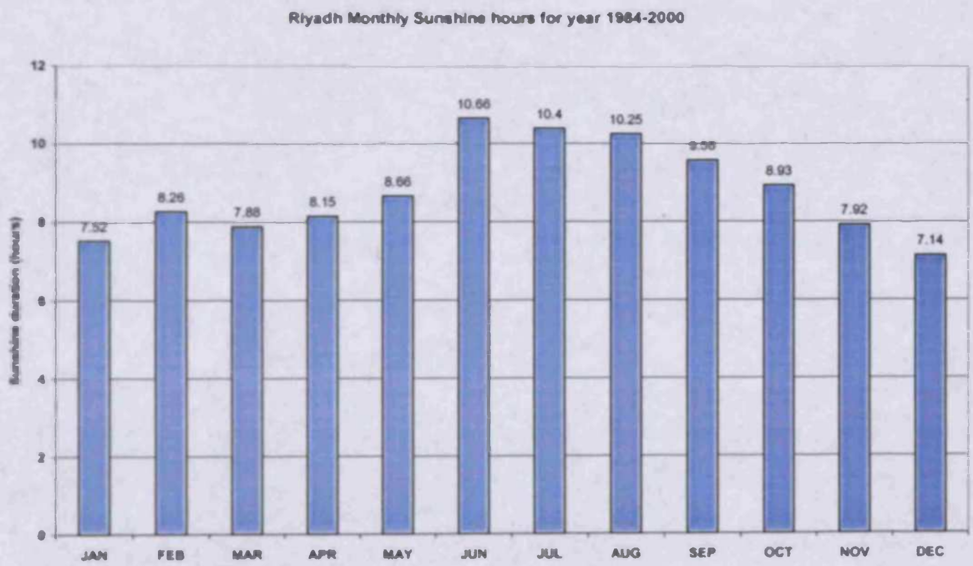


Figure (2-16) Riyadh Monthly Sunshine hours for year 1984-2000, by the author using the weather data of MEPA [(2-16)].

2.4.1.5.10 Solar Radiation

The mean monthly solar radiation for Riyadh City is illustrated in Figure (2-17), as an average for the year 2002. The maximum and average solar radiation values range from a minimum of 310w/m^2 recorded in December to maximum of 580w/m^2 in June. Both solar radiation and the number of sunshine hours are regarded as the important factors influencing evaporation.

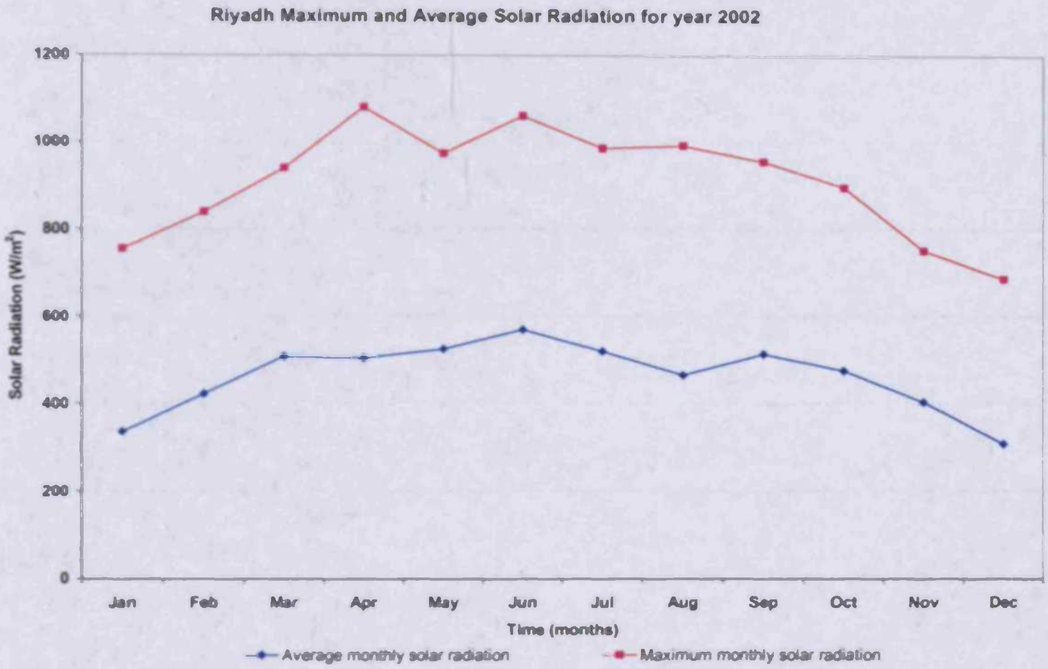


Figure (2-17) Riyadh Monthly Solar Radiation for year 2002, by the author using the weather data of KASC [(2-15)].

The climatic data for Riyadh City was obtained from The Ministry of Agriculture and Water and Ministry of Defence and Aviation (MEPA). The elevation of the climatic stations varies between 430 and 645 m above the sea level. The monthly values of air temperature, relative humidity, precipitation and evaporation for Riyadh City for thirty-five years (1964-1998) are given in Table (2-1).

Table (2-1) Mean monthly climatic parameters for Riyadh (1964-1998). Source: Ministry of Agriculture (2-16).

Parameters	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Avg. Mean Temp.	15	17	20	25	31	33	34	34	31	26	20	16
Avg. RH %	53	46	43	40	32	24	23	23	26	35	48	52
Avg. sunshine (hr)*	7.5	8.2	7.8	8.1	8.6	11	10	10	9.6	8.9	7.9	7.1
Radiation cal/cm^2/day**	323	394	451	486	525	580	570	544	513	461	385	320
Wind speed (km/day)	4.5	5.1	5.6	5.3	5.2	5.6	5.8	5.1	4.0	3.5	3.6	3.9
Evaporation (mm)	101	132	196	234	305	352	380	356	293	228	133	104
Precipitation (mm)	15	8	23	23	6	0	0	0	0	2	4	13

RH: Relative Humidity, * : Period (1971-1986), ** : Period (1965-1986)

2.5 Climate Design Tools

One of the objectives of this research is to find the most appropriate, applicable and effective passive strategies in hot arid region of Riyadh City. This objective can be achieved through understanding the climatic conditions of the area. In order to ensure that the building interior will be comfortable (or adapted to the climate) for the occupiers, there are many methods for designing and testing the performance of the house and the surrounding areas. A number of traditional design tools exist to assist at the early stages of climatic integrated design. One of these which has been and still is a useful tool is the Mahoney's tables, which will be used to analyse climatic data of Riyadh City. It is based on temperature and humidity as its main factors, describing the thermal stress of each month and expressing the climate as indicators which are finally used to suggest a general solution in terms of climatic design consideration for a specific building on the site.

On the other hand, it is a useful to use modern tools in the same context to improve climatic performance of buildings and for comparison. Today's computer simulation tools present the advantage of rapid, flexible assessments and allow the integration of most of the elements involved in building heat exchange. It was needed to find software that was simple to use, quickly to learn and produced reasonably accurate results. However, it should be noted here that the choice of modern tools to be used to analyse the climatic data for this study was needed and indisputable. This is due to the fact that the software programs which will be used for assessing temperatures inside the case studies, their performance and cooling or heating loads required in this study to be used in the simulation prediction for active modification of indoor climate. Therefore, it would not be practicable on grounds of time and cost to assess such a large volume of data manually, as temperature, humidity, wind, solar radiation and cloud cover data all have to be taken into account. To carry out such an analysis manually would be very tedious and extremely expensive, and out of the time limitation of this research. Fortunately in the Welsh School of Architecture a set of computer programmes has been introduced. Among them is ECOTECT software which provides a simple to use and appropriate mechanism for this purpose. In addition to that, ECOTECT feature provides arrange of options to export a full data file including configuration for the building construction and the climatic data to be used in other software programs that will be used in building simulation. Thus the selection of the Weather Tool v1.10 computer program in ECOTECT was made to be used to analysis the hourly data of Riyadh city. It is an analysis program for hourly climate data and for passive design analysis, it display in visualisation and including both 2D and 3D graphs as well as wind roses and sun-path diagrams. ECOTECT written and developed by SQUARE ONE PTY. LTD, more information about the tools can be found in (http:// www.squ1.com.).

The programs of Weather Tool require hourly weather data to run and display its analysis for the climate. The accuracy of weather variables are very important in the calculation of the hourly data of Riyadh city, the information of the weather variables must be obtained. Hourly climatic data which is needed for detailed thermal analysis could not be obtained simply from the meteorological office or government organisations. In Riyadh City, where this research is focussed, this kind of detailed data is only available at airports or King Abdulaziz City (KACST). Enquiries at the airport indicated that they only supply it as a hard-copy print-out, not in electronic form. Converting such a data from a hard-copy print format into electronic form leads to significant errors and wasted time typing, which in turn may lead to invalid results.

Therefore the actual hourly climate data for the year 2002 of Riyadh city has been obtained from KACST, for analysis of the climate of the Riyadh area for thermal modelling of the buildings. The Weather Tool computer program is used for that purpose due to the feature and availability of ECOTECT and its flexibility to manage such huge data of one year. The data installed in the program is used for analyzing. The data collected from KACST is a full year of hourly weather data presented as an Excel spreadsheet containing Air Temperature, Relative Humidity, Direct Solar Radiation, Diffuse Horizontal Solar Radiation and Wind speed. This data was then converted to a WEA file using the Weather Tool (refer to reference 2-18 for more details about the Weather File Formats).

2.5.1 Result From Traditional Tools: Mahoney Table

The Mahoney table is an ideal design tool as it is easy to use and interpret. It provides a guide to the design of building in relation to the climate. The table requires the most easily available climatic data such as the dry bulb temperature, relative humidity, amount of rainfall and wind direction. When gathered and entered into 4 simple tables, recommendations are immediately established to assist the designer in formulating the basic design parameters such as form, orientation, opening sizes, building materials, etc...

Plotting climatic data for Riyadh on the Mahoney tables (see Appendix B of Chapter Two for Mahoney Table) gives following recommendations:

- Compact layout of buildings.
- Orienting the building on the East and West axis.
- Use of heavy materials for walls and roofs. (About 8 hours time lag).
- Provision of outdoor place for outdoor sleeping.
- Size of openings between small to medium of wall service area.
- Ventilation requirements varied between (no provision of air movement) and (the use of openings in windward exterior walls and internal walls) as well.

2.5.2 Riyadh's Climatic Analyses by Modern Tools

As the general aim of this chapter is not only to represent but to analyse data relating to the climate of Riyadh and its environs, this objective is best achieved by using the analytical tools available through ECOTECT. Thus the following tasks can be achieved:

- Hourly analysis of the climatic data.
- Visualizing of the hourly climate data.
- Analysis of passive system.

2.5.2.1 Analysis Hourly Climate Data

Fortunately ECOTECT has a wide range of important climate data of the international weather that affects human comfort and the actual hourly data of Riyadh city is set in the Weather Tools file (Wea tool data (WEA)) of the ECOTECT software which is needed to perform an analysis of the climatic context. *The 'Synthesise Data'* feature in the weather tools used to introduce the actual hourly data as seen in Figure (2-18). The climate data can be used in the analysing and modelling in this research.

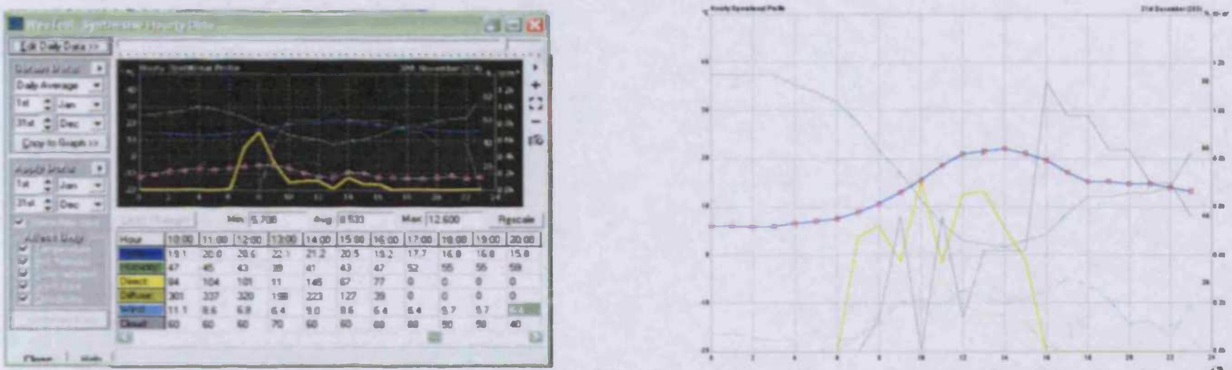
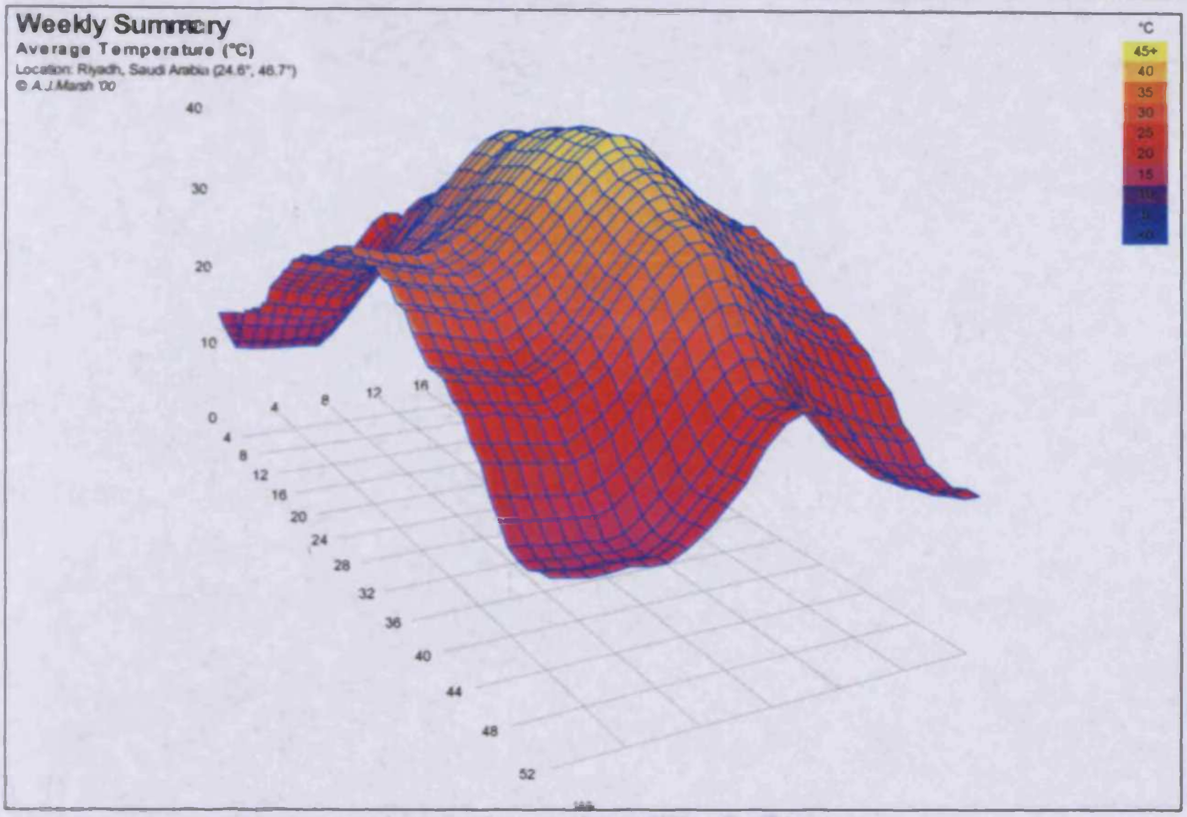


Figure (2-18) The '*Synthesise Data*' features in the Weather Tools software. Source: The Weather Tools [(2-18)].

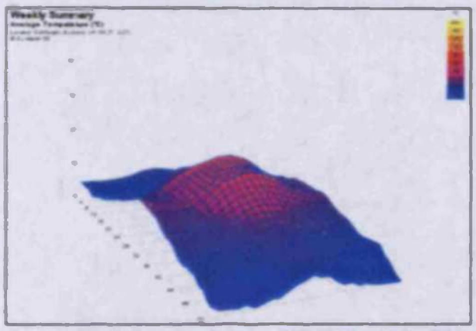
2.5.2.2 Visualizing the Climatic Data

The Weather Tool has many options for displaying the climate data. Without some sort of reference, it is difficult to appreciate what the individual data means. Thus, in order to present a visual comparison of the climatic extremes in Riyadh, comparative graphs showing the same information for Karachi and Edinburgh are shown as insets immediately below each Riyadh graph.

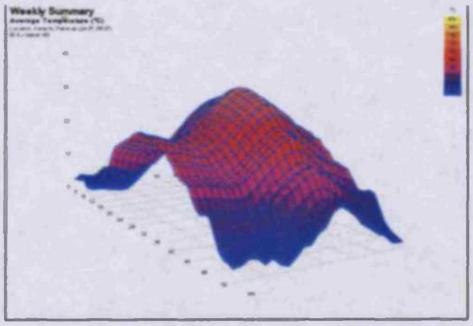
For this, 3D projections of average weekly values for temperature and relative humidity are used, where the X axis represents the weeks of the year, the Y axis being hours of the day and the Z axis being the range of values as seen in Figures (2-19, 2-20).



Average temperature of Riyadh City.

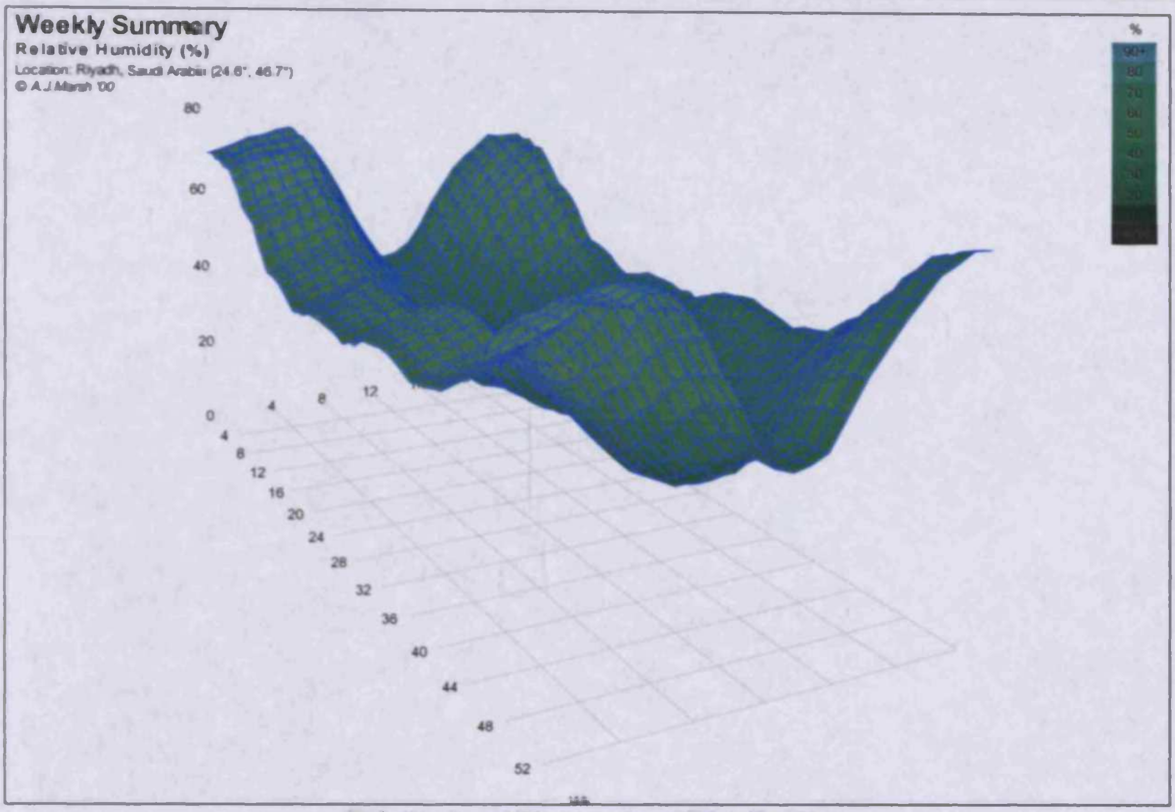


Average temperature of Edinburgh City, UK.

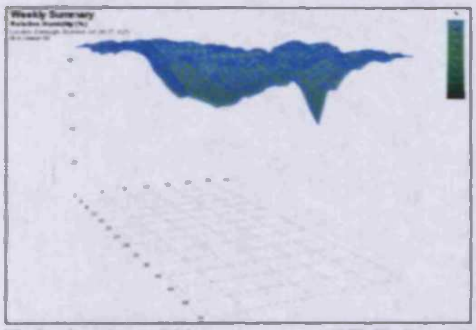


Average temperature of Karachi City, Pakistan.

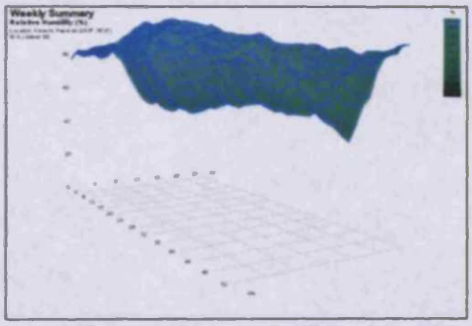
Figure (2-19) A compression between the average temperatures of Riyadh, Edinburgh and Karachi cities, by author using Weather Tools.



Relative humidity average of Riyadh City.



Relative humidity average of Edinburgh City, UK.



Relative humidity average of Karachi City, Pakistan.

Figure (2-20) A compression between the average humidity of Riyadh, Edinburgh and Karachi cities, by author using Weather Tools.

2.5.2.3 Weekly Summary of Riyadh Climate

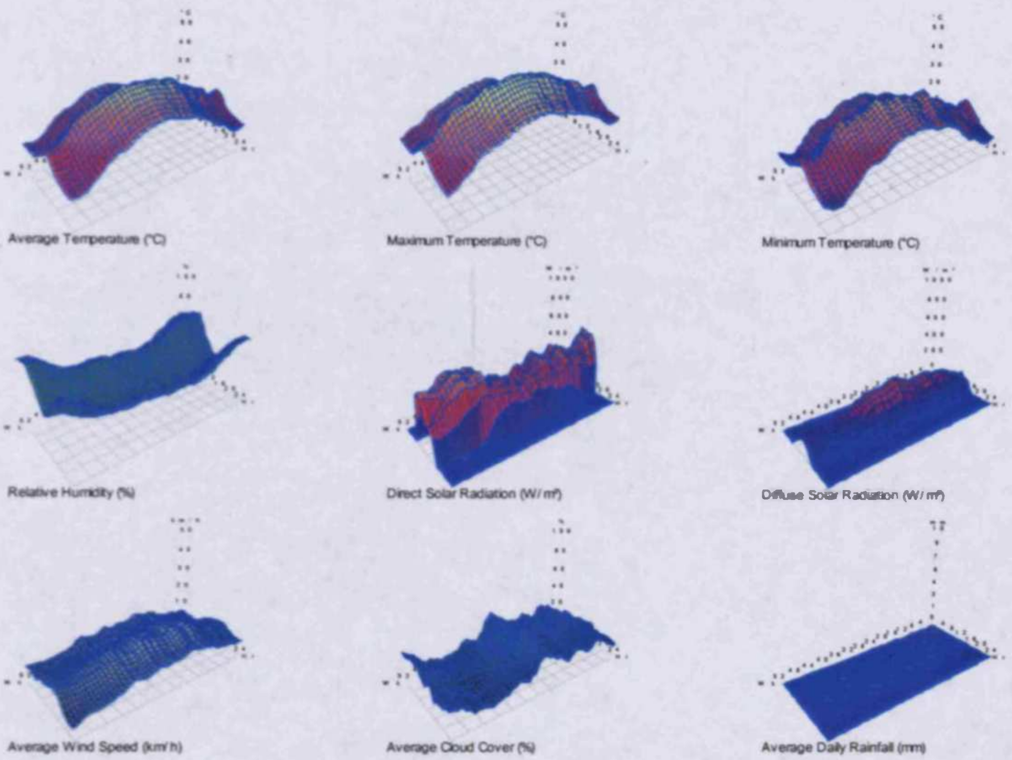


Figure (2-21) Riyadh region climate summery, by the author using Ecotect Weather Tool Software.

2.5.2.4 Analysing the Climate Data

2.5.2.4.1 Classify the Climate of Riyadh Region

As described before the features in the weather tool can show the climatic classification for the city of Riyadh. The values of the average monthly maximum are plotted on the psychometric chart laid on it the climatic classification over lays. Each zone represents a period of the year, this period of the year is classified and all the other periods of the year also classified. However the Riyadh's climate for the whole year lies on the hot and warm dry zones with a small part lies in the moderate zone. Figure (2-22) shows the characteristic of Riyadh region. The line represents that most of climate data located in two different climatic zones which are warm dry, hot dry. Thus Riyadh is considered as a hot and arid climate.

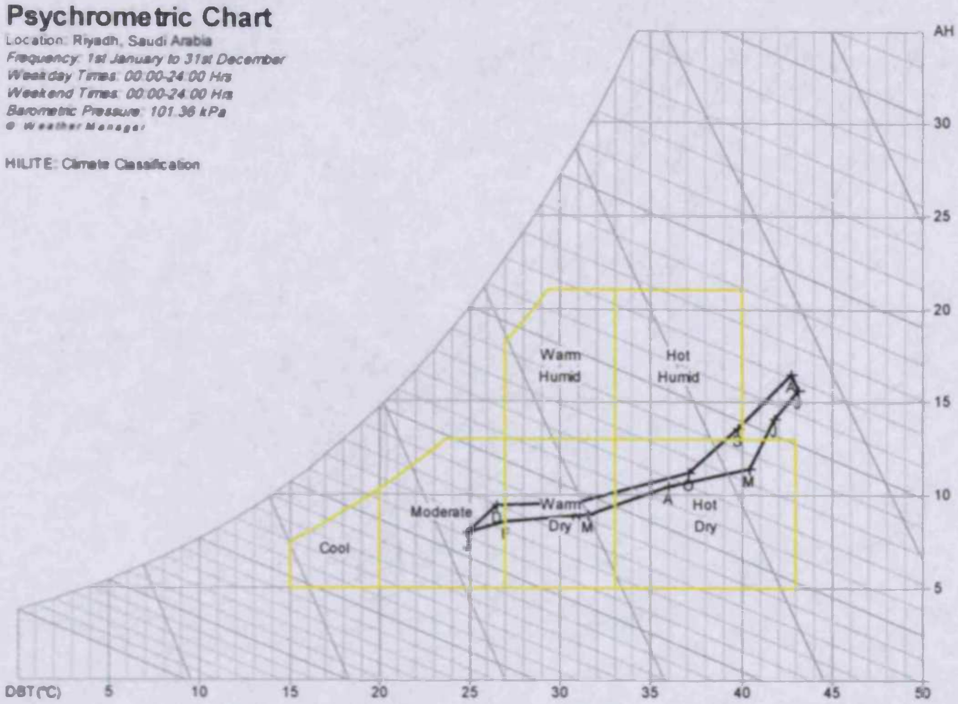


Figure (2-22) Climatic classification of the Riyadh region, by the author using Ecotect Weather Tool Software.

2.5.2.4.2 Heat and Solar Load of Building

The plotting of the degree hours for heating, cooling and solar load is one of the most accepted ways used as a sign in the buildings. Weather Tools provide the three values over each month of the year in chart form. It is obvious that the main issue in this climate that the need for both cooling and heating. The cooling is the most intensive need than the heating which is away from the graph scale where it almost more than 10,000 Degree per Hour. However, the heating need is not that much.

This gives a clear image of the harsh climate of the Riyadh region in comparison with other regions of Saudi Arabia. (Figure 2-23) shows the heating, cooling and solar degree hours.

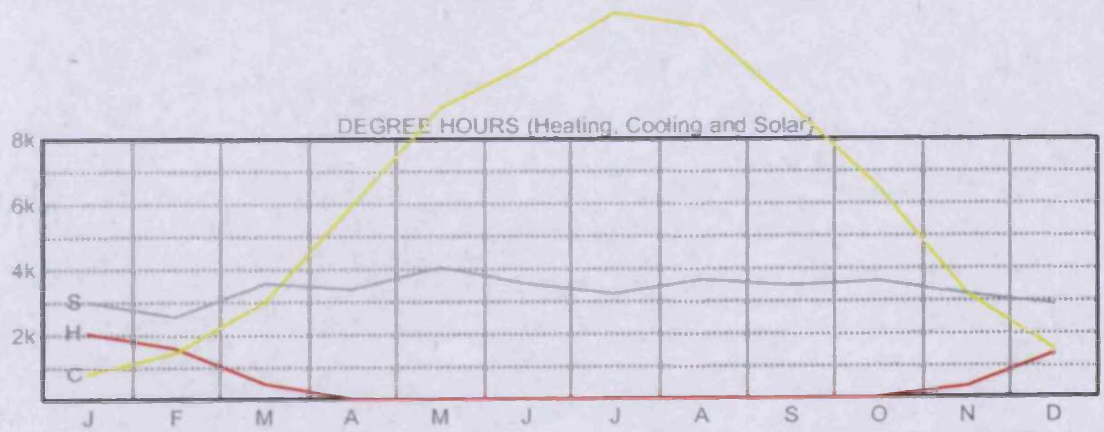


Figure (2-23) Heating, Cooling and solar degree hours, by the author using Ecotect Weather Tool Software.

2.5.2.4.3 Optimum Solar Orientation:

The weather tool features can plot the solar radiation values for the over- heated/under-heated periods during the year at different orientation, and can calculate the solar radiation on a 1 m^2 vertical surface over 360 degrees. This can help to determine unwanted solar gains in summer "This is used to determine the most favourable range of orientations for passive solar heating, whilst still considering the effects of unwanted solar gains in summer". Figure (2-24) Shows that the best optimum orientation for Riyadh city was found to be 172.5° C.

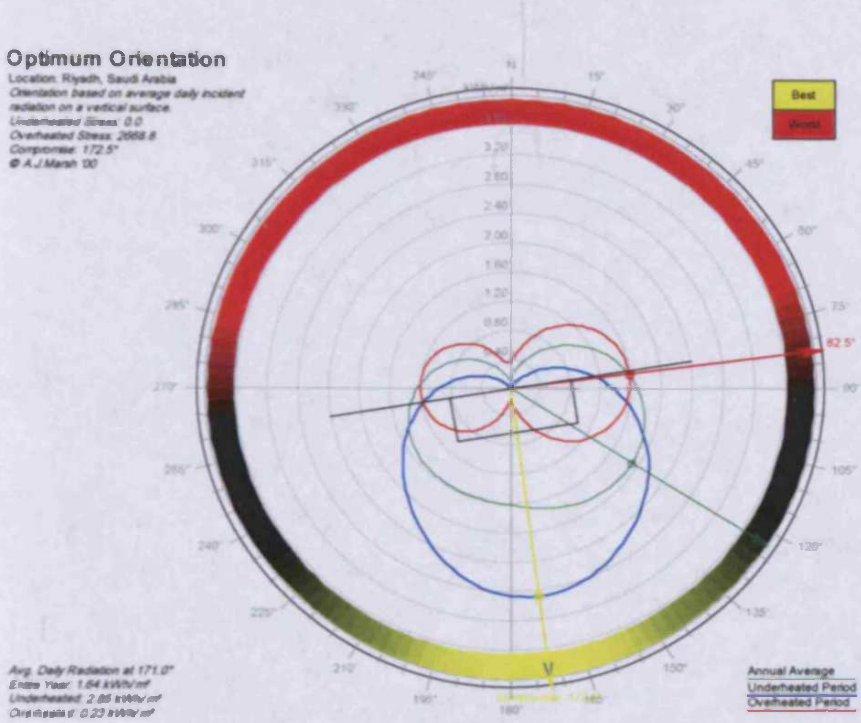


Figure (2-24) The optimum solar orientation for Riyadh, by the author using Ecotect Weather Tool Software.

2.5.2.4.4 Passive Design Strategies Analysis

Weather Tolls is based on (S. V. Szokolay, 1987) (2-18) method of psychrometric analysis to determine the potential effect of different passive strategies. Also, it can evaluate multiple combinations of passive strategies. Figure (2-25) shows the hourly data is plotted as points on the graph, and the relative effects range of passive design techniques on the comfort zone are overlaid. This makes it possible to identify which systems are most appropriate to this climate. Figures (2-26 to 2-27) show the most effective passive systems for the Riyadh region. However, it is clear that the selected design techniques for this region from this Figure as following:

- With comparison with other strategies, it is clear that the greatest impact on human comfort in this climate is the thermal mass which is the most effective than others.
- Due to the low humidity levels in this region, evaporative cooling has some impact.
- Natural ventilation is another influence which is probably needed during the night more than the day.
- Exposed mass and night-purge ventilation.

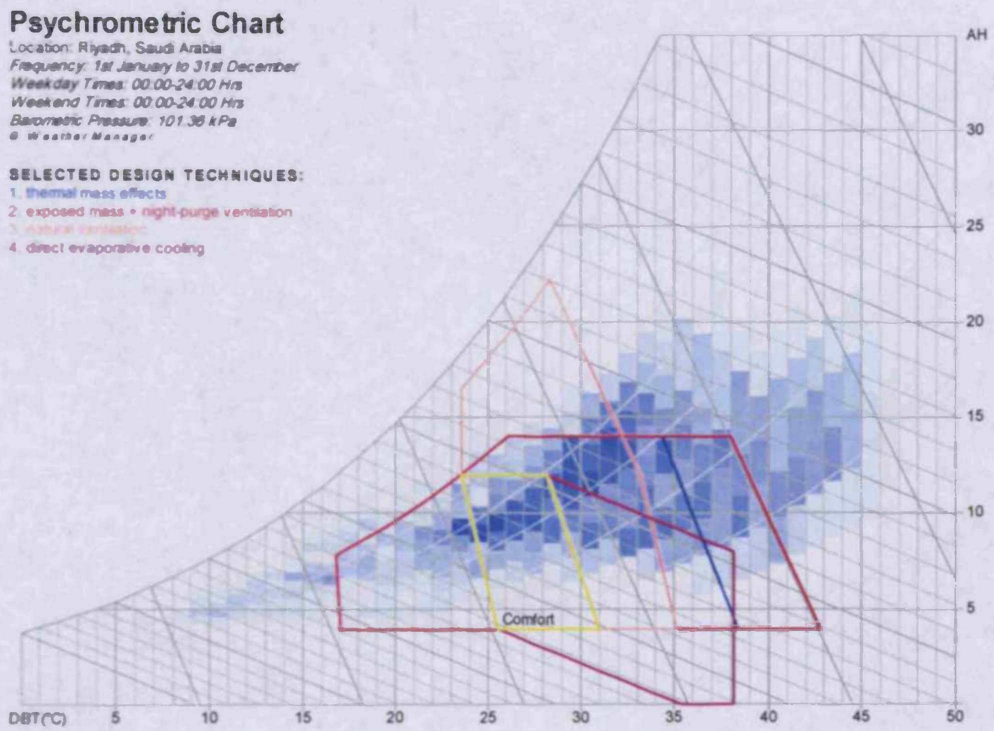


Figure (2-25) The effect of using passive design measure on comfort zone, by the author using Ecotect Weather Tool Software.

Figure (2-26) Comfort percentage before selected design techniques, by the author using Ecotect Weather Tool Software.

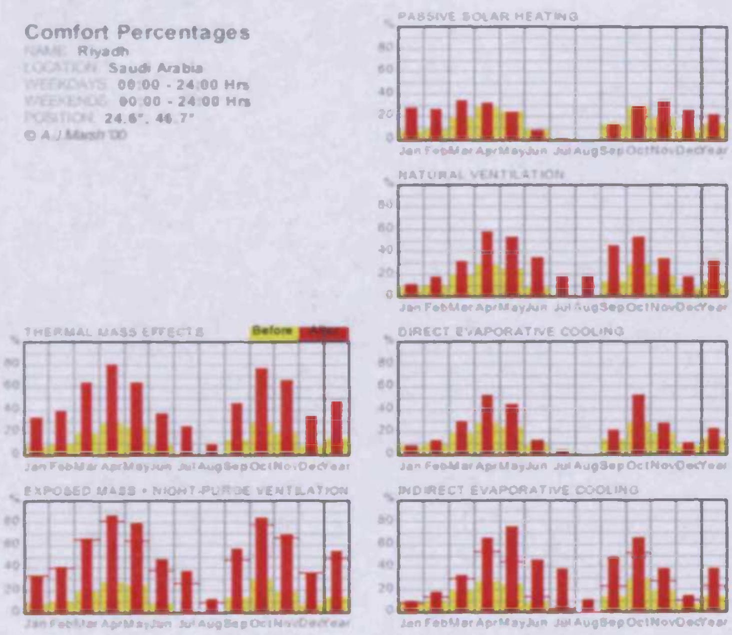


Figure (2-27) Comfort percentages before and after using different passive strategies, by the author using Ecotect Weather Tool Software.

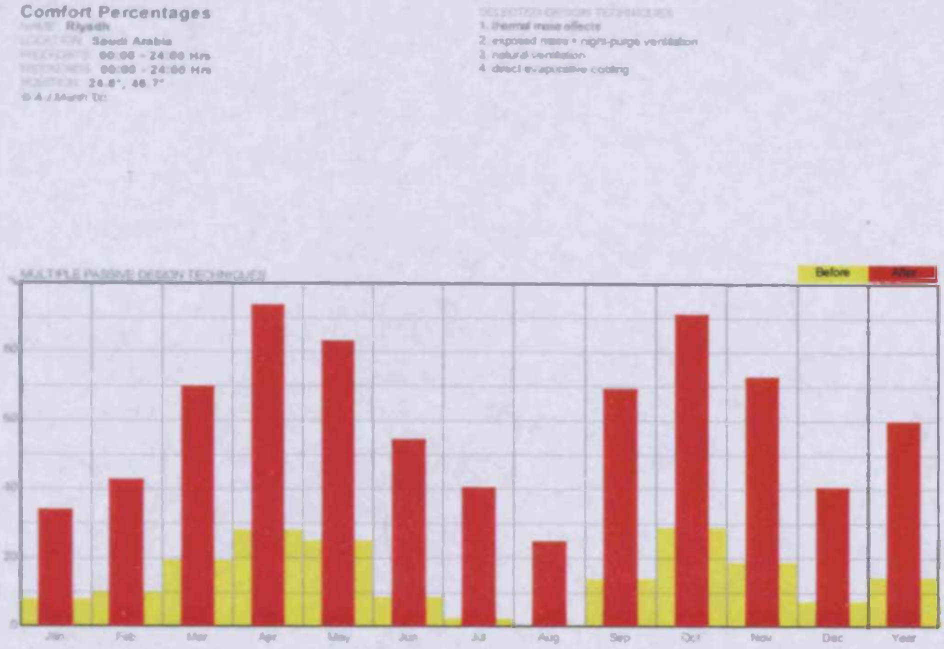


Figure (2-28) Comfort percentages before and after using the combination of thermal mass, night purge ventilation, natural ventilation and direct evaporative cooling, by the author using Ecotect Weather Tool Software.

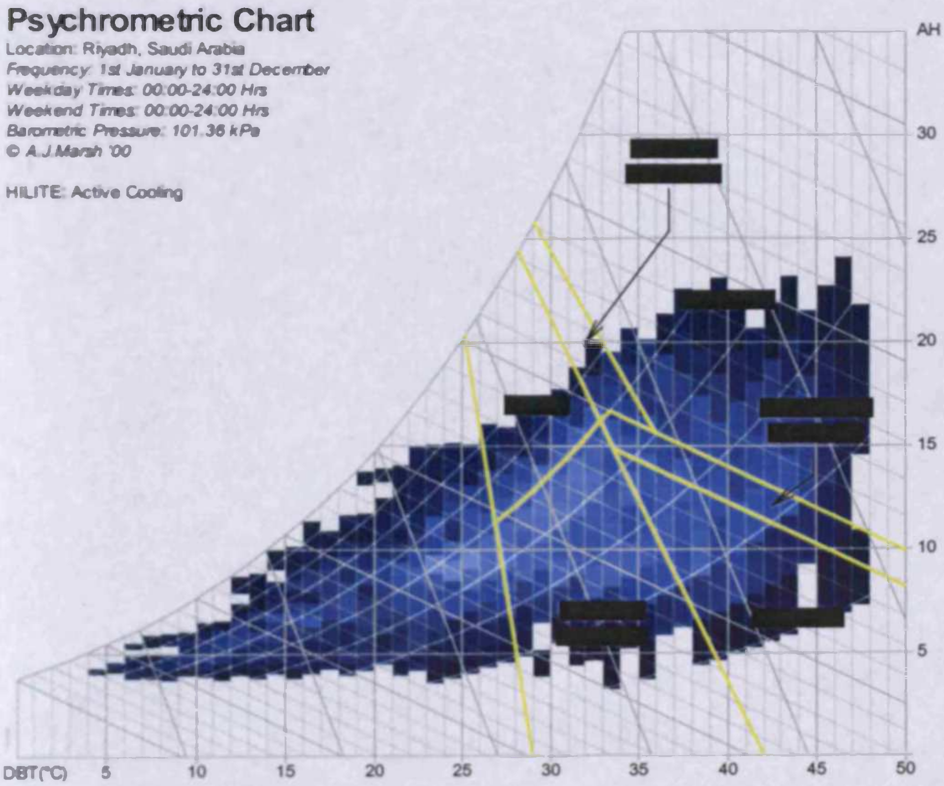


Figure (2-29) Psychrometric Analysis, by the author using Ecotect Weather Tool Software.

2.6 Conclusions

This chapter has briefly analysed the different climatic regions of Saudi Arabia, with the climate of the central region analyses in more detail. It can be seen from the data collected that the climate of Riyadh region is fairly complex, but it could be considered as hot and arid, because it is hot and dry in summer and cold in winter. Two main seasons can be distinguished in this region. The hot season spans over seven months, while the winter is only three to four months. Understanding the climatic conditions of Riyadh and the passive strategies is very important for assessing the thermal performance of the building and will help to give a clear image of how buildings perform and how are they adapted to the climate.

However, according to the analysis of outdoor climate and the psychrometric chart, it can be concluded that the use of a combination of the four (thermal mass, evaporative cooling, natural ventilation, exposed mass and night-purge ventilation) passive design strategies would lead to comfortable indoor conditions in building design in hot, arid regions. The next chapter will focus on the thermal comfort of buildings as a main factor in design and the strategies that have been used in Riyadh to meet the human requirements of those who inhabit this harsh environment.

CHAPTER THREE

THERMAL COMFORT

3.1 Introduction

During the past several years, indoor environmental quality has become an important concern for many corporations and building owners. As a result, architects and engineers are being asked to present building systems that are responsive to the demands for high-quality interior spaces. One of the most important issues associated with indoor environmental quality is thermal comfort. It is generally accepted that thermal comfort plays an important role in human productivity, Fanger (1970) mentions that an increased interest in environmental conditions has occurred as a result of people spending most of their lives in an artificial climate, due to the growing mechanization and industrialization of society [(3-1)].

Thermal comfort can be achieved only when air temperature, radiant temperature humidity and air movement are within a specified range often referred to as the "comfort zone". This chapter aims to explain the human thermal comfort and its definitions, affecting factors as well as methods of determining the human thermal comfort criteria.

3.2 Definition

There are many definitions for thermal comfort. The basic definition of thermal comfort is the condition in which the individual feels neither too cold nor too warm while wearing an amount of clothing suitable to the particular task they need to perform.

It can be defined negatively as the situation where no feeling of discomfort occurs [(3-2)]. Thermal comfort has been defined in ISO 7730 standard as "that condition of mind which expresses satisfaction with the thermal environment" [(3-3)]. It has also been defined by Givoni as "the range of climate condition considered comfortable and acceptable inside building" [(3-4)]. Another definition by O'Callaghan, (1978) defined comfort as the study of the effects of climatic impact on human response [(3-5)].

However, the response of the individual human body to the thermal environment depends on many factors like the person's age, gender, clothing, geographical location and the activity being performed. Perception of human comfort usually varies from culture to culture according to physical conditions and physical activity.

The human body exchanges heat with the environment by a complex combination of radiation, convection, conduction and evaporation as briefly explained in section 3.1 in Appendix C of Chapter Three (separated to avoid any interfere with the main stream of the discussion). However, the thermal comfort of a human being is dependant on the thermal balance of the body, which is in turn dependant on two human factors and four environmental factors as shows below:

- **Human factors:**
  - Clothing insulation.
  - Activity level.
- **Environmental factors:**
  - Dry bulb temperature.
  - Mean radiant temperature.
  - Relative humidity.
  - Air velocity.

Both human and environmental factors are discussed in the following sections.

3.3 Factors Affecting Thermal Comfort

There are several factors which can affected thermal comfort. Factors like age, gender, culture etc. affect thermal comfort, clothing and metabolic rate of an individual and his surrounding environment as air temperature, relative humidity, mean radiant temperature and air movement can all be related to the above mentioned factors. Consideration of human factors and environmental factors is imperative in dealing with thermal comfort control inside a space. In the coming two sections, human and environmental factors will be discussed which will identify those factors that control human requirements for thermal control as explained in Figure (3-1) below.

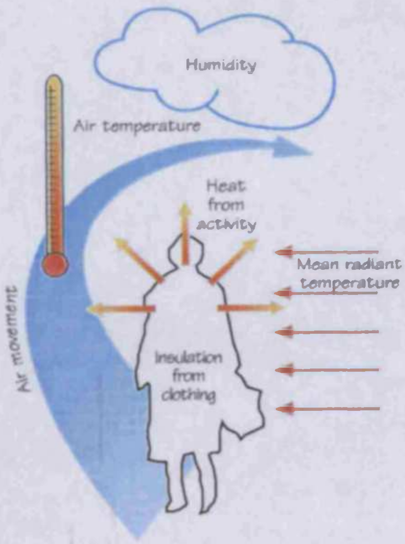


Figure (3-1) Shows the six factors affecting thermal comfort. Source: Borer, P. and Harris, C. (3-6).

3.3.1 Human Factors

3.3.1.1 Clothing Level

The human body temperature is affected by the clothing that prevents the convective heat exchange between the body and its surrounding environment, and acts as an insulating layer. Any activity that affects this layer reduces the thermal resistance of the actual fabric. For example, this protective layer of clothing is affected by air velocity in open areas, but is less affected in indoor areas (3-7).

Clothes are the most important human factor that affects thermal comfort directly because it is really difficult for human beings to survive without clothes, especially in extreme environments, where the temperatures are typically more or closer to body temperature such as Riyadh City, where the temperature is about 48°C in summer time.

The unit which has been used to control the factor of clothing thermal comfort is known as the insulation value (clo). One clo unit equals (0.155 m^2 K/W) of insulation and values range between 0 clo to 4 clo. (3-8). Figure (3-2) and Figure (3-3) show the clo value of different types of clothing and typical combination worn in different situations.

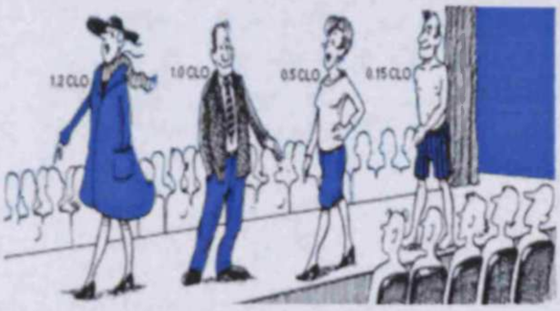


Figure (3-2) Insulation values for different combination of garments. Source: Innova booklet [3-9].

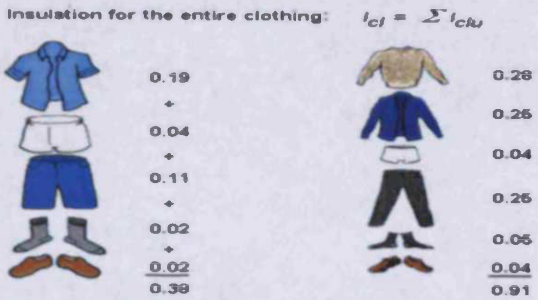


Figure (3-3) Calculating the over all insulation value for a certain clothing garment. Source: Innova booklet [3-9].

It is very difficult to assume an accurate value of clothes which vary from culture to culture. Choice of clothing is influenced by social and cultural factors, such as fashion, custom or religion, and changes in clothing types inevitably result in different levels of warmth and insulation [3-11].

Besides that, also, human body position affects clothing insulation, in sitting, sleeping and standing positions, insulation value of clothes is different, for instance, in the case of sleeping the bed and thick blankets may provide thermal insulation which could achieve more than 2.0 clo units. Table (3-2, 3-3) in Appendix C gives a list of the effect of clothing insulation values for individual pieces of garments and the thermal insulation for typical combinations of garments by the ISO 7730 Standard (ISO).

Clothes are one of the easiest parameter that can be adjusted by individual in order to achieve thermal comfort within given conditions. Actions can be carried out according to climate, during summer removing some garments or adding some during winter.

Clothing works in a number of complex ways to regulate body heat. In hot climates, layers of light, loose clothing are frequently worn, as these allow air to be circulated and thus assist heat loss. When individuals sweat profusely, loose garments also provide a greater surface area from which heat can evaporate, and allow the space between the skin and the inner layer of clothing to cool, with the result that the effects of solar radiation are less severe [3-12].

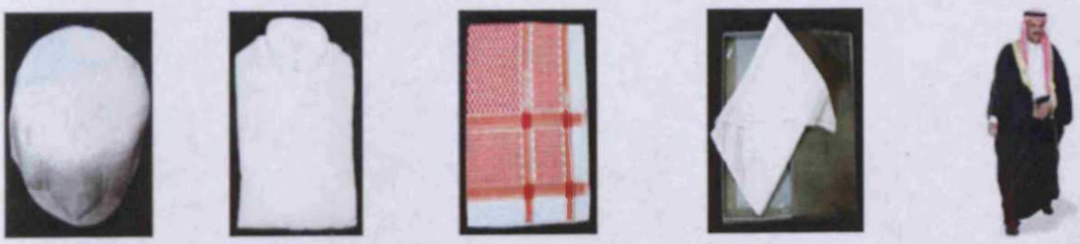
However, in the case of Saudi Arabia, the traditional clothes that the people of Saudi Arabia wear today have their roots in ancient history and are indigenous, having evolved over the centuries in response to the specific needs of the people and the challenges of their physical environment. The women dress according to the rule of Islam that she has to cover all her body in public except her face and hands. This kind of dress may have developed before Islam for women living in harsh desert environments where constant exposure to solar radiation causes damage to the skin surface and its sustained glare can have a harmful effect on the eyes, thus, wearing a slight veil is a practical measure.

Over the millennia, wearing a veil has also become a sign of modesty and virtue for women. Others, who are living in different climate conditions, such as rural women in south western Saudi Arabia where the environment is characterized as the rainy region, wear hats made of palm fronds over a scarf while outside the home.

For men, the traditional clothing begins with the headdress, which consists of three parts. First there is a skull cap, known as the *tikyah*. It is generally white in colour. A square head cloth known as the *ghutrah*, folded diagonally to form a triangle, is worn over the *tikyah*. It comes in either white or checkered white and red known as *shomaq*. In the old days, Bedouins when travelling in the desert wrapped the *ghutrah* across their face, leaving a slit open for the eyes to protect against sandstorms. Saudi clothes were made originally from cotton or occasionally from other fabrics. The m ain garment worn by m en is the *thobe*, which is an ankle-length shirt, generally white, although other colours are also worn.

The thermal resistance of such as clothing or *thobe* could be approximated as 0.3 clo. This because of *thobe* is a light colour and almost white, also, according to the author's own experience this kind of material is the most suitable dress for the hot and arid climate of Riyadh. Figure (3-4) below shows the Saudi traditional a dress for men [(3-13)].

According to Nielsen (2002) the amount of clothing equal to about 0.3 clo that can be worn in hot climate [(3-14)]. This amount can help the cooling effects of air movement to be felt. However, for the Saudi traditional dress the clo unit it might be up to 0.5 due to fabric characteristics and the design of dress that has bright colour and an open weave.



Tikyah *Thobe* *Shomaq* *Ghutrah* *Bishet*

Figure (3-4) Saudi traditional clothes. Source: Saudi Embassy Magazine [(3-13)].

3.3.1.2 Human Metabolic Rate (Met).

Metabolism is defined as the sum of the chemical reactions which occur within the body [3-15]. The rate at which heat is produced depends primary on our metabolic rate. Metabolic process is a kind of fuel for the human body. The amount of muscular activity done by the human body determines the amount of energy released by the metabolic process. The rate of metabolic energy depends on the level of muscular activities of the person engaged. Figure (3-5) shows the relationship between different activities and their related metabolic rate.

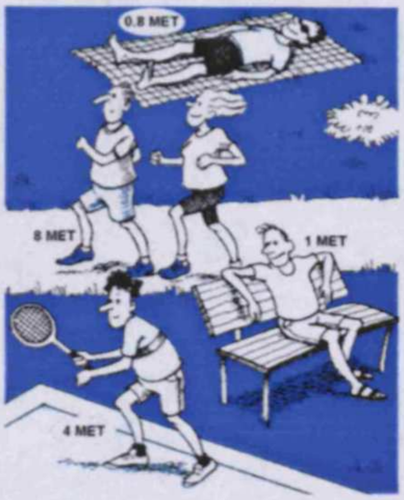


Figure (3-5) Different metabolic rates associated with different activities. Source: Innova booklet [3-9].

Metabolic rate and thermal comfort are related. Metabolic heat energy affects thermal comfort through different factors, and is itself affected by different factors in return.

The unit of the metabolic rate is expressed in MET units (1 MET=58.2 W/m^2). One met is equal to the energy produced per unit surface area of a steady person at rest and the surface area of human body, on average, is 1.8 m^2 [3-7].

The standard list of metabolic rate stated in the ISO 7730 which gives the metabolic rates for various typical activities is presented in Table (3-1). However, it is very difficult to calculate precisely the metabolic rate of persons living in buildings in Riyadh since spaces differ greatly, as do the activities taking place within them, but it is probably safe to use a measurement based on the activity carried out by the individual during the hour before assessment. [3-9].

Table (3-1) Metabolic rates of different activities. Source: ISO 7730, (3-3).

Activity	Metabolic rates	
	W/m²	Met
Reclining	46	0.8
Seated, relaxed	58	1.0
Sedentary activity (office, dwelling school, laboratory).	70	1.2
Standing, light activity (shopping, laboratory, light industry).	93	1.6
Standing, medium activity (shop assistant, domestic work, machine work)	116	2.0
Walking on level:		
2 km/h	110	1.9
3 km/h	140	2.4
4 km/h	165	2.8
5 km/h	200	3.4

3.3.1.3 Human Physical Characteristics.

a) Age

Because of their lower metabolic rate, it is generally assumed that older people prefer a warmer environment than younger people. Although this may be true, there is no evidence that older people universally prefer warmer temperatures, and in all probability this is a matter of individual preference. A study carried out by Fanger on the effects of age on comfort found that the comfort temperature is the same for the old and the young and there is no significant difference in the required thermal comfort between young and old persons (3-1).

b) Sex

Females generally prefer slightly warmer temperatures than males, but it may be because of differences in clothing insulation. According to Fanger's research in 1970, there is no significant difference between the thermal comfort requirements of males and females in the same activity (3-1). In Moslem countries, such as Riyadh the Islam requires that women should cover their bodies in public, with the exception of the hands and face. For this reason, women living in Riyadh might prefer cooler temperatures than men. However, there does not seem to be any physiological difference in the metabolic rates of men and women due to the cultural aspects which play the important role.

C) Acclimatization

Acclimatization happens when someone move from one national or geographical region to another one that has different climate conditions. According to Givoni and Goldman's study in 1973 (3-4), the human physiological adjustment can be achieved in the new climate within two weeks. Fanger states that national geographic location does not have a significant influence on the thermal condition. On the other hand, several studies have shown that heat acclimatization on people who live in hot countries results in a preference for higher temperatures than those suggested by American or European standards (3-1).

a) Body Build

As might be expected, owing to the insulating properties of body fat plumper people feel warmer than thinner people in a similar environment. This is might be right because of the amount of fat under the skin which works as an insulator by reducing the conduction from the deep body to the surface. However, Fanger in his experiments (1970) indicates that body build does not have a significant influence on the comfort conditions of sedentary subjects (3-1).

3.3.2 Environmental Factors

There are four main environmental factors that determine the level of heat exchange between the human body and indoor environment. They interact with each other and the effect of any factor depends upon the level of the other three factors. These factors are discussed in details in the following section.

3.3.2.1 Air Temperature (DBT).

Air temperature plays the most important role on contributing to thermal comfort, because it affects thermal the rate of heat convection and evaporative heat loss. The range recommended by CIBSE to achieve comfort indoors is that the air temperature is between 19°C and 23°C in winter, while in summer it is less than 27°C (3-16).

However, there is no exact ideal temperature for comfort, the best temperature is the one at which most people feel comfortable. Air temperature is commonly measured with calibrated mercury or glass thermometer and the reading is referred to as the dry bulb temperature. If an appreciable amount of radiant heat is present, the dry bulb temperature will not be a reliable guide to the effect of this heat transfer on individuals.

3.3.2.2 Mean Radiant Temperature (MRT).

According to Givoni (1981) mean radiant temperature is the "weighted average temperature of the surfaces surrounding the space" (3-7). The mean radiant temperature, which depends on the temperatures of the surrounding surfaces, has a great an effect on thermal sensation as air temperature. It is responsible for an individual's heat loss and gain by radiation, and thus on his thermal comfort.

A human's thermal comfort depends significantly on the heat exchanged by radiation between them and their surrounding. For example a person sitting close to a window in winter would feel cooler than another sitting in the middle or close to any interior wall in the same room and in summer the opposite effect would occur. Heat gain to the human body by radiation takes place when the MRT is higher than the body surfaces, while it loss heat when the MRT is lower.

Because of the temperatures of the room surfaces vary and may significantly differ from air temperature, in most comfort standards the temperature of surroundings is assumed to equal the air temperature (3-17).

It should be noted that the MRT, which is dependent on the indoor air temperature, should be kept equal or close to the air temperature, but not more than about 3°C below it. If this does not occur, the environment will be stuffy (3-8). Figure (3-6) shows the effect of activity and clothing on comfort zone.

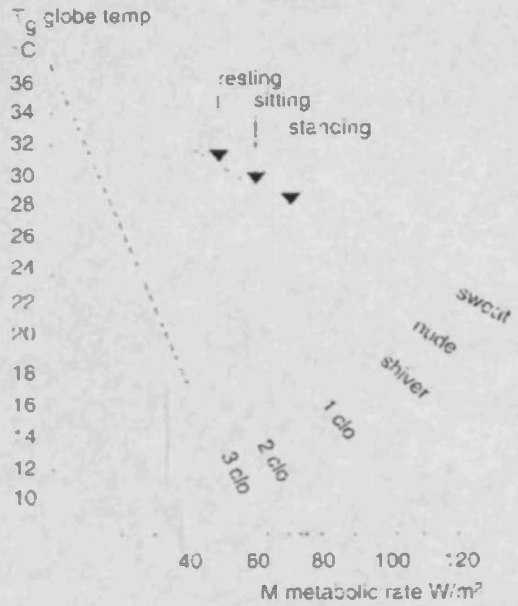


Figure (3-6) The effect of activity and clothing on comfort zones. Source: Baker N. and Steemers K, (3-18).

3.3.2.3 Relative Humidity (RH).

Humidity is a major factor not only for affecting comfort levels inside a space, but also the health of those who use it. It can be measured either as Absolute Humidity or Relative Humidity.

Absolute Humidity is the amount of moisture present in a given volume or mass of air and is described in grams of water per kilogram of air, or grams of water per cubic meter of air.

Relative Humidity is the amount of water vapour in the air described as a percentage of the total water vapour which can be held in the air at a given temperature [(3-19)].

Relative humidity gives a direct indication of evaporation potential and so it is more important and useful as a measurement tool than absolute humidity.

The effect of humidity on human thermal balance and to thermal comfort is very complex [(3-7)].

According to Givoni, it is not sufficient to balance the metabolic heat production of the body activity when the dry heat loss includes the evaporation within the lungs. Figure (3-7) shows that relationship between air temperature and relative humidity.

For instance, if the air temperature is 24 °C the relative humidity is varied between 20% and 60%.

Thermal comfort is affected by relative humidity as relative humidity affects the sweat evaporation rate and sweat evaporation rate affects heat dispersal from human body. However, many other factors such as the partial pressure of water vapour in the air and the vapour pressure of the sweat on the skin also determine the rate of sweat evaporation.

The recommended optimal range of humidity is from 40 % to 70 %. Above and below these limits there appears to be an increased tendency to ill effects (3-8) (3-20).

Szokolay (1980) (3-21) and Martin Evans (1980) (3-19) revealed that from the health point of view both of extremely low and extremely high humidity have bad affects. Relative Humidity of less than 20% can cause discomfort due to dryness in the air and this may cause mucous, cracked lips and sore throat. Relative Humidity more than 90% reduces evaporative cooling and it could make people feel wet and damp.

Therefore, from the health perspective and the thermal point of view, it is imperative to control humidity inside the buildings.

In hot dry climates such as Riyadh City where the relative humidity is about 10% in summer time, people spray water in the courtyards and on the roofs of buildings at noon in order to cool the air, increase relative humidity and enhance the comfort level.

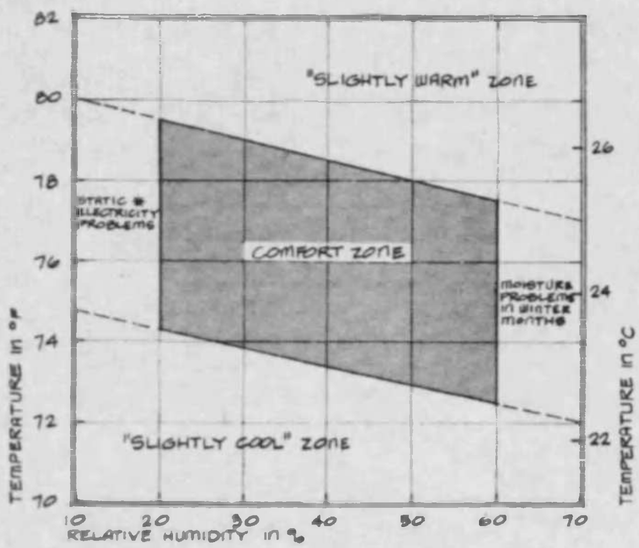


Figure (3-7) Average zone for human thermal comfort. Source: David Egan (3-22).

3.3.2.4 Air Velocity

Air movement not only means air speed but also air direction and air temperature. In fact, temperature of moving air is more important than its speed. This is demonstrated by the fact that cool air and hot air at the same speed have different effects on the human body. Human body temperature and air temperature are inter-linked. For example, the sense of cooling is increased if a person is sweating because air enhances the effect of sweat evaporation. When air speed is less than 1 meter per second, it could create a feeling of stuffiness, but if the air speed is higher than this, discomfort will be caused, with added inconvenience that office paper may be blown around [3-19]. Figure (3-8) shows the comfort zone and the relation between the air velocity and moving air stream temperature. The recommended air motion levels and recommended temperature for different activities inside buildings listed in Table (3-4) and Table (3-5) in Appendix C.

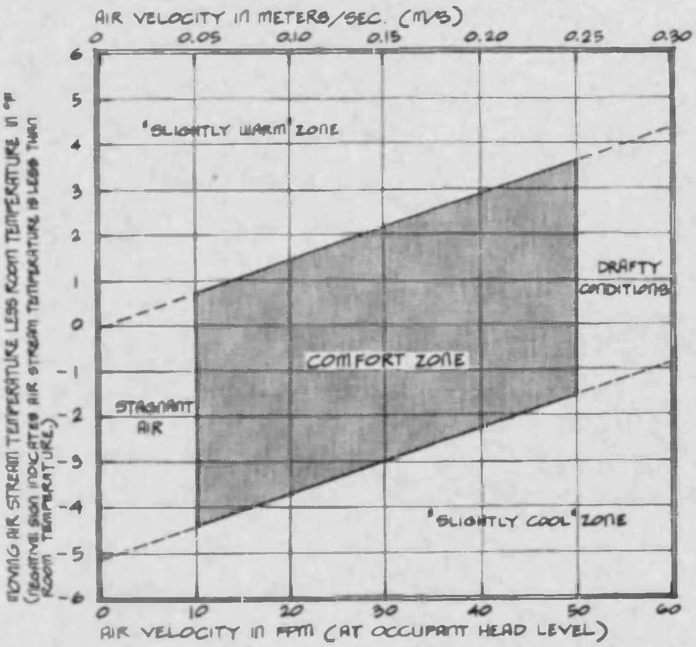


Figure (3-8) The average zone for comfort and the relationship between air velocity and moving air stream temperature. Source: M. David Egan [3-22].

3.4 Thermal Comfort Indices

Thermal comfort is a complex concept, which is affected by many factors and at the same time does not have the same affect on all individual. Thermal comfort prediction needs a testable mathematical model in order to discover the relations between the different factors relating to the thermal comfort [3-23].

One of the goals of the designers, when beginning any project is to ensure acceptable levels of comfort within the building. This will depend on the climate, the function of the building and a range of cultural, social, human and environmental factors as mentioned above. Comfort levels can be achieved through calculation or by using models or analogues to test the behaviour of the design under any conditions.

However, a number of indices have been developed through the last decade in order to assess environments on terms of thermal comfort.

The effective temperature (ET) is one of the early indices, which has been developed by the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) in (1923-1925) (3-4) as comfort indices by Houghten, Yaglou and Miller (3-24). The ET scale is obtained by combining the effects of temperature, humidity and air speed on the sensation of warmth or cold felt by the human body, and does not measure radiant heat. It was adjusted by Bedford in (1946) to include the effect of mean radiant temperature and thus become known as the Corrected Effective Temperature (CET). Figure (3-9) shows the CET after adjustment (3-25).

According to Szokolay (1980) (3-21) those indices can be divided into the following major types:

a) Empirical indices, depending on social investigation such as comfort vote by using environmental measurements and later correlation.
b) Analytical indices based on a set model of physical and physiological conditions which is give a clear image of human and environment interaction (3-6).

Example of the first type are Humpherys's and Auliciems's adaptive models, which are based in field investigation using the outdoor, dry bulb temperature and the average indoor temperature (3-23), Fanger's Predicted Main Vote (PMV) and Gagge's Standard Effective Temperature (SET) are examples of the second type of index. The adaptive model and PMV are commonly used indices for comfort, and will be discussed in detail in the following section.

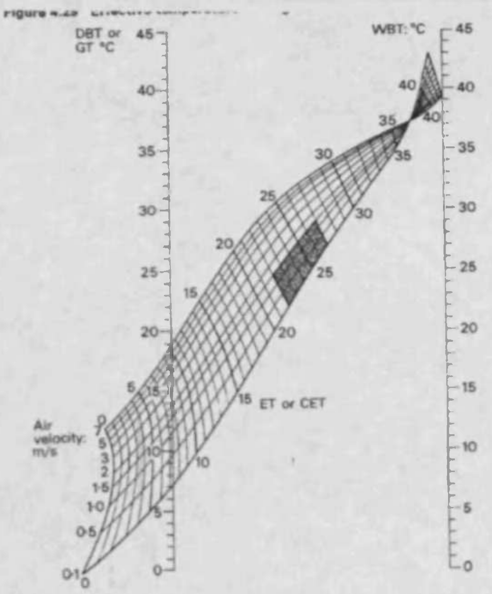


Figure (3-9) CET normal Scale. Source: S. V. Szokolay [3-21].

3.4.1 Predicted Main Vote (PMV)

Since 1984, Fanger's PMV index, developed in 1972, has been used as the basis of the International Standard Organization ISO-7730 to evaluate moderate thermal environment. This index is based on a complex calculation of mathematical function, involving human activity, clothing and four environmental factors. He used a mathematical model based on a steady state energy balance to calculate the PMV [3-24].

Fanger's assumption was that thermal comfort can be derived from the human heat balance equation on a seven point scale of thermal sensation. A large number of people were exposed to a certain environment and comfort was determined as a function of the activity, clothing, air temperature, mean radiant temperature, air velocity and humidity. The scale of ASHRAE ranges as shown below from +3 which correspond to hot t hrough 0 which corresponds to neutral, and is the value for comfort, to -3 which corresponds to cold, while the comfort range of comfort is between -1 and +1.

Thermal Sensation Scale - a seven point psychological scale. Source: Fnger [3-1].

Scale Value	Sensation
+3	Hot
+2	Warm
+1	slightly warm
0	natural comfort
-1	slightly cool
-2	Cool
-3	Cold

Fanger's final equations are quite complex and so the PMV is usually solved by computer programs or by tables and graphs for a wide range of metabolic rate, climate condition, and clothing values [3-1].

3.4.2 Predicted Percentage Dissatisfied (PPD)

Fanger created a second equation of the Predicted Percentage Dissatisfied PPD for people exposed to the same condition and reported discomfort from PMV, where it defined as those who vote – 2 (cool) or – 3 (cold), + 2 (warm) or + 3 (hot) on the PMV. Figure (3-10) shows this relationship based on the criteria that the individuals voting –3, -2, +2, or +3 on the ASHRAE voting scale.

Under ideal thermal condition (PMV = 0) a minimum of 5% dissatisfied is found [3-1].

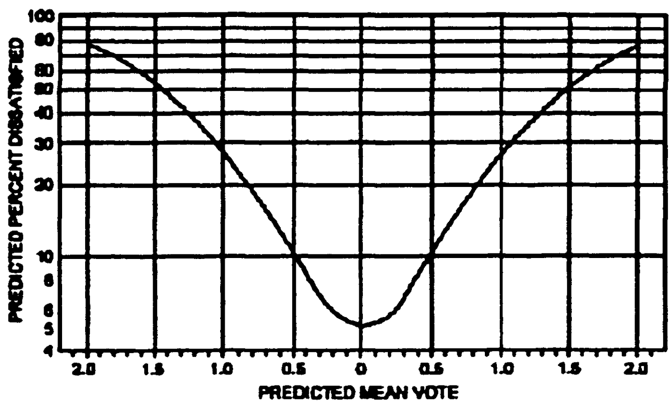


Figure (3-10) The relationship of the (PPD) and (PMV). Source: ASHRAE [3-26].

3.4.3 The Adaptive Approach

Instead of using a climate chamber experiment to calculate the heat balance between the man and his environment as done by the work of Fanger, Humphreys's adaptive approach in 1975 drew attention from the observation that there is a range of actions that people can take to adapt their surrounding environment in order to achieve thermal comfort, Humphreys in 1994 (3-27) summarized the most commonly used methods of securing comfort by a simple model as follow:

- Modifying the internal heat generation (change activity level).
- Modifying the rate of body heat loss (alter clothing).
- Modifying the thermal environment (open/close window, light a fire).
- Selecting a different environment (find another spot, visit a friend).

However, Humphreys presented an analysis of data from around the world of more than 30 field surveys of thermal comfort. He found out there is a very strong relationship between the comfort temperature (T_c) indicated by respondent in free running buildings and the mean monthly air temperature (T_o), as people adapt them selves to outdoor climatic conditions. he concluded that the thermal comfort also depends on the individual cultures of different countries; the temperature comfort for England and Russian is located lower than average, for example, while the comfort temperature for North America is located higher than the world average (about 2K) (3-24). According to Humphrey's study, thermal comfort can be achieved by people themselves taking action to control thermal conditions.

Figure (3-11) below shows the result of Humphreys analysis, which is conducted in free running building, where the related indoor comfort temperature (T_c) is close to the temperature measured in accommodation, this could be taken as evidence of the occupants of a building having taken effective action to adapt to their conditions. The relationship was derived from the line of best fit for the range of comfort data points. (3-12) (3-27) (3-24).

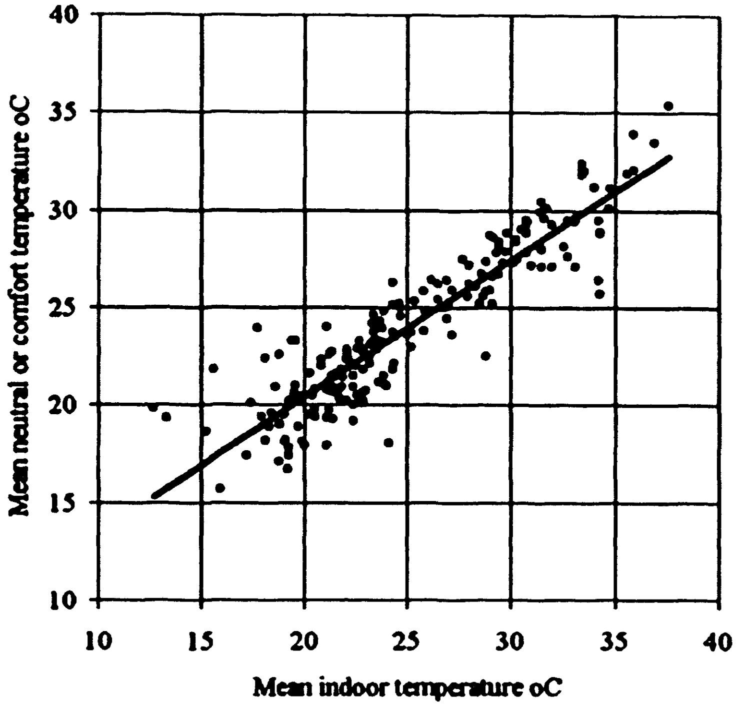


Figure (3-11) This graph shows how the mean comfort temperature varies with the mean indoor temperature. Each point in the graph is the mean value for a whole survey. Source: Mulcom (3-24).

As a result from the (T_c) in a free running building and its accuracy, this can allow us to predict the comfort with a standard error of only 1 °C and applies to a range of $10 \leq T_m \leq 34$ °C.

For a mechanically heated and cooled building, comfort can be predicted with a standard error of 1.4 °C and applies to a range of $-24 \leq T_m \leq 23$ °C and $18 \leq T_h \leq 30$ °C (3-24).

The equations for calculating the indoor comfort temperature from the outdoor monthly mean temperatures are given as follows (3-23).

Free running building:

$$T_c = 11.9 + 0.534\, T_o$$

Heated or cooled building:

$$T_c = 23.9 + 0.295(T_o-22) \exp ([-(T_o-22)/33.941]^2)$$

Unknown system (an average of all buildings):

$$T_c = 24.2 + 0.43(T_o-22) \exp (-[(T_o-22)/28.284]^2)$$

Figure (3-12) shows the relationship between the obtained data from surveys about the internal comfort temperature (T_c) and the mean prevailing outdoor air temperature (T_o), obtained from meteorological tables.

It is clear from the graph that the range of (T_c) is located in a very narrow band and the range of (T_c) is from 17 °C to 32 °C at any value of (T_o) (3-24). By comparing the temperature occurring in the building with the mean indoor temperatures favoured by the occupants, Humphreys found that the mean indoor temperatures were higher than the comfort temperature. As a result the average mean indoor air temperatures in the free running building is about 2.4 °C higher than the comfort temperatures in the corresponding values for heated or cooled buildings, which is 0.6 °C (3-24).

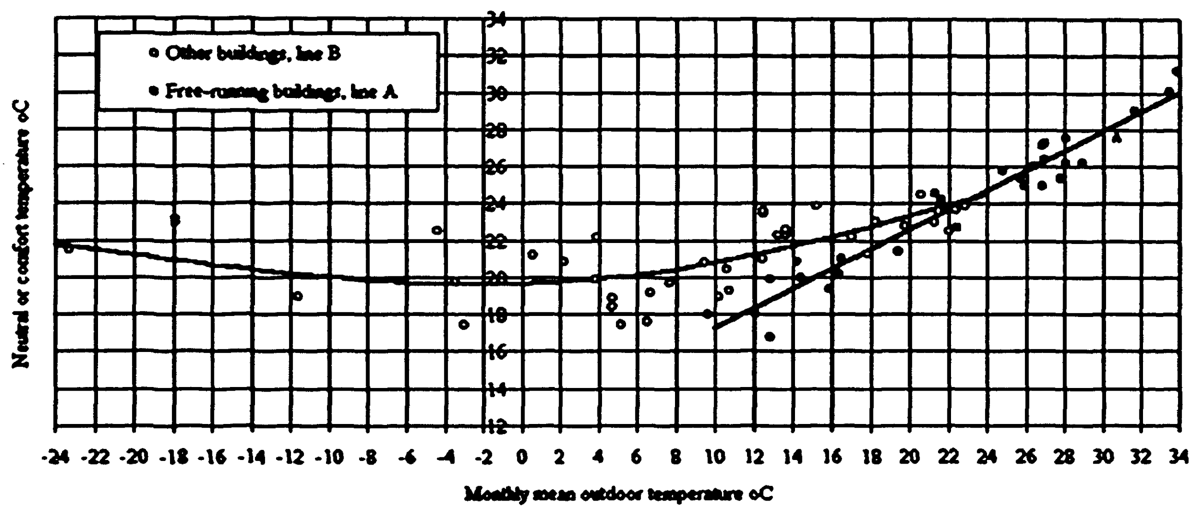


Figure (3-12) The relation between the internal air temperature and mean outdoor air temperature, solid dots show free running building and circles show other buildings. Source: Mulcom (3-24).

Auliciems (3-28) combined the predictive power of the correlation shown in Figure (3-11) with that in Figure (3-12) and put an equation which predicts the (T_c) jointly from the indoor mean temperature (T_i) and the out door mean temperature (T_o) through the following equation:

$$T_c = 9.22 + 0.48\, T_i + 0.14\, T_o$$

Further evidence of adaptation was made by Humpherys in (1972) through his work on school children. He found a relationship between the children's responses as individual in their use of clothing changes at different temperature. Humpherys states that clothing change is one of the important measures taken by people to adapt to changes in climate (3-29).

The adaptive model has recently been included in the new ASHRAE Standard 55-1992R to identify the indoor operative temperature that guarantee the human thermal comfort in naturally conditioned space.(3-26).

3.5 The Climate Design for Riyadh

According to MacIntyre, (1980) there is no absolute value for comfort, which is generally relative to personal experience and expectation. An individual will be free to do what makes him feel comfortable (3-30). In addition, it is difficult to satisfy sensation for everyone in the same condition since the comfort is a subjective sensation. There is no such thing as ideal combination of condition. Even when the ideal comfort is achieved, some of the occupants may feel comfortable while other may not. It should be noted that the average variation in temperature during the daytime may also influence comfort as well as the wind speed and the variation between temperature and radiation (3-19).

Suggested thermal comfort limits vary from study to study and are generally dependent on tests and experiments carried out in respect of different places and cultures.

It should be noted that any variations in preferences for comfort temperature found between people in warm and those in cold climate related not only to differences in clothing and acclimatisation, but to other variables which should be taken into account, relating to physiological, psychological and social factors. Variation happens not only between different population, but within the same population and that will be apparent in buildings in all of the regions of Saudi Arabia, demonstrating how people adapt to their climate, and even more remarkably, develop skills to accommodate their situation. The success of this human adaptive ability is remarkable.

Nevertheless, it is obvious from the analysis of Riyadh's outdoor climate that the main climatic conditions can be summarised as hot dry days in summer and very cold in winter (refer to chapter two for more details). Any designs intended to achieve thermal comfort should take into account the use of passive cooling strategies such as sufficient thermal massive materials providing good protection against ambient heat with natural night ventilation and open courtyards to provide shade throughout the day and thermal control on the facades surfaces of the building within the same context.

3.6 Conclusions

Human thermal comfort depends on both environmental and personal factors. People living in hot climates have been shown to be more comfortable when they wear their traditional dress. Such dress expresses equality and is also perfectly suited to the hot Saudi climate as it is loose, provides protection from the Sun and promotes air circulation around the body even when indoors. White clothing is cooler than dark clothing in the sunlight. Head coverings are also very important for protection against the sun and can be used to cover the mouth and the nose during sand storms or cold weather.

It is this adaptive quality of the people living in Saudi Arabia that is the most important point to come out of this comfort analysis. The clothing, activity rate and wind speeds are all subject to human intervention and long-term acclimatisation, so it is not practical in this climate to specify a particular comfort zone. However, temperature relative humidity and mean radiant temperatures are a function of the built environment, so the aim should be for buildings to reduce these values as much as possible in order to provide people with as great a potential as possible for adapting to their own comfort levels.

Chapter four will explain the traditional houses in the all regions and many lessons can be learned from these buildings. Many of the important factors to be taken into consideration are the material and the techniques used in traditional buildings to adapt to their environment and how in the absence of air conditioning, people react to the extreme climate by using their skills to adapt to this kind of environment by using thick walls and thick roofs and different strategies to obstruct the flow of heat and to deal with their particular cultural, religious and, social characteristics.

CHAPTER FOUR

REGIONS TRADITIONAL BUILDINGS

4.1 Introduction

Saudi Arabia, like many other countries in the world, has recently been enriched by the discovery of oil. In the 1930's the country became one of the fastest growing nations in the world. Unfortunately most of its vernacular architecture has now been replaced by western modern architectures, which is often unsuitable and based on a poor understanding of the local environment, cultural and social needs.

Many lessons could be taken from the builders who have developed, over many centuries, the techniques of building that adapt to their climate, culture, economy and religious needs. This chapter gives a background to Saudi traditional buildings and provides evidence of the considerable interaction between man and his environment throughout the centuries and how climatic and environmental conditions effects buildings in all five regions of Saudi Arabia.

4.2 Region Traditional Building Types

As mentioned in the previous chapter, each region of Saudi Arabia has a different climate and different designs of traditional buildings which reflect the interaction between many variables such as culture, economic and religion, with regard to contact with other countries and the world outside their immediate sphere of knowledge.

> *"Adobe architecture varies widely in different regions, at different heights and according to the cultural background"* (4-1).

There is a marked difference in the amount to which certain regions are affected by foreign contacts and cultures.

Some are intrinsically altered by such social interaction and some, with little or no such contact, remain very much the same in outlook and action as they have been for centuries.

Each region has different local building materials available in its surrounding area. This indicates that each region has various and characteristic ways of meeting the needs of their community whilst also paying regard to the laws of Islam. Considering Saudi Arabia as a whole, traditional houses consist of tents, mud houses and houses made of stone. In most regions, the building industry used mud and stone until the comparatively recent discovery of oil in the nineteen thirties. Traditional ways of building and of living were preserved before the discovery of oil as the economy was not bolstered by natural resources. Also with regard to regional variations in building design and use of materials, the location affects building design because consideration has to be given to topography and climate. The five regions of Saudi Arabia are distinguished as described in the following Table:

Table (4-1) Summary of traditional buildings, materials and houses.

Region	Cities, Town, Villages	Types of Construction	Location	Remarks	Sample
Eastern	Dammam, Qatif, Jubail ,Others	Rubble Stone	Located on the sea shore	Stone is quarried from the sea shore	
	Hafuf	Adobe	Desert Arid Zone located 100 Km away from the shore	City sun-dry bricks manufactured on site	
Central	Riyadh, Buraydah, Unazan, Al-Rass	Adobe	Occupy the centre of Arabian peninsula Desert Arid Zone	City sun-dry bricks manufactured on site	
Western	Macca, Medinah, Jeddah, Taif, Yanbu, Others	Stone and Clay bricks	Limited between the Red sea shore and Sarawat mountains	Stone is used in lower parts of the buildings and bricks in the upper parts. Stone is quarried from nearby mountain	
Northern	Hail, Qaisoumah, Others	Adobe	Continuaton of the Central Region		
	Tabuk, Wajh, Ula, Jawf, Others	Stone	Located in the northern part of Sarawat Mountains Zone	Variable Techniques of using stone	
Southern	Baha, Abha, Khmis	Stone, Adobe & Stone	Located in the highest part of Sarawat Mountains (Rainy Region)	Some buildings are completely constructed in stone and others in adobe with slices of stone	
	Najran, Bishah, Al-Khurmah	Adobe	Desert Arid Zone located on the eastern side of the mountains	Clay sun-dry bricks manufactured on site	
	Jizan, Abu Arish, Sabiah Tihama	Stone, reed huts	Located on the Red Sea shore	The common construction types is straw huts similar to similar African huts	

This next section will explain the type of architecture in the desert. Also, it will focus on the type of the traditional building in each region of Saudi Arabia to give an idea of the various kinds of the traditional buildings materials used throughout the country.

4.2.1 Nomadic Dwelling (Tents)

In the deserts of the Arabian Peninsula the majority of Bedouin tribes are found in the Al-Rub Al-Khali, Al-Dahna and Al-Nofod deserts, where modern life has not yet encroached. The Bedouin are the nomadic desert dwelling [(4-3)] people who have for centuries made their homes in the deserts. They are a traveling people, continually sending male scouts ahead to find fresh grazing land. They pitch their tents in a suitable area that contains water and green fields to build their dwelling and stay as long as the available pasture can sustain their livestock.

The Bedouin used to live in a black tent, and they have evolved the design of their shelter to protect them from the harsh environment and to provide an exclusive shelter which reflects their skills and culture.

> *The tribe is not merely a social structure. It is a whole way of life attesting to man's ability to adapt to his environment* [(4-4)].

The traditional tent or as it known local the *Bait Alshar,* was the home and shelter of Bedouin in Saudi Arabia which is easy to carry, simple to construct and dismantle or repair.

When they have found a suitable place to stay for a while, they construct their dwellings in such a way that groups of tents are combined into tribal groups. Each tent is an independent household. There may be a single family occupying one tent or, also, a small group of tents may be constructed together and this group is made up of parents and their grownup sons with their spouses and children.

During traditional use, the Bedouin tent provides shade and protection from the sun, privacy for the family, the necessary segregation of the genders and shelter from the harsh wind of the desert. The tent is highly portable, put up and taken down very quickly. It was carried on the camels during travelling.

The roof and the sides of the tent are usually woven from animal wool. The wool mostly used to weave tent-making material in Saudi Arabia is taken from a goat that is quite dark in colour. The colour of this naturally obtained fabric lends its name to the dwellings, which are subsequently known as 'black' tents (Figure 4-1, 4-2).

Figure (4-1) Bait Al-Sha'r pitched on three poles. Photo by author.

Figure (4-2) Decoration of Bait Al-Sha'r. Photo by author.

The wool from which the tents are formed is woven in stages. Goat's hair is the most desirable wool to use, because it is of sufficient length for the required purpose, and because it can stand tension. However sometimes the goat hair is mixed with sheep's wool and with either a combination of sheep and camel wool or simply with one or other of the two (Figure 4-3).

Figure (4-3) Traditional Bedouin weaving. Source: Bani Hamida [4-5].

Mixing sheep and camel wool together obtains a more suitable yarn, because the sheep's wool provides length, it stretches under tension and the camel wool is short and strong. Therefore mixing obtains the necessary length and strength in the wool to be spun. It is spun with a simple, hand-drop spindle. The yarn is woven into long sheets of fabric and these sheets are sewn together to form the roof and the sides of the tent.

Depending on the region through which the nomads normally wander, the tents may be structurally different. The structural difference concerns how many poles are used to support the tent during and from erection and the arrangement of these poles.

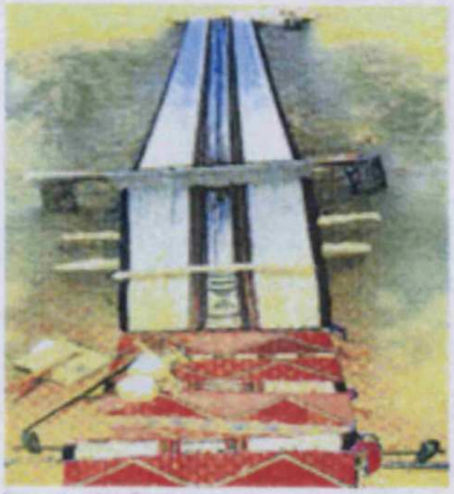


Figure (4-4) Bait Al-Sha'r waving. Source: Alrwasi (4-6).

Figure (4-5) Bait Al-Sha'r wool. Source: Alrwasi (4-6).

The people of the northern region use an 'Iranian' type of tent (4-3). In this type of construction the rear awning of the tent is stretched and supported by an anchor and the front of the tent is supported by two rows of poles, as is the center (Figure 4-6 and 4- 7).

This type of tent when compared with the tents used in the Southern and Central region is lighter to carry when traveling. This is because in both the Central and the Southern region there are more poles used during construction.

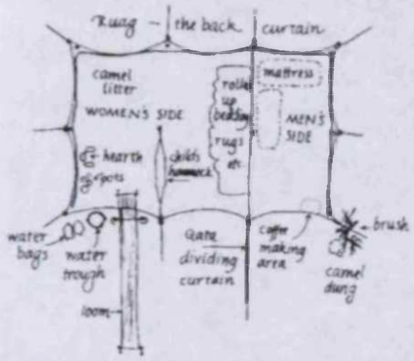
Figure (4-6) Bait Al-Sha'r waving and tent guyed down tightly to keep out rain and wind. Source: Alhariri (4-4).

Figure (4-7) Bait Al-Sha'r wool. Source: Alhariri (4-4).

The Central Region features tents using three rows of wooden poles per tent, with three poles in each row and the poles in the central row are higher, while Southern Region tents use two rows of wooden poles with three poles in each row.

The layout of the tents based on factors such as privacy and protection from the harsh environment. The design of the tent is divided into three sections by curtains, the men's section, the family section and the kitchen. There are separate entrances on either side of this dividing curtain. One entrance is for the men, and one for the women. This maintains complete gender segregation (Figure 4-8).

The women's section is always on the left side of the tent and is called the *'Mouharam'*. All cooking and general housekeeping activities are undertaken here. Some of the space in this area is also given up to the storage of food, water, bedding and general items used in the process of daily housekeeping.



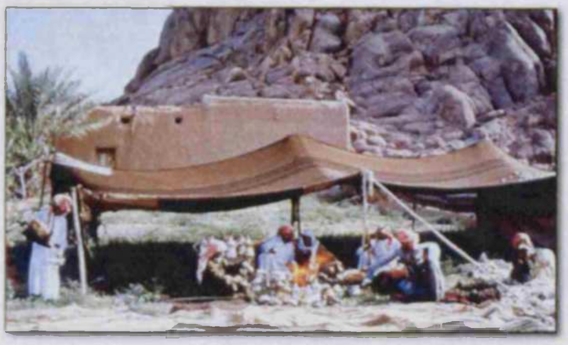


Figure (4-8) Bedouin Tent Layout and tent sitting in summer, where the wool partition end walls often removed to allow for crossing ventilation. Source: Faegre and Government of Riyadh (4-7, 4-24).

The *'Majlis'* or male section is used for entertaining guests and other more leisurely activities. It may have coffee making equipments, and contains mattresses to sit on. This is so that guests can be entertained and visitors received and news shared. It is situated on the right-hand side of the dividing by a *riwaq* or woven curtain (Figure 4-9).

Figure (4-9) Men reception. Source: Saudi Arabia Magazine (4-8).

To stay away from the harsh desert climate, the tents are pitched in an east facing Macca or in the south in order to avoid the strong wind or the direct rays of the sun while the tent made of wool and hair, it does provide protection from cold (4-7). The characteristics of the tent's fabric also mean that it can work as a filter from the dust storms. Some tents have ventilation systems created by twisting the curtain strip or loosing it to work as a wind catcher (Figure 4-10). Another technique that the Bedouins use is to splash some water on the inside of the tent wall, which makes the air that comes in through it feel nice and cool (4-9).

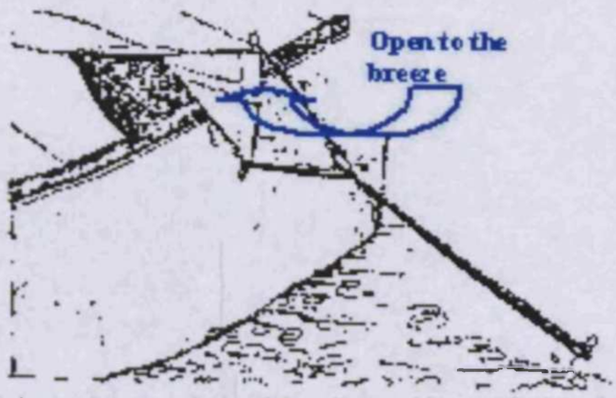


Figure (4-10) Curtain works as a wind catcher to provide ventilation. Source: Al Bakri (4-9).

4.2.2 Central Region

The Central Region is hot and dry. It is isolated from the outside world and it is situated at the center of the Arabian Peninsular and surrounded by three deserts in total. Unlike the others regions, limestone was not available here and the most available building material was soil or mud collected from the *wadis* (dry riverbeds) after the seasonal rains.

With water, straw and other fibers, the mixture was used to make mud bricks that were laid along horizontal layers for walls, which were made thick for added structural support. Tree trunks, most often those of the date palm, and palm trunks covered with mud formed the roofs.

Houses usually had one or more internal courtyards which worked as climate modifiers, keeping the house on shade for most of the day because of its high walls and the exterior windows were small both for privacy and to keep the house from heat.

The central region houses are situated close together with narrow streets which create shade and the mud plaster used to cover the buildings contained decorative elements for visual purposes. The result was a structure, which reducing the exposed surface area of the house and consequently its exchange of heat with the outside provided excellent insulation against heat (4-4). The traditional planning and design was not based on pre-planned concept. This type of building was a result of the people's actual needs to face the extreme heat. The next chapter will explain Central Region with more details as a case study of this work (Figures (4-11) to (4-14) show the materials and the type of Riyadh houses.

Figure (4-11) Courtyards and narrow streets in the Central Region. Source: Albini [4-1].

Figure (4-12) Narrow streets offered protected area against heat in Riyadh. Source: Tatweer [4-10].

Figure (4-13) Buildings. Source: William Facey [4-11].

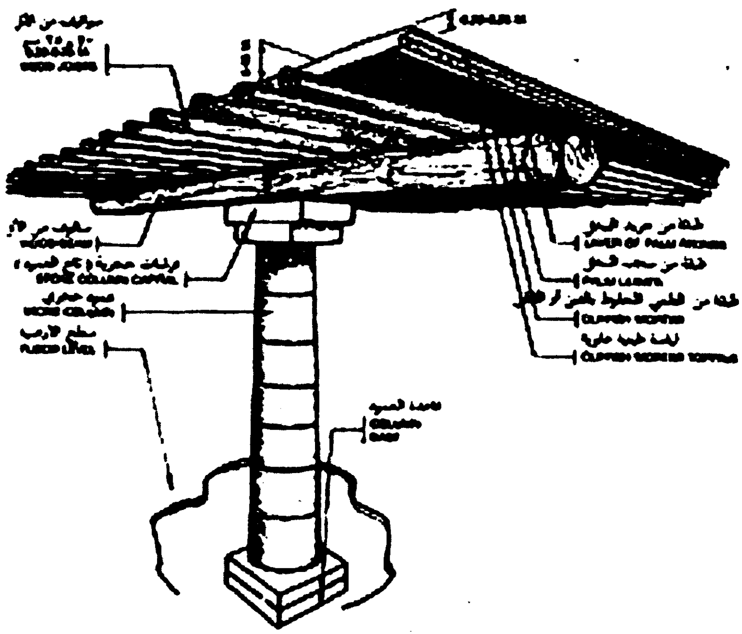


Figure (4-14) Details of column and roof construction. Source: Antiquities and Museum Affairs [4-12].

4.2.3 Western Region

The Western Region is located along the coast of the Red Sea and because it has the two holy mosques, it has been influenced by the many pilgrims who have visited the region. During the Islam's month of *Dhu alijjah* one to two million pilgrims gravitate from all over the world to this Western Region of Saudi Arabia. As a result of this contact with pilgrims from far and wide, and the resulting exchange of ideas, culture and influence, the knowledge and building techniques of the Islamic world in general are available to this region.

Pilgrims who come to the Western Region sometimes settle there and set up business, with the result that new skills are imported. In addition, during the Ottoman occupation, the architecture was influenced by the Turkish troops. This influence has resulted in the erection of multi storey houses decorated with wooden facades known as *'Mashrabiyas'*, which can be defined as "*wooden screens allowed cross ventilation and provide privacy to the house users*" [4-13] it also defined by Talib as "*wooden decorative over a period of time*" [4-3].

In hot and humid parts of this region, such as Jeddah, consideration has been given to obtaining maximum air movement. Therefore houses are built in groups that are not tightly crowded. The aim in this manner of building is a greater circulation of air and a reduction in the effects of high humidity. There is, therefore, a contrast between the way heat is dealt with in the hot and dry areas of the Central Region and the hot and humid area of the Western Region [(4-14)].

The smaller lattice screens throughout the building have all been hand-crafted without glue or nails, in a combination of vertical and horizontal elements of small pieces of wood as seen in the (Figures (4-15) to (4-20) below show the building character.

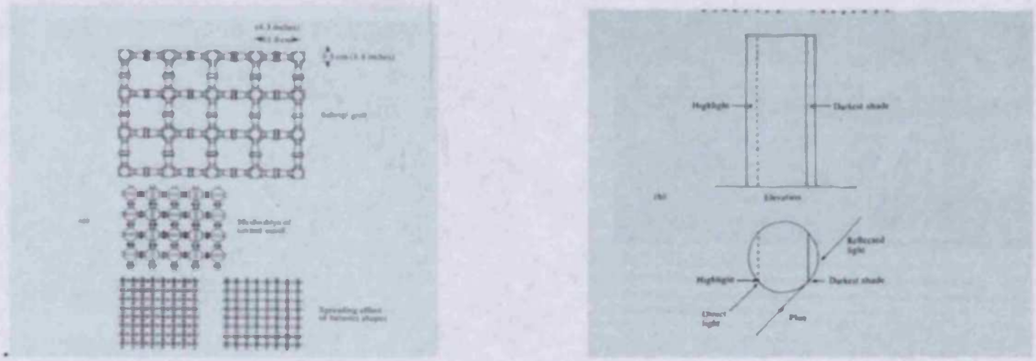


Figure (4-15) Analytical studies carried out for wooden details. Source: Fathy [(4-13)].

Figure (4-16) *Mashrabiya* used for privacy and shading in Jeddah buildings. Photo by author.

Figure (4-17) Type of *Mashrabiya's* style in Jeddah buildings. Photo by author.

Figure (4-18) Huge *Mashrabiya* in Jeddah buildings. Source: Farsi [4-15].

Figure (4-19) Jeddah houses. Source: Archnet [4-16].

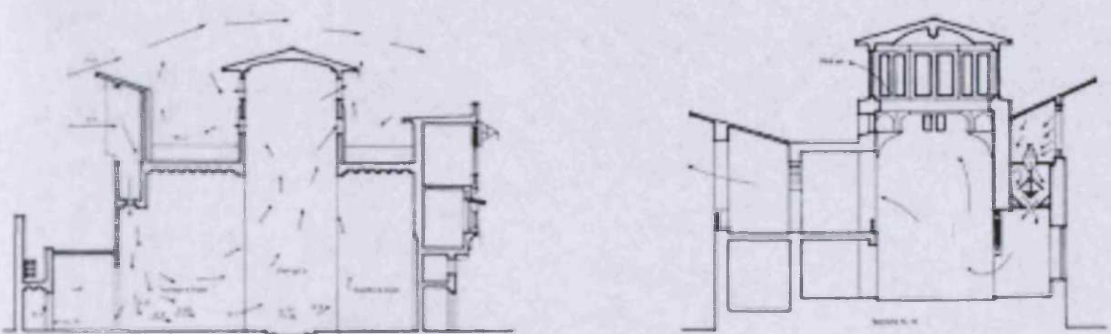


Figure (4-20) Air movement inside *Malqaf*. Source: Fathy [4-13].

According to Fathy the *Mashrabya* has several functions. It is provides privacy for the household members by allowing them to see outside while, on the same time, it prevents those out side from looking in an occupants.

It is designed to control and break up the sun's glare while providing shade, and has the advantage of allowing the light to pass through the devices screen, but not vision. Beside this, it allows cool breezes to enter inside the house in the heat of summer. It is used to cool water in clay pots, known locally as *Jars*, which are filled with water and placed inside *Mashrabya*. It also provides evaporative cooling in dry climate such as Macca, where the humidity of air passing through the screen increases after contact with water. Lastly, it is also a decorative feature [(4-3)].

4.2.4 Eastern Region

The Eastern Region is similar in climate to the Western Region in that the climate is also hot and humid. It is situated on the coast of the Arabian Gulf and the traditional buildings are built with two types of materials; adobe and rubble stone which are abundant in this area.

To construct the walls and tree trunks fixed between the walls to form the roof, which was covered with the fronds of palm and mud.

The people living in this land had to deal with an extremely humid and hot climate. The main characteristic of traditional building in this area is the wind tower (*Badgirr* or *Malqaf*) that contributes to reduce the interior air temperature. This type of system consists in a tower that cuts through and rises above the houses, with edged windows opened up in its upper part and a conic partition in the centre. Fathy in his book *Natural Energy and Vernacular Architecture* defined the *Badgirr* is "*A type of wind-catch into which wind can flow from several directions, generally four, but also two. A septum that is the height of the vertical channel prevents wind from flowing in one entrance and out another*". The *Badgirr* was introduced to the Hafuf area, which is located in the eastern cost, from Iran where it has been used widely over many years as a sample of air conditioning [(4-17)]. The main purpose of this system is to allow the draught to cool and refresh the air of the interior rooms of the house. Figures (4-21) to (4-23) explain some of the *Badgirr* types.

The design of the wind tower is usually found in the houses in Iran and Gulf Estates in the coast areas of Saudi. It has four faces and is constructed higher than the roof to cover the wind direction. The base of it is open so, whichever way the wind blows, the tower will always catch the prevailing breeze to cool the inner room of the building and ensure ventilation with the air movement, making a fresh and comfortable living environment during the hot months of summer to the users.

However, during the winter months the wind tower is closed completely which prevents cold air from entering the building and retains the warm air inside (Figures (4-21)-(4-23).

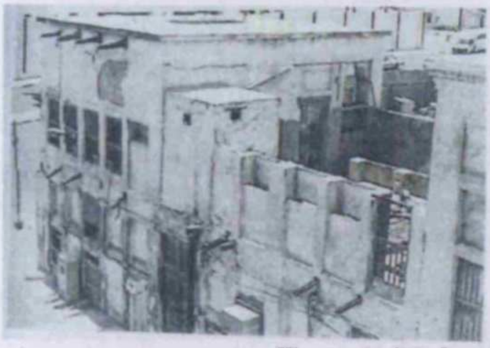


Figure (4-21) Open wall *Badgirr*. Source: Al-Naimi [(4-18)].

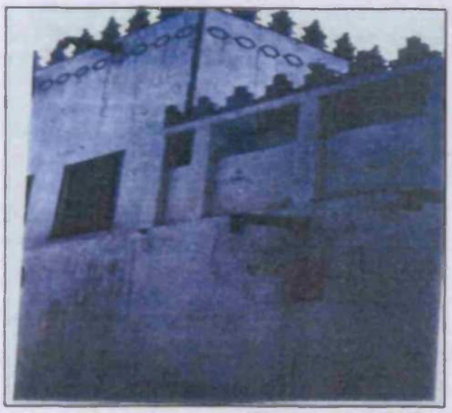


Figure (4-22) Open wall *Badgirr*. Source: Al-Naimi [(4-18)].

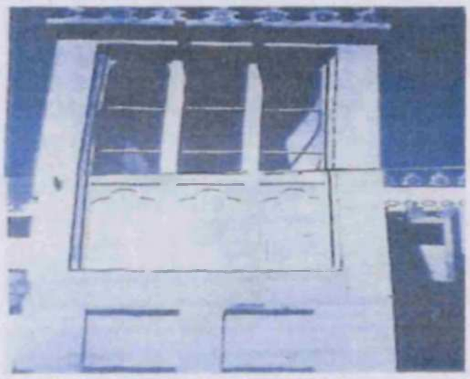


Figure (4-23) Types of wind tower. Source: Al-Naimi [(4-18)].

4.2.5 Northern Region

Buildings of the Northern Region are built of stone and adobe similar to those found in the Central Region.

The architectural style of the houses consist of a thick mud walls, courtyards and the streets which are built narrow to provide the maximum shadow. Many of the two storey houses have rooms hanging over the street to provide a shadow to the streets and the pedestrian as shown in Figure (4-24).

Figure (4-24) The buildings style in Northern region. Source: King (4-19).

4.2.6 Southern Region

The Southern Region is relatively cold in the mountains but hot and humid along the Red Sea coast. Because of the more humid coastal conditions, reed houses are common in these areas. In more mountainous regions, though, the buildings are completely different from these reed constructions. They are built of mud and stone, with large plates of stone forming an overhang outside the buildings as a protection against rain as explained in Figures (4-25) to (4-27).

Architecture in southern region is influenced by the climate, topography, local material and the methods of construction of Yemen and Africa (4-3). Figure (4-25) shows the topography of the high land. *Usha* or the reed system is only used in southern Tiham, Jizan, Sabiah and Abu Arish. The houses of Asir style are tall with three to four storeys. Figures (4-26) to (4-28) show the types of houses in the southern region.


Figure (4-25) The style of architecture and topography of the high land region. Source: Al-Hariri [4-4].

Figure (4-26) Mud buildings in southern region. Source: King [4-19].

Figure (4-27) *Raqaf* hanging on the mud houses to protect from the heavy rain. Source: Mauger [4-20].

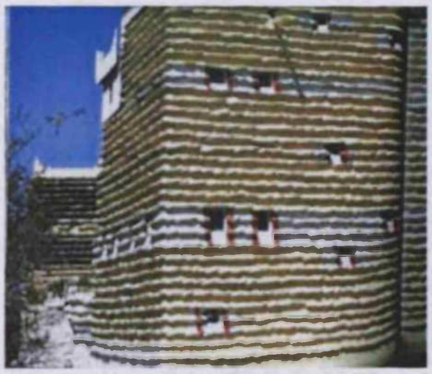



Figure (4-28) Plates of stone overhang outside the buildings as a protection against rain. Source: Al-Hariri and Mauger [4-4, 4-20].

4.3 Traditional Buildings Materials

Building materials vary according to different regions, and the nature of a building is strongly influenced by the materials used. However the system of building, the names given to materials, the skills employed, and the techniques applied are also different from region to region. Mud is used in the Central Region, stone in Western and through the coast and coral also is used in coastal of Eastern Regions. In general, the most commonly used building materials are mud and stone. This section focuses on building materials and systems used in house building and cover the following major materials, which may be divided into five groups: mud, stone, coral, reed and wood.

4.3.1 Mud

Sun-dried mud brick (*labin*) is the main building material used in the Riyadh (*Najd*) and Al-Hassa and parts of Asir in the southern region. The methods for preparing mud and the method of construction of mud walls vary from area to area [4-19].

There are several different types of mud house. The climate and the natural texture of the area have an influence the style of house constructed.

The houses built in the dry and open desert obviously have different style from those in the mountains where there is more rainfall. The walls of mud buildings in Riyadh usually rise from two to three stories and the thickness of the walls at the base starts from 40 centimetres to 100 centimetres according to the houses dimensions. In the Al-Dir'ya area houses were built mostly with mud, the general thickness of walls about 90 cm to 100 cm. Sun-dried mud brick is the main building material for wall construction. It is made traditionally by adding clay soil, straw and water. This is mixed well and compacted into a mould. It could be used directly or allowed to dry for two to three weeks. Once dried the bricks were removed from the wooden frame (*Malban*) to be ready for use [4-11]. The dimensions of bricks can be made into large or small bricks depending on the construction where they were to be used. In Riyadh the bricks made in size were about 40 centimetres to 20 centimetres, Figure (4-29) shows the mud bricks used in Riyadh. The reason for using mud in construction is because it was available locally and easy to use. It is also well adapted to the local environment because of its low thermal conductivity.

In the Southern Region, Najran, which is located in the mountains of Al-Sarawat and close to Yemen, the mud constructed houses are completely different from those of the Central region.

This area has more rainfall than the rest of Saudi Arabia. The houses here are built from a mixture of stone and mud. Due to climatic and topographical differences, multi stories houses are built in this area and have been adapted to suit the region.

The mud building technique of preparing mud for construction is different in Najran City, south east of the Abha. The only difference in house construction between the Najran and Abha regions is that the Najran's houses are built entirely of sun dried mud. Layers of mud mixed with straw and hay are constructed to a thickness of approximately thirty to forty centimeters per layer. For forty eight hours the newly constructed layer is left to dry in the sun. After each layer is seen to be completely dry, another layer is applied over it. This is applied all around the house and the basic building material mixture of sun-dried mud, hay and straw, is known by the traditional name of *'Madmak'*. The finished house has small windows which can be closed with wooden shutters (Figure 4-30).

Another method used in the south east of the city of Abha for mud construction is known locally as *Raqaf*. Builders in the south area used to build the house's wall by hanging large plates of stone, forming an overhang outside the buildings, because of their highlands areas where rain is plentiful, the *Raqaf* hangs parallel to the face of the wall to protect it from the heavy rain (Figure 4-31).

Figure (4-29) Section through the mud wall sun-dried mud brick (*labin*). Source: Mud Construction [4-21].

Figure (4-30) *Madmak* constructions (cob). Source: Al-Hariri and Mud Construction [4-4, 4-21].

Figure (4-31) *Raqaf* constructions. Source: Al-Hariri, Fadan and Mud Construction [4-4, 4-21].

4.3.2 Stone

Stone is the major buildings material in the high land of the north, west and the south west of the country. These areas were influenced by surrounding countries such as Jordan and Yemen. Stone collected from the mountains was used to build multi storey buildings in the western and southern regions. The techniques used to build the houses vary depending on the location and the craftsman who is responsible to design the house in consultation with the client [(4-19)].

In the centre of the country, the use of stone is more limited. It is occasionally used for foundations and cylinders of stone for columns in the courtyard, which are then covered by plaster.

There are two ways to construct stone building in the west. The first is stone with a layer of mud or lime. The second is a solid-stone that constructed without using mortar. Small pieces of stone were used to fill the gaps between the larger stones. The thickness of the load bearing walls is about 50 to 70 centimeter. These which are supported by flat wooden beams (Figure 4-32).

In some region such as Asir area, the external and the internal walls were covered by layer of lime. These types of building protect the interior space from harsh environmental condition.

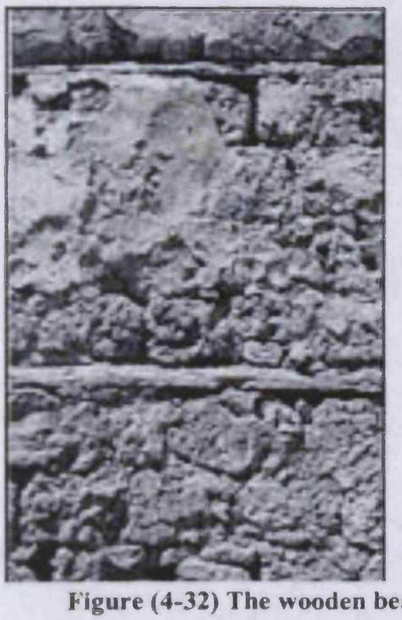


Figure (4-32) The wooden beams construction of the coral wall. Source: King [(4-19)].

4.3.3 Coral

Coral is a material commonly used in Africa coast, Indian Ocean and gulf countries. In the case of Saudi Arabia, coral was used as a construction building material in eastern and western towns.

Choosing of material in the traditional buildings was based on availability and applicability to the local environment. It was collected by either cutting the reefs underwater or by using the fossil coral that was found in the sea shore. The fossil coral is more suitable for the load-bearing walls because of its strength and the fresh coral that was collected from the sea bed was used as a decoration.

Horizontal bands of wood were also used to reinforce the coral material, which makes the buildings stronger. The wooden beams were placed horizontally, fixed at every 1.2 meters and tied to the other cross beams to make the other floor as shown in Figure (4-33) to strength the construction of the building. Furthermore, lime plaster was used on exterior and interior surfaces to insulate the facades from the harsh climate and to protect the building from rainfall, humidity and salt. The roof was protected by a layer of mud, which is plastered by lime to protect the building roof against rain.

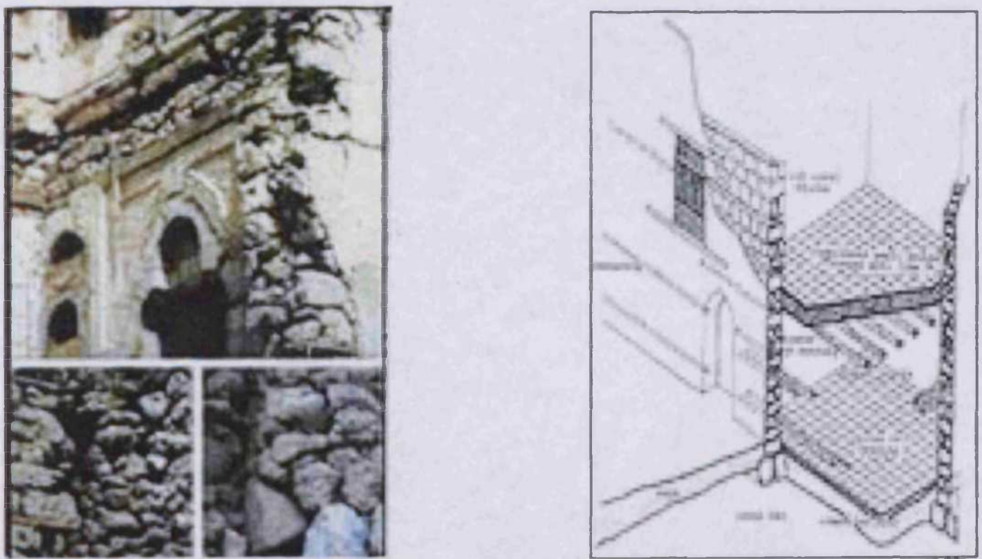


Figure (4-33) Construction of the Coral wall in Jeddah. Source: Eunice M. Lin [4-22].

4.3.4 Reed

In the southern cities of Jizan, Sabiah and Abu Arish the system of reed construction or as it is known locally, *Usha* was used as a building material. The influence of the African architecture system which is adapted to the humid weather in costal areas is obvious in the traditional houses.

The construction of *Usha* is very simple. it creates a conical shape by (built the wall with thick bunched branches) with vertical reed sticks that also fixed in the ground in a circular shape, jointed together with rope at the top and then framed by flexible twigs woven horizontally. The frame of the reed house was covered by dried reed and straw. Figures (4-34 to 4-36) show the exterior surface of reed houses which are covered by straw and reed to form the roof and the wall. It also shows the exterior wall, which could be plastered.

The diameter of *Usha* is about 4 meters or more with no opening other than one or two doors which are set at a 45° angle to each other in the wall.

The interior surfaces of the wall are generally covered with mud plaster mixed with cow-dung and whitewashed with lime. However, in this particular house using the cow-dung is to make the mud mixture light and permeable to allow low-level ventilation for the hut [(4-3)], and the interior wall could be decorated with colourful painting and symbols by the women of the house.

However, each *Usha* is a single room and two to four *Ushas* were used for a single family, this compound of *Ushas* contains an outdoor cooking area, one or more sleeping areas, storage and toilet areas. The compound was surrounding by a wall were all of the activity of the family's took place.

Figure (4-34) Reed houses. Source: King [(4-19)].

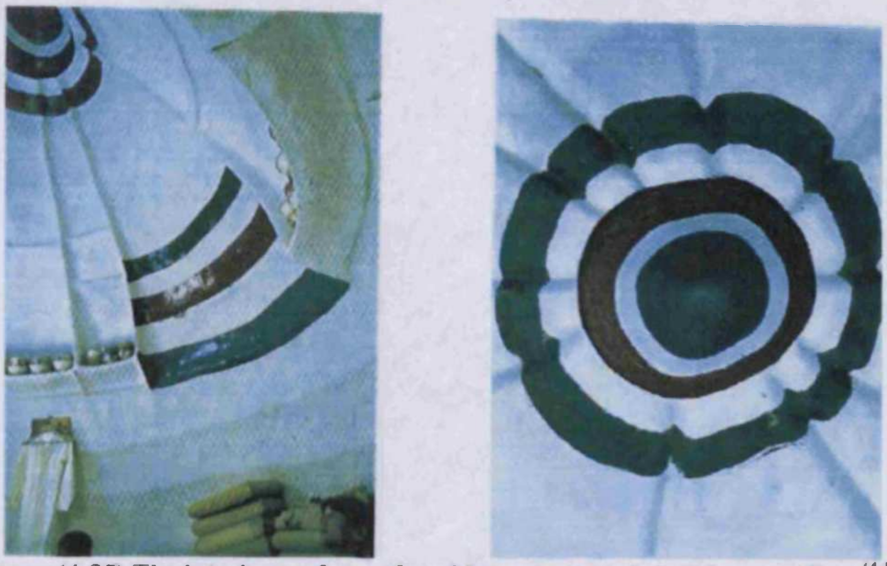


Figure (4-35) The interior surfaces of reed house were painted. Source: King [4-19].

Figure (4-36) The compound of reed houses surrounding by wall. Source: Klee, H.al [4-23].

4.3.5 Wood

Wood is one of the most important structural materials in buildings. In most of Saudi Arabia regions, wood was used in the structure and in the decoration of the buildings. In Jeddah and Macca Cities wood was used in the construction of both walls and roof. It was also used in the decoration of facades. The type of the wood that was used is a mangrove pole, which was imported from India or East Africa to Arabian coast.

The width of the room span was dependant on the length of the wood, which is about 2.8 meters. In addition, wood was used in the buildings construction as a wall support. Flat beams of wood were placed between the stones lyres of the walls as mentioned in the previous discussion. Wood also used as main exterior decorative elements for most windows, which called *Mashrabiya* and doors of the building to give a complex and beautiful pattern. As mentioned in the previous section, air movement is an important factor in this region to reduce the heat in interior spaces. As a result, builders choose the wood as a window cover *Mashrabiya* because of its low conductivity to reduce the air temperature that flows through it.

In the centre and other regions of Saudi Arabia, Tamarisk as known as *Athel* and palm were used as building construction materials. Builders used wood in the roof structure and lintels of the windows and doorways, known as *Ataba*. The roof was made of the palm leaves and the *Athel* was used as beams to build the roof because of its availability and ability to shrink and expand in summer and winter. It resists the cracking that caused by the climatic changes, which makes it more durable (4-19) (Figures 4-37 and 4-38 show the wood type for roof construction).

Figure (4-37) Roof constructions of mud houses in south region. Source: Mauger (4-20).

Figure (4-38) Roof constructions in Riyadh house. Photo by author.

4.4 Conclusions

This chapter has introduced the traditional architectures in each region of Saudi Arabia and gives examples of the ways in which people have dealt with the impact of the physical environment in relation to their culture, religion and economy.

However, it was found that the main characteristic of these regions was the use of local materials in building constructions to form the final shape and give each region its own character. In addition, the review showed that each region has a different climate and geography which reflected in the architectural design of the building. For example, weather conditions and the availability of materials in the northern region led to the use of courtyards and high thermal mass while different methods of construction were used in the rainy climate of the southern regions. There are also differences in the coastal areas – in the east the wind tower was used as a traditional cooling system whereas the west used the *mashrabia.* These examples of varying methods and techniques in the construction of buildings highlight the ability and expertise of the people to adapt to their conditions. In this way different architectural styles were created in accordance with the peoples needs and the climate in the region.

However, there would be considerable advantages to be gained from re-examining traditional building materials and techniques with a view to incorporating some of them into current building design. The next chapter will explain and discuss mud houses in Riyadh as well as the urban fabric and other building features.

CHAPTER FIVE

RIYADH'S TRADITIONAL BUILDINGS

5.1 Introduction

The traditional architecture of Riyadh is similar to that of other parts of the Saudi region, with economic, religious, social and cultural factors all playing influential roles. However the central region has a different geography and environment. As a result, buildings designed in the central region have been influenced by its local climate. This chapter will focus on the traditional buildings of this central region of Saudi Arabia, using them as a case study in this work to provide a background of the urban pattern within Riyadh city and the solution that has been made by the people in their traditional building, which has evolved in response to social, cultural, and religious influences, as well as being adapted to the climate. An explanation for the rapid economic change experienced in the region will also be considered to give an idea about the changes that have been applied in the built environment.

5.2 Historical Background of Riyadh

Before oil was discovered, settlements tended to be small and primitive, and were usually located close together. There are many important lessons to be learned from the traditional style and urban pattern of Riyadh traditional buildings. Traditional buildings are important for investigation not only because they are old fashioned and give a link to past history, but it is now realized that the real significance of the methods and techniques used to build these houses is that they dealt with an extremely harsh environment and can give designers and architects lessons and solutions that can be used in modern buildings. These lessons can help to improve the building quality of today's development.

> *"Tradition is not necessarily old fashioned and is not synonymous with stagnation. Furthermore, a tradition need not date from long ago, but may have begun quite recently''* (5-1)

Another, and more important aspect is the inherent significance of the environment which is part of our social and cultural upbringing. Rudofsky in his book *Architecture Without Architects* commented, "*There is much to learn from architecture before it became an expert's art''* (5-2).

Climate and culture are the two most important aspects in determining housing typologies (5-3). Climate, lifestyle and availability of building materials are all factors that have had considerable impact upon the evolution of architectural built forms throughout history.

Traditional architecture was well adapted to its environmental context, including climatic factors, which were recognized and hence well responded to through architectural planning and design. This can be easily recognized in the urban scale of traditional towns and also in detailed designs of buildings.

However, Riyadh is the capital of Saudi Arabia and lies on the great limestone plateau of Najd in the centre of the Arabian Peninsula, at a height of approximately 600 meters above mean sea level. It is located at latitude 24° 38' North and longitude 46° 43' East. In the 19th century, Riyadh was an oasis on the Central-Arabian plateau. Surrounded by forbidding deserts which were isolated from the outside world for centuries, the area only opened up after oil was discovered in 1933. The name Riyadh means "a place of gardens" in Arabic. It was a small settlement formed at the confluence of several *wadis* (rivers).

Riyadh today is one of the fastest growing cities in the world. In half a century, it has grown to more than a hundred times its original area, its population increasing from 20 thousand to about four and a half million people. Future projections of Riyadh's population anticipate that it will exceed 10 million by the year 2025 [5-4].

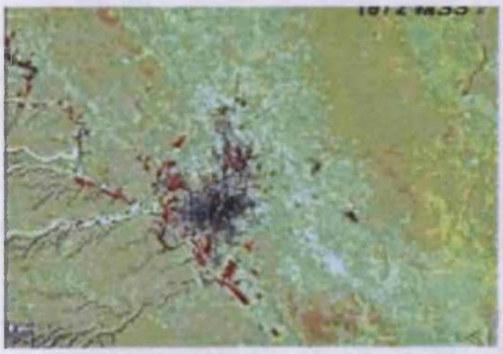


Figure (5-1) Riyadh in 1972. Source: USGS [5-5].

Figure (5-2) Riyadh in 1990. Source: USGS [5-5].

Figure (5-3) Riyadh streets in the past. Source: Municipality of Ar-Riyadh [5-4].

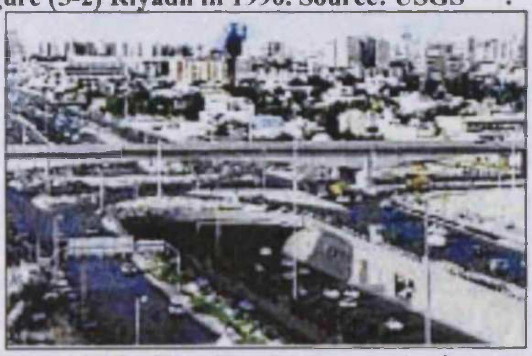


Figure (5-4) Riyadh development. Source: Municipality of Ar-Riyadh [5-4].

5.3 Traditional Settlement Pattern

In general, Riyadh City was built according to patterns existing in most traditional Islamic cities. Traditionally, Riyadh's buildings were planned with clearly defined open areas and narrow lanes. This traditional architecture in the central region had some features dating from earlier ancient local architecture of which most elements were developed through an awareness of local social, cultural, environmental and religious context.

There is no imposed urban planning regulation for the traditional settlement in the central region. It was mainly produced by the local people. Towns were not designed at all but just grew organically as the population increased. The climate and natural features of the area have a bearing on the way a region-specific house is constructed.

Generally the settlement was built with narrow twisting streets and open courtyards. The centre of each settlement in town has an open space. The buildings were constructed in very close pattern inside the settlement as seen in Figures (5-5 to 5-7), which was densely built sharing a number of its walls. A number of narrow streets and irregular walkways were used to connect the town. Public and private courtyards provided the open spaces.

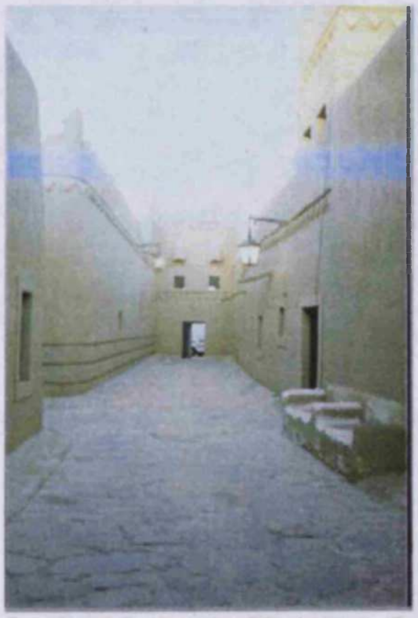


Figure (5-5) Narrow walkway to create shade for the façade of the houses. Photo by author.

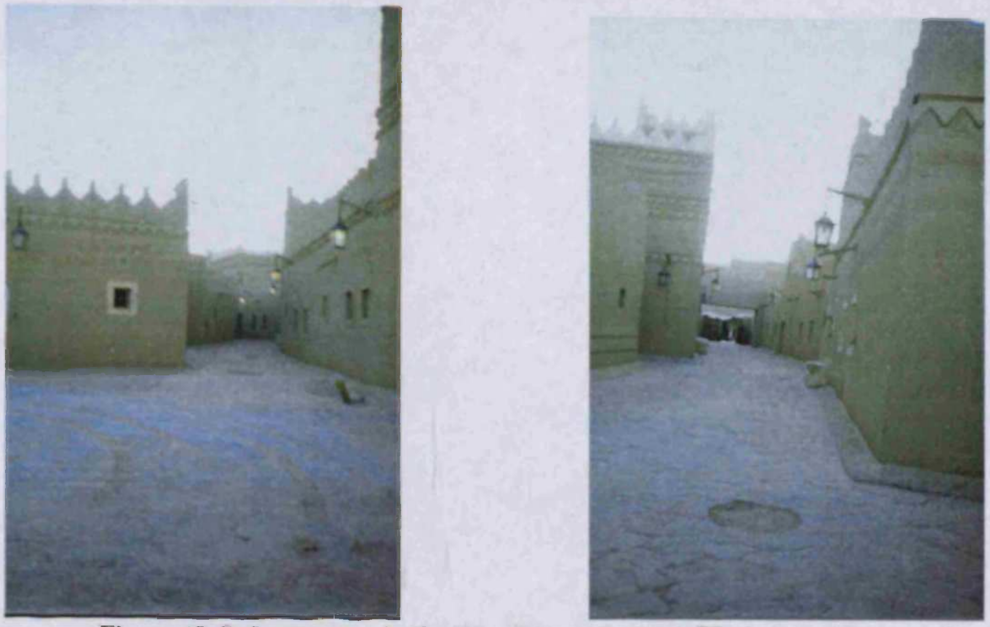


Figure (5-6) Open space in the Riyadh's settlement. Photo by author.

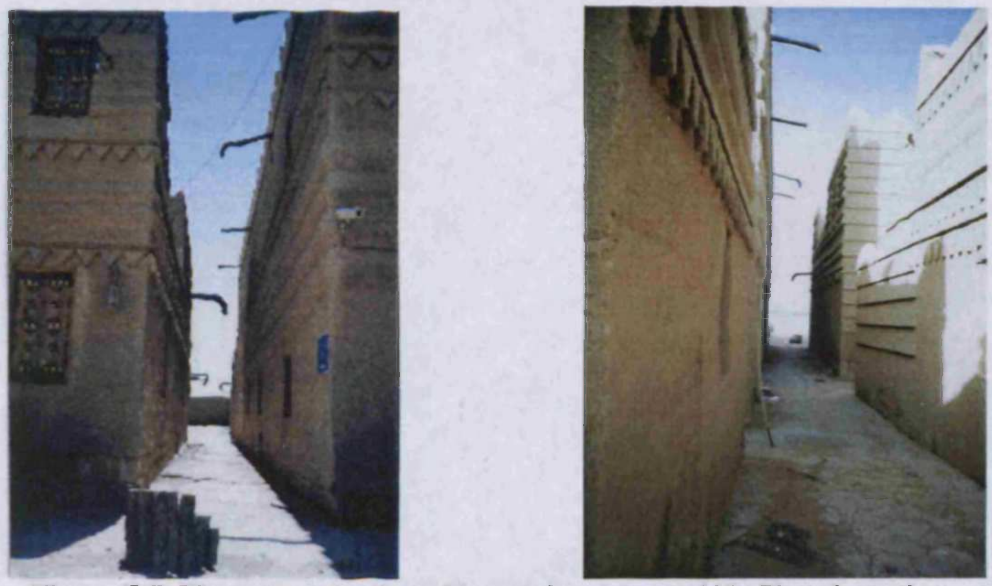


Figure (5-7) The narrow streets could reach 2 meters in width. Photo by author.

Outside the central area, the settlement was divided into a number of neighbourhoods containing local mosques and shops, showing the integration at a local level of social, economic and religious systems. These areas were connected to the centre by a series of roads radiating outwards to the outskirts of the town.

There are main roads branching from the town centre and connecting it directly with larger roads joining other towns. These act as main roads through which goods reach the market. These main roads are joined to narrow residential roads that branch into different courts, passing through neighbourhood courtyards.

Usually these spaces suit different levels of usage regarding intensity and specification. Therefore moving from the market and main roads towards residential areas and courts, the degree of satisfaction and responsibility increases and the number of users decreases.

There are also communal places within each neighbourhood, considered to be private for a small number of houses. An example of these places are the closed road or dead-end (a road blocked at the end) onto which women's doors open, joined to the neighbourhood yard or a narrow minor road. Figures (5-8 to 5-10) show the urban design for Riyadh settlements.

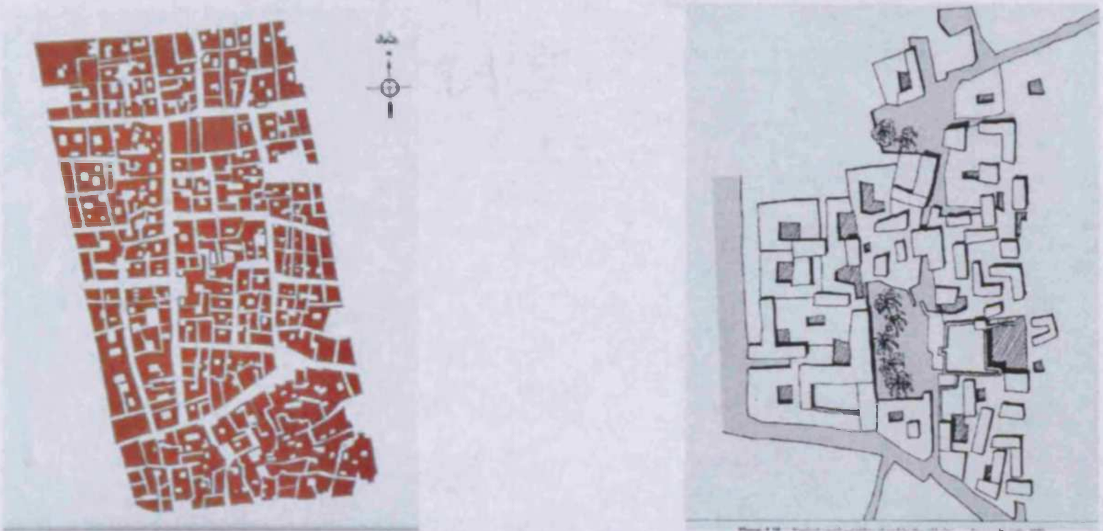


Figure (5-8) A part from the old city of Riyadh and its urban structure. Source: Daghistani [5-6].

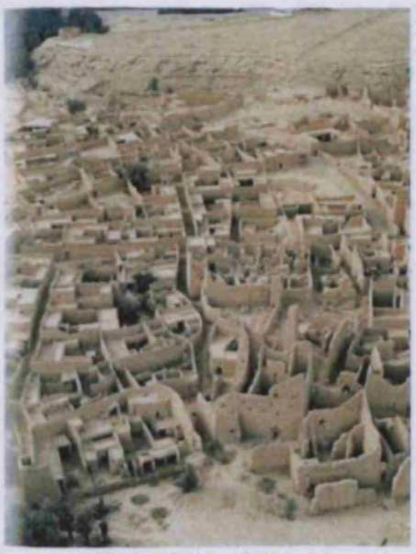


Figure (5-9) The compact design of Dir'yah traditional houses. Source: William Facey, [5-7].

Figure (5-10) The dense type of structure in Riyadh houses. Source: William Facey [5-7].

The dead-end road is an attractive and popular place for neighbourhoods to meet each other, especially during the late morning hours. It is also the primary place for young children and toddlers to come together, get in touch and play under the supervision of their mothers [5-8].

One of the most important aims in designing and planning the narrowness of the roads is to protect and restore the balance between privacy and communality required by the residents, as well as providing shaded areas and thus giving welcome protection from the sun. In addition, the irregular streets reduce the effect of dust storms and wind heat. Moreover, it is designed to be full of life, an ideal area for social activities. The residential road also preserves the privacy of the neighbourhoods, their quietness and tranquillity, the security, physical and mental rest of their inhabitants. Figure (5-11) shows the wind movement over the settlement.

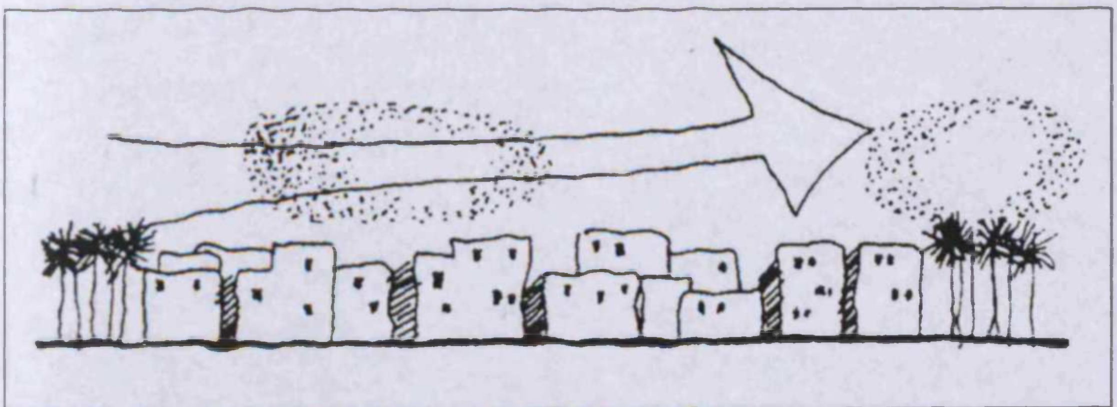


Figure (5-11) Dust movement. Source: Tailb, [5-8].

5.4 Riyadh's Traditional Houses Type

The traditional architecture of Riyadh was based on the resultant requirements of people in their adaptation to the surrounding environment, as well as the availability of durable building material.

The courtyard building type was the traditional style used in Riyadh till the end of the 19th century. It provides the houses with a comfortable internal environment, providing calm and air during the long, hot dry weather. These types of houses satisfy climate as well as social needs for privacy of Riyadh people [(5-8)].

The mud house construction was already known in the Arabian Peninsula for a thousand years back to pre Islamic times [(5-7)]. Houses in Riyadh typically consisted of one or two floors, though sometimes up to three floors, with a flat roof and courtyards surrounded by rooms, which also served as part of the living area. These houses would have been occupied by extended families, and were regarded as small for this purpose.

As described in section 5.3 there are no imposed urban planning regulations on traditional settlements in the central region. Communally, houses were very close together and shared many external walls with other neighbours, with narrow streets between them. As a result, the house may have only one or two facades, the other sides being attached to neighbouring properties by common walls as seen in Figure (5-12). In less populated regions, other types of houses were designed as more stand alone, as can be seen in Figures (5-13, 14).

Figure (5-12) The effect of the hot climate reflect on the design of Riyadh houses. Source: Marco Albini [(5-9)].

However, the majority of houses were built with one courtyard and sometimes two, according to the size of the house and the family, so that both guests and family have a courtyard exclusive to themselves. In the case of an expanding family, building can encroach into the courtyard area, both horizontally and vertically (5-8). As has been said, Arabian houses were never a completed project. As family size increases, more rooms are built on any adjoining unused land. The courtyard house may be described as a community that grew from the centre of a small single family house to an extended family house. Figures (5-13, 14) show the type of houses in the central region.

Figure (5-13) Two storeys of Riyadh houses in Al-Athreyah area. Photo by author.

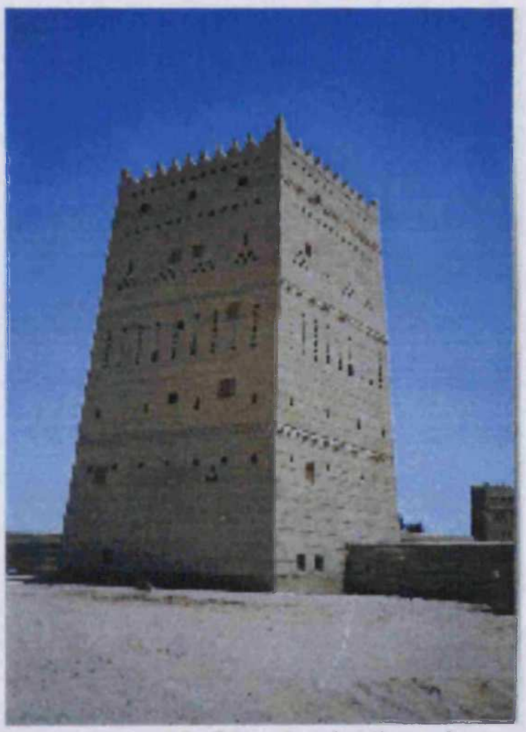


Figure (5-14) Three storeys mud building in Al-Athreyah area. Photo by author.

The internal courtyard and its surrounding rooms are used in the daily activities of the family of the house. It provides an interior private space for family members, especially women. Its floor is covered with clean sand and sometimes has trees or plants inside it. The border of the courtyard is surrounded totally or partially by an arcade, or as it called locally *riwaq*. The *riwaq* area is protected from the sun's heat, and is used as a sitting area in the summer time and as a link between the entrance and the house. Figure (5-15) show courtyard houses in the central region.

Figure (5-15) The *riwaq* surrounding the courtyard. Photo by author.

The internal design of the house usually, had a section for men and guests. It also had a large section for the women and the rest of the family. So the outdoor activities can be enjoyed by the family with complete privacy because such activities can take place in the courtyard. The houses are designed according to Islamic rules, the segregation between women and men is an important factor in the design the house. This is sometimes extended such that some of the houses have two entrances, one for men and the other for women. It may also have two staircases rising throughout the height of the house and two toilets.

The men's section is usually in the front part of the house which is called locally *"dewanyah" or "majlis"* as seen in Figures (5-16, 17, 18). This guest's gatherings room contained a *wijar,* which is the place to make tea and coffee that would be served by the head of the household. The walls of this room are generally plastered and decorated by white gypsum. This room is usually rectangular in plan and furnished in a manner typical of almost all mud houses rooms, whether they are used for eating, sitting, sleeping, or all three. The *majlis* is also usually located close to the outside main entrance, away from the rest of the house. Women guests gather in a room inside the house and sometimes get to their gathering room from an outside entrance particularly assigned for female visitors.

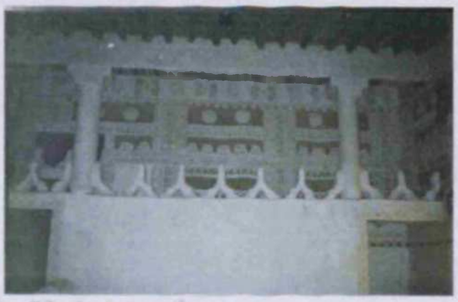


Figure (5-16) The decoration of the reception room for men. Photo by author.

Figure (5-17) Wijar is essential part of reception room. Photo by author.

Figure (5-18) The wijar in the reception room for coffee and tea. Source: William Facey [5-7].

The maximum numbers of rooms are located on the ground floor. Livestock, grain and dates were kept in this area, which also contained the entrances and all links to the street. The entrance never exposed the women's part of the house. The men's reception (or guest) room tended to be located closest to, or directly near, the entrance lobby of the house so that visitors would not meet the female household. The ground floor, as mentioned before contained one or more courtyards, depending on the size of the house. The animal court was located to the rear of the house, away from the eyes of visitors. The kitchen, which was available for all in the house to use, was usually small and functional and opened onto a courtyard or onto the roof through a semi-open space. The family occupied the central part of the house, which was joined to the male reception areas by a transitional space called the *dehreez*.

The first floor consisted of areas for the family and guests. It was mostly used for sleeping, and was kept completely separate from the men's section. The women's part of the house was larger than that of the men. The majority of the rooms had large windows facing the courtyard and none at all or small opening windows at a high level facing the street, built to avoid the extreme heat from outside and to add privacy for the occupants.

5.5 Material and Methods of Building

The climate and environmental factors played an important role in choosing building materials for protection against heat and cold [(5-10) (5-11)]. On any geographical location, houses, in general, reflect the resources of the surrounding environment. People in forest areas build their houses with wood; in mountain areas with stone; in icy lands, with ice; and in areas where mud and sand are available, they build them with mud and sand. Furthermore, an essential element influencing landscaping and the existence of gardens and fountains is the availability of water. In the Riyadh area, with an arid climate, the most important issue was to harvest water, and the scarcity of water led to the use of systems of *biur* (artesian wells) to collect water, some of which were used in Riyadh as shown in Figure (5-19).

These factors have influenced the choice of materials for these buildings and have been developed by builders in Riyadh.

Figure (5-19) The well method of harvest water by Riyadh's people due to the scarce of rain in the desert climate. Source: William Facey [(5-7)].

The traditional environment of Riyadh is normally surrounded by sand dunes, mud grounds, mountains and valleys which form resources for building materials. In most of Riyadh's traditional houses, mud is regarded as the most suitable material for building walls, while stones are used for building columns, foundations and enclosure walls. Stones, however, are not used intensively for other purposes because of the high cost of labour and the low heat isolation of stones compared to mud. Also, there is a general lack of stones suitable for building in this harsh environment.

Building with mud is widespread in the middle region because of the abundance of valleys where mud is found. Mud is a soft material, which can be shaped easily in addition to its availability at low cost and its ability to isolate against heat. This is a desired character in deserts with continental climates where temperature rises in summer and during the day, and decrease in winter and during the night. In these climates the daily and annual temperature range can be significant.

Mud building material is made of the soil normally brought from nearby places known locally as *geaan*, which are low-lying lands that hold rain water and are exposed to washing of salt by rains. The de-salted soil of these low lands is characterised by having more strength than normal mud, making it suitable as a main material in making bricks and plastering walls.

The mud used for building is available in valleys around cities, and in the area where drainage of rainwater collects and is kept for long periods of time. Mud is made of small rocks dismantled by erosion factors and mixed with organic materials of plants or animals. Mud, therefore, is a result of breakdown factors such as air erosion, chemical degradation and other factors such as the formation of new minerals and mineral salts [(5-11)].

If mud is not available in the valleys and lowlands where water collects, it is usually prepared by fetching the pure dark soil from certain places chosen by the builder or person who prepares the mud. The debris is removed from the soil which is then carried in large sacks and moved by camels or donkeys, or on wooden wagons. Soil is then collected in the form of conical piles and fine hay is scattered and mixed with it. A hole is then made in the top of the pile where water is filled to reach all parts of the mix. It is mixed with feet and spadework, left for one or two days to ferment and then squashed by feet or the hooves of camels if it is a large amount. When mud dries up it becomes pliable, and can be shaped in different forms. Mud is used in the Central Region in three main ways: building with mud bricks where it is widely used in Riyadh buildings, building with mud cob or *Madmak* (refer to Chapter Four, section 4.3.1), and using mud in coating.

In addition to the middle region in Saudi Arabia, building with mud is widespread in most places. Mud is highly affected by humidity, and areas which use it need to find solutions to this problem. The inhabitants of the south-west region of the kingdom (Asir) were able to use a local technique in which they shaded the external surfaces of walls with stony plates inclined downwards in a special way to avoid the effect of heavy rain (refer to Chapter Four, section 4.2.6). Figures (5-20, 29) show the process of making mud bricks.

Figure (5-20) The straw added to increase the strength of adobe brick. Photo by author.

Figure (5-21) Mud and straw is ready to be mixed. Photo by author.

Figure (5-22) Wooden frame is open in both sides. Photo by author.

Figure (5-23) Mixed by foot to speed up the process. Photo by author.

Figure (5-24) The mould is filled by mud and packed down. Photo by author.

Figure (5-25) Remove wooden mould for other bricks. Photo by author.

Figure (5-26) The mud brick left to dry in the sun. Photo by author.

Figure (5-27) The new mud brick is black, while the old is cream. Photo by author.

Figure (5-28) Straw is used to increase the strength of mud bricks. Photo by author.

Figure (5-29) Sun dried mud bricks left to be dried in the sun. Photo by author.

5.6 Basic Construction Materials

The materials used in construction for traditional buildings totally depended on availability from local resources. The materials used in traditional buildings for construction are limestone, adobe and wood. The limestone is used for the foundations of the walls, adobe for walls and roofs. The wood, which is taken from the tamarix tree known locally as *athel,* is used for the structure of the roof, doors and windows. All the materials were collected from the surrounding site of the area and were perfectly integrated within the natural environment. The technique of house construction is simple and responds to the building characteristics of materials, these traditional materials are listed below:

- Mud (Sun-dried mud brick, Cob)
- Limestone
- Wood
- Gypsum

5.6.1 Mud

5.6.1.1 Sun dried mud brick

Adobe or mud brick, is an ancient building technique, the word "adobe" coming from the Arabic word *attubah*, which means mud blocks or bricks. The word itself is widely known in Spain and North Africa [(5-12) (5-13)]. The sun dried mud brick is one of the oldest and most common building materials known to man. Traditionally, adobe bricks were never fired. Unbaked adobe bricks consisted of sand, sometimes gravel, clay, water, and often straw or grass mixed together by hand, formed in wooden moulds, and left to dry in the sun. Mud is the traditional building material in much of the Middle East in the past, and the majority of buildings in an Islamic city were made of this material.

Due to the harsh climate, which influences the characteristics of the building type in the central region, the sun dried mud brick is the building material of choice for most mud houses in this area and is the main building material for wall construction. It is made traditionally by adding one cubic meter of clay soil, fifty kilograms of straw and 1-1.50 m^3 of water. The paste is mixed well and compacted in the mould before being allowed to dry for two to three weeks [(5-14)].

The foundation of the ground floor was constructed with thick adobe walls varying from 40 to 90 centimetres in depth, with a reduction in thickness according to the growing height of the wall under construction.

Figure (5-30) Walls constructed by using sun dried mud bricks. Source: AHC. (5-15).

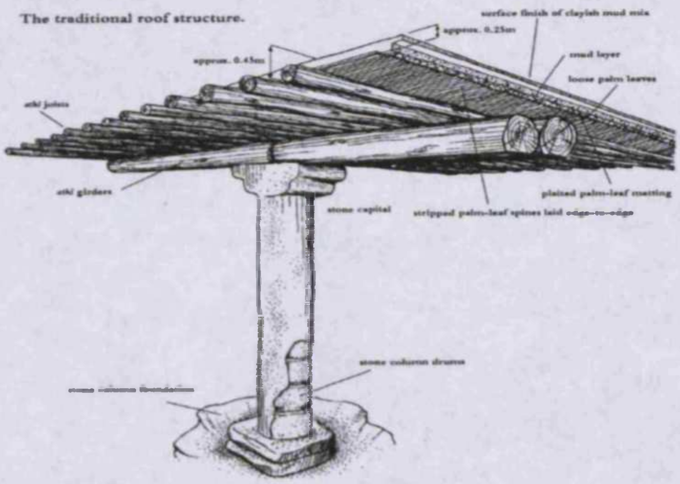


Figure (5-31) Roof details in mud buildings. Source: William Facey (5-14).

5.6.1.2 Mud layers (Cob)

Mud is prepared as described before, left for four days to ferment and then carried to a covered place. Cob or clay lump is then passed to the builder by hand in the form of rough lumps by the 'provider' or the worker assisting the builder. The builder will then place these masses together along the wall to form a layer. The thickness of the layer is dependent on the height of the house which could start from 30 to 60 cm. It is left for two days to dry before another layer is made. After one day of positioning the layer, the *mumalis* or leveller will level the sides of the layer using a wooden device called a *mubaymah*. Normally, the walls of a three-storey house will take nearly three months to build.

However, building with mud bricks is quicker than building with layers, because the layer takes a long time (three days) to dry before another layer is set on top of it.

5.6.2 Limestone

Limestone in the central region was used in the some building construction for foundations and columns. It is found at the top level of the earth's surface in horizontal beds with good natural joints. It was easy to take out by using a crowbar, after which the craftsman cut it to size and finished by using a chisel. Limestone is used in mud houses as a central support for columns, which are made of stones laid in a circular shape and then covered with mud plaster. In buildings with two floors the column extends to support the upper floor. However, limestone is also used for the purpose of increasing the strength of the external walls in some houses, and also to make the walls more durable. Layers of limestone are added in the first three to five layers in the foundation of the external walls of mud houses. Therefore, it is found that all old houses, and some more recent ones, have foundations and columns of stone, walls of mud, and roofs, doors and windows made of tamarisk trunks and palm leaves.

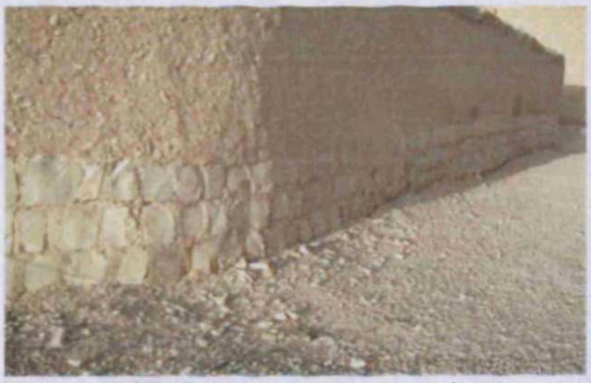


Figure (5-32) Limestone was used in the some building for foundations. Photo by author.

Figure (5-33) Limestone columns, Photo by author

5.6.3 Wood

On the land around Riyadh there are unlimited numbers of tamarisk and date palm trees, which are efficiently used structurally for roofs, doors, window-frames and roof drains. The tamarisk trunks and date palm leaves are used largely for structural and decorative purposes. The roofs are built of either tamarisk wood or date palm trunks. The next section will explain the types of wood used in the mud houses.

5.6.3.1 Palm Tree

There are plenty of palm trees (*Phoenix dectylifera*) surrounding the central region, and the branches and leaves of palm were traditionally used in the construction materials. Palm tree trunk was used mainly to fill the space in door panels and for doors and window lintels. In general the use of palm tree trunk in roof construction in the central region was limited.

Figure (5-34) The date palm trees were used in mud building in Riyadh. Photo by author.

5.6.3.2 Athel

Tamarix aphylla, *or Athel* tree, is also plentiful in the Riyadh region. It is very easy to grow, requiring surface water only during its first year. The trunks of these trees are used to construct the roof of the mud house. Straw mats are thrown over the tamarisk trunks as a covering and a thickly layered mixture of mud and hay is placed, to form a slab, on top of the straw mats. They are also used in construction for the beams, doors and window frames, lintels or *atabah*, water gutters or *mirzam* and to support the mud staircase. The quality of its trunks and branches allows it to be used in a number of different ways. Because of its length and thinner branches, and its capacity to expand and resist cracking and water, it appears to be well suited for construction.

Figure (5-35) *Athel* tree in Riyadh area. Photo by author.

Figure (5-36) The trunk of *athel* tree used in roof construction. Photo by author.

5.6.4 Gypsum

Gypsum, or as it called locally *juss* (a fine white material), is also used in plastering some of the house surfaces, such as the external façade and the top of the parapet in order to protect it against the effect of rain, as well as serving as a protection against erosion. Furthermore, this white plaster is also used as decoration for internal rooms and for plastering the drainage channels because of its waterproof quality. The interior walls of rooms are coated with white gypsum up to a half or two-thirds of their height. The exterior windows are framed in white plaster. Gypsum is very important in building and decorating houses for many reasons, including its availability, cohesiveness, enormous ability to absorb humidity in arid environments and the internal cooling it provides to rooms. Figure (5-37) show the white *juss* plaster in mud surface.

Figure (5-37) Gypsum is the traditional material for plastering. Photo by author.

5.6.5 Traditional Surface Coatings

Mud plaster like adobe is composed of clay, sand, water, and straw or grass. After walls are built they are coated, inside and outside, with mud prepared as described previous section, but the fermentation may take two to four weeks for the inside walls. As for the external walls, fermentation may take several months until the hay decomposes and becomes soft, black and smelly. Walls made using the fermentation process have the ability to resist rain as well as providing thermal isolation. Mud is also used in covering the floor of the rooms and corridors, this process being known as *Shiba'ah* or saturation of the ground with fine mud. Mud plaster requires little skill, as it can be done by hand or by simple tools.

5.7 Traditional Buildings Features

For a thousand years the people of Riyadh have sought to structure a physical environment for their inhabitancies to combat the hot arid climate. The result of their techniques and their skills is a suitable environment for both settlements and individual dwellings. These houses were built without any help from architects and without using electrical or any mechanical devices for cooling or heating. It was produced and developed by collaboration between the users of the houses and the builders.

5.7.1 Courtyards

In hot climates such as Riyadh where cooling is a necessity, building types, such as courtyard buildings, have been developed to face the harshness of the climate. Buildings with internal courtyards are considered the most "appropriate" in many hot regions, especially in deserts [5-10] [5-17] [5-18].

> *Internal courtyards maximize the thermal interaction between the building and outdoor environment, introducing the outdoor into the heart of buildings core. It is commonly assumed that such internal patio help in maintaining cooled indoor temperatures in hot climate*[5-19].

However, usually the Riyadh's houses traditionally had a courtyard at the centre of each house. This courtyard is a distinguishing feature of the houses in the Central Region. This *'Sahn Al-Dar* or *'Fena Al-Dar'* as it is known locally is a specific feature of Islamic architecture. It is open to the sky, surrounded by rooms and all daily family activities take place in it. The courtyard provides privacy for inhabitants and furthermore a place of safety for the occupants of the house. Therefore, it can be used as an exterior living space or even for sleeping during nights when it is cooler than inside. Hence the courtyard fulfilled the predominant social requirements of privacy.

Moreover, the courtyard works as a climatic modifier by various means, depending on its design and features. For the purpose of retaining shade most of the day, the courtyard's walls were built to heights that were always greater than any of its horizontal dimensions, being deeply situated in the building mass. Because the courtyard is mostly shaded during the day, the amount of heat reaching rooms adjacent to the courtyard is greatly lessened. It also offers a protected area for the o ccupants against hot, undesired winds while introducing at night-time relatively cool air. The courtyard houses provide the advantage of using a single row of rooms built on three or four sides surrounding the open space. This inner and open-topped space is a natural means of light and of ventilation, with all the doors and windows of rooms able to open on to it. During the night, the warm air of the courtyard which was heated during the day rises and is gradually replaced by the already cooled night air from above. The exposed surfaces radiate to the night sky and provide planes cooling to the surrounding air. The courtyard acts to collect this cool night air and, if designed well, duct it into surrounding rooms at ground level. As the courtyard is shaded by its four walls and surrounding rooms, in the morning the air of the courtyard heats slowly and remains cool until relatively late in the day when the sun shines in directly from above.

The outdoor courtyard is also a place where vegetation is grown and fountains built in some houses. In the Riyadh, it can be seen the courtyard usually included elements, such as plants, which reduce reflected heat from the sun and provide extra shade and increase the level of humidity.

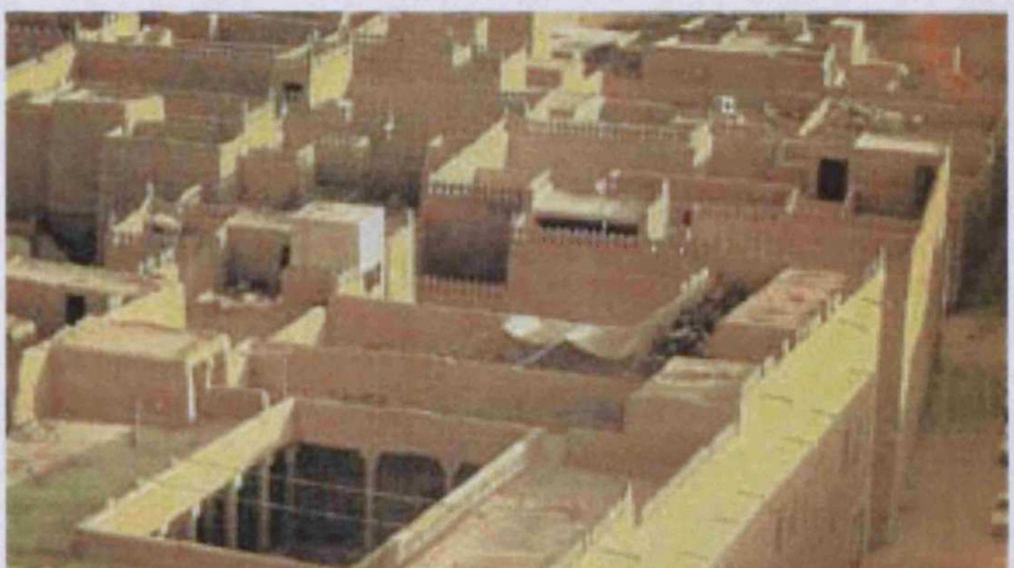


Figure (5-38) Internal courtyard of traditional house. Source: Daghistani [5-6].

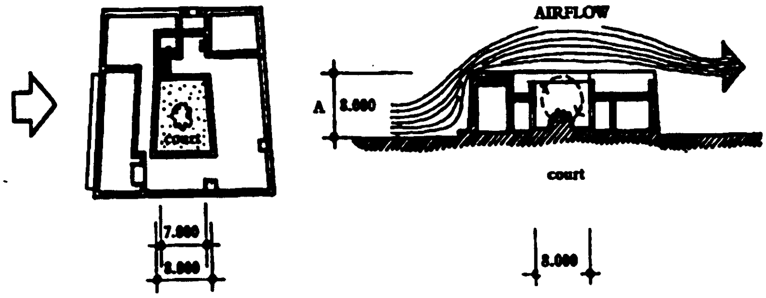


Figure (5-39) Air flow through a square internal courtyard, which is offer good protection against windblown and dust and sand. Source: William Facey (5-14).

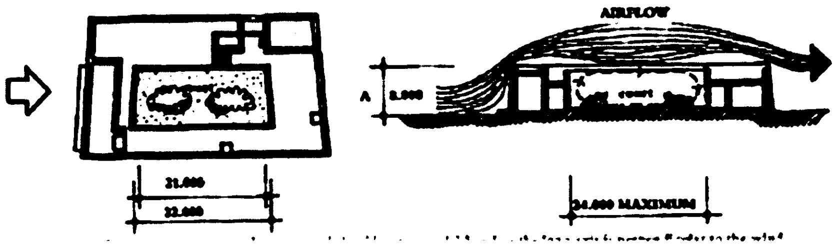


Figure (5-40) Air flow through a rectangular internal provide protection against windblown and dust and sand. Source: William Facey (5-14).

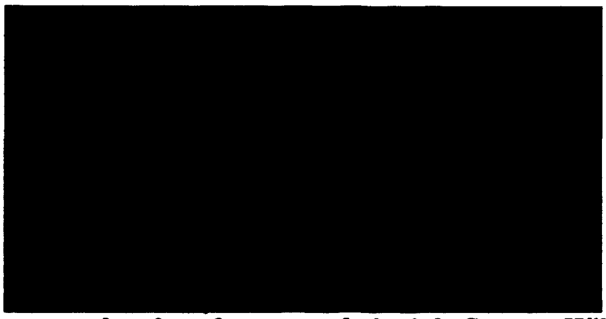


Figure (5-41) During night courtyard and roof act as cool air sink. Source: William Facey (5-14).

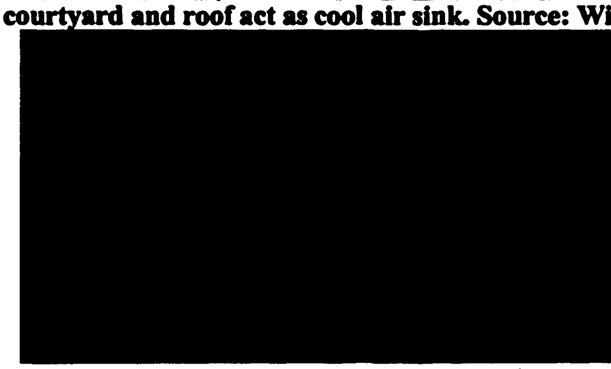


Figure (5-42) During day the sun heats the courtyard by warming air creating chimney effect and pulls breeze through rooms. Source: William Facey (5-14).

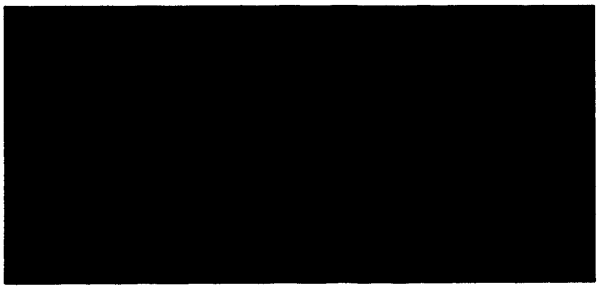


Figure (5-43) During evening the courtyard and building retain heat then give it off as night air cools. Source: William Facey [5-14].

Figure (5-44) Courtyard houses. Photo by author.

5.7.2 Sabbat

Many of the two storey houses have bridged rooms hanging over the street known locally as *sabbat*. These rooms are widely scattered on the main roads, while in private streets and closes they are found at shorter distances, a pattern of distribution related to the way they are used. This kind of room forms an additional element to the spaces of the houses and also works as a shelter for the activities of children and a seating area for the family.

In hot climates, such as Riyadh where shading is a necessity, these rooms throw shade on pedestrians and provide communication between the neighbouring areas owned by an extended family. Also, the front side of those rooms usually opens to the north and south side to allow the gentle summer breezes to pass through them. Figure (5-45) show some examples of *sabbat rooms*.

Figure (5-45) Irregular streets in design, which may end with dead end. Source: Al-Nowaiser [5-11].

5.7.3 Roof

Another important space was the flat roof of the house. The roof is the major source of heat gain in the houses of the region. The design of the roof ensures some protection against heat impact. It was used as an extension of the living area, and during the summer also provided sleeping space. The rooftop was an important social space for the family, who met there in the evenings, especially during the summer. This gave the family freedom to enjoy sitting and sleeping during cool summer nights. The roof of most houses has different levels and heights according to function and floor area size. Each one of the levels on the roof is separated from others and has a different height parapet surrounding it. The heights of the parapets rise from 60 cm to 200 cm, depending on the roof function. The height of the parapet wall provides a cooler place by throwing shadow on the roof and also provides a degree of privacy and safety. In the three storey height of some houses, the tall wall of the parapet adds additional protective shade on the narrow street.

In addition, the roof is generally constructed from *athel* tree trunk, having palm tree leaves laid over them and being covered with adobe on the palm leaves. These layers reach a total thickness of about 30 cm, which acts as an additional insulation.

To allow the rainwater to flow down on other surfaces or away from the roof, the surface of the roof slopes towards the drain, which is made from half hollowed lengths built into the roof construction and notched at the outer end to provide a drip to throw water away from the walls. On the exterior surface of parapet walls, a numbers of inverted solid projections grouped in a triangular pattern are also used, both to deflect rain from the high walls and as decorative elements (Figures 5-46, 47, 48)).

Figure (5-46) The roof pattern in Riyadh to protect the surface from rain and to reduce the impact of emersion. Photo by author.

Figure (5-47) The wood and the mud in roof construction of Riyadh houses. Photo by author.

Figure (5-48) The roof divided to use as a sleeping during summer time. Source: Daghistani [5-6].

5.7.4 Materials

Protecting inhabitants from the overwhelming heat of summer has always been the principal objective of residential architecture in Riyadh. As a result, houses have been constructed of heavy, massive materials providing thick internal and especially external walls for insulation. In fact, the thickness is greater than would be needed for a wall bearing structure, with a few windows and devices designed to take advantage of any breeze that might potentially be cool. Such massive materials are sufficient to keep out the worst of the heat, and provide good protection against ambient outside heat.

The high heat capacity material that stores heat during the day and gives it off to the interior space at night is required in the large diurnal temperature of a hot-dry region like Riyadh. Consequently, sun dried mud bricks are also chosen for wall and roof construction in this harsh environment, where there is no necessary assistance from mechanical air-conditioning. Furthermore, the thermal conductivity of adobe is greater than some materials such as concrete and gypsum.

In addition, the heat insulation advantage of adobe lies in the thickness of the walls as seen in Figure (5-49). The dense mass structure of Riyadh's traditional houses serves two purposes: it acts as a heat sink which stores thermal energy (storage capacity), and acts as a large capacitor, resisting rapid temperature changes (moderating effects) in the structure where there are large variations in day and night temperatures [5-21].

The adobe may be regarded as a suitable material in promoting greater environmental responsibility as it is well adapted to the local climate. The diurnal range can be as much as 20°C owing to the significant differences between day and night temperatures in dry desert climates. The thermal mass of the adobe enables the storage of heat gained during the day to be slowly released in the cooler night, by a process termed time lag [5-8].

However, according to Hassan Fathy traditional homes built by mud brick have several advantages over more modern materials. Most people find such buildings warmer in winter and cooler in summer. They are also much cheaper, can be produced locally using abundant local materials and have only minimal environmental impact [5-1].

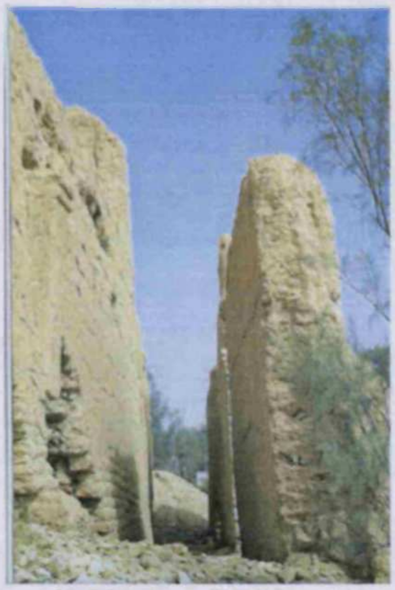
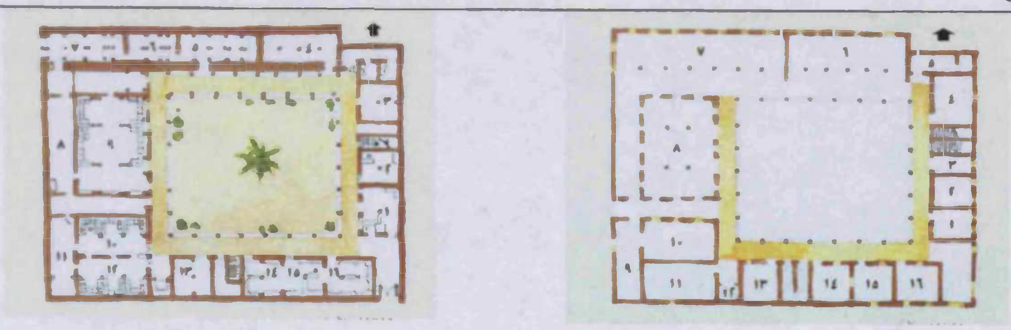


Figure (5-49) The wall thickness about one meter in Dir'yah Area. Source: William Facey [5-7]

5.7.5 Orientation

Another feature that demonstrates how traditional houses have been carefully adapted to the local environment is that they are approximately rectangular in design, which is efficient in term of heat gain and loss as with two or three walls shared with its neighbours, the longest façade of the building always faces north and south, so that the impact of radiation is minimal. Thus, the amount of radiation received does not exceed a certain limit; in another words the house absorbs the minimum possible heat during the day time houses [5-6] [5-20]. Figure (5-50) shows the typical form of mud houses.



Ground Floor. First Floor.

Figure (5-50) The typical plan of Riyadh houses. Source: Al-Ruwashed A.[5-22].

5.7.6 Streets design

One more common feature of Riyadh traditional townscapes is that buildings were built very closely together, with only narrow and shady alleyways in between, while buildings kept each other in the shade by sharing their walls or by other means of shading; therefore, some houses had a hanging bridge over the streets, extending from the first floor of some houses and providing protection for pedestrian movement against heat in the local hot, sunny climate (see Figure 5-51). Also, in some cases streets were partly shaded using light structures like canvas or light wood. However, the primary purpose of their being clustered together in this style was to prevent sand storms entering the narrow streets or courtyards of the houses, as well as creating a shade from the harsh climate [5-8].

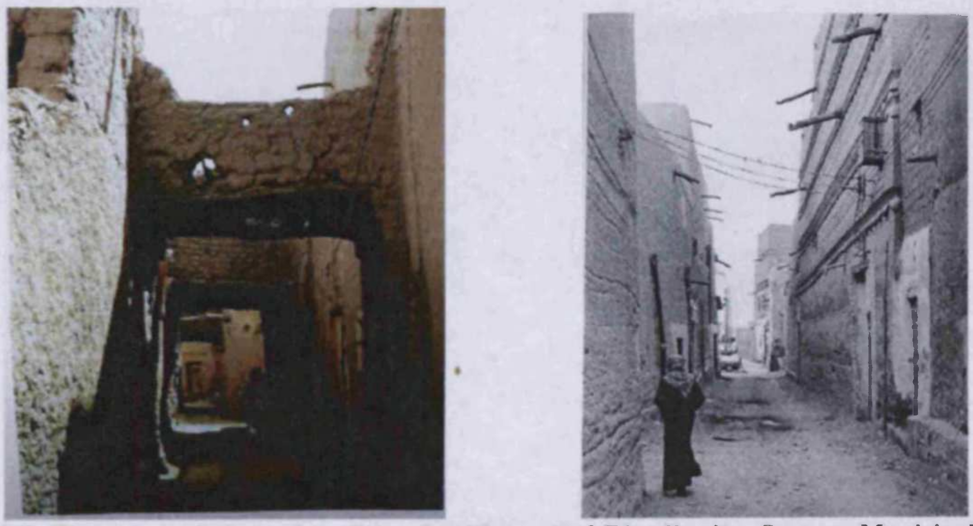


Figure (5-51) The streets design of traditional settlement of Riyadh city. Source: Municipality of Ar-Riyadh [5-4].

5.7.7 Building Design

Houses were also compact, sharing as many as three walls with each other. Buildings consequently kept each other in the shade, whether by close buildings or by other means of shading, so that in many cases the house had only one exterior façade, resulting in reducing the exposed surface area of the house and consequently its exchange of heat with the outside, hence providing more protection against hot ambient external conditions.

Figure (5-52) Buildings sharing the external wall in three sides kept each other in the shade. Source: Al-Nawaiser [5-11].

5.7.8 Openings

Not only the house mass, envelope and materials proved to be successful in terms of climatic design, but also the openings, another feature carefully dealt with in the same context. The size of doors and windows was kept minimal, so as to avoid excess heat coming into the building. The windows in a traditional courtyard house can still be seen mostly on the inside, looking in towards the courtyard. Most of the windows are also protected by wooden shutters, which possibly close throughout a sand storm [5-8]. The perimeter of the courtyard is surrounded wholly or partially by a colonnade and this adds to the shading effect, so that direct sunlight is filtered and loses its glare. Also, direct sunlight will never penetrate the rooms, so necessary comfort is provided to optical light level in the middle of the day. The numbers of windows in the exterior walls are often limited or there are no windows at all. Small rectangular and triangular openings in some houses are set high in the external walls, close to the ceiling. They were designed to admit light to the interior and to encourage air circulation, without allowing too much of the intense summer heat into the building [5-23].

At the same time, these triangular openings allowed smoke from the hearth to escape. They also provided ventilation and privacy, as well as being decorative. During the winter months these opening may be plugged with mud plaster to avoid the entry of winter cold and help retain heat. (See Figures 5-53, 54).

Figure (5-53) Rectangular and triangular opining on the external facade. Photo by author.

Figure (5-54) The amount of light is limited through the internal space. Photo by author.

5.8 Impact of Economic Changes

5.8.1 Riyadh's Economic Changes

The discovery of oil had a dramatic impact on Saudi Arabia's economy. Whereas it had previously been poor, primitive and simple, oil provided a massive source of revenue for the country. Oil excavations brought with them modern technology, increasing c ommunication with the outside world and modernising the lives of Saudi citizens. Workers in oil fields, and their families were provided with settlements by oil companies. Oil was produced in large amounts and Saudi Arabia became one of the world's chief oil-exporting countries.

5.8.2 Economic Prosperity and Society

After a long period of economic privation, which had taken its toll on morale, the citizens of Saudi Arabia were keen to enjoy the luxuries of modern life available to other countries. Rapid social, cultural and economic change occurred in ways never known to the citizens before. The whole of Saudi Arabia saw the establishment of local and governmental offices, which provided citizens with improved working conditions, and motivation to work. Every citizen's objective became to find a governmental or administrative job. Free education, health-care and accommodation were provided for the citizen by the government.

5.8.3 Economic Prosperity and Architecture

However, none of these changes could have happened without having an impact on architecture. The sharp upswing in economic prosperity had a significant impact on the construction industry. After the oil boom, new buildings and houses took advantage of construction methods, finishing materials and architectural styles imported from other countries. New kinds of buildings were built: office buildings, shopping malls, hospitals, schools and hotels. The provision of easily-acquired loans and guarantees for citizens meant increased prosperity for the construction industry. Also, because of the demand for buildings, there was an increase in the Real Estate Development Fund (REDF), which was established in 1974 to provide Saudi citizens interest free, long-term credit to build private and residential units for a growing population, to help introduce this new type of buildings [5-24].

All kinds of buildings introducing numerous styles appeared in the suburbs. The prospect of a stable monthly income and comfortable modern living resulted in an influx of people from the countryside to the cities.

The impact on traditional buildings was that many fell into disrepair because traditional architecture was no longer considered desirable and many younger builders lacked the skills necessary to repair traditional buildings. Consequently, traditional methods were frequently replaced by unsuitable modern techniques. The population in Riyadh City was increasing and foreign workers were also invited to contribute in the development process of the country. Economic prosperity and the need for an increased workforce attracted large numbers of foreign workers to the country.

As a result, new development was sprawling to meet the demands of a population explosion. The population of Riyadh was estimated to be 83,000 in 1950, or 16.3% of the total population of the kingdom. By 2007, the population of Riyadh City is expected to reach 6 million, Figures (5-55, 60) explain the development change in Riyadh.

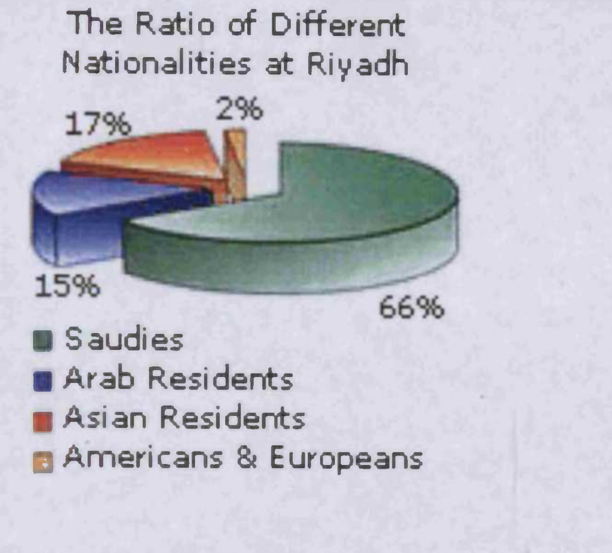


Figure (5-55) Population of Riyadh city. Source: Arriyadh High Commission (5-25).

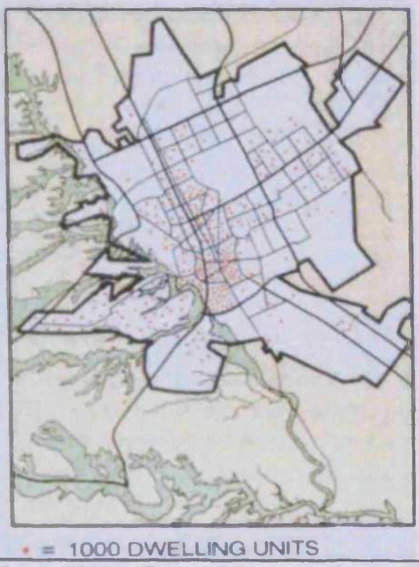


Figure (5-56) Map of Riyadh mud houses. Source: Arriyadh High Commission (5-25).

Figure (5-57) The mud buildings demolished for development purpose. Source: Geoffrey King (5-23).

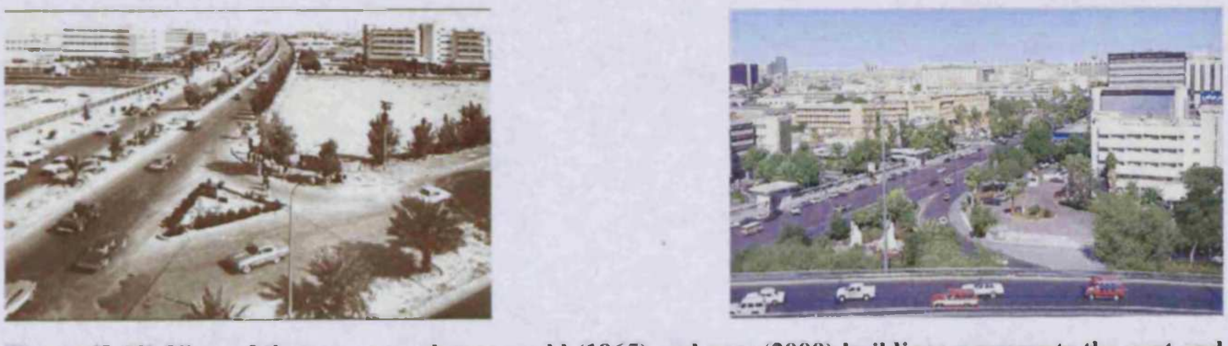


Figure (5-58) View of the same area between old (1965) and new (2000) buildings represents the past and the present of Riyadh. Source: the Government of Riyadh (5-4).

Figure (5-59) The new net of Riyadh city. Source: Municipality of Ar-Riyadh (5-4).

Figure (5-60) View of Riyadh city. Source: Municipality of Ar-Riyadh (5-4).

5.9 Riyadh Contemporary Architecture

The Riyadh region has been faced with an explosion of economic growth during recent decades by extensive residential development both in the city and in construction materials. A new range of housing and settlement pattern has been introduced. The newest and latest trends in technology and material have been brought without any concern to the climate.

> *"New materials have been introduced with little thought for how they might be used. Their adoption may also have undesirable economic side effects in developing countries"* (5-26).

Architects designing new buildings in the city of Riyadh have introduced elements of architectural styles and materials, such as air-conditioning and glass coverings, from other parts of the world.

However, the types of modern houses now appearing in Riyadh are villas, apartments and duplexes (attached to other). The modern type usually consists of one or two storeys, with the size of the house and number of rooms dependent on the family income and social status (see Figures (5-61 to 5-72)). The common type of house used in Riyadh is the villa type. The external walls of the house are not shared with the neighbours, allowing the house to have large windows on all the four sides, to obtain lighting from the outside while being unprotected from the hot sun. These houses have an open area border on all sides, resulting in a box structure.

The most common material used in construction is reinforced concrete as a frame structure and hollow blocks for walls. The roof is constructed by using reinforced concrete slab or *hordi* systems (concrete blocks or fired clays used to place within the concrete structure), supported by reinforced beams and columns. The internal and external walls are usually built from 15 cm concrete hollow blocks, and the window is glazed. The cement used is plaster as a final cover for the roofs and for both internal and external walls, while in some houses the external cover is marble. The window type air conditioning has become very common in the region as a cooling system, which may increase heat in the environment and on the exterior surfaces of the house as well. Moreover, the air-condition units are placed outside buildings, causing visual pollution to the built environment. Riyadh modern settlements have been designed by foreign companies. The response to climate prior to the advent of mechanical conditions is reflected by the architectural designs of the Riyadh region, which have been neglected by the new developments.

> *Historical studies of settlement show that even the ancient civilisation recognised regional climatic adaptation as an essential principal in creation of architecture* (5-27).

Building regulations and codes are following modern planning and design. For instance, the Greek Doxiadis consultant plan and program for the city of Riyadh started in the mid seventies, introduced a new design of urban settlement and a new system to the region. The regulations of house design determine that houses be separated from each other with two meters between them as a minimum distance all around the houses for the purpose of window opening. Also, the Doxiadis regulations control the height of buildings, their form and the width of streets. All of these changes have taken Riyadh city far from its original layout, to follow a western pattern of grid design (5-4).

The result has been a poor quality of design, the buildings totally dependent on air conditioning. As most of the new houses are designed look outward with large opening windows and almost all of the exterior walls exposed to sun from the environment, an unpleasant environment has been created inside the house. Poor thermal performance is clearly as a result of the use of new western design and new imported materials with the latest western technology, without paying any attention to adapt to climate and social need. Thermal inefficiency is increased in areas without green spaces by the use of tiling on the exterior of buildings. The cooling load on the building is increased by the reflection of solar radiation from the surrounding surfaces which is further increased by the radiation produced by the tiling. Apart from that, privacy has not been achieved by the new housing design. The overlooking of neighbours to each other's yard or each other's rooms through the balcony or their room is a very serious problem. Privacy is a very important factor for most residents and different means are used to prevent overlooking. Some close their windows and their balcony while others build a huge partition surrounding the house to create privacy for the family. Unfortunately, the result of these solutions increases the heat inside the house and prevents ventilation.

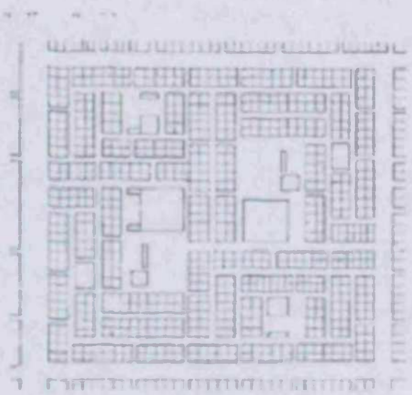


Figure (5-61) The grid plan of Doxiadis for Al-Araja area. Source: Al-Hathloul [5-28].

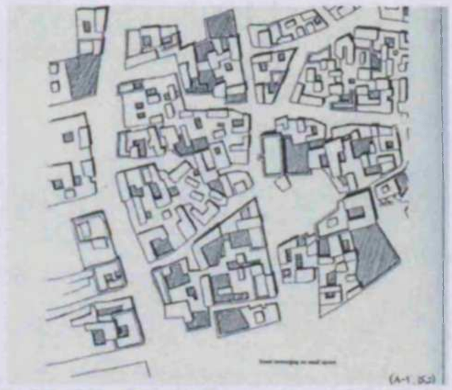


Figure (5-62) T he D oxiadis s tudies o f R iyadh urban plan. Source: Daghistani [5-6].

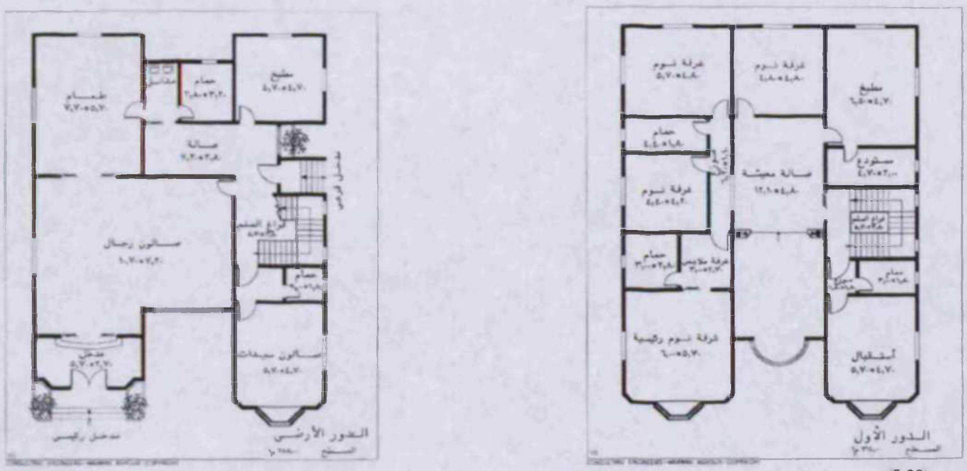


Figure (5-63) The new regulation of design of Riyadh's houses. Source: Maroun Ashour [5-29].

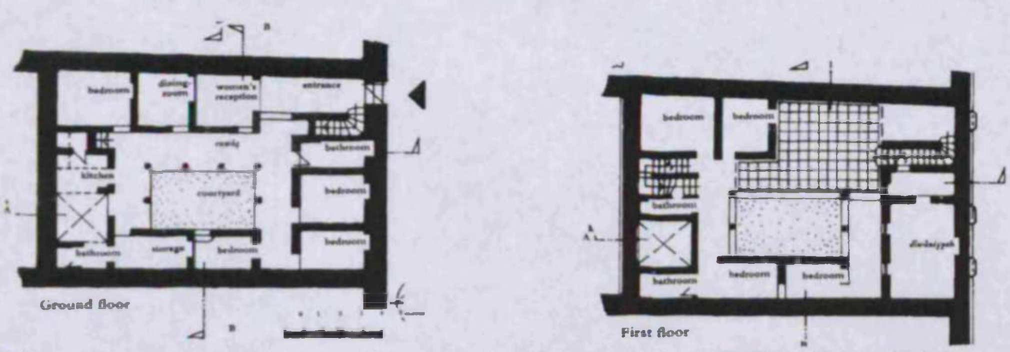
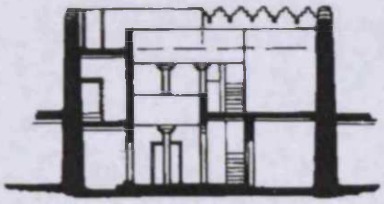


Figure (5-64) Traditional houses design with respect to climate. Source: William Facey (5-14).



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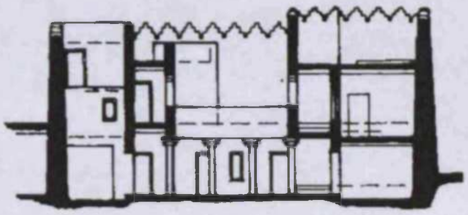


Section AA

Figure (5-65) Traditional houses massive walls to protect against heat. Source: William Facey (5-14).

Figure (5-66) The privacy is important factor in Riyadh region, this villa is surrounding by metal partition. Photo by author.

Figure (5-67) The deference between the climate treatment in glaze building with the other mud building next to it. Photo by author.

Figure (5-68) The heavy traffic in Riyadh city. Photo by author.

Figure (5-69) The western design of the roof is clear in this new villa. Photo by author.

Figure (5-70) New villa with western design in the roof almost finish, where the rain is scarce in this region with three meters of partition sheet for privacy and air conditions added in the truss. Photo by author.

Figure (5-71) Top view shows the amount of mud houses in Riyadh city. Source: Municipality of Ar-Riyadh (5-4).

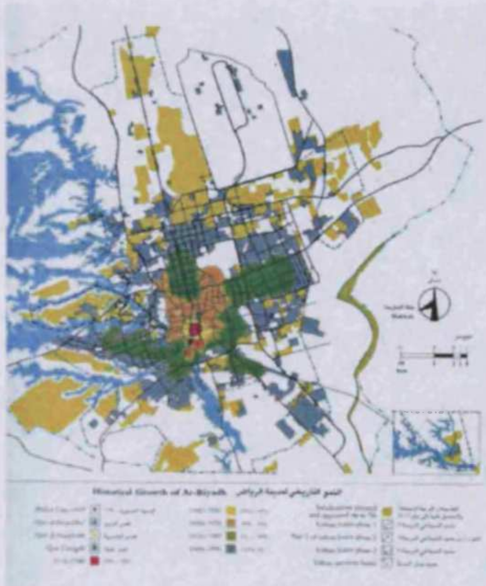


Figure (5-72) The rapid growth of Riyadh city during the last decades. Source: Municipality of Ar-Riyadh (5-4).

5.10 Conclusions

It is obvious from this chapter that the main lesson is that the traditional urban patterns and house design in the central region are well adapted to the climate. Most of the design solutions in this area were environmentally efficient and fulfil the needs of inhabitants and the religious requirements of Saudi society.

The above analysis also shows the importance of understanding the features of traditional building environments as a guide for improving existing and future designs of buildings. It is clear that the main architectural elements used in this region were the courtyard, high mass materials and small openings as well as other features to modify the extreme hot climate. In order to achieve thermal comfort on modern buildings, the mechanical air conditioning system must be operated constantly during the hot season, resulting in increased fuel consumption, while traditional building methods can provide a useful thermal performance.

To understand the performance of traditional houses the next chapter will give an explanation of the experimental work that has been conducted in the mud houses of Riyadh City, taking into consideration the measurements of the globe temperature and relative humidity, external temperature, internal temperature, and dry bulb temperature.

CHAPTER SIX

FIELD WORK OF ADOBE HOUSES

6.1 Introduction

Field investigation of selected case studies is a useful way to answer research questions related to the thermal performance of traditional houses. The use of selected case studies was chosen because they allow the researcher to evaluate conditions and conduct a deep and intensive study [(6-1)]. Thus, field investigations of the spaces are considered an essential step in understanding thermal performance of traditional houses in Riyadh.

This chapter describes the experimental work which has been conducted in the adobe houses, taking into account the measurements of the air temperature and globe temperature, external temperature, internal temperature, in order to understand the performance of the traditional houses.

6.2 Experimental Location

Gaining access to any of the adobe houses in order to conduct long-term measurements proved quite difficult. The search started in the old Dir'aiyah area, 25 km northwest of Riyadh. This was the first capital of the Saudi state (1745-1818), where all of its buildings were constructed traditional mud buildings over thousand of years.

Unfortunately, the search found that most of the old buildings in this area had been demolished, because the occupiers left them, without any maintenance, to fall into disrepair. A few of them were in good condition and abandoned, but they were not secure (see Figures 6-1 to 6-5). The survey showed that almost all of the houses are not occupied; only a few have been rented to people of non-Saudi nationality and under circumstances (related to privacy) which make conducting an experiment impossible. Furthermore the function of some houses has been changed by new materials being added or by their being used as storage.

Figure (6-1) Dir'aiyah area, where the first survey starts. Source: Arriyadh [(6-2)].

Figure (6-2) Riyadh city view. Source: Arriyadh [(6-2)].

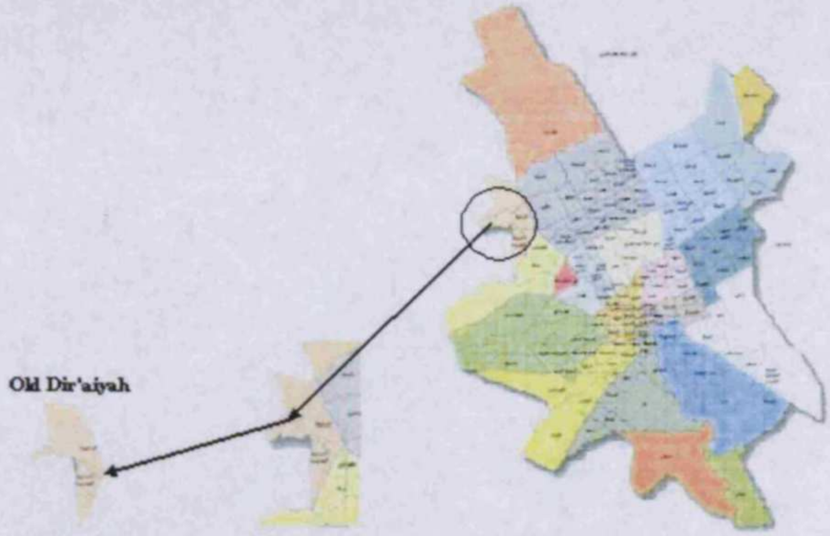


Figure (6-3) Riyadh city map with the Old Dir'aiyah on the northwest. Source: ADR modified by the author (6-3).

Figure (6-4) Parts of Dir'aiyah houses. Photo by author.

Figure (6-5) View of Dir'aiyah. Photo by author.

However, the choice had to follow certain criteria in order to prevent it from becoming spurious choice. The criteria demanded that the houses used as a case study should fulfil the research requirements. These houses represent the requirements as follows:

- They meet with the scope of the research.
- They present a traditional housing dwelling.
- They are representing the house design context of Saudi society and culture.
- They are constructed in the same traditional local materials in Riyadh and use common building features.
- To be secure where the equipments are placed.

After conducting a pilot investigation and comparing available options, the kind of housing required was found in the heart of Riyadh city (Figure 6-6 to 6-10), which represents the typical hot climate and provides a good experiment environment. The choice was made in three types of mud housing which are safe and secure and not occupied. Furthermore, the location is under the supervision of the high Authority for the Development of Riyadh (ADR) and these houses consist of a large trapezoidal courtyard surrounded by rooms giving easy access to them.

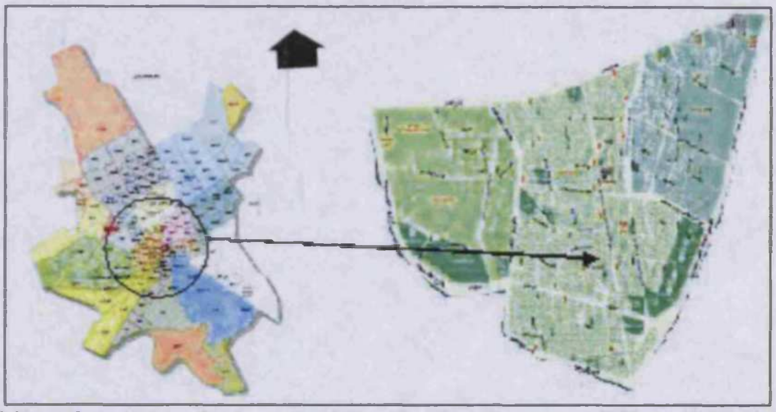


Figure (6-6) Buildings located in the heart of Riyadh City. Source: ADR modified by the author [(6-3)].

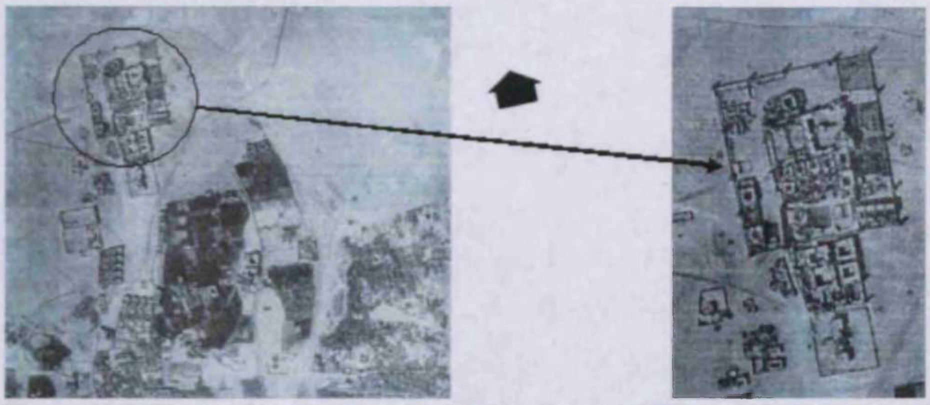


Figure (6-7) The mud buildings areas in 1950. Source: ADR modified by the author [(6-3)].

Figure (6-8) T he t hree b uildings s ite p lan b efore a nd a fter r estoration. S ource: ADR modified b y t he author [(6-3)].

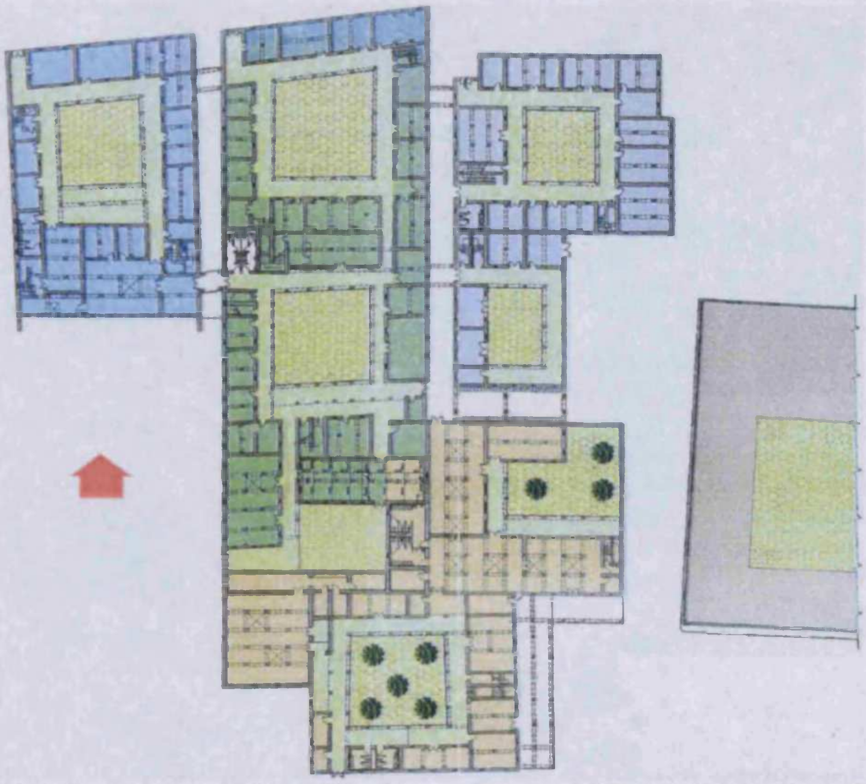


Figure (6-9) Ground floor of the mud buildings. Source: ADR modified by the author (6-3).

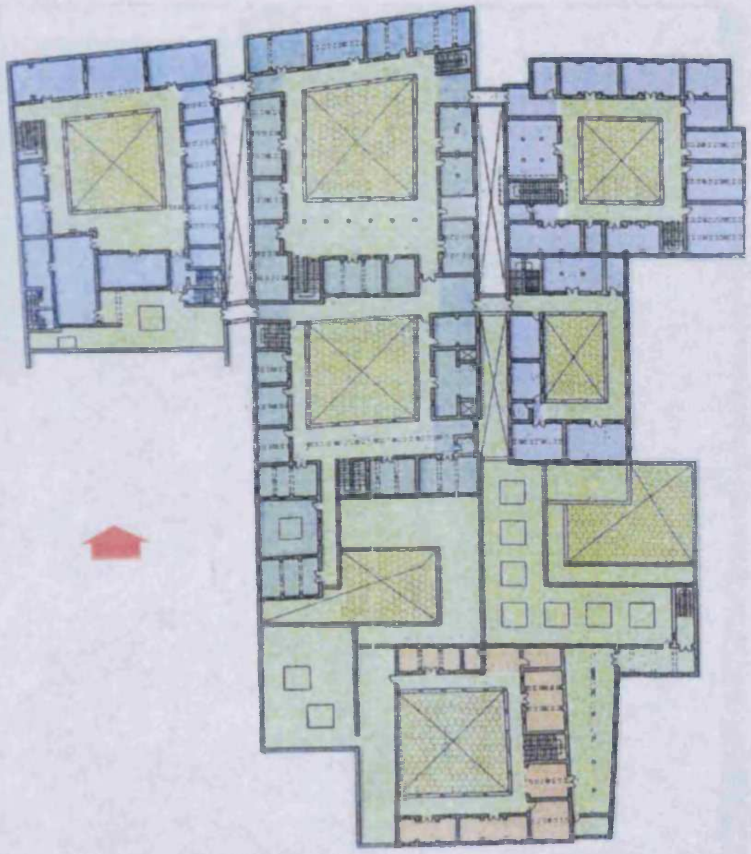


Figure (6-10) First floor of the mud buildings. Source: ADR modified by the author (6-3).

6.3 Experimental Equipments

A group of Gemini Tiny Data Logger recordings were taken in these buildings, in order to measure the thermal performance of the houses and their globe temperature and external temperature, internal temperature, dry bulb temperature. Figure (6-11) shows the devices provided by the Welsh School of Architecture.

Figure (6-11) Group of data loggers used in the experiment.

6.3.1 Room Selected

It was not possible to measure all of the rooms in each building due to limitations in the numbers of recording devices available and the time required to carry out this work. The selection of rooms in each building was therefore based on achieving:

- a representative range of orientations and storey heights, and
- a representative average size for the functions likely to be performed in these buildings.

Thus, the concern was to obtain a balance, locating the devices on the most important orientations (south, east, west and then north in that order) without taking into consideration other rooms such as bathrooms, kitchens and stairwells.

For this experiment a time step of 15 minutes was chosen, allowing the loggers to store exactly 22 days of data. The use of 15 minute intervals allowed for fast changes in conditions to be tracked and any spurious events to be checked against chronologically proximate data. Access to these buildings was arranged with permission from the Authority for the Development of Riyadh. They allowed visits to the site by the author three times during the experimental period. This gave the chance to check all the sensor readings and to find out any mistakes within the sensors that can lead to errors. As shown in Figures (6-12, 13) below the sensors were located as close to the centre of each room as possible to minimise mean radiant effects and to prevent direct solar radiation coming from the windows on measurement sensors.

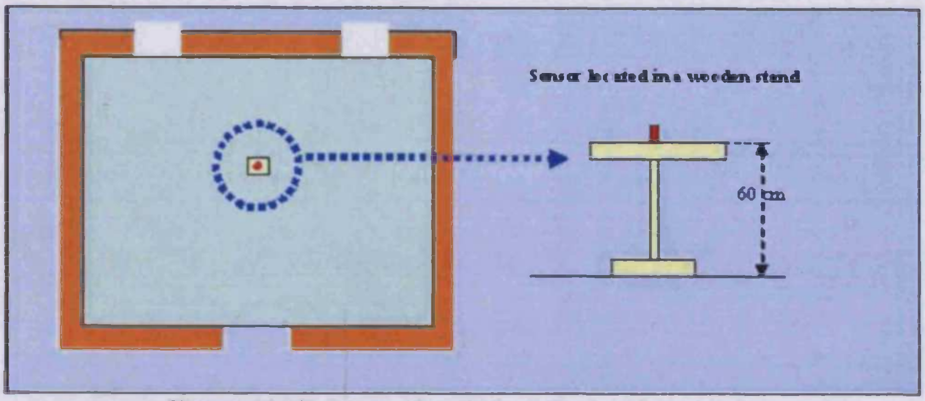


Figure (6-12) Sensors located on the wooden stand.

The outdoor air temperature measurement needed to be taken at a location away from solar radiation. Thus, a wooden cover was made to provide protection from the direct sun, as seen in Figures (6-17, 18). For the shaded courtyard air temperature measurement, the sensor was hanging roughly 0.60 cm from the roof, where it was kept at a location away from solar radiation and shaded from direct and strongly reflected sunlight, as seen in Figures (6-19, 20).

Figure (6-13) The data loggers inside were the measurements start. Photo by author.

Figure (6-14) The door kept close during the experiment. Photo by author.

Figure (6-15) Set up the data logger. Photo by author.

Figure (6-16) Download the data from logger. Photo by author.

6.4 Experimental Method

Traditional climatic design was a compatible part of the architectural design, depending upon the practical experience gained through successive generations, hence constituting the first stage of deeper specialized climatic design whose main tools are observation and realizations of ambient climatic circumstances.

This experiment aims to evaluate the thermal performance of the mud house in terms of climatic performance; it is thought of as performing climatically well in summer because this is the more thermally stressing season.

It should be noted that the internal doors and windows for the rooms were kept closed at all times during the experiment, to prevent the heat from permeating the rooms. The experiment was conducted in the summer time for a month. The experiment starts on the 3rd of August 2002 and lasted until the 9th of September 2002. Due to the limitations of the equipment, only some of the rooms have been selected for this test.

6.5 Experimental Buildings

6.5.1 Outdoor and Internal Temperature Measurements

The outdoor temperature was measured on the roof of building two, while the internal temperature was conducted on the shade courtyard on the same building. Figures (6-16, 17) show the data logger on the roof and Figures (6-18, 19) show the logger hanging on the ceiling of the corridor surrounding the courtyard. The outdoor temperature and the shade courtyard temperature are shown in Figure (6-20)

Figure (6-17) External temperature data logger. Photo by author.

Figure (6-18) External data logger device. Photo by author.

Figure (6-19) Hanging the internal data logger in the ceiling. Photo by author.

Figure (6-20) Internal temperature data logger. Photo by author.

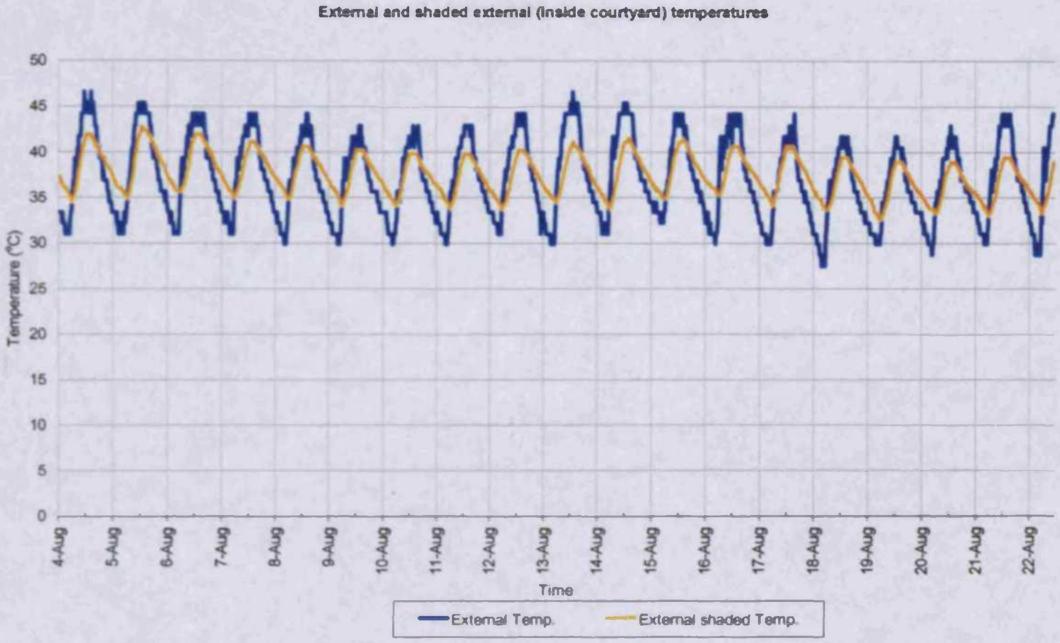


Figure (6-21) External and shaded external (inside the courtyard) temperatures in the field work.

6.5.2 Case Study of the First Building (B1)

The first building chosen has two stories and an internal courtyard. It contains several rooms on the ground floor and the first floor surrounds it. The dimensions of the house are 25 by 29 meters. The house is approximately square in plan and shares its wall with other buildings in the south side. It has a link to another building on the west side: the distance between the two buildings is about two meters. On the north side there is a building about 10 meters away, and on the east side another building about 8 meters away. The house has two main entrances: one for men on the north side and the other for women on the west side. The building has a link to the other houses on the first floor. It was built in 1938 and refurbished by the RAD in 1999 by using the same construction methods. Figures (6-21, 22) show the ground floor plan and the first floor plan. Figures (6-23, 24) show the north elevation of the house and Figure (6-25) shows the narrow street on the west side. The internal courtyard and the east side of the building are shown in Figures (6-26, 27).

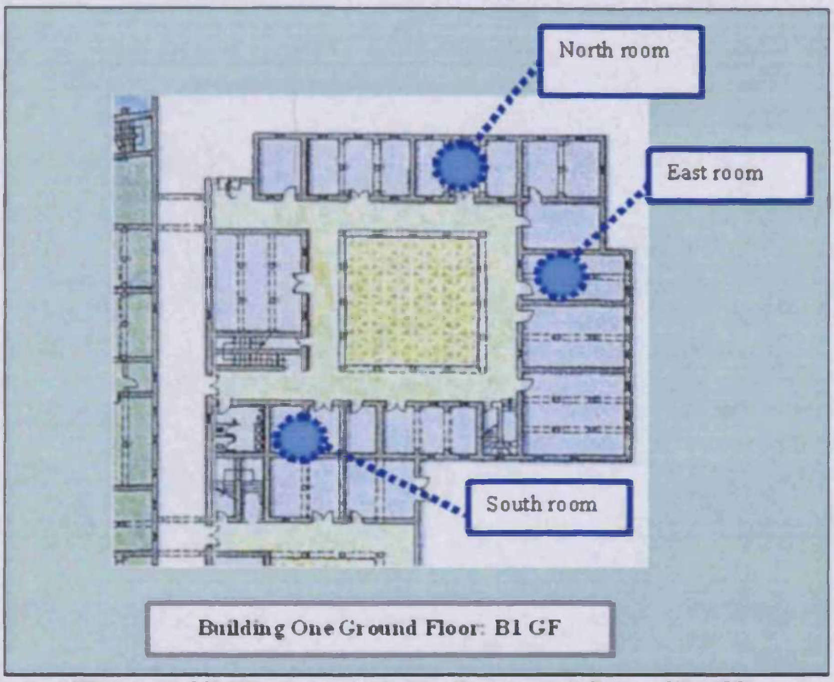


Figure (6-22) The room tested in the ground floor of B1 GF.

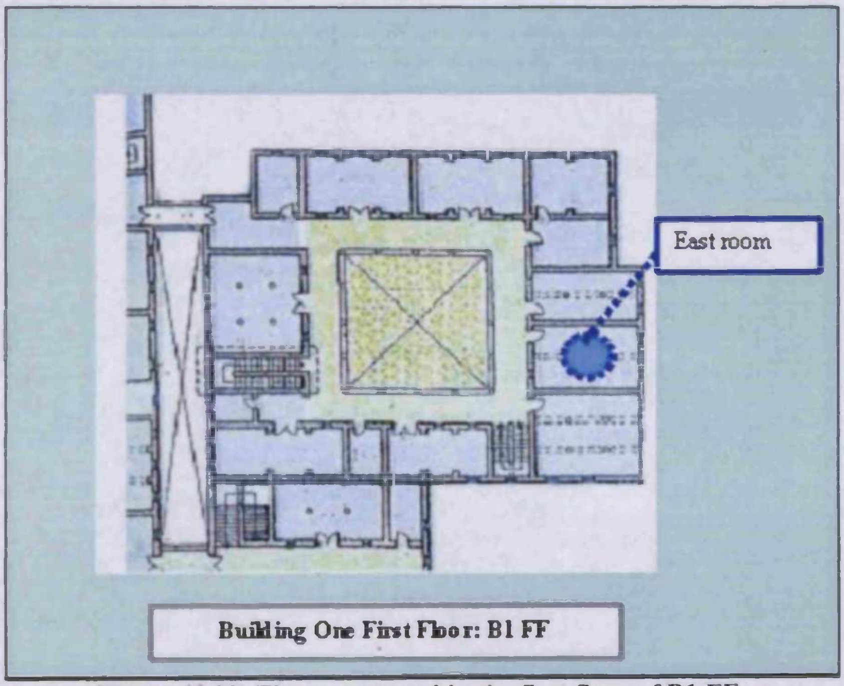


Figure (6-23) The room tested in the first floor of B1 FF.

Figure (6-24) North facades of Building One. Photo by author.

Figure (6-25) Building One with its neighbours in the north side. Photo by author.

Figure (6-26) link with other building, and the narrow street on the west side of Building One. Photo by author.

Figure (6-27) The internal courtyard of Building One. Photo by author.

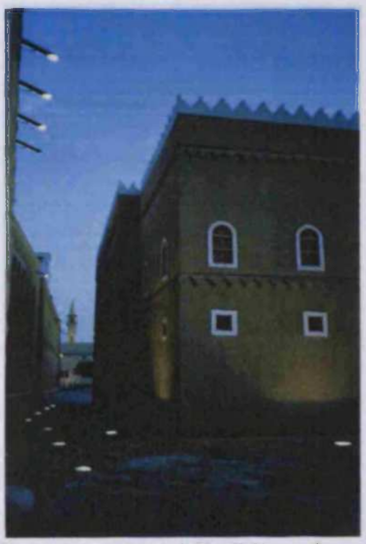


Figure (6-28) The east side of Building One. Photo by author.

6.5.2.1 Tested rooms

Three rooms have been chosen on the ground floor and one on the first floor. On the ground floor the air temperature was measured for two selected rooms on the south and east sides and the air temperature was measured for one room in the north side. On the first floor, the air temperature and globe temperature were measured in one room in the east side. Tables (6-1, 6-2) show the summary of the room size, their location and type of measurements of building one. The data collections of these rooms are shown in Figures (6-28 to 6-31).

Table (6-1) Room size and location for building one.

Building-1				
Floor	**Room location**	**Total Area** m^2	**Floor Area** m^2	**Volume** m^3
G. Flr.	South Room	137.91	22.47	108.97
	East Room	162.05	28.09	136.23
	North Room	195.51	36.77	178.53
F. Flr.	East Room	200.66	36.98	191.54

Table (6-2) Type of measurements in building one.

Room No.	Floor	Direction	Tempt	Globe
1	GF	South	√	-
2	GF	East	√	-
3	GF	North	√	-

6.5.2.2 Data collection for B1

The Figures below for case study one showed that measurements have been taken for temperature and globe temperature. The collected measurements for this building showed that the average temperature ranging from 33-39°C.

Ground Floor

6.5.2.2.1.1 B1GF South room

Figure (6-29) Air temperature in building 1, ground floor south room.

6.5.2.2.1.2 B1 GF East room

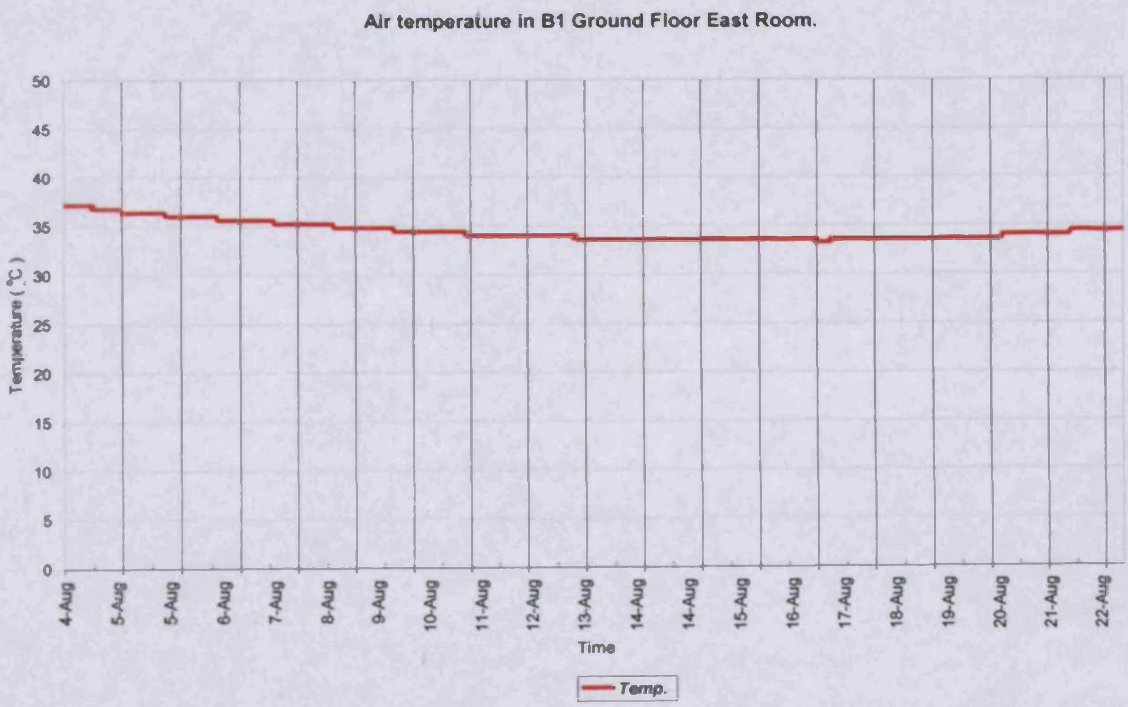


Figure (6-30) Air temperature in building 1, ground floor east room.

6.5.2.2.1.3 B1 GF North room

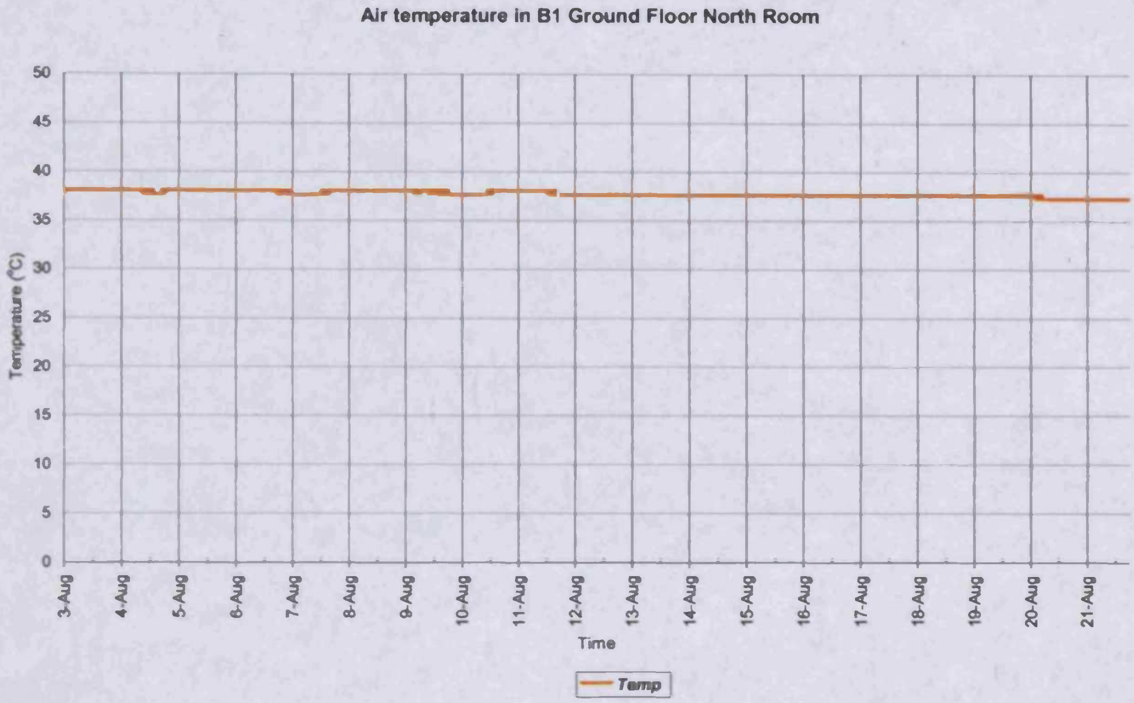


Figure (6-31) Air temperature in building 1, ground floor north room.

6.5.2.2.2 First Floor

6.5.2.2.2.1 B1 FF East room

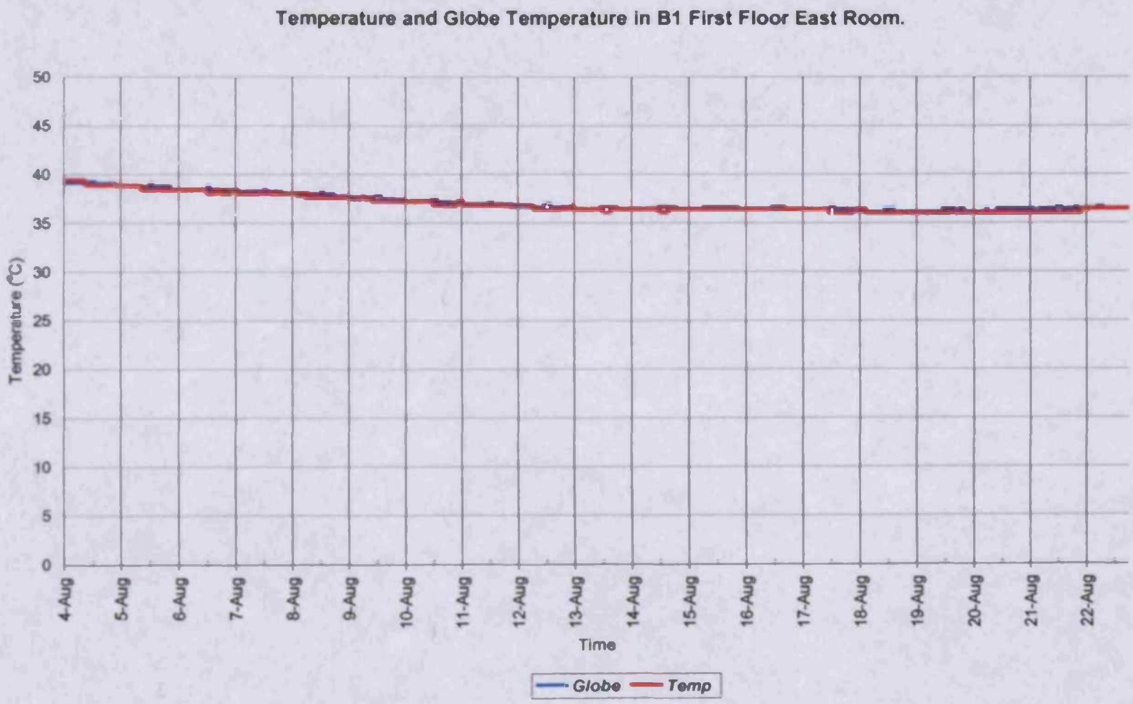


Figure (6-32) Air temperature, globe temperature in building 1, first floor east room.

6.5.3 Case Study of the Second Building (B2)

The second building chosen has two stories and an internal courtyard. It contains several rooms on the ground floor and the first floor surrounds it. The dimensions of the house are 25 by 39 meters. The house is rectangular in plan and shares its wall with another building on the east side, to which it is linked. There is only one building on the east side: the distance between the two buildings is about two meters. On the other sides is an empty area. There are two main entrances: one for men on the north side and the other for women on the east side. The building has a link to the neighbouring houses on the first floor and on the south side. It was built in 1979 and refurbished by the RDA in 1999. Figures (6-32, 33) show the ground and the first floor plan Figure (6-34) shows the north elevation of the house and Figure (6-35) shows the internal courtyard. Figures (6-36, 37) show the other side and surrounding area of the house. There are three rooms that have been tested on the ground floor and one on the first floor.

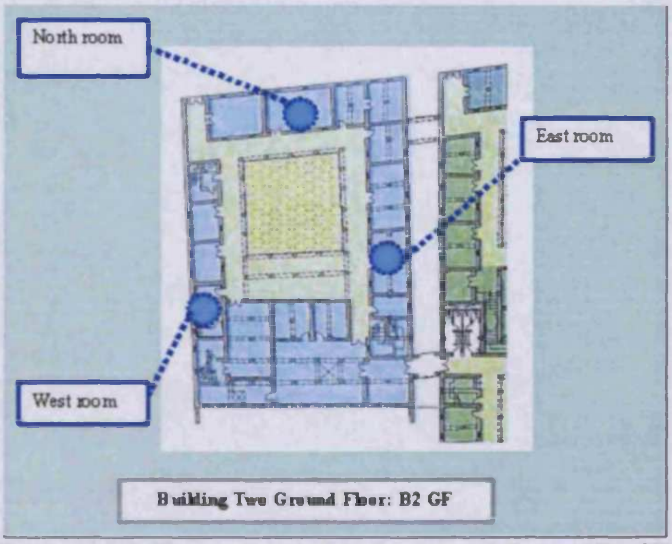


Figure (6-33) The room tested in the ground floor of B2 GF.

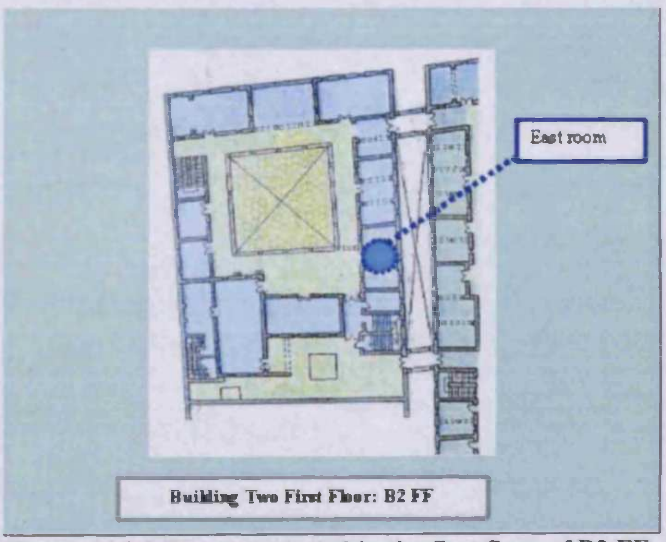


Figure (6-34) The room tested in the first floor of B2 FF.

Figure (6-35) North façade of Building Two. Photo by author.

Figure (6-36) Internal courtyard of Building Two. Photo by author.

Figure (6-37) The north and the west facades of Building Two. Photo by author.

Figure (6-38) The w est s ide o f B uilding T wo. Photo by author.

6.5.3.1 Tested rooms

Three rooms on the ground floor and one on the first floor have been measured in this building. On the ground floor the air temperature was measured for two selected rooms in the west and north sides, while air temperature and globe temperature were measured for one room on the east side. The air temperature was measured for one room in the first floor. Table (6-3, 6-4) show the summary of the room size, their location and type of measurements of building two. The data collections of these rooms are shown in Figures (6-38) to (6-41).

Table (6-3) Room size and location for Building Two.

Building-2				
Floor	Room location	Total Area m^2	Floor Area m^2	Volume m^3
G. Flr.	East Room	136.48	24.87	107.17
	West Room	107.27	16.97	72.72
	North Room	181.82	37.36	159.80
F. Flr.	East Room	152.62	24.87	127.11

Table (6-4) Type of measurements in Building Two.

Room No.	Floor	Direction	Tempt	Globe
1	GF	East	√	√
2	GF	West	√	-
3	GF	North	√	-

6.5.3.2 Data collection for B2

The following Figures showed the actual measurements on temperature and globe temperature in building two. The collected measurements showed that the average temperature ranging from 34-40°C.

6.5.3.2.1 Ground Floor

6.5.3.2.1.1 B 2 GF East room

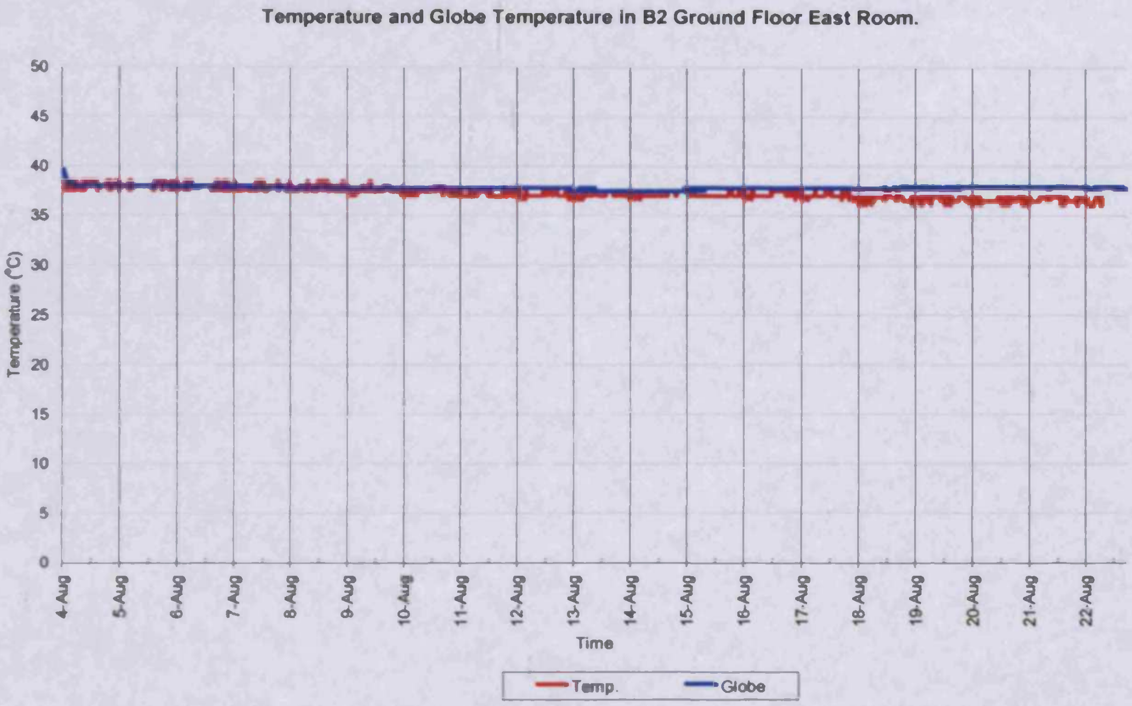


Figure (6-39) Air temperature, globe temperature in Building Two.

6.5.3.2.1.2 B 2GF West room

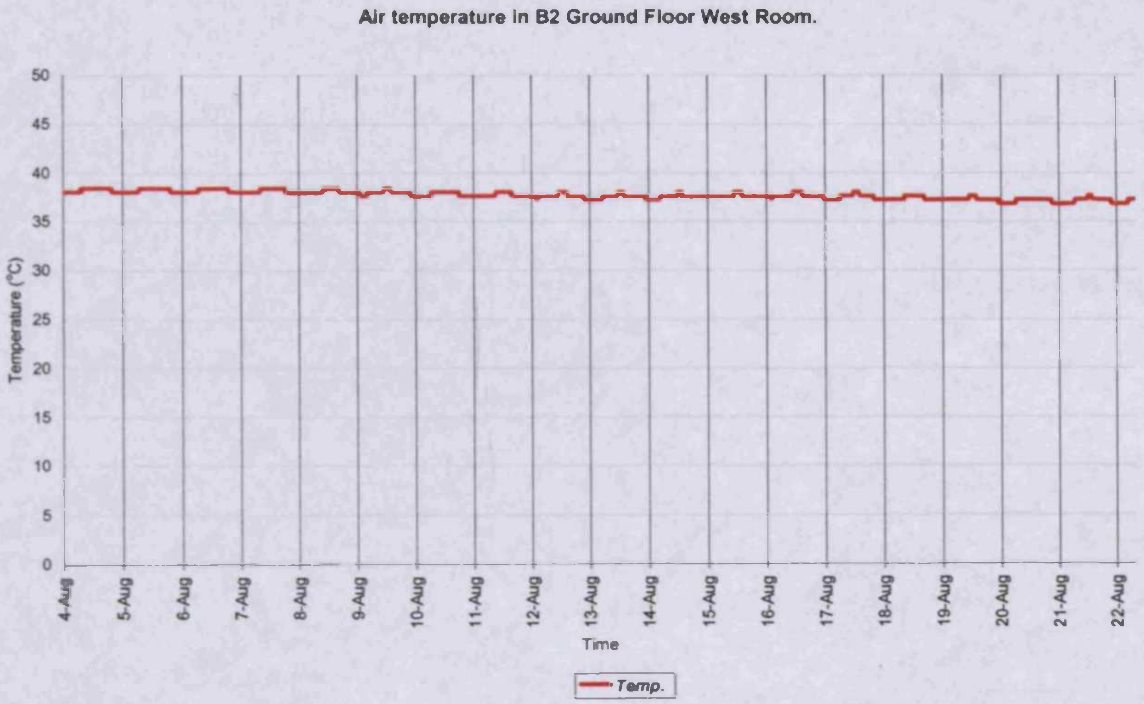


Figure (6-40) Air temperature in Building Two, ground floor west room.

6.5.3.2.1.3 B 2 GF North room

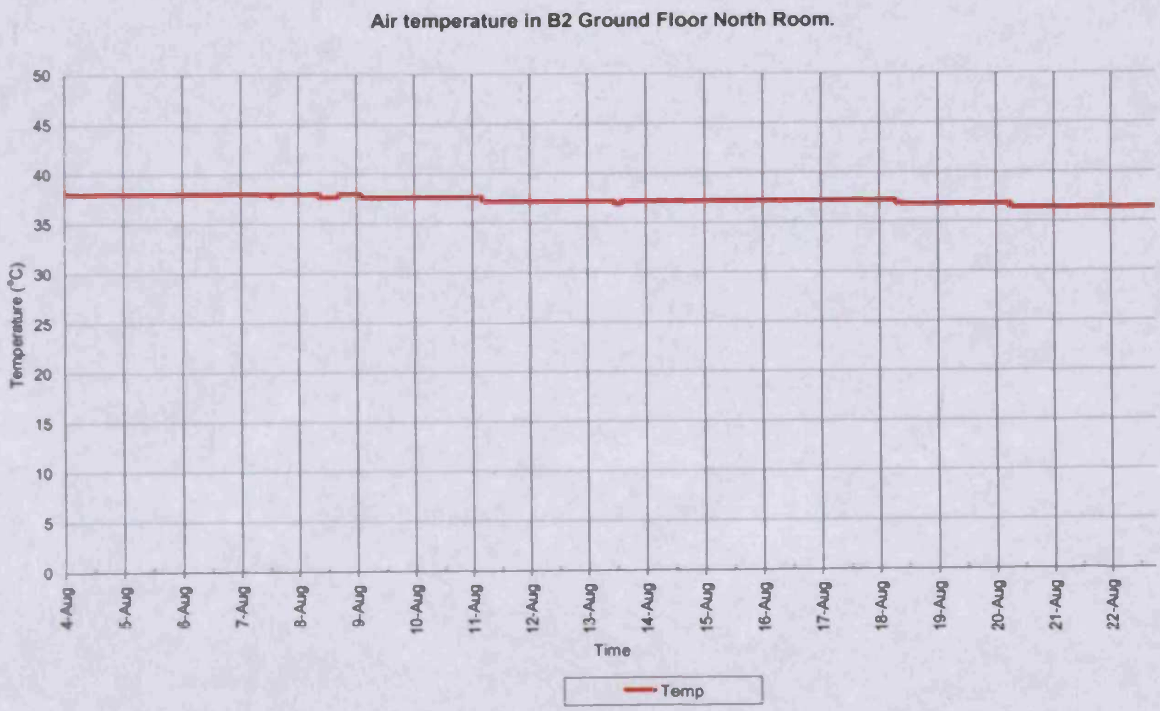


Figure (6-41) Air temperature in Building Two, ground floor north room.

6.5.3.2.2 First Floor

6.5.3.2.2.1 B 2 FF East room

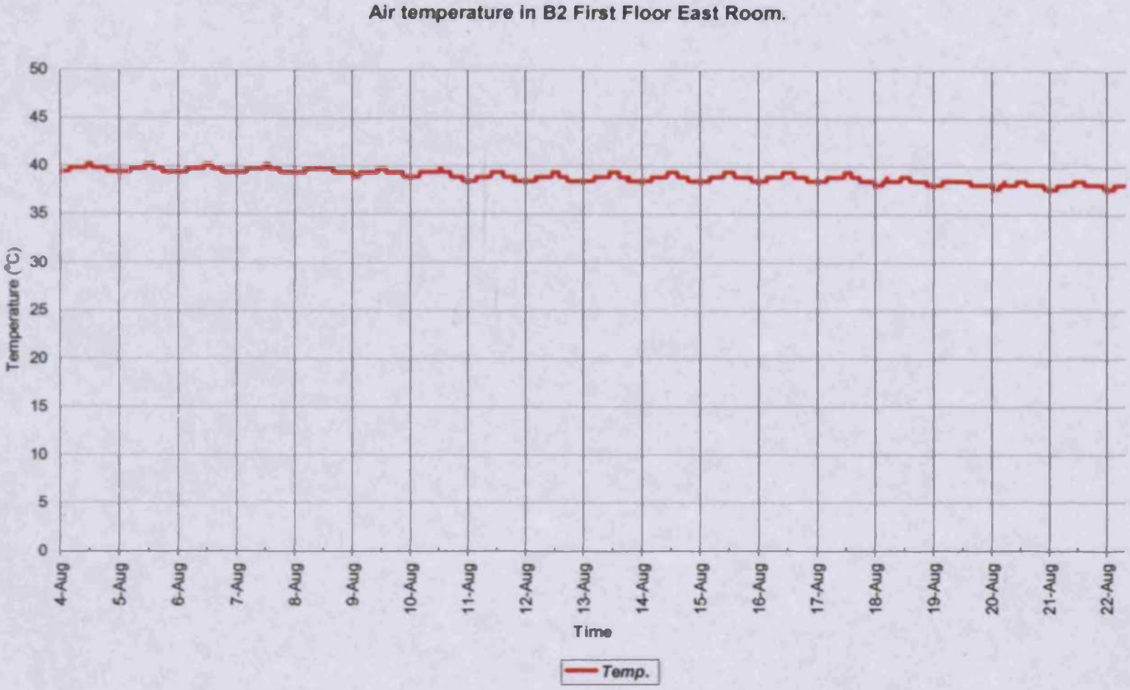


Figure (6-42) Air temperature in Building Two, first floor west room.

6.5.4 Case Study of the Third Building (B3)

The third building chosen has two stories and an internal courtyard. It contains several rooms on the ground floor and the first floor surrounds it. The dimensions of the house are 26 by 27 meters. The house is square in plan and shares its wall with other buildings in the north side. The main entrance is on the east side and the building has a link to the other houses. It was built in 1979 and refurbished by the RDA in 1999. Figures (6-42, 43) show the ground floor plan and the first floor plan. Figures (6-44, 45, 46) show the internal courtyard and elevation and Figures (6-47 to 6-51) show different views of the house.

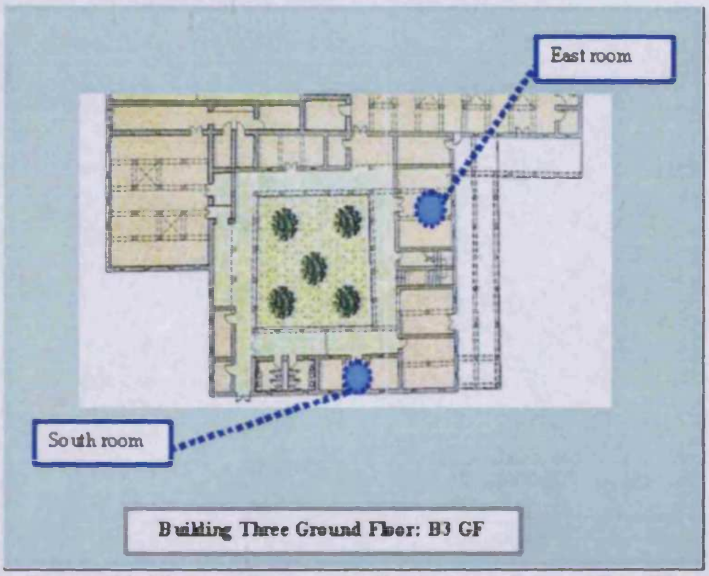


Figure (6-43) Tested rooms in the ground floor of B3 GF.

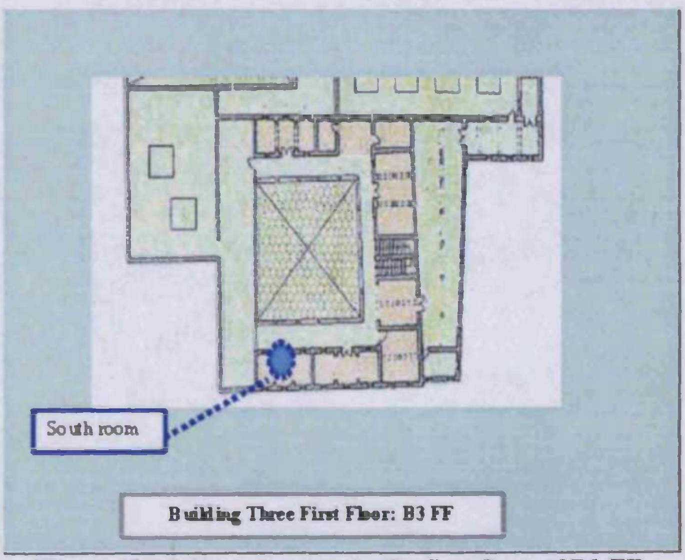


Figure (6-44) Tested rooms in the first floor of B3 FF.

Figure (6-45) The courtyard of Building Three in the north side. Photo by author.

Figure (6-46) Courtyard of Building Three in the south side. Photo by author.

Figure (6-47) The courtyard of Building Three in the north side. Photo by author.

Figure (6-48) Part from south façade of Building Three in the north side. Photo by author.

Figure (6-49) The east façade of Building Three. Photo by author.

Figure (6-50) The south façade of Building Three. Photo by author.

Figure (6-51) Internal courtyard of Building Three. Photo by author.

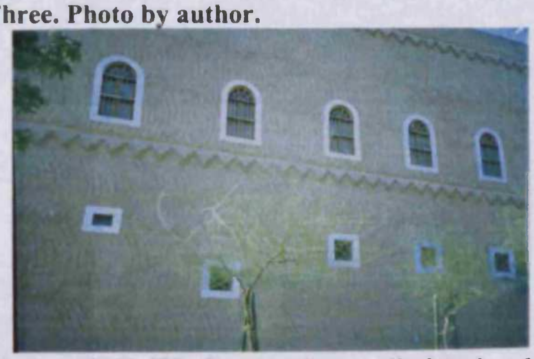


Figure (6-52) Windows in the south façade of Building Three. Photo by author.

6.5.4.1 Tested rooms

Three rooms have been tested on the ground floor and first floor. The thermal tests were carried out in two rooms on the ground floor located at the sides of the house, one room in the east and other one in the south sides as seen in Figure (6-44). The other tested room was on the first floor in the south side. On the ground floor the air temperature was measured for one chosen room in the east side, while air temperature and globe temperature were measured for one room in the south side. Air temperature and globe temperature were measured for one room in the south side located in the first floor.

Tables (6-5, 6-6) show the summary of the room size, their location and type of measurements of building three. The data collections of these rooms are shown in Figures (6-53) to (6-55).

Table (6-5) Room size and location for Building Three.

Building-3				
Floor	Room location	Total Area m^2	Floor Area m^2	Volume m^3
G. Flr.	East Room	208.13	41.15	193.41
	South Room	142.94	22.61	106.00
F. Flr.	South Room	166.46	26.82	129.57

Table (6-6) Type of measurements in Building Three.

Room No.	Floor	Direction	Tempt	Globe
1	GF	East	√	-
2	GF	South	√	√
3	FF	South	√	√

6.5.4.2 Data collection for B3

The graphs below show the measurements for the air temperature and globe temperature in building three. The results of the measurements data in the ground floor rooms showed that the average temperature ranging from 36-38°C. The collected data in the first floor room (Figure (6-54) showed that something seems to have happened during the experimental period, which appeared as significant fluctuations in temperature beginning on the 13th Aug. A possible explanation for the sudden change from a relatively stable internal temperature to significant diurnal fluctuations is that a door or window was opened and left that way. This would have resulted in greater airflow within the space, resulting in temperatures more closely following outside conditions. The minimum temperature was 31.1°C and the maximum temperature reading was 40.4°C for both temperature and globe temperature, while the minimum RH reading was 5.4% and the maximum reading was 22.0%.

6.5.4.2.1 Ground Floor

6.5.4.2.1.1 B 3 GF East room

Figure (6-53) Air temperature in Building Three, ground floor east room.

South room B 3 GF

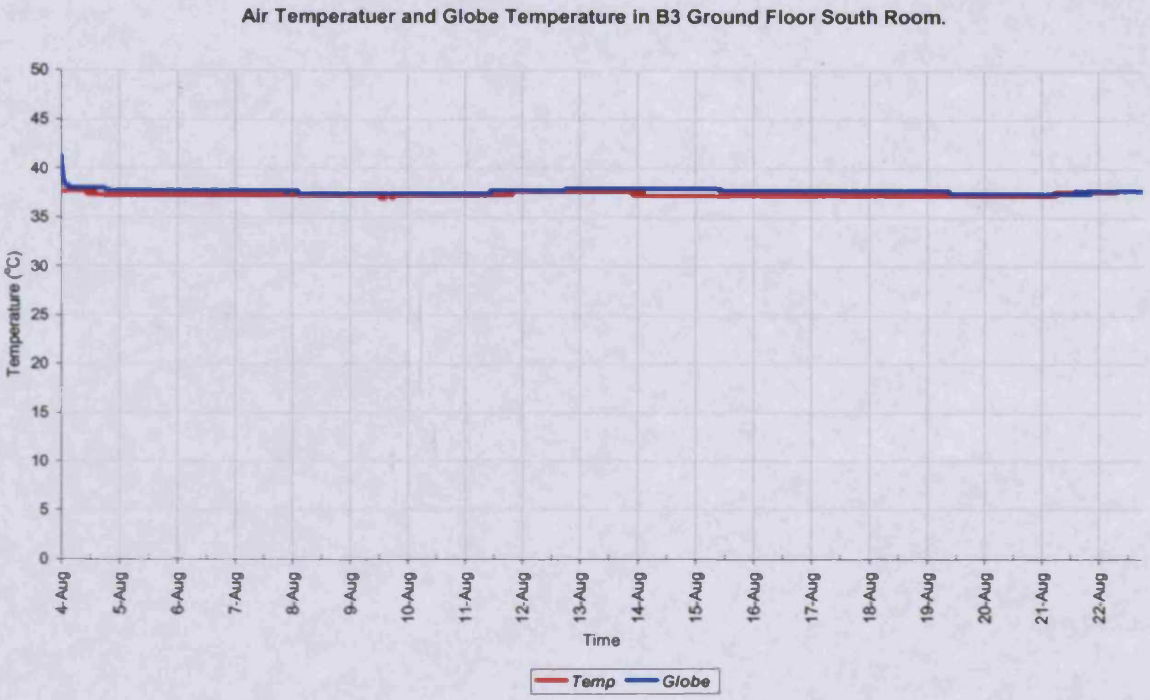


Figure (6-54) Air temperature and globe temperature in Building Three.

6.5.4.2.2 First Floor

6.5.4.2.2.1 South room B 3 FF

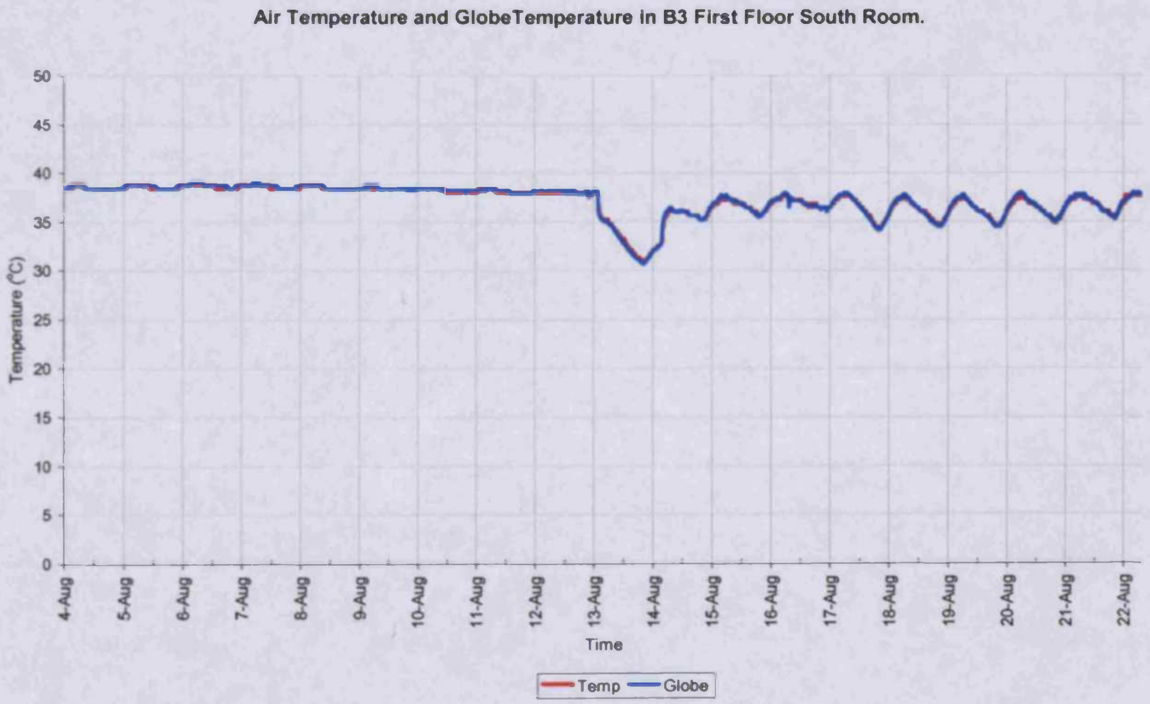


Figure (6-55) Air temperature and globe temperature in Building Three.

6.6 Data Analyses

The collected results show that outside air temperatures have an average diurnal range of 13°C and that they can range from 30°C at night to well over 45°C during the day. Temperatures within the shaded courtyard differ slightly with temperatures of 35°C being recorded at night increasing to around 43°C during the day. In contrast the closed rooms averaged temperatures of 36-38°C with barely any noticeable diurnal change. It is clear from these results that this is due to the affect of the high levels of exposed thermal mass of the adobe wall construction. Adobe material has the ability to absorb and store the heat if there was no ventilation. Breaks in natural ventilation, such as completely sealed doors and windows, which hinder the air movement inside the rooms and the low infiltration allow the warm air to stay inside the rooms which kept temperatures high, but reasonably constant. Table (6-7) presents a summary of each room tested in the field experiment.

Table (6-7) Summary of each room tested in the field experiment.

Test number	Case Study	Room Name	Room Location	Room Code	Globe Temperature Test	Temperature Test
1	Building 1	South Room	Ground Floor	B1 GF SR	No	Yes
2	Building 1	East Room	Ground Floor	B1GF ER	No	Yes
3	Building 1	North Room	Ground Floor	B1 GF NR	No	Yes
4	Building 1	East Room	First Floor	B1FF ER	Yes	Yes
5	Building 2	East Room	Ground Floor	B2 GF ER	Yes	Yes
6	Building 2	West Room	Ground Floor	B2 GF WR	No	Yes
7	Building 2	North Room	Ground Floor	B2 GF NR	No	Yes
8	Building 2	West Room	First Floor	B2 FF WR	No	Yes
9	Building 3	East Room	Ground Floor	B3 GF ER	No	Yes
10	Building 3	South Room	Ground Floor	B3 GF SR	Yes	Yes
11	Building 3	South Room	First Floor	B3 FF SR	Yes	Yes

6.7 Conclusion

As mentioned at the beginning of this chapter finding a house which can provide all the requirements to conduct an experiment was a very difficult issue as many of the houses found had deteriorated and were insecure, not having some windows or doors. The houses which have been under experiment were under the supervision of the high authority for Riyadh, where they maintained them by using the same construction methods of the traditional buildings. This made them suitable as a traditional building, secure and easy to perform the thermal test.

The result of the experimental work in this chapter will be considered during the building's refurbishment strategies. Strategies were simulated using the tools model to upgrade the thermal performance of the building's elements and were effective at reducing indoor temperatures. However, in this chapter the initial steps of this research have been presented: the data which has been collected from existing traditional buildings in the area of Riyadh and the climatic analysis of the area will form the basis to understand the performance of traditional houses and how are they have been adapted to the climatic conditions of the area. The next chapter will discuss the computer simulation for the same climatic inputs. This will make it possible to anticipate the efficiency of passive strategies applicable to living spaces and improving the occupier's quality of life.

CHAPTER SEVEN

THERMAL MODELLING TOOLS

7.1 Introduction

In order to evaluate the thermal performance of adobe buildings, and determine how this performance might be improved with effective passive strategies, a series of thermal simulations of typical buildings were used. The usefulness of thermal simulation and analysis tools as both a research tool and as part of the building design process has been demonstrated many times [7-1, 7-2, 7-3].

This chapter describes the thermal analysis tools used in this study and discusses the basis on which they were selected. It also introduces the three example buildings used in the analysis.

7.2 Thermal Analysis

Thermal analysis basically means mathematically simulating the interplay of thermal processes within a building model. Burdene describes simulation as:

> *"Simulation is the process of developing a simplified model of a complex system and using the model to analyse and predict the behaviour of the original system. Why simulate? The key reasons are that real-life systems are often difficult or impossible to analyse in all their complexity, and it is usually unnecessary to do so anyway. By carefully extracting from the real system the elements relevant to the stated requirements and ignoring the relatively insignificant ones (which is not as easy as it sounds), it is generally possible to develop a model that can be used to predict the behaviour of the real system accurately"* [7-4].

These simplified models allow not only the comparison of simulated results with real situations, but also the ability to predict what effect design changes might have on the overall behaviour of a building. This can be very useful for the designer, allowing them to choose between different design options based on their performance. Clarke (2001) has pointed out that:

> *"It is not hyperbole to suggest that the better design of new building would result in a 50-75% reduction in their energy consumption relatively in 2000 levels, and that appropriate intervention in the existing stock would readily yield a 30% reduction. Added together, this would significantly reduce a nation's energy bill. ...... it is in response to this deficiency that building simulation has emerged for use to appraise options for change in terms of relevant issues - from human health and comfort, through energy demand reduction, to sustainable practice, substantial attempt are being made to transfer the technology into practice"* [7-1].

Thus, this research aims to use thermal analysis methods as an aid to the determination of the most effective passive design strategies to improve the thermal performance of existing adobe buildings in Riyadh.

7.3 Thermal Analysis Methods

Traditionally, building designers have depended on calculation methods based on empirical considerations or simplifying assumptions such as steady state behaviour or perfect control. Such methods have many deficiencies and are often not clear or accurate enough in terms of energy evaluation. It is often not possible to calculate these manually, owing to the large number of inter-related processes occurring in a building. For example, energy consumption is affected not only by conductive heat loss but also by ventilation heat loss and solar gains. Each of these factòrs varies over time and are in turn dependent on external conditions, requiring a large amount of hourly climatic data describing outside temperatures, relative humidities, wind speeds and solar radiation over the whole year. Processing such a large amount of data manually would be virtually impossible, however there are now a significant number of computer programmes available that *can* deal with this. With the development of more intuitive user interfaces, these can be readily used by architects and engineers to design more energy efficient buildings.

Many computerised models for thermal analysis have been developed in the last few decades and are now widely used for the estimation of the indoor thermal conditions. Their benefits lie mainly in the ability to quickly compare the effects of many small changes to the building design, allowing the designer to more closely control both performance and cost issues with much greater certainly.

However, not only are there many different analysis methods available, but also many different implementations of each method in different software packages. Also, being essentially a simplification of a more complex system, each method has its own set of benefits and limitations determined by the specific assumptions upon which they are based. Thus, no single simulation method or implementation is likely to be entirely suitable to every condition or building type. The results of the Building Energy Simulation Test (BESTEST) [7-5] clearly show wide variations in the results of different software, and even with different operators of the *same* software.

Thus, to achieve a high level of confidence in the analysis of adobe buildings in Riyadh, the decision was made to use several different thermal analysis methods and compare their results. The next section explains the basis for the selection of these tools and gives a general description of the programmes used to simulate traditional dwellings which have been measured in Riyadh City.

7.4 Choosing an Analysis Method

There are many techniques for evaluating energy flows in to and out of buildings. However, there are essentially two main approaches, known as 'steady state' and 'dynamic' systems. Steady state systems assume that internal and external conditions are different but do not change over time. This allows some characteristics of the building envelope to be understood, but not all. One the most important characteristics not fully considered in the steady state approach is the effect of thermal mass [(7-4)]. As the adobe buildings being studied here rely to a large extent on thermal mass, and because conditions in Riyadh vary quite considerably even over a single day, it was considered more appropriate in this research to use a dynamic approach.

Even with a dynamic approach, there are a number of different algorithms that can be used. These vary from a relatively simple pseudo-dynamic system, as used in the CIBSE Admittance Method [(7-8)], to much more complex systems such as the response factor and finite difference methods. Once again, in order to increase confidence in the results, it was decided to use tools that implement *different* methods to determine if any were more or less appropriate to the specific conditions in Riyadh City.

Many of the more commonly used simulation tools have been developed over the last few decades. The building energy software tool webpage (DOE 2004) [(7-9)], run by the US Department of Energy, lists over 282 tools, extending from research grade software to commercial products. Testing and grading *all* of these tools was not possible within the scope of this research so, given their availability and international reputations, the decision was made to use the following three different software tools for analysing the thermal performance of traditional building.

- ***ECOTECT***
- ***HTB2***
- ***EnergyPlus***

7.5 Reason for Selecting Tools

These three analysis tools were selected for the following reasons:

- They were readily available to both the author and to designers and engineers likely to work in this field within Saudi Arabia. EnergyPlus is freely available for download on the internet. HTB2 is a product of funded research within the School and is available to the public as a research tool. It is intended that it will soon be freely available to the public on its next release. Whilst ECOTECT is a commercial program, it is relatively inexpensive and available in many universities.

- They each implement different thermal analysis algorithms. ECOTECT uses the much simpler CIBSE Admittance method whilst EnergyPlus takes a more complex heat-balance approach, using a modified Response Factor method for its fabric model. HTB2 uses the finite difference method in which each material in the model is split into finite layers to calculate the 1-dimensional fabric heat flows.

- One of the features of ECOTECT is that it can ***export*** geometry directly to a range of other tools, including those used in this work, which makes it easier to carry out a simulation using multiple tools. Also, when reviewing previous doctorate students over the past eight years, particularly in the Welsh School of Architecture [7-11, 7-10, 7-12, 7-13, 7-14], it was noted that most of them have used ECOTECT and HTB2 software tools in depth. This could be regarded as an advantage in the selection of programs since previous doctorates have used them for prediction in different climatic regions, and have validated their findings with reasonable accuracy.

- The choice was also influenced by the fact that learning the models would be slightly easier as the staff that developed them were already available in the school to provide advice and support.

- The selection of EnergyPlus was based on its history and reputation. The program of EnergyPlus was written and developed by the US Department of Energy. EnergyPlus is supported by a number of research groups, including the U. S. Army Construction Engineering Research laboratory, the University of Illinois, Lawrence Berkeley National Laboratory, Oklahoma State University, GARD Analytics, Florida Solar Energy Centre and DOE. EnergyPlus is an all-new program based on the most popular features and capabilities of BLAST (written in the early 1970s) and DOE-2 (written in the late 1960s).

In the following sections each tool will be described individually.

7.6 Research Tool Description

This section gives an overview of the three different simulation programs were selected.

7.6.1 ECOTECT.

ECOTECT is "*a software package with a unique approach to conceptual building design. It couples an intuitive 3D design interface with a comprehensive set of performance analysis function and interactive information display*" (7-4).

The thermal analysis in ECOTECT which will be used as a thermal prediction tools in this research is based on the CIBSE Admittance Method, and its limitations lie in the limitations of this method, which is based on the somewhat limited concept of cyclical variation. Therefore, this method is appropriate in conditions where energy inputs and temperature swings are changing steadily, while not appropriate when there are sudden alterations in the values, such as when large heating devices are turned on. Additionally, the Admittance Method does not track solar radiation once it passes through a window and enters within a space. With the Admittance Method, solar radiation becomes a space load at the moment it contacts a window and is not followed to find which internal surface it subsequently contacts. It is known that this method is a pseudo-dynamic method only in that it is based on calculated variations about a mean value.

ECOTECT is a conceptual stage building modelling and analysis tool that deals directly with all aspects of a building's performance including the thermal, acoustic, lighting and solar design issues (7-4). The software includes compliance testing functions for local building regulations such as the new UK Part-L. ECOTECT has over 2500 licensed users world wide and is taught at approximately 90 universities mainly in Australia, UK and the USA. It comes with supporting tools such as, weather data tools, solar tools, psycho tools, terrain tools, lumen tools, sound tools, life cycle analysis tools, and conversion and equation tools. It has a wide range of features that add to its accuracy of thermal modelling such as inter-zonal adjacency testing and the fact that model can be easily be exported to other programs such as EnergyPlus, HTB2, ESP-r and Radiance without the need to re-model. It is written in C++ and some of its features can be found in reference (7-4) and in section (7.7) of this chapter. Figures below show some examples of ECOTECT thermal simulation.

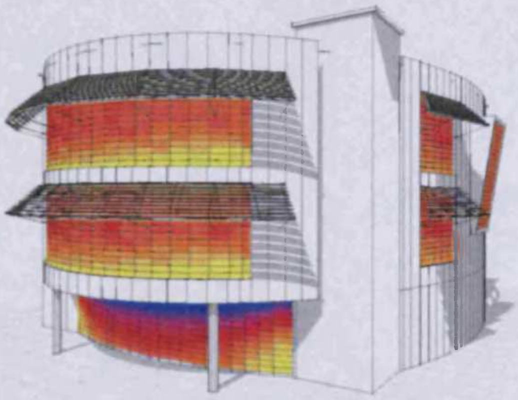


Figure (7-1) Available Light in ECOTECT. Source: Square One [7-4]

Figure (7-2) C FD a nalysis in E COTECT. Source: Square One [7-4].

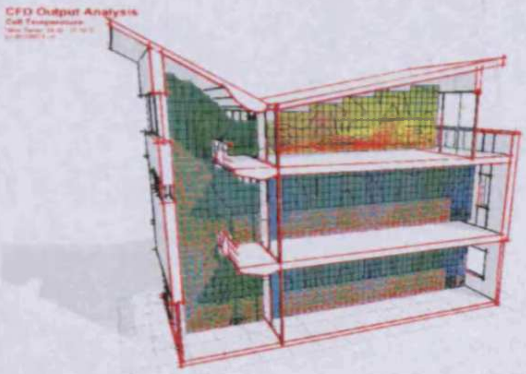


Figure (7-3) Internal temperature analysis. Source: Square One [7-4].

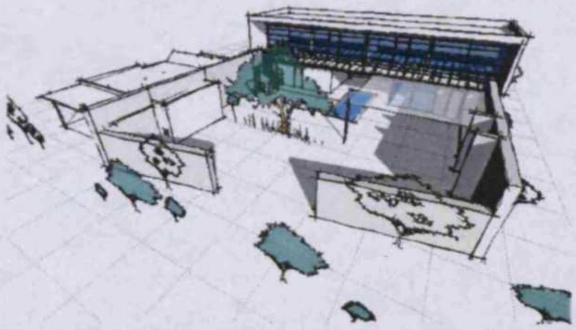


Figure (7-4) Modelling sample. Source: Square One [7-4].

7.6.2 HTB2

HTB2 is a thermal modelling program written by Don Alexander at the Welsh School of Architecture, Cardiff University, which uses the Finite Difference heat transfer model. To quote the manual, HTB2 is *"a computer program designed for simulating the thermal performance of energy efficient occupied buildings. It is aimed at providing scientists/programmers, perhaps working with a research architect or design team, with a flexible tool for studying the detailed operation of a building on a short time scale, of minutes rather than hours"* [7-15].

It is designed to simulate the thermal performance of buildings, form, climate, fabric, occupant activities and ventilation rate. This program originated from the early model of heat transfer buildings (TB) which first developed in 1971. HTB2 has been written in the flexible computer language of Fortran-77. HTB2 program has many features that help the researcher to simulate their models, some of which include:

- Calculate fabric heat transport.
- Relative transfers between internal surfaces.
- Up date external condition.

The inputs data file of the HTB2 model is divided into three levels, top level, second level and third level. The top level file contains required information for operating the simulation and controls the input data. The second level contains two groups of files, the first one contains the third level and the second group contains the general data of the main and the subsystem. The third level contains the bulk of the data which is required for running, and located in the sub-system. Figures (7-5 and 7-6) show the summary of the input data and structure for HTB2. Figure (7-7) shows interactions between the fundamental building processes.

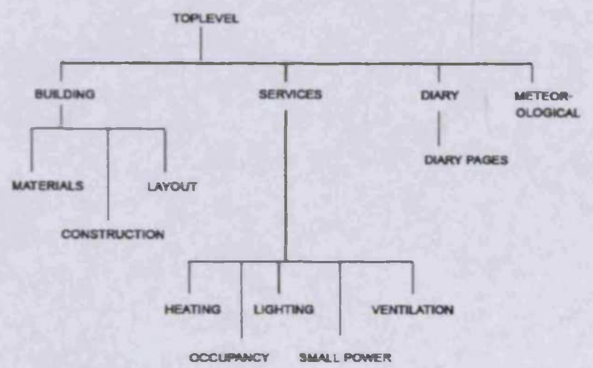


Figure (7-5) Summary of the input data and hierarchy for HTB2. Source: Alexander (7-15).

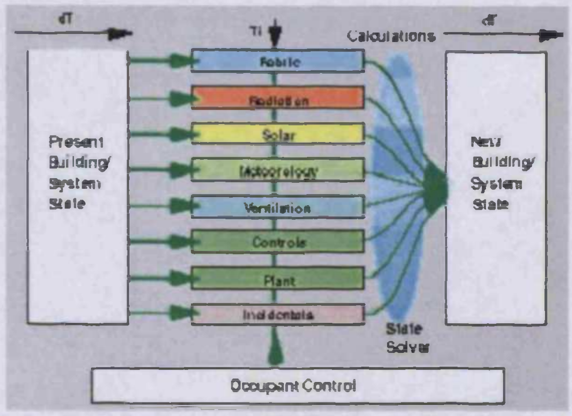


Figure (7-6) Structure of HTB2 shows the processes and partitioning. Source: Alexander (7-15).

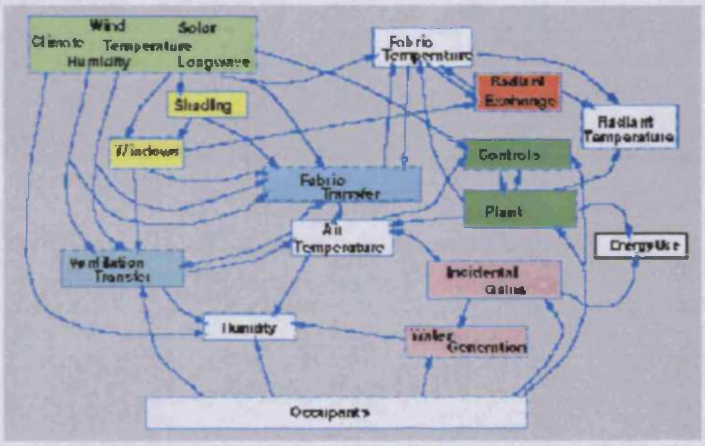


Figure (7-7) The interactions between the fundamental building processes. Source: Alexander (7-15).

7.6.3 EnergyPlus

In 1996, The U.S. Department of Energy (DOE) began developing a new building energy simulation tool named EnergyPlus. EnergyPlus is a new production building energy simulation program the first version of which was released in April 2001. It is a simulation program designed for modelling buildings with all their associated heating, cooling, lighting, ventilating and other energy flows. EnergyPlus is result of the combination of both DOE-2 and Blast, based on the fundamental heat balance method. EnergyPlus is written in

FORTRAN 90 as a programming language and has many features such as low temp radiant heating/cooling, thermal comfort modelling options, user-configurable modular systems that are integrated with a heat and mass balance based zone simulation and input and output data structures tailored to facilitate third party module and interface development. Other features of EnergyPlus can be found in webpage:
(http://www.eren.doe.gov/buildings/energy_tools/energyplus.htm).

The program consists of three basic components or modules. These components are the Simulation Manager, a Heat and Mass Balance Simulation module (based on BLAST), and a new Building Systems Simulation module (see Figure 7-8, 7-9). The Simulation Manager controls the complete simulation process of EnergyPlus [(7-16)]. The design of input and output data files of EnergyPlus is illustrated in Figure (7-10).

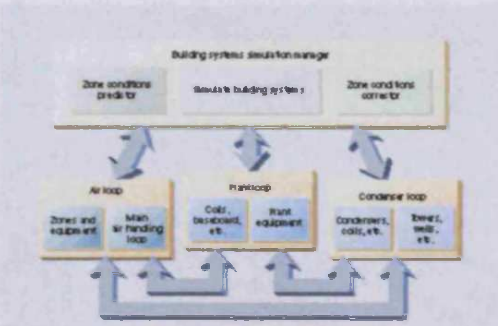


Figure (7-8) Simulation manger of EnergyPlus. Source: Drury B [(7-16)].

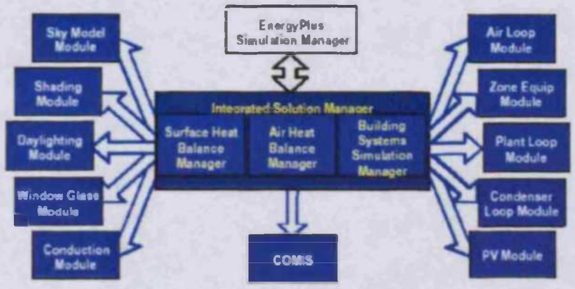


Figure (7-9) Integrated simulation manger of EnergyPlus. Source: Drury B [(7-16)].

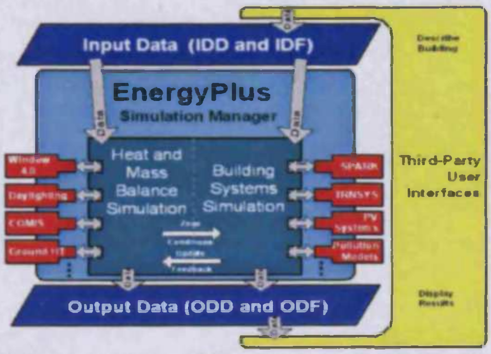


Figure (7-10) Overall EnergyPlus Structure. Source: Drury B [(7-16)].

7.7 Modelling Tool

The building model was generated using modelling tools within the ECOTECT software. There were several benefits of modelling the building in ECOTECT:

- ***Internal Analysis Engine***

  As ECOTECT includes its own thermal analysis engine, it encourages the user to continually test and check for errors as the model is being developed. This meant that simple modelling mistakes were picked up after only the first few zones and, after consultation with the help files, the rest of the zones to be created faster and more accurately.

- ***Exporting in Native File Formats***

  As described in Section 7.6.1, ECOTECT can export its building model to a range of other analysis tools, including EnergyPlus, HTB2 and ESP-r. On export, it generates input files for each tool in their own native file format. This significantly reduced potential discrepancies that can occur if using an interim conversion format such as DXF or 3DS. It also meant that the author could see exactly how model parameters in ECOTECT were being translated in each tool, allowing the base model to be appropriately refined.

- ***Centralisation of Building Information***

  Maintaining all of the building model data in one tool meant that changes could be made only once, and then propagated to each analysis tool automatically. This made the comparative analysis much easier as there was no requirement to manually edit the files for each tool, the modified model was simply re-exported and the new analysis run. This also meant that unit differences and the translation of different parameters were always consistent and based on the software author's own intentions.

- ***Additional Related Analysis***

  A major benefit of generating the model in ECOTECT was that it could be subjected not only to thermal analysis, but a wide range of related analysis such as shadow animation, solar radiation and air-flow modelling.

7.8 Buildings Description (Case Studies)

The selected buildings of the case studies that described in Chapter Six are constructed of massive adobe walls and an earth constructed roof. The walls were constructed with 400 mm adobe bricks plastered internally and externally with mud. The roof construction consists of mud and soil about 350mm in thickness, supported with *Athel* trunks and date palm fronds. The openings consist of wooden doors of different sizes and windows, which are designed with wooden frames and small glazed apertures. The building and the details of construction of case studies buildings are shown in Figures below and in Table (7-1).

Figure (7-11) North facades of Building One with its neighbours. Photo by author.

Figure (7-12) North facades and Internal Courtyard of Building Two. Photo by author.

Figure (7-13) North facades and Internal Courtyard of Building Three. Photo by author.

Table (7-1) Construction details of the case study building

Buildings Definition	
	***Doors Detail 1600X2500mm*** - Traditional *Athel* Wood Door. - 35X 150 mm Wood Panels. - *Athel* Wood Packing of 25x50mm.
	***Windows Detail 750X1500mm*** - 40X40mm Traditional *Athel* Wood Frames. - 6mm Highly Reflection Glass 350mmX 230mm, 62%.
	***Windows Detail 580X580mm*** - 500X500mmTraditional *Athel* Wood. - Traditional *Athel* Wood Frame of 40X40mm. - 6mm Highly Reflection Glass, 86%.
	***Sky Windows Detail*** - 2300X530mmTraditional *Athel* Wood. - Traditional *Athel* Wood Frame of 40X40mm. - 6mm Highly Reflection Glass, 86%.
	***Walls Description*** - 400 mm Adobe Sun Dried Brick. - 30mm Mud Plaster.
	***Roof Description*** - 100mm of Soil stabilized layer. - 100mm of Clay soil layer. - 30mm of date palm fronds. Ø150-100 mm of *Athel* trunk.

Thermal simulation of the case studies was carried out based on the above information, which also included the location and the site hourly climate data as well as the thermophysical properties of the model construction materials.

7.9 Model Generation

As described in section 7.7 choosing ECOTECT to generate the model has many benefits for modelling the building. Therefore, the decision was made to create the model in ECOTECT due to its features and all of the requirements and information about the buildings were prepared and introduced to be modelled firstly in ECOTECT and used to compute the indoor temperature for the adobe building in Riyadh.

Thus, the first step is creating the geometric model in ECOTECT, and then the same model will be exported from ECOTECT into other tools files.

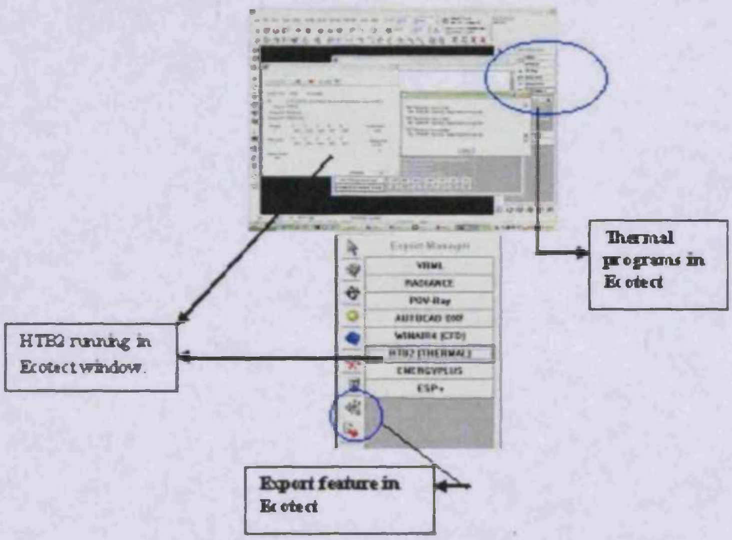


Figure (7-14) Export facilities in ECOTECT software.

7.9.1 Division of Each Building into Zones

7.9.1.1 ECOTECT Zone Geometry

The ECOTECT system allows for advanced and detailed simulation exercises, however, as previously stated, the simplicity of the program and the small amount of detailed information required to create a model make it perfectly suited to early building design analysis and for use by non-experts. In ECOTECT, the 3D geometry model is represented as a grouping of fully enclosed thermal *zones*, each representing a room or space within the building. The zone thermal calculation of each tested building was analysed and calculated separately as shown in Figures (7-15 to 7-19).

During the creation of a simulation model it is essential to be able to set and check the thermal characteristics of zones and surfaces, as well as the correct surface connections between zones. With the ECOTECT interface this is can be done, and provides a 3D visual representation of these different surface types during the data import and allows the user to ensure correct geometric definition.

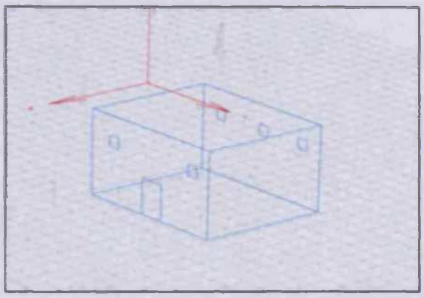


Figure (7-15) Zone Vertex in Ecotect Model.

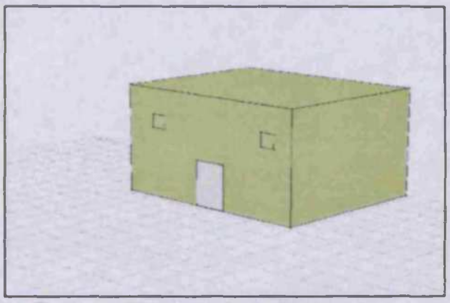


Figure (7-16) Zone Geometric in Ecotect.

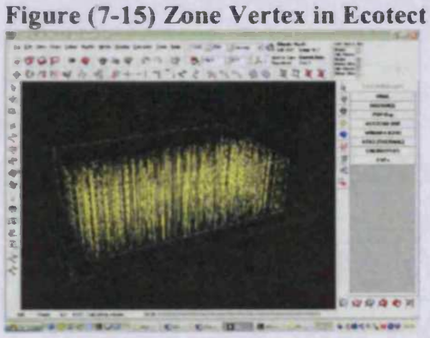


Figure (7-17) Thermal calculation of the model as it shown in Ecotect Interface.

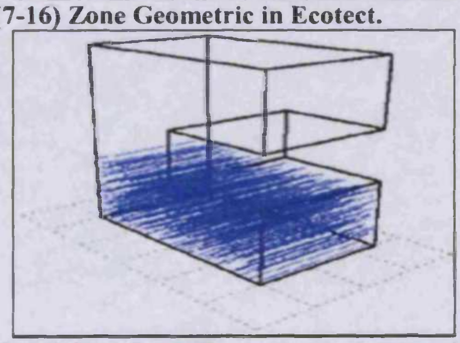


Figure (7-18) Detail of Thermal calculation of the model.

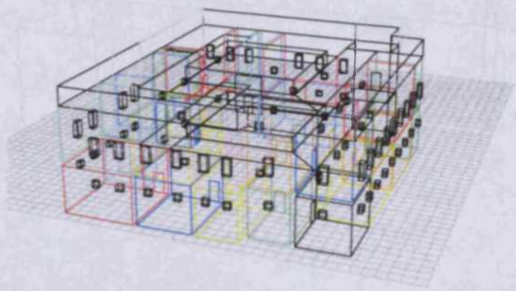


Figure (7-19) The 3D geometry model represented as a grouping of fully enclosed thermal zones.

ECOTECT contains many features that contribute to the accuracy of the modelling, like the Inter-Zonal adjacency test *"Adjacencies dialog controls the calculation of overlapping surfaces between zones and overshadowing tables for exposed surfaces"* (7-4). It also gives descriptions and controls for all components that form the model and allows the user to specify whether each zone is naturally or mechanically ventilated. *"Allows the definition of all types of elements as on or off, open or closed etc. The resulting thermal analysis using scheduling, takes into account how spaces are used, as well as the use of appliances and equipment within a space"* (7-4). Figure (7-20) shows the Model Dialog Properties in ECOTECT.

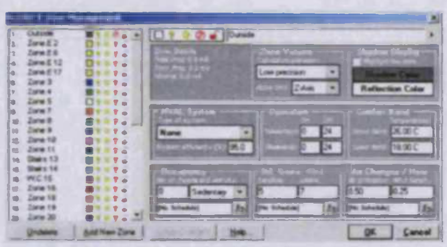


Figure (7-20) Model Dialog Properties in ECOTECT.

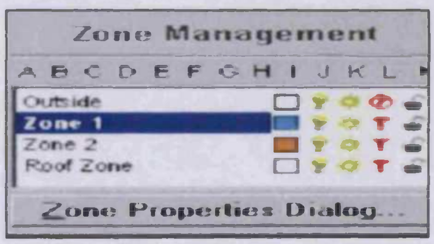


Figure (7-21) Part of zone management in ECOTECT.

The whole model of each building consists of many interconnected thermal zones. The zone management in ECOTECT as shown in Figure (7-21) above allows control of the zone condition by different images adjacent to each zone pointing to its current state, whether it is hidden/displayed, on/off, locked/unlocked, thermal /non- thermal, and its colour, the red T, controls each thermal zone. All zones have to be geometrically complete, which means that they have surfaces surrounding their full volume.

Using ECOTECT's thermal calculations, it is possible to calculate hourly internal temperatures within each zone. After this, ECOTECT can analyse the external climatic data and the internal temperatures and apply the adaptive model algorithm of Humphrey's [(7-4)] to determine comfort periods.

In order to model the effects of adjacent building units, adjacent zones were constructed in ECOTECT to be included in inter-zonal adjacency calculations. Inter-zonal adjacency calculations were also used to detect those party walls between the rooms not exposed to the outside and to provide the correct self-shading during the overshadowing calculations. Figure (7-22) shows adjacent shows of the building were constructed in ECOTECT.

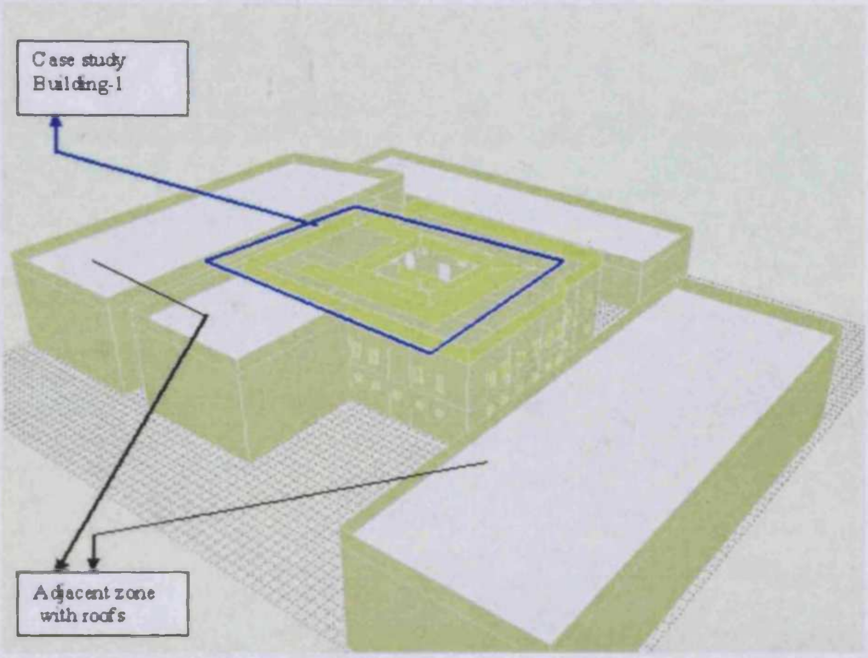


Figure (7-22) 3D model of the building-1 and the adjacent zone in Gary colour from the other dwellings in grey colour, by the author using Ecotect.

7.9.1.2 ECOTECT Modelling Requirements

In order to set up a realistic computer model, it was necessary to find and collect related information on the building such as geometry, constructions, usage, etc. The computer model of the ECOTECT building was developed on the following basis:

- Geometric information extracted from drawings,
- Physical properties were determined on the basis of detailed architectural drawings, manufacturer data and engineering handbooks.

With the help of the above sources, a detailed computer model can be set up, which represented the buildings. The following sections explain the modelling issues during the generation of the model.

7.10 Implementation of the Model

As mentioned before in section (7.9) the model geometry of the case studies first constructed to ECOTECT. This is because of the tool feature which allows the user to test the model in different tools. For this purpose the programs has facilities that allow the automatic creation of an "export file" of a model as well as its own engine. However, after the model is constructed in ECOTECT program the user moves through a number of interface windows (Figure (7-14) in section 7.9 as an example for the entire attribution process). In every window the user specifies certain model data (general construction data, local construction and window data, zone types, climate data. etc.).

After having completed the current task the user moves via the "Export" button to the next window which shows the Export Manager for the other programs (HTB2, EnergyPlus, etc). These programs check that all the data that relates to the current task has been defined and is consistent. If this is not the case it is pointed out to the user and it is not possible to move to the next task. This gives the user confidence when using the program and also ensures that only complete models are created. However, the exportation of the geometric model to different simulation advanced simulation program is not insignificant task. This due to several issues happened during exportation with other tools such as HTB2 and EnergyPlus. As a result several errors occur during geometry exportation and thermal analysis running in these tools. This is because that each tool has different requirements on the geometry they will receive, also each tool has own calculation method and limitation to create its own geometry model. This causes complex error that should be taking into account during the definition of the models. The following section illustrates these issues.

7.11 Modelling Issues

7.11.1 Zoning Issues

7.11.1.1 HTB2 Zoning Issues

In the initial export to HTB2, it would consistently crash with very high internal temperatures for one particular zone. This zone was the bottom of one of the stairwells, separated from the top by a VOID object to allow the exchange of heat and air. On experimentation it was found that just a slight increase in the volume of this zone solved the problem. This may have been due to the fact that the zone itself was long and thin, resulting in quite a high ratio of surface area to volume.

To overcome this issue when many automated exports were made, the bottom and top stairwell zones were merged into a single zone stairwell, which worked and resulted in much more reasonable temperatures. This zone was not one of those measured so is not very important, however it does show the sensitivity of different tools to the basic geometry of zones and the ratio of surface area to volume. Figures (7-23, 7-24) show stairwells of the building were constructed in ECOTECT.

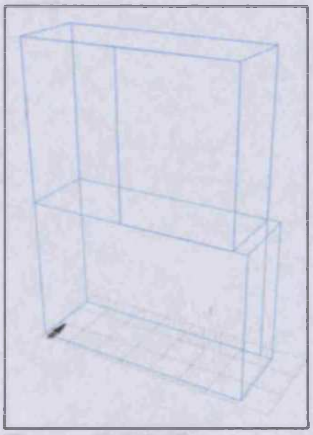


Figure (7-23) The staircase as it constructed in ECOTECT.

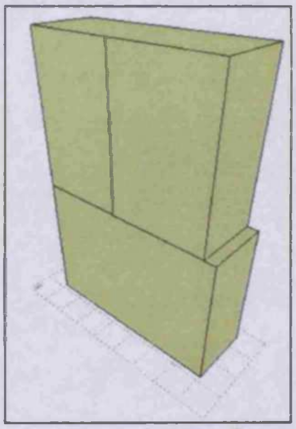


Figure (7-24) The staircase as it visuals in ECOTECT.

7.11.1.2 EnergyPlus Zoning Issues

The other complex issue within EnergyPlus tool is that its limitation on the geometry zone surfaces to be accepted. This means the entire model surfaces have to be constructed to match the requirements of this tool. Due to this limitation and to manage that the zones surfaces divided into simple liner lines to be able accepted in EnergyPlus. Figure (7-25) shows an example of one of the zones that modified to be totally compatible with other tools.

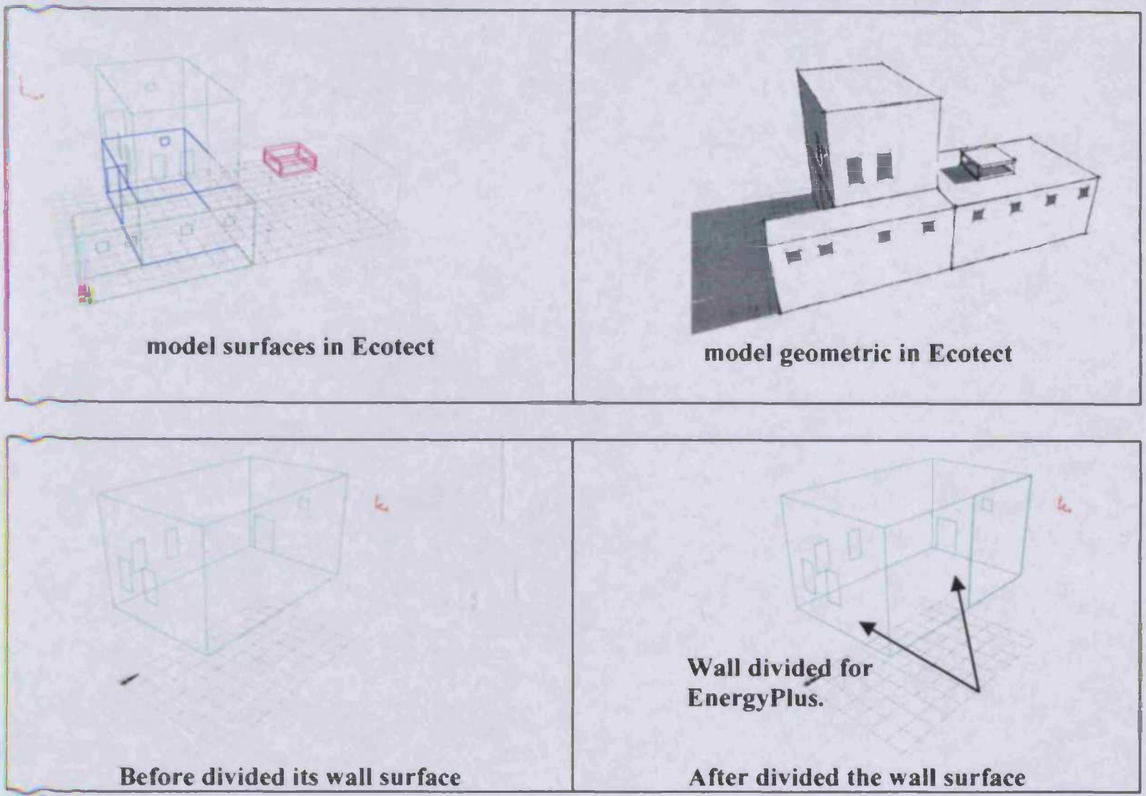


Figure (7-25) Illustration of convex non convex zones to be compatible with EnergyPlus requirements.

7-11.2 Windows Issues

7-11.2.1 Window Shape

In hot dry climates the amount of heat gain or loss within a building can be effected from the function of the area of the windows, i.e. the larger the area of the windows the greater the amount of heat gain or loss. Therefore, the form of the model, each window type and its shape are important elements that affect the overall performance of the building, so they need to be introduced to the tools accurately. The window in the case study buildings is constructed with an arch at the top, as can be seen in Figure (7-26). This shape of window can be easily modelled in ECOTECT, however, the version of EnergyPlus being used required rectangular window shapes only. Therefore, the window had to be modified in order to be exported to EnergyPlus. To do this, the arched shape had to be translated into a rectangle with the same area and the glass percentage of the real window, as shown in Figures (7-27 and 7-28). The window calculation can be found in Appendix D.

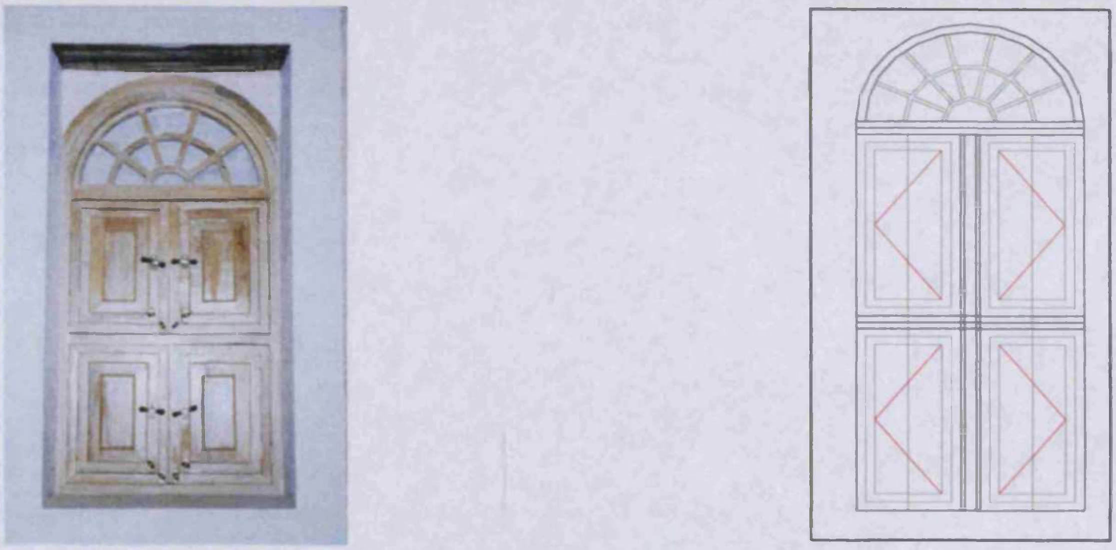


Figure (7-26) Window shape picture as it appeared in adobe building and in Cad drawing

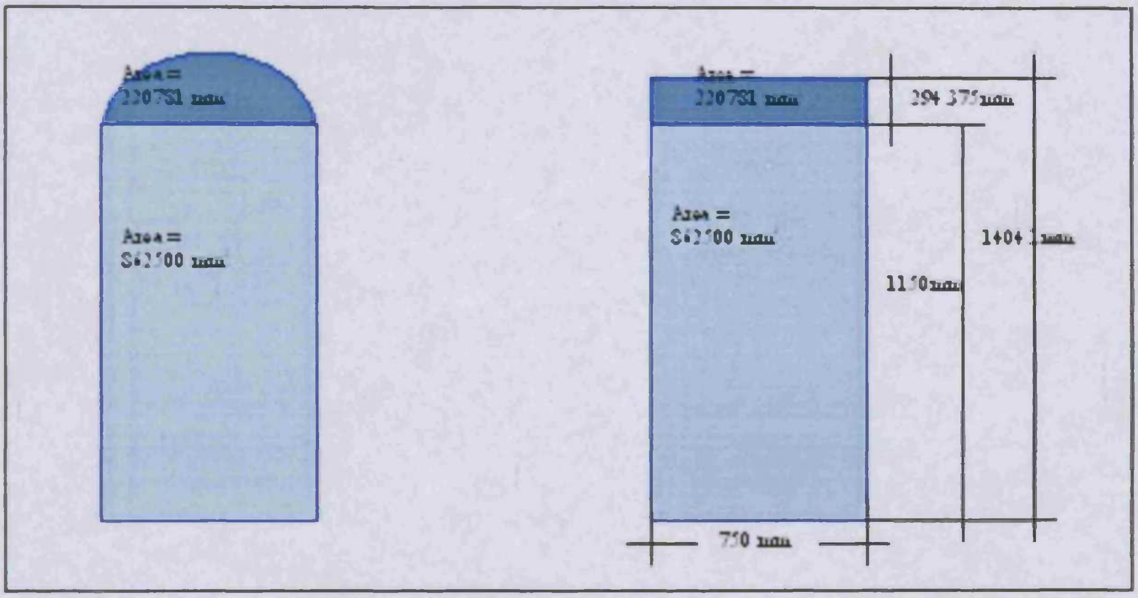


Figure (7-27) Window shape calculation modified to be abdicable with EnergyPlus and HTB2.

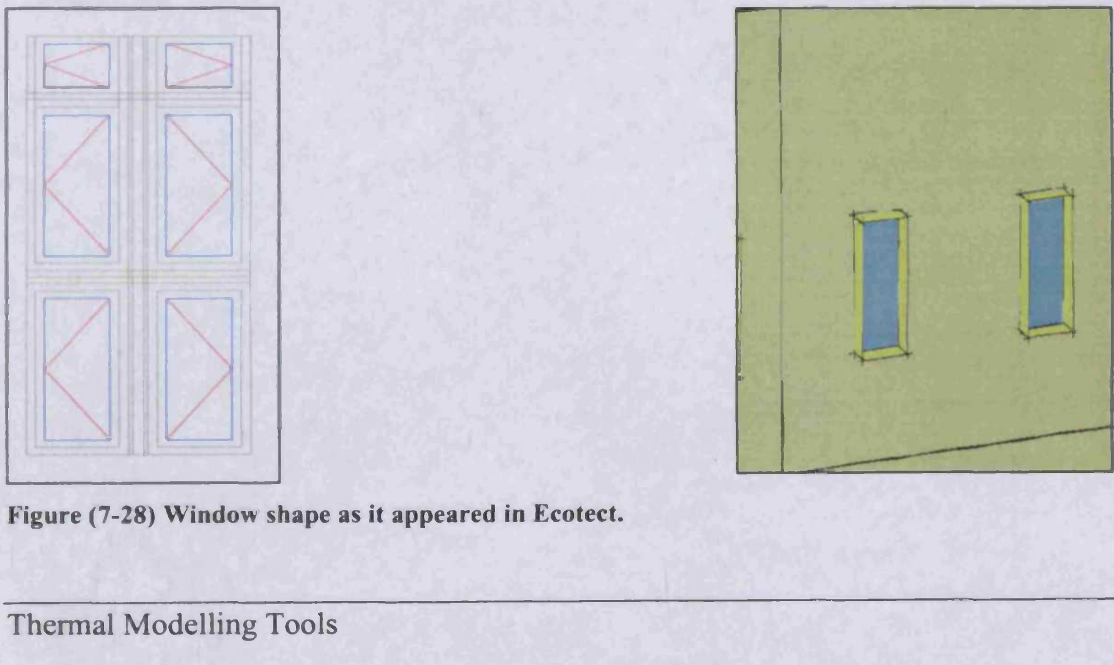


Figure (7-28) Window shape as it appeared in Ecotect.

7.11.2.2 EnergyPlus Skylights issue

Building Three included a raised skylight in two of its zones (see Figures (7-29, 7-30)). This had to be modelled carefully in order for EnergyPlus to accept it. It was created by first inserting a rectangular void in the roof of the zone, and then covering this with a simple rectangular prism structure of the same shape as the raised section. Four windows were then inserted into the vertical up-stands.

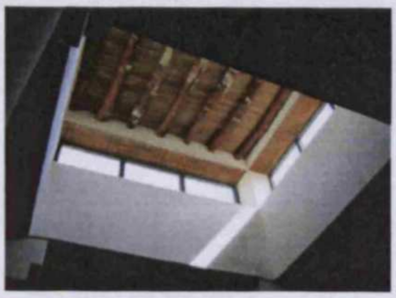



Figure (7-29) The external and internal skylight in the building.

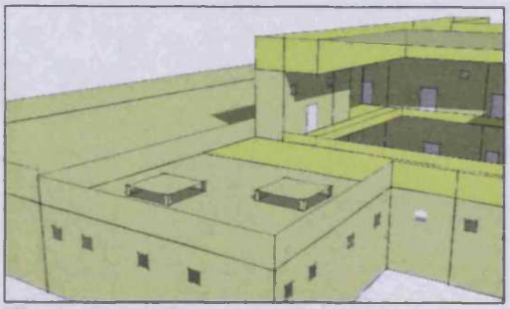
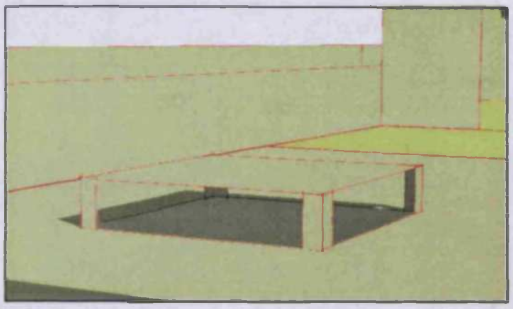
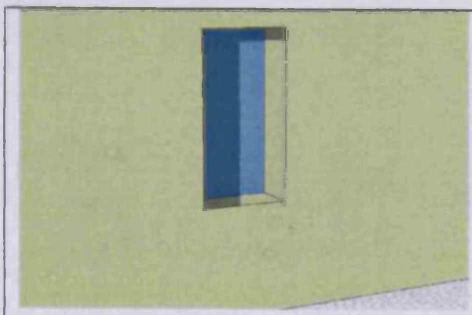



Figure (7-30) The external skylight in the model in Ecotect.

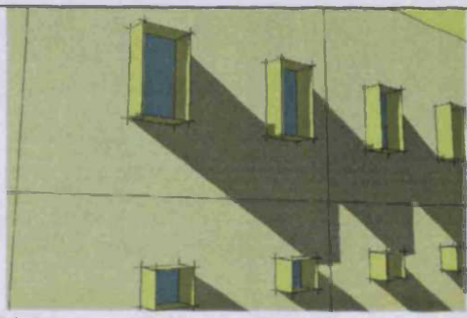
7.11.3 Wall Thickness and Windows Issues

7.11.3.1 EnergyPlus Wall Thickness

The effect of wall thickness was another issue in EnergyPlus. As the wall thickness in the case studies has the benefit of shading the window openings, this needs to be accounted for during the simulation. As all the thermal analysis tools used here use infinitely thin planar descriptions of all zone surfaces, it is necessary to model the effects of wall thickness separately. This was done by simply extruding the sides of each window by an amount equal to the thickness of the surrounding walls. The shading effect of these extruded surfaces on the window itself is equivalent to the effect of the walls. However, in doing it this way, these extruded surfaces will also have a shading effect on the walls that really isn't there, as shown in Figure (7-31) below.



Wall thickness and its shading in window by using Ecotect.



Wall thickness and its shading in window by using Ecotect.

Figure (7-31) The effect of wall thickness as drawn in Ecotect.

As ECOTECT and HTB2 use shading masks for the calculation of incident solar radiation, it was simply a matter of first calculating the shading for the windows with the extruded shades on, and then later for the walls with the shades turned off. This results in the correct shading effect within ECOTECT, which then exports the appropriate shading masks to HTB2.

EnergyPlus, however, requires that all external shading devices be defined in the geometric model, from which it calculates its own shading factors. This presented a problem in that the extruded planes would also cast shadows on the walls containing the windows. The option to avoid this was by using much higher shading co-efficient for the windows and not including the extruded planes. However, some preliminary calculations showed that the shading effect on the walls was negligible in EnergyPlus as the shaded area was moving each hour and the additional sol-air temperature effects made very little difference to overall heat flows though the wall. The decision was therefore made to include the extruded surfaces in order to more accurately model the shading on the windows, but knowing that there will be a small effect on heat flows through the walls themselves.

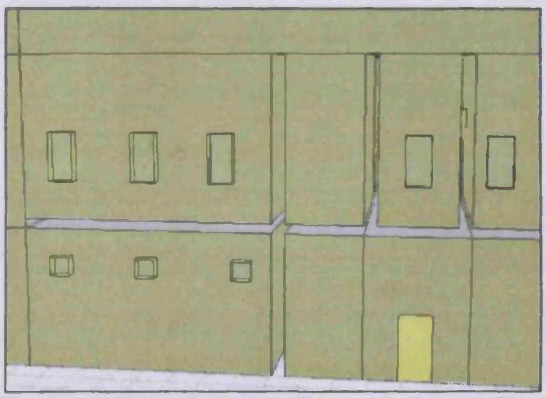


Figure (7-32) Adjacent wall issue in EnergyPlus.

7.11.4 Material Definition

In order to achieve accurate modelling prediction, the thermophysical properties of the material must be taken into account. ECOTECT software, like other tools, includes a database library of the materials used for modelling. The items in the material library are displayed in the dialogue box. This includes a display of each item's thermal properties, thus allowing the user to edit materials in both the current model and the main library. Figure (7-33) shows the Dialog Box of Ecotect library.

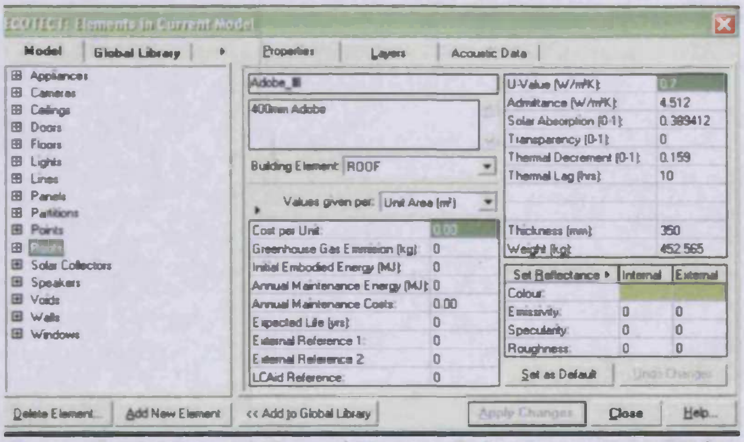


Figure (7-33) Material library displays dialog box in ECOTECT.

Accurate modelling of thermophysical properties is of prime importance in conduction heat transfer simulation. For accurate thermal calculations, however, the thermal properties of adobe as a material for walls and roofs were not available in the ECOTECT library. As these were that needed for geometric analysis, it was necessary to collect relevant information regarding the properties of the adobe materials used in the construction of the buildings in the case studies in order to improve the accuracy of the simulation. All the details of the new material properties that need to be added have to be checked carefully to ensure that they are valid.

7.11.4.1 Wall Properties

However, after a comprehensive review of available data, the researcher concluded that it would not be possible to find all the potential properties of adobe brick wall in one resource. This is due to the lack of available information and the differences in the values of the thermal properties (conductivity, density, specific heat, etc...) of the adobe material that have been collected from different references [(7-17) - (7-40)] (see the references from (7-17) to (7-40) for the material properties). Therefore, due to these differences in all collected references the decision has been made to classify the collected properties for the wall into three groups as average values, maximum values and minimum values, to be introduced to ECOTECT for the walls of the buildings.

Each one of these groups will be modelled separately in each building and then exported using ECOTECT's feature to be simulated in all above mentioned programs in order to achieve as accurate as possible a picture of the properties of the materials. This will allow the thermal properties data to be used at the earliest possible stage in the simulation process when uncertainties are greatest. Additionally, by identifying all the sources of uncertainty, systematic sources can be removed from the model description. The classified groups of the physical properties of the material used in the computer model of the ECOTECT building can be found in Tables (7-2) and in Appendix D.

Table (7-2) Thermal Properties of the Base case.

Fabric Elements of the Base case						
1	**External wall**	- 400 mm Adobe Sun Dried Brick. - 30mm Mud Plaster.				
		U-Val	Adm.	T lag		
Max		1.1	5.167	12		
Ave		0.9	4.8395	11		
Min		0.7	4.512	10		
2	**Internal wall**	- 400 mm Adobe Sun Dried Brick. - 30mm Mud Plaster.				
		U-Val	Adm.	T lag		
Max		1.1	5.167	12		
Ave		0.9	4.8395	11		
Min		0.7	4.512	10		
3	**Roof**					
		U-Val.	Adm.	T lag		
Max		1.205	5.167	11		
Ave		1.182	4.8395	10		
Min		1.141	4.512	9		
4	**Glazing for Windows and Skylight**	**Normal**				
		6mm clear float glass with timber frame				
		U-Val.	Adm.	Sh.c	Trans	R. idex.
		5.1	5	0.94	0.92	1.74
5	**Door**	**Normal**				
		U-Val	Adm.	Time lag		
		2.31	3.54	0.4		
6	**Wall Colour**	**light**				
		Brown				
7	**Roof Colour**	**light**				
		Brown				

However, the groups have been introduced to be modelled in ECOTECT separately to find out if there is any difference between their properties. After several runs for the three groups, it was found that the three models have no differences. Therefore, the decision was made to use the average properties group to be introduced to the other simulation tools.

7.11.4.2 Roof Properties

Also, the thermal properties of earth roof buildings need to be introduced to the material library of the ECOTECT program.

However, it has been seen from the literature reviews, that the thermal properties of earth roof buildings are not well known due to the differences in the roof type construction and the variation in the value of the thermal properties of the elements used in construction. The variations among different research results also limited their applications. Thus, the thermal properties of each layer of the traditional house roof needs to be calculated in order to achieve the requirements of simulation. The advantage of calculating the thermal property values of the roof is that they allow for more realistic and accurate assessment of thermal performance.

The roof is constructed from multi layered materials that comprise *Athel* (tamarisk) trunk topped with a layer of palm fronds, carrying a layer of adobe roof covering and a soil stabilized layer, as seen in Figure (7-34).

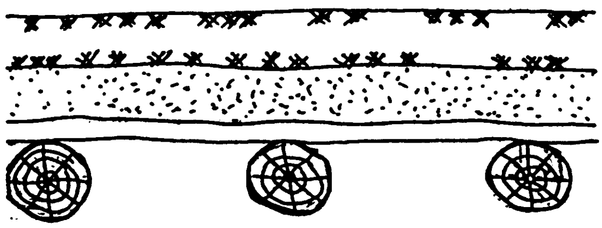


Figure (7-34) Traditional roof construction in the adobe building, drawing by author.

The materials, however, are evaluated for thermal performance based on measurements known as the thermal resistance (R) and the thermal conductance (K) values. Therefore, thermal conductivity values (K) for each material needs to be obtained in order to calculate the thermal resistance of heat for both layers.

The value of thermal transmittance (U) can be calculated as a reciprocal sum of all the respective thermal resistances (R) of the component materials and the internal and external surfaces resistances as seen in the following equation:

$$U = \frac{1}{Rn + R_1 + R_2 + R_3 + \ldots Rm}$$

Where:
U= thermal transmittance in w/m^2k.
Rn= thermal resistance of internal surface in m^2k/w.
Rm= thermal resistance of external surface in m^2k/w.

Due to the type of roof construction, the calculation of the heat transference through the roof layers is divided into sections, which are **A** and **B** as seen in Figures (7-35, 7-36). The first calculation is for heat transference from the wood trunk into other layers in section **A** and the second is through the layers in section **B** of the roof layers. The calculation will be made for each section individually, and then the total sum of the thermal transmittance (**U**) values for both sections will be introduced to the geometric model.

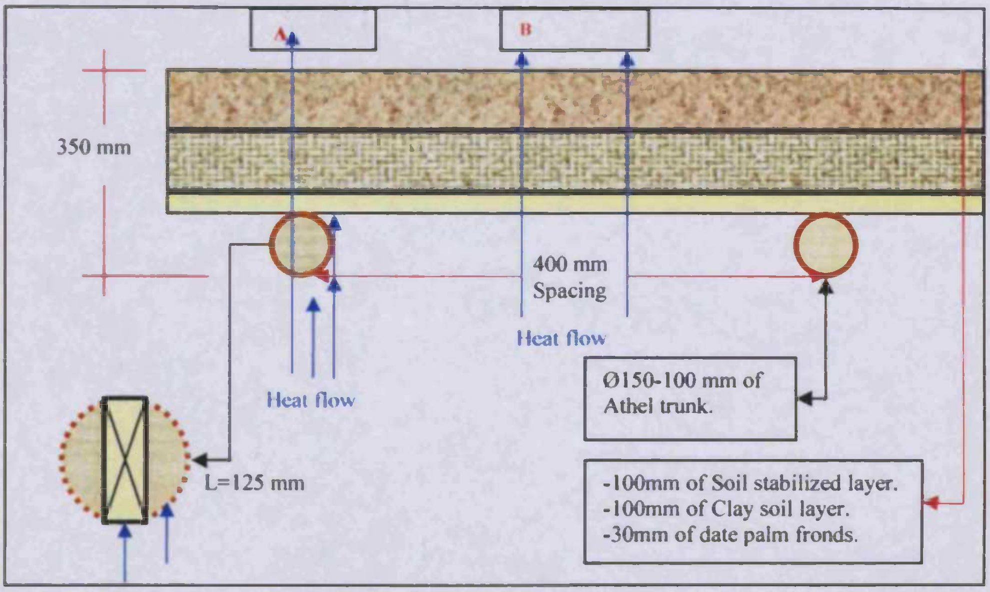


Figure (7-35) Conceptual diagram of heat flow (U-value) through adobe roof section.

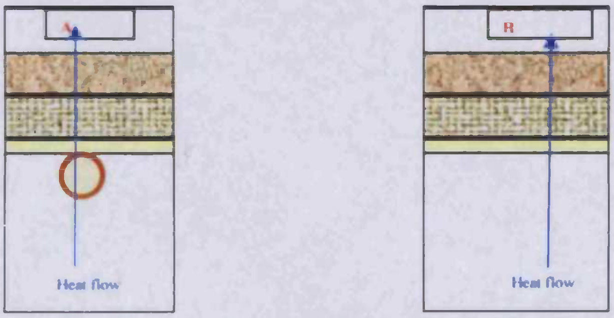


Figure (7-36) Heat flow (U-value) for both sections in A and B.

Various sources dealing with different qualities of wood and building resources generally were investigated in order to establish the thermal conductivity value of the *Athel* tree trunk species as it called in Arabic, or as it called in Latin, *Tamarix aphylla*. Unfortunately, it has not been possible to find the thermal properties for the same species among the many different species of wood, as these are not identified in the literature available. Therefore, the decision was made to use the thermal conductivity values of the hardwood to calculate the thermal properties of tree trunks used for roofing. The same was done for the layer of palm tree fronds that compare with the plywood thermal properties values.

It was found in the literature that most values of thermal conductivity for different types of wood lie within the range from approximately 0.16 W/m°C (7-41, 7-42), and the thermal conductivity of plywood made from most timbers is within the range of approximately 0.102 W/m°C (7-43, 7-44).

Thus, the (K) value for the 125mm *Athel* trunk that compares with hardwood value that has been chosen is approximately 0.16 W/m°C, and the (K) value for plywood is approximately 0.102. W/m°C has been chosen for the 30mm palm tree fronds that were used to calculate the thermal transmittance. The thermal transmittance calculation for the traditional adobe roof is illustrated in Appendix D.

The calculation result of the roof layers shows three values of the thermal transmittance. Like the wall, these values are classified into three groups as an average, maximum and minimum. Each group has been introduced to be modelled in ECOTECT separately. The result after several runs for the three groups shows that the three models have no differences. Thus, the choice was made to use the average properties group to be used in the modelling. The values of the roof properties can be found in Table (7-2).

7.11.4.3 Roof layers issue

On initial export, both HTB2 and EnergyPlus reported an error in the roof material as it used an air layer (in this case the equivalent of studwork) as an internal surface. In ECOTECT this was done to accurately model the effect of the *Athel* trunks supporting the roof. As these are spaced approximately 350-400mm apart, these trunks do act as an air layer (see Figures 7-37 to 7-39), however it was not possible to export this directly.

To overcome this technical issue, the roof layers were altered by taking out the trunks and adding their average thickness as a sheet to be recognised in HTB2 and EnergyPlus as a solid internal surface layer, as can be seen in Figure (7-40, 7-41).

Figure (7-37) The wood trunk carries the roof layer as it constructed in the case studies.

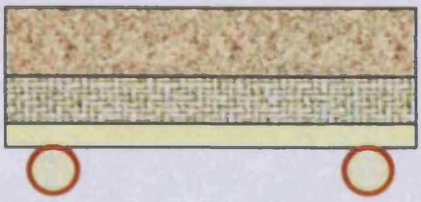


Figure (7-38) The wood trunk carries the roof layer as it constructed in the case studies.

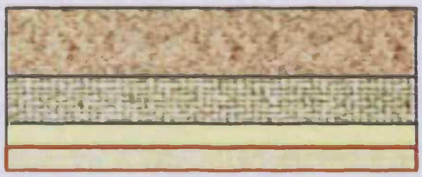


Figure (7-39) The trunk after modified to be accepted in HTB2 the roof layers.

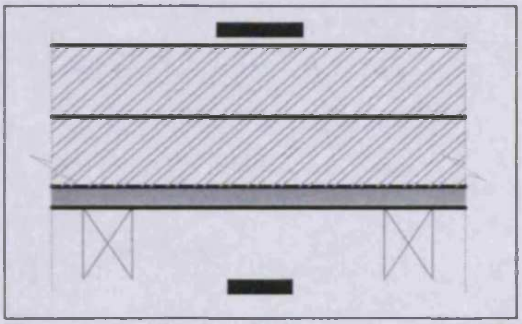


Figure (7-40) Roof layer in ECOTECT material library.

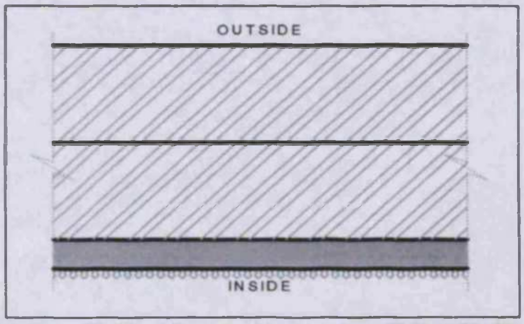


Figure (7-41) Roof layer in ECOTECT material library after changed to be compatible with HTB2.

7.12 ECOTECT Siting

It is should be noted here that the buildings were not occupied during the real experiment, thus the zones of three buildings are set to be occupied by one person which does not effect real measured data conditions. Also, the artificial lighting was turned off during the data recording to avoid any heat that may have an effect on the data logger. The artificial lighting simulation was performed to be turned off. The zone air change rate was set to 0.1 inside the measured rooms to be compatible with the same condition of the measured buildings since the windows and door were kept closed. The climatic data of the site obtained for the whole year and introduced to the climatic tools of ECOTECT to be matched the weather climate of the actual measured data.

Whilst significant effort was spent on the material data, the occupancy and ventilation sitings in the building are to be the subject of a detailed sensitivity analysis so their actual values are not important at this stage. However, in order to compare overall trends in temperature data, the following settings were used:

- All the occupants of the buildings are set to be doing sedentary work (70wattes/m^2). But we assumed no occupancy.
- The upper and the lower limits of the comfort band are 26 °C and 18 °C respectively.
- The zone volume calculation accuracy was set to be low since the forms of the modelled zones are rectangular and square shapes.
- The zone air change rate was set to 0.5 ach and wind sensitivity is 0.1 ach.
- Since there were no equipments and the lighting is likely to be turned off most of the time, in each zone a general level of sensible and the latent heat gains of 5 Watts/m^2 was used.

Once the model is established in ECOTECT, ECOTECT has the capability to display the performance results from the different simulation tools used to model the adobe buildings, as discussed in the next sections.

7.13 Visual Building Model

After model definition in ECOTECT, a variety of significantly different approaches can be taken when using ECOTECT as simulation tool to analyse and potentially improve the performance of a building. The following sections show the analysis of shading and the annual and daily sun path of the case studies buildings that can be obtained from the tool.

7.13.1 Case study 1

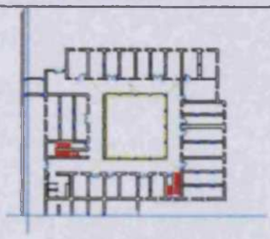
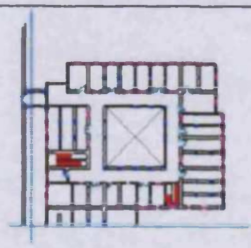
Building-1	
Ground Floor	First Floor
	

Figure (7-42) Case study one plans.

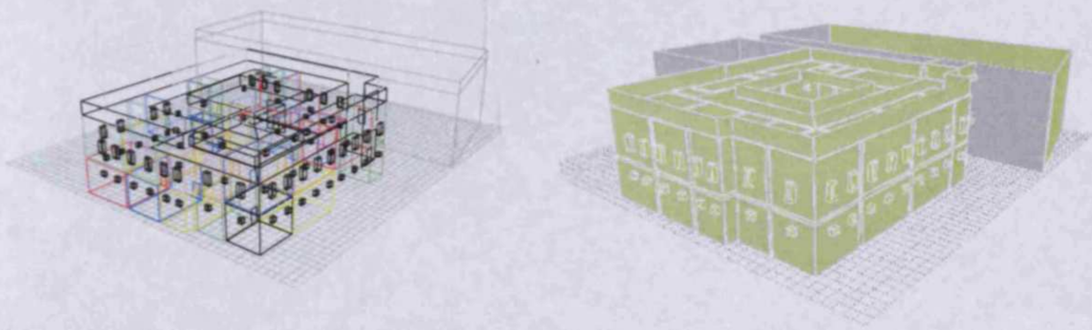


Figure (7-43) The geometry of the simulation model, by the author using Ecotect.

Figure (7-44) The external view of Building One by ECOTEC.

Table (7-3) Zone Summary of Building One obtained by using ECOTECT.

Building 1 Zone Summary					
Zone Name	**Floor Area (m²)**	**Surface Area (m²)**	**Exposed Area (m²)**	**Window Area (m²)**	**Volume (m³)**
Zone. E 2	838.68	4846.33	2147.02	48.26	136.23
Zone. E 6	36.77	195.51	77.37	1.8	178.53
Zone. E 12	22.47	137.91	26.68	0.36	108.97
Zone. E 17	36.98	200.66	94.14	2.65	191.54
Zone 3	36.98	192.59	53.32	1.08	179.34
Zone 4	24.94	149.27	43.63	0.36	120.97
Zone 5	25.81	150.6	50.24	1.08	117.43
Zone 7	36.77	195.52	77.37	1.8	178.53
Zone 8	16.42	112.14	56.87	0.72	79.63
Zone 9	54.6	253.33	111.89	1.8	264.8
Zone 10	31.86	179.73	63.8	1.44	154.71
Zone 11	10.62	86.09	12.61	0	51.51
Stairs 13	16.46	108.43	59.72	0	4.7
Stairs 14	11.25	88.84	26.93	0.36	54.62
W.C 15	17.57	116.47	40.67	0	85.19
Zone 16	44.68	219.06	77.04	1.44	216.72
Zone 18	28.09	169.25	77.5	2.65	145.49
Zone 19	24.94	155.9	71.25	1.15	129.2
Zone 20	25.81	157.34	79.43	3.44	133.68
Zone 21	36.77	203.81	119.13	4.16	190.46
Zone 22	36.77	203.81	119.13	4.16	190.46
Zone 23	16.42	117.53	77.66	1.15	85.05
Zone 24	54.6	263.14	174.1	4.16	282.81
Zone 25	9.07	80.55	48.95	1.15	46.97
Zone 26	31.86	189.15	101.53	3.01	165.23
Zone 27	40.03	221.84	94.58	2.66	207.37
Zone 28	10.62	90.5	24.09	0	55.02
Stairs 29	15.53	124.14	73.88	0	80.61
Stairs 30	11.23	93.28	39.72	0	58.19
Zone 31	44.68	227.88	127.27	4.59	231.46
Shade	0	801.84	109.67	0	0
OpenGL Views	0	376.17	332658.4	0	36.17
Wall. Thickness	0	95.33	0	0	0
Neighbour-W	748.17	2940.71	2940.71	0	0
Neighbour-S	424.78	1164.77	9235.56	0	0
Neighbour-N	667.27	1551.73	1551.73	0	0
Neighbour-E	851.53	3960.85	3960.85	0	0
TOTAL	4369.1	20584.07	354751	96.52	4161.6

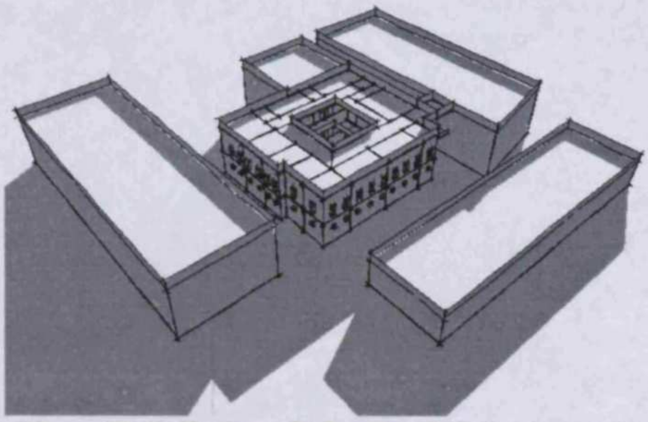


Figure (7-45) Shading effect on the building surfaces.

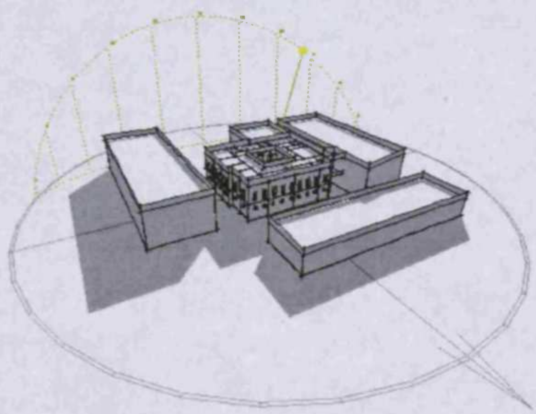


Figure (7-46) Daily Sun Path on the 6th of January at 14: 45 by using Ecotect.

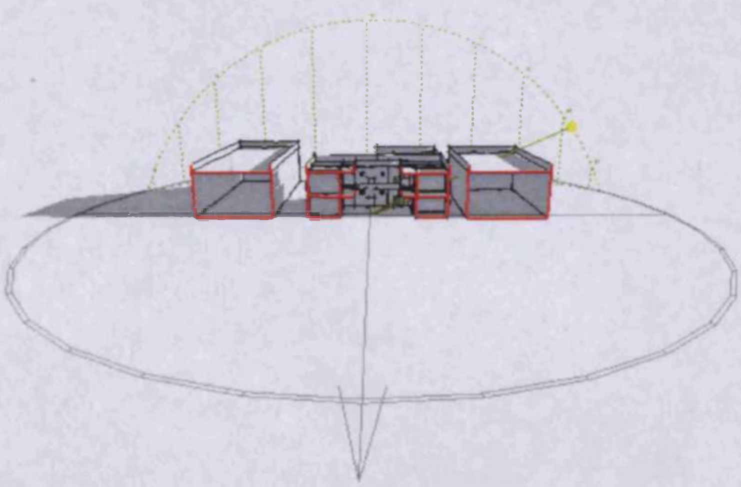


Figure (7-47) Different view for the Daily Sun Path.

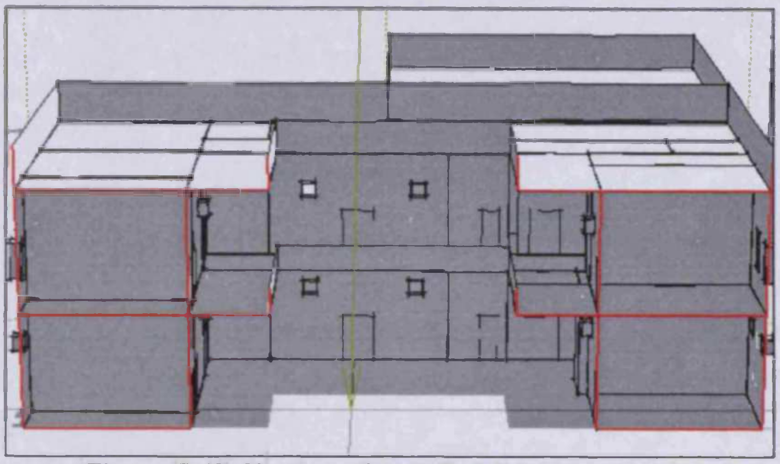


Figure (7-48) Shading effect in Building's courtyard.

7.13.2 Case study 2

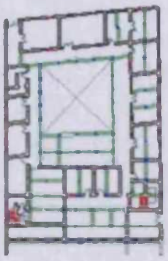
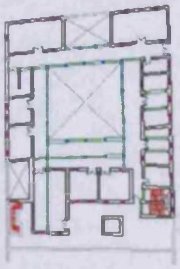
Building-2	
Ground Floor	First Floor
	

Figure (7-49) Case study-2 floor plans.

Figure (7-50) Zoning and building-2 form, by the author using Ecotect.

Figure (7-51) Modelling of Building Two, North Side by the author using

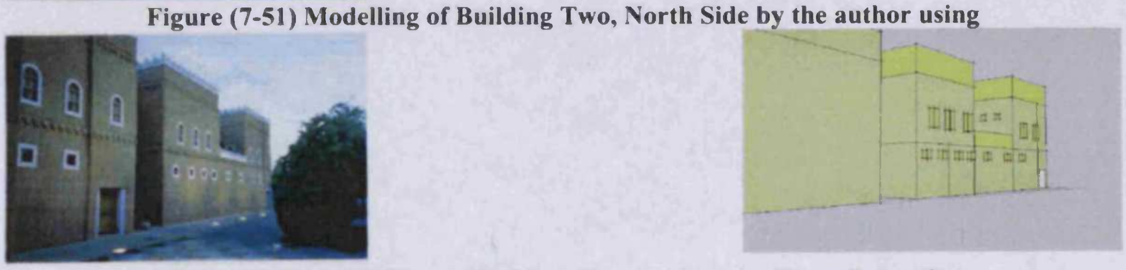


Figure (7-52) Modelling of Building One and Two by the author using

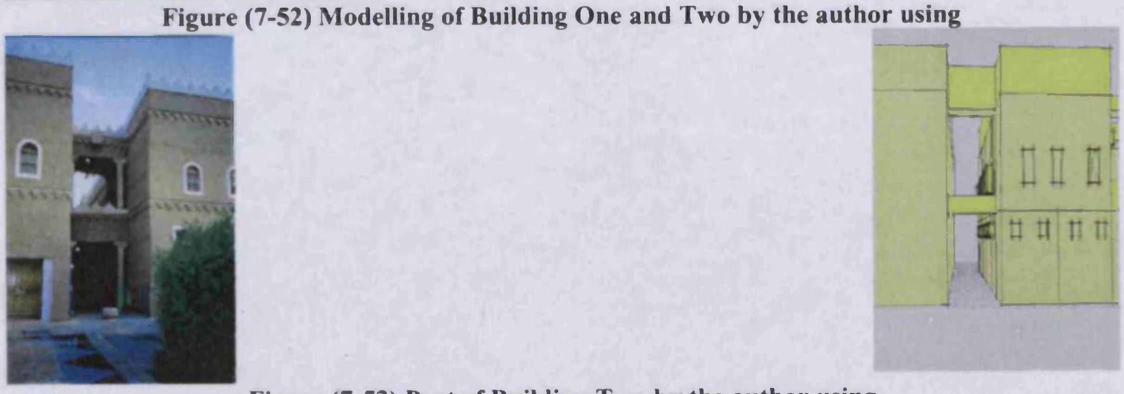


Figure (7-53) Part of Building Two by the author using

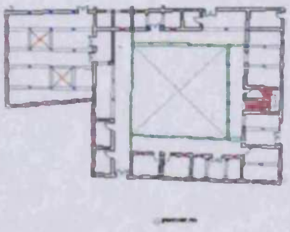
Table (7-4) Zone Summary of Building Two obtained by using ECOTECT.

Building 2 Zone Summary					
Zone Name	Floor Area (m^2)	Surface Area (m^2)	Exposed Area (m^2)	Window Area (m^2)	Volume (m^3)
B2GFN2	39.4	189.35	106.41	1.44	169.57
B2GFN3	26.6	143.39	53.19	1.08	114.74
B2GFW1	18.26	113.32	49.24	0.72	78.18
B2FFE3	26.6	166.47	93.2	3.8	144.1
B2FFNE	43.08	232.79	189.71	4.88	232.11
B2FFNW	32.01	193.82	161.81	3.74	172.97
B2FFE1	11.49	98.47	64.24	1.51	61.84
B2GFN1	32.01	162.08	76.28	1.08	137.31
B2FGN3	21.09	121.71	36.17	0.72	89.82
B2GFNE	21.99	125.06	40.7	0.72	94.72
B2GFE1	23.51	131.07	60.2	1.08	99.87
B2GFE2	37.44	186.76	74.97	1.8	159.65
B2GFN4	15.01	97.05	29.93	0.36	64.57
East Entrance	28.43	148.68	79.74	0.72	122.46
B2GFS1	21.25	122.05	59.83	0.72	91.38
B2GFW2	14.56	95.89	39.13	0.72	62.39
Stairs W	15.87	206.19	159.14	0	153.38
W.C	23.76	136.98	78.57	1.08	102.12
B2GFS2	22.62	127.14	21.93	0.72	97.26
B2FFW1	18.26	132.97	97.35	2.3	98.02
B2FFS1	19.55	134.68	90.46	2.65	105.69
B2FFS2	20.81	140.16	69.99	2.65	112.49
B2FFW2	14.56	112.97	63.86	2.29	78.35
B2GFS5	69.59	284.95	144.41	7.24	300.47
B2GFS6	21.91	145.92	88.47	1.44	94.31
B2FFS3	58.08	285.5	202.9	4.95	313.63
B2FFS5	15.01	114.19	52.76	1.15	81.09
Stairs Gd-East	20.56	119.21	41.14	0.36	88.59
Stairs F. Floor	20.56	139.18	95.65	2.29	111.26
B2GFS4	58.08	251.01	46.66	0.36	249.75
B2FGER	37.44	215.37	131.34	4.16	200.49
TOTAL	849.41	4874.37	2599.4	58.74	4082.6

7.13.3 Case study 3

Building-3

Ground Floor First Floor



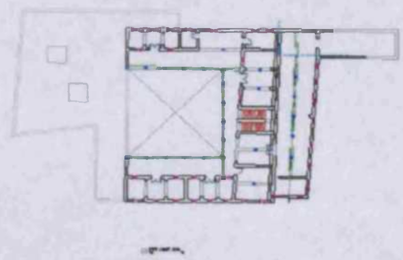
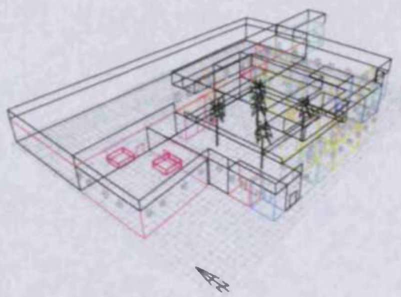


Figure (7-54) Floor Plans for building-3.



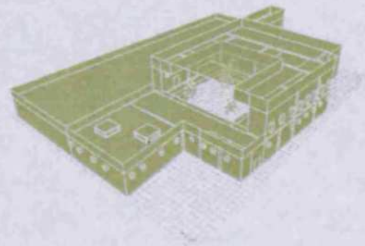


Figure (7-55) The 3D model of building-1 showed the different thermal zones, by the author using Ecotect.

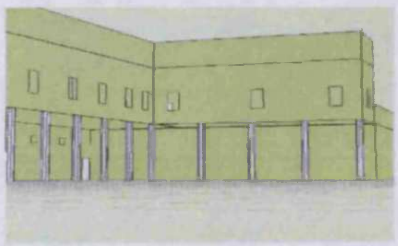


Figure (7-56) Ecotect visual image for Building Three Main Elevation, by the author using Ecotect.

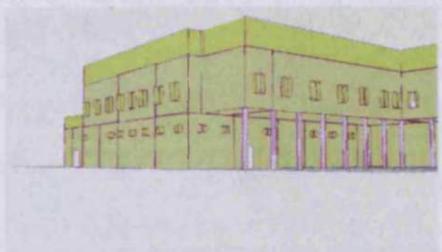
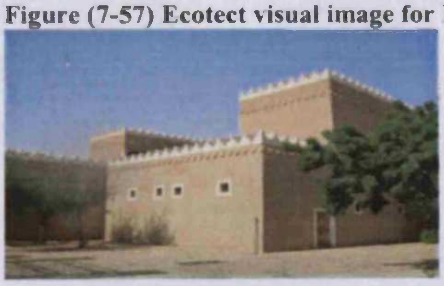


Figure (7-57) Ecotect visual image for Building Three, East side, by the author using Ecotect.



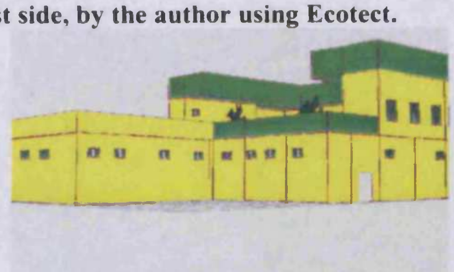


Figure (7-58) Ecotect visual image for Building Three, West side, by the author using Ecotect.

Table (7-5) Zone Summary of Building Three obtained by using ECOTECT

Building 3 Zone Summary					
Zone Name	Floor Area (m^2)	Surface Area (m^2)	Exposed Area (m^2)	Window Area (m^2)	Volume (m^3)
B3FFSW.M	26.82	166.46	124.93	4.16	129.57
B3FFE	41.15	210.8	123.85	0.36	197.52
WC.GF	13.66	97.87	55.99	0.72	64.05
WC.GF	13.17	95.44	39.95	0.72	62.01
B3GFSE	24.48	144.02	80.81	1.44	114.71
Stairs	18.09	117	58	0	84.65
Electric R	6.52	61.11	37.12	0	30.61
B3GFN	16.04	118.4	75.08	0.72	70.63
B3GFW1	9.69	80.16	59.28	0.72	45.89
B3GFSW	8.74	74.32	54.55	0.36	40.9
B3GFW	161.81	581.39	422.43	11.68	749.84
B3GFNE,Electric	11.84	91.46	45.68	0	55.46
B3FFN	16.04	120.24	92.72	4.16	77.05
B3FFN1	6.52	62.13	44.26	1.15	31.27
B3FFNE	11.75	92.52	58.21	2.3	56.32
Stairs. FF	18.09	118.71	77.32	0	86.45
B3FFNE	24.61	146.49	107.01	2.29	117.37
B3FFS	22.61	145.02	93.14	4.16	108.25
Hanging Rooml	125.82	511.76	511.6	9.18	607.34
Hanging Room2	15.29	109.9	109.9	1.15	73.09
Hanging 3	50.28	259	258.84	5.74	242.48
TOTAL	706.78	3755.26	2680.53	53.89	

7.14 Computational Fluid Dynamics (CFD) Tools

The CFD tool is needed in order to analysis the potential for ventilation in the case study buildings. The computer tools that simulate airflow in building are based on concept of computational fluid dynamics (CFD). The next section will describe briefly the use a CFD computer program, WinAir4, to simulate natural ventilation conditions in the case studies buildings.

7.14.1 WinAir4

WinAir4 is a computational fluid dynamics solver developed by Prof. Phil Jones and Don Alexander at the Welsh School of Architecture. It is based on a standard finite volume approach using the Navier-Stokes equations to solve fluid flow problems and is used primarily for research and demonstration purposes within the School.

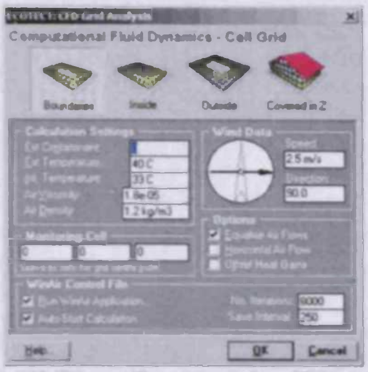


Figure (7-59) The cell-grid of the CFD in Ecotect.

It was used in this work to test the concept of using natural cross-ventilation to achieve air movement within both the courtyard and its surrounding spaces if apertures were left open under a range of wind conditions. It was also used to test the ability to generate pools of cooled air beneath the vegetation in the courtyard under very low wind conditions on a hot day.

The ECOTECT software can export models directly in the native file format for WinAir4 so it was relatively easy to generate the analysis base. Boundary conditions were based on thermal analysis results generated in ECOTECT and HTB2 for each element in the model and the corresponding external environmental conditions.

7.15 Conclusion

This chapter has briefly described the programs that will be used in this research for modelling. It concludes that there is a need to use thermal simulation models rather than simplified options to improve and understand the performance and the design of buildings and different passive energy conservation techniques that are used in hot arid areas. Also it explained that using the programs ECOTECT, HTB2 and EnergyPlus to predict outcomes will help to create an understanding of how heat is transferred between buildings and the exterior environment. The next chapter will compare the simulated results and their reliability within the main experiment of the mud buildings as well as comparing the tools result themselves. It also will include the sensitivity analysis of all parametric and measure their impact in the selected buildings.

CHAPTER EIGHT

POTENTIAL PASSIVE STRATEGIES

The exact nature of this relationship is not particularly important as it is likely to vary significantly with other factors, however it clearly illustrates how the author believes that there exists some threshold above which savings are only possible by increasing the efficiency of the air conditioning or air-cooling systems. If internal conditions can be reduced below this threshold, then greater savings are possible by completely eliminating the need for the air conditioning. However, as outdoor air temperatures regularly reach 50°C in summer, lowering indoor temperatures below this threshold by passive means alone is going to be quite difficult. The aim therefore is still to reduce internal air temperatures as much a possible using passive means, as this will at least reduce the times when air-conditioning is required and, when it is on, reduce the overall loads that it must meet. This, in combination with education of building users in both the adoption of alternative strategies for the provision of cooling other than the use of air-conditioning, and greater tolerance of short transitory periods of discomfort, will have the greatest energy saving potential in these buildings.

Thus, the work in this Chapter is focussed on two major aims:

- To reduce internal air temperatures as much as possible, and
- To reduce internal space gains as much as possible.

Therefore the metrics used to measure the effectiveness of the proposed passive strategies will be their effect on peak average air temperatures and total internal gains within each building zone.

8.3 Identifying Sources of Heat Gains and Losses

In order to determine the exact sources of heat losses and heat gains in each zone of the model, it is possible to view the contributions of different components within a coloured chart. This can be done using the thermal models described in Chapter 7 directly within ECOTECT and for the other analysis tools using the DataManager plug-in. Load breakdown calculations were performed for all spaces and are included as Appendix E. Some example graphs are shown in Figure (8-2) below for Zone E.2 of Building One to demonstrate the insight they provide.

As ground effects in some zones are so important, strategies to maintain these as much as possible will then be examined. This will be followed by consideration of conduction through the building fabric, which will also include indirect solar effects as these eventually manifest as conduction gains as well. Finally the effects of shading will be examined, however it is clear that direct solar gains form only a very small component of overall gains.

8.4 Passive Strategies (Climate Modification)

Prior to the electrically powered air-conditioning system, inhabitants of this region only had passive cooling systems to rely upon for maintaining their comfort throughout the heat of summer. Thus, it must be possible to provide at least tolerable conditions, even if 'comfortable' cannot be achieved. Thus, the analysis and possible application of passive cooling in these buildings is important even if air-conditioning is used as their effect will be to reduce overall energy consumption by either reducing the total time AC systems will be run or the instantaneous loads to which each zone is subjected.

Passive cooling techniques use no external or auxiliary energy to function, relying solely on the ambient energies already within the system being utilised. Thus the natural buoyancy of warm air, the evaporation of moisture and the capacitive effects of thermal mass all feature strongly in passive systems. Of course the most effective method to cool a building is to keep the unwanted heat from entering it in the first place, which is most important in the case of ventilation and infiltration gains.

8.4.1 Natural Ventilation

As the major source of heat gains in the zones displayed above, reducing the ventilation rate during the day will help to reduce heat build up inside. However, being a hot dry climate, temperatures become much more moderate at night so it is also important to make effective use of this variation in diurnal range by increasing the ventilation rate at times when outside conditions are most favourable. This dual requirement can lead to design problems, constructing a well sealed building during the day but one that can open up as much as possible at night.

The idea of minimising ventilation during the day and maximising it at night obviously assumes that the ventilating air is at the same temperature as the outside air. However, if this air can be significantly cooled by passive means before it actually enters the building, then day-time ventilation may actually be desirable. In the context of the approach taken here, any cooled inlet air will be provided by controlled systems such as a wind-catcher, solar chimneys or passive downdraught evaporative cooling system. The need to effectively seal uncontrolled ventilation and infiltration pathways is still important in any such system configuration. Thus, this section will look first at the means of limiting unwanted ventilation, and then at techniques for controlling and cooling ventilating air.

8.4.1.1 Limiting Unwanted Ventilation and Infiltration

In addition to heat losses and gains through the material of the building, one must also consider the energy content of outside air that passes through openings in the building envelope. Such openings might be doors or windows that are not tightly sealed, or even gaps and cracks in the construction itself. This leakage of air can often reduce the comfort of occupants if it us uncontrolled and may also affect indoor air quality by allowing in dust and noise. In addition, this air leakage accounts for between 25 and 40 percent of energy used for cooling in a typical residence (8-1). Therefore tighter building construction can improve energy efficiency and offer increased air quality and comfort by significantly reducing this unwanted ventilation and air infiltration.

This can be achieved using available technologies such as house wraps, sealants, foams, and tapes to reduce the overall level of air leakage in the building. These tools can seal the cracks and gaps in door and window framing, along with those created when installing equipment and electrical wiring. Also, using some applied surface treatments to porous materials in the building can prevent some of the infiltration that occurs through the fabric itself.

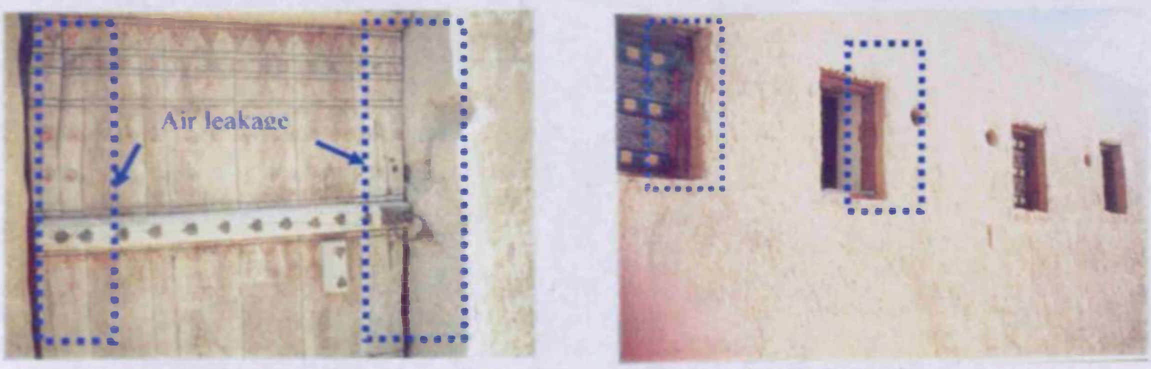


Figure (8-5) Infiltration in door and window. Photo by author

carefully sized, with openings on upper and lower floors reflecting the occupancy patterns and the activities carried out in each space.

In traditional Saudi culture, spaces on the upper floors tended to be bedrooms and occupied only at nights whereas ground floor spaces were inhabited more during the day. This suggests that there should be differences between the openings of spaces on different floors.

A literal interpretation of this would be to use significantly larger opening on the upper floors compared with lower floors. However, modern usage patterns are likely to make this more complicated. For example, in some families, teenagers tend to accumulate entertainment systems and computers in their bedrooms, leading to occupancy of this space during the day as well. Thus the idea should really be to design in the *potential* for more ventilation by using larger opening areas but providing adequate means of control to facilitate some use during the day.

If the outside air can be moderated in some way, then it may be desirable to actually induce ventilation on a still night or even during the day. Several strategies exist to achieve this, however their effectiveness is directly dependant on the mechanism used to cool the air prior to entry into the space. Thus, these strategies will be discussed in detail later in this Chapter in the sections covering evaporative cooling techniques.

8.4.1.3 The Effectiveness of Ventilation

Evaluating the effectiveness of natural ventilation using simulation programs can be quite complex. The simplest approach is to dynamically alter the air change rate of each zone, exchanging more or less outside air at different times of the day within the calculation. For un-moderated outside air this can be reasonably accurate, assuming that variations in selected air change rates are realistic. However, for moderated outside air, which first passes through vegetation or over a pond for example, the degree of cooling must first be calculated. This can be a very complex calculation based on the speed of the air, the surface area of exposed leaf and the transpiration rate under the current conditions, all of which are difficult to define or obtain information on. Even if exact information could be obtained for the specific trees used, the calculation would also depend upon the dynamic effects of wind direction and speed and the microclimatological effects of the surrounding buildings and site conditions. The effect of evaporatively cooled inlet air will be discussed later in this Chapter.

8.4.2 Internal Gains

The internal heat gains appear as the second most significant source of heat in the spaces as displayed in Figure (8-4). Internal heat gain, sometimes called casual gain, is that heat which comes from sources inside of the house given off by occupants, lighting, refrigeration, cooking equipment and even some components of the cooling system itself. Reducing internal heat gains provide energy savings not only by introducing less heat energy into the building, but also because this usually results in less energy being used by the equipment itself.

8.4.2.1 Reducing Internal Heat Gain

Obviously the quickest and simplest way to reduce internal gains is to not install heat generating equipment in a space or, if it is already there, not to use it. This is not always practicable or even desirable. However, limiting the use of and implementing proper operating/maintenance techniques for equipment can significantly reduce energy consumption and related heat output. Also, the appropriate zoning of spaces or grouping equipment into one well-ventilated space can have significant effects. The following sections give different suggestions for general operating techniques to reduce the internal gains.

8.4.2.1.1 Lighting

Lighting is a primary participant in both annual electricity consumption and the generation of heat in buildings causing greater cooling loads on the AC system. In hot climates, one strategy is to control lighting heat gains by keeping direct solar energy from entering the interior space while allowing reasonable diffuse radiation and visible light for daylighting. The luminous efficacy of daylight, in terms of energy (W) per lumen of light, is much higher than most commonly used artificial lighting systems, so it results in less heat for the same lighting level in well daylit building [8-3].

Improving the efficiency of the lighting system also reduces internal gains. Using fluorescent lamps instead of incandescents, for example, can halve the internal gains and electrical consumption for the same overall level of lighting [8-3].

Removing unnecessary lighting, switching to energy efficient lamps and maximising the use of natural light are relatively inexpensive energy saving measures that will also reduce the load on the cooling system by reducing the amount of heat given off by lighting. In addition, lighting fixtures can be designed to suit the purpose of specific rooms. For example, focused or task lighting in a study or general wide-spread lighting in a family or living room. Using lamps with aluminized reflectors or reflective interior coatings can also increase the amount of light emitted in specific directions, thus increasing their efficiency slightly. It is also possible to add in dimmers, motion detectors and automatic turn-off switches where appropriate to reduce the amount of time the lighting is actually on.

Evaluating the effects of internal gains using simulation tools is relatively easy as they can be applied as room-averaged values or as output from individual objects in the model. As a base load in the example buildings, a general level of sensible and the latent heat gains within each space of 5 and 3 Watts/m^2 respectively has been assumed in each zone. The sensitivity of each example building to different levels of internal gain will need to be determined to see if this particular value will have undue influence on the results.

However, the real issues in designing for reduced internal gains are not something that can be simply modelled. It involves considering a whole range of strategies for the location of frequently-used and high heat-generating equipment, a task usually unique to each situation.

8.4.2.1.2 Zoning

Careful design of the spaces in each building can sometimes mean grouping the most active zones, such as the living room and the kitchen area, close to each other. This allows strategies such as high-ventilation to be applied to varying degrees in different areas to take out any generated heat. Living areas and the kitchen are usually the most important locations for passive cooling as they are used by families in both the day and evening. The kitchen is a major source of heat gain from cooking and from the operation of electrical equipment. Reducing the heat generated in the kitchen by using devices such as exhaust hoods when cooking can help to draw plentiful quantities of air from a room. However, if the only inlet for air is located in the living area, then the exhaust hood is likely to draw in replacement air directly from the outside through the living area. In the evening this may be desirable, however during the day in Riyadh this situation would be a problem. Thus, even the location of vents in grouped zones must be carefully considered.

Other strategies in the kitchen include turning off food warmers when not in use and using microwaves for after hours cooking of small quantities of food. These procedures will not only cause less waste heat to be released into the air conditioned space but will lower the energy needed for the cooking itself.

8.4.2.1.3 Occupancy Heat Gain

Occupant behavior and heat gains associated with people and their activities influence internal gains. According to the activity, clothing and temperature of the environment, the human body releases energy at varying rates and as both sensible and latent heat. Sensible heat has an immediate impact on the space whereas latent heat is the additional moisture vapour from the evaporation of sweat and breathing, released into the space later when the air cools and the moisture condenses.

The effects of occupancy are easily modelled in simulation tools in much the same way as other internal gains, either as a person per square metre value or as an additional gain. Controlling these effects is somewhat different as the primary purpose of each space in the building is to accommodate its occupants. Thus, the analysis of different occupancy levels is important to see how sensitive internal temperatures and loads are to this factor.

8.4.3 Inter-Zonal Gains and Ground Losses

The graph in Figure (8-4) shows that inter-zonal gain is a major source of both heat loss and heat gain over the year. Inter-zonal gains refer to the flow of heat between spaces at different temperatures within the model. However, it also include losses to the ground, as this is effectively a zone with a relatively constant annual temperature.

It is important to note in Figure (8-4) that inter-zonal gains and losses occur at almost the opposite times to all other heat gains and losses. For example, the greatest amount of inter-zonal heat loss was during the peak of Summer whilst the greatest inter-zonal heat gains were in mid-winter. A quick look at relative room temperatures shows that there are no significant differences between adjacent spaces in the building, thus the only source to explain this must be the effects of the floor.

Given the large diurnal range in temperatures throughout the year, the annual average ground temperature in Riyadh, however, around 23-25 deg C. Compared to the very high internal air temperatures reached in each zone, the floor therefore acts as a moderating heat sink in summer and a heat source in winter. As this is a very desirable situation, it is important to keep the ground floor exposed as much as possible when designing rooms that are to be occupied during the heat of the day in summer. This can be done by avoiding the use of floor coverings with high thermal resistance material. High-resistance floor coverings such as plush carpets, furs, rugs and pads effectively insulate the floor.

This is only really applicable to ground floor zones with a floor with good contact with the ground. However, even on the upper floors there will be some heat loss to the spaces below as upper floor zones tend to be slightly hotter, though the overall effect is much less.

8.4.3.1 Fabric Gains

The other source of heat flow is via conduction through the building fabric itself. This is due to differences in temperature between the inside and outside surfaces of each material on all exposed sides of a building. In the example buildings used in this study, the majority of exposed external surfaces are very thick with a high thermal mass. The effect of this mass is to act as capacitative insulation, absorbing heat and delaying its progress through the material. However, a significant amount of heat can travel by conduction through the roofing materials on the upper floors. As discusses in Chapter 7, the U-value of the timber roofs is 1.182 W/m^2K, whilst the average for the thick adobe walls is 0.9 W/m^2K.

Conduction flow through the roof is particularly significant as it is often exposed to direct solar radiation throughout the day. Incident radiation on such a material can increase its external surface temperature by as much as 30°C above the ambient outside air temperature, resulting in a much higher effective temperature difference across the material - with a commensurate increase in heat flow. As the thermal lag and decrement of the roof is slightly less than the walls, the exposed hot roof material then radiates this additional heat energy into the first floor space.

The locations of external walls can also affect the conduction flow across them. In certain situations, east and west facing walls can be exposed to similar levels of solar radiation in the mornings and evenings when the Sun angles are closer to normal incidence.

However, heat flows in to and out of a building from conduction can be reduced with high levels of insulation in the roof, external walls, windows and doors. Similarly, the effects of direct solar radiation on surfaces can be reduced by increasing the reflectance of the surface, basically making it lighter. Thus, from a design perspective, it is important to be able to determine the relative amounts of conduction flows induced solely by air temperature differences compared to that from incident solar effects. The following section explains the strategies that can be used to reduce the effects of conduction through the building fabric. The section following this looks at the means of controlling the effects of incident solar radiation.

8.4.3.1.1 Insulating the Roof and Walls

The exterior walls of many buildings are exposed to heat from the Sun, gaining heat during the day and losing some of it during the night. Generally, in hot climates such as Riyadh, heat transfer through the walls is considered much less significant than that from the roof, which is more exposed to the effect of the sun's heat striking it from all directions. This is in part due to the thickness of the walls compared to the roof, and their corresponding increased capacitative resistance, but also to the density of building construction where many walls are shaded for much of the day by adjacent buildings.

Once the surface temperatures of a material begin to differ, heat gain and loss through the fabric depends mainly on the thermal properties of its constituent materials. Thus, in turn, depends on their density, thickness, specific heat and conductivity. The U-value of a construction can be reduced either by increasing its thickness or by the addition of an effective insulation material.

Insulation materials such as polystyrene foam can be used as an internal surface treatment on the walls and roof of adobe buildings, or applied as a fabricated board. Adding insulation material such as these does not require any significant modification to the building construction as they are very light in weight, reasonably durable in strength and can be fixed directly to the adobe or attached to wooden frame.

8.4.4 Indirect Solar Gains

Solar radiation gets to the external surfaces of the building in the form of direct, diffuse and reflected radiation (Figure 8-8) and enters the interior spaces through transparent elements. Radiation entering through a transparent material is referred to as direct solar gain as it will have a direct and immediate effect on internal conditions. Radiation falling on an opaque surface is referred to as indirect solar gain as its first effect is the on the external surface temperature of each object and only effects internal conditions after being conducted through each material. Source: a corresponding time lag.

The aim when selecting an external material is to find one with a low absorptivity for short-wave radiation but a relatively high emissivity for long-wave. This allows it to reflect solar radiation during the day whilst radiating long-wave radiation at night to assist cooling. The downside to this is that materials with a high emissivity usually have a high absorptivity for long-wave radiation. Thus, when buildings are located close together, the amount of short-wave radiation is reduced by the effects of shading, but the amount of long-wave radiant exchange between adjacent buildings is increased. On a very hot day this is desirable as the amount of solar radiation is very high, however at night the amount of loss can be greatly reduced as each wall is basically exposed to an adjacent surface with roughly the same ambient surface temperatures – hence virtually no radiant exchange. This is not an issue with the roof of most buildings as they radiate mostly to the night sky.

Traditional materials such as whitewash, gypsum and earth are suitable to offer high reflectivity for hot climates [(8-5)]. Table (8-1) shows the different values of emissivity and absorptivity of some material properties and Table (8-2) shows the reflectivities of various materials and paints.

Table (8-1) Average emissivities and absorptivities for some common building surfaces under relevant conditions. Source: Hassn Fathy[(8-6)].

Surface	Emissivity or Thermal Absorptivity at 10-38 °C	Absorptivity for Solar Radiation
Black non-metallic surfaces	0.90-0.98	0.85-0.98
Red brick, concrete, and stone, dark paints	0.85-0.95	0.65-0.80
Yellow brick and stone	0.85-0.95	0.95-0.70
White brick, tile, paint, whitewash	0.85-0.95	0.30-0.50
Window glass	0.90-0.95	Transparent
Gilt, bronze, or bright aluminium paint	0.40-0.60	0.30-0.50
Dull copper, aluminium, galvanized steel	0.20-0.30	0.40-0.65
Polished copper	0.02-0.05	0.30-0.50
Highly polished aluminium	0.02-0.04	0.10-0.40

Table (8- 2) Reflectivities of various materials and paints. Source: Hassn Fathy[(8-6)].

Material or Paint	Reflectivity (%)
Red brick or stone	30-50
Slate	10-20
Asphalt bituminous felt	10-20
Galvanized metals (new)	36
Dark paints	10-20
Aluminum paints	40-50
Polished metals	60-90
Whitewash or white paints	80-90

close presence of some adjacent buildings. This is backed up by the fact the effects of direct solar gains are slightly greater in the upper floor zone. Whilst not significant in these particular cases, it is still an important design consideration in situations where there are exposed windows or where internal walkways may not be used.

The best strategy for keeping a building cool is to keep it from getting hot in the first place. This means preventing outside heat from getting inside, and reducing the amount of heat entering a space. Using shading devices is a very important strategy for controlling solar radiation through windows in hot climates.

8.4.5.1 Shading

8.4.5.1.1 Exterior Shading Devices

Windows play a major role in modifying indoor thermal conditions. Effective ways to control heat gain in the summer is by using exterior and interior shades for the window openings, or through the use of solar control glass. Generally exterior shades and highly reflective glazing are more effective than interior shades and heat absorbing glass because they exclude sunlight before it enters the window.

Shading devices can be either fixed or flexible, or some combination of the two. There are six main types of exterior shading devices:

- Roof Overhangs and pergolas,
- Awnings,
- Shutters,
- Louvers,
- Blinds, And
- Solar Screens.

The design of external shading device should allow visibility whilst excluding solar radiation in the hot season. Figures (8-10) shows an example of metal shading devices retrofitted by occupants in order to reduce solar radiation through windows in Riyadh City. However, such is the desire for shading that many people do not realise that the use of exposed steel plates in the window can actually *increase* the heat flux entering the space by conduction, as well as significantly reducing the potential for ventilation and views. This clearly demonstrates the need for more careful consideration in the application of external shades.

between the blind and the window. However, internal shading is much easier to control and significant lower in cost.

8.4.5.1.3 Courtyard Shading

In many arid, desert regions, buildings are designed with flat roofs, small openings, and heavyweight materials. Courtyards in most of the regions are a common architectural element in traditional buildings, particularly those with warm ambient climates. With high walls, these outside/inside areas provide shade and a relaxing environment for their inhabitants for social gatherings, evening entertainment, food preparation, and domestic work such as laundry.

The courtyard as a design strategy acts as a thermal regulator (8-8), working as a climatic modifier whose effectiveness depends upon its geometry and the treatment of its elements. In traditional designs, the courtyard height is always greater than any of its horizontal dimensions, causing it to be shaded in some periods of the day (8-6).

Courtyards can provide a pleasant outdoor environment and also improve indoor conditions by the use of simple details. Such details include, for example, a combination of different strategies like evaporative cooling, shade covering of the courtyard roof, green grass covering the ground and other mid-level vegetation to reduce ground reflection. In addition, the use of mist or fog created by evaporation might be an appropriate strategy in such hot arid climates. In this way, the warmer air in the courtyard that rises up due to the incident solar radiation in the courtyard during the daytime can be replaced by cool air from the ground level flowing through the louvered or tent openings of its roof, thus facilitating the flow of air. This concept can very well be applied in a shaded environment inside the courtyard where the courtyard is kept cool by shady trees and other vegetation.

The surface treatment of courtyards is an important factor to be considered. A courtyard with a hard floor such as concrete tiles or with soil often has higher air and radiant temperatures than the outdoor environment because while the courtyard is sheltered from the wind, the sun can still reach parts of the courtyard area. Therefore, the total solar radiation striking parts of the space in an open courtyard is the same as the open horizontal earth (8-7).

An un-shaded courtyard without any green area or other sources of shade or evaporation will probably have a higher internal temperature. Several design solutions can be used in order to reduce the impact of solar radiation in courtyard space. A shaded courtyard with evaporation

8.4.6 Evaporative Cooling

Passive evaporative cooling is a technique that has been used for many centuries in the Middle East and other parts of the world with hot arid climates. Cooling by evaporation in hot climates can be effective where the relative humidity in summer is below 10 % and the temperature is quite high. Evaporative cooling depends on the use of water to cool incoming air into the building. Evaporative cooling can be either direct or indirect. Both systems use the latent heat of vapourisation that occurs when moisture evaporates to draw heat from the air as part of the cooling process. An example of direct evaporation cooling is a cooling tower that humidifies the ambient air. An indirect evaporating cooling system may be a roof pond, for example, which does not raise the indoor humidity [(8-13)]. Evaporating cooling can also be termed hybrid when the system has to be controlled or powered by means of some mechanical device, making it part-active system instead of purely passive. The application of both direct and indirect evaporating cooling systems is explained in Appendix E. The following section explains direct and indirect evaporative cooling.

8.4.6.1 Direct Evaporative Cooling

In this system, the air is passed over water to be cooled by evaporation, and the latent heat is taken from the air (sensible heat reduced and latent heat increased) and then supplied to the interior of building. This cool and more humid air absorbs heat from the enclosed space. In this strategy, the air supplied to the building is kept humid and the relative humidity will always be higher than the outdoor spaces. Evaporative cooling works successfully in hot arid climate where the humidity is always below the requirements of comfort as has been found in these climates, such as the Riyadh region.

One example of this traditional system is the cooling tower which guides outside air over water-filled porous pots, inducing evaporation and bringing about an important drop in temperature before the air enters the interior. The physical process of evaporative cooling and the way it works are explained in Appendix E.

8.4.6.1.1 Effect of Direct Evaporative Cooling

Givoni (1994) [(8-13)] in his book *Passive and Low Energy Cooling of Buildings* reports that the measured performance of a down-draft tower tested by Cunningham and Thompson in Tucson, Arizona was very remarkable. The test results showed an outdoor temperature DBT of 40.6°C and an indoor WBT of 21.6° C. The exit air temperature from the tower was 23.9°C

8.4.6.2.1 Effect of Indirect Evaporative Cooling

Fountains, sprays, pools and ponds as indirect evaporative cooling are particularly effective passive systems. The rate of evaporation from a wetted surface is controlled by the air velocity and the difference between the water vapour pressure and the air pressure next to the moist surface. The cooling potential of this system is calculated based on the summer weather, giving an evaporation rate between 150-200 $W.m^2$ (8-14). The effect of this system can be tested through simulation as can be explained in the next sections.

8.4.6.3 Vegetation

It has been accepted as a matter of tradition in hot climates that vegetation is one of the most important factors helping to improve the microclimate surrounding a building. Shading by trees and vegetation is a very effective method of cooling the ambient hot air and protecting the building from extreme solar radiation. The solar radiation is absorbed by the leaves of plants or trees and is mainly utilized for photosynthesis and evaporative heat losses.

In many traditional houses, the use of palm and *athel* (tamarix) trees planted around and inside the courtyards not only provides an additional source of food and construction materials, but also provides external shade to parts of the building and its surrounding area. The best place to plant shady trees is to be decided by which windows admit the most sunshine during peak hours in the hottest months of the year. Placing trees to provide shading to the wall surfaces that receive the most summer heat can also offer excellent natural cooling. The east and west oriented windows and walls usually receive about 50% more sunshine than the north and south oriented windows and walls (8-15).

However, the main ways to create useful shade are through planting vegetation in combination with placing architectural obstructions such as overhangs and awnings between the Sun's direct light and the house. Low ground covers, such as grass, small plants and bushes, can also significantly reduce temperatures around a house (8-7). Additionally, when designed with care, external paving around the building can play a major role in modifying the ambient temperatures when shaded and dampened in summer and alternatively, when dry and exposed to the sun in winter.

8.4.6.3.1 Effect of Vegetation

Saini B. S. in his book *Building in Hot Arid Climates* (1980) (8-16) gave examples of the effect of plants and grasses on solar radiation by the researchers Deering, Trapp and Geiger. Also, Givoni B. in his book *Climate Considerations in Building and Urban Design* (1997) provides plenty of actual field data for different studies on the thermal effect of planted areas.

Saini, quoting from Deering, claims that the heat load on exposed surfaces can be reduced by plants and grasses that blocking the passage of solar radiation. He also refers to the findings of Trapp, that 80% of the incident solar radiation is checked within the foliage itself and only 5% passes through and reaches the ground. Another observation by Geiger (8-10) on mixed forests showed that they cut only 69% solar radiation.

A study by Parker (8-5) has indicated that the use of plants, shrubs and ground cover can reduce the ambient air temperature by up to 5.5°C. Compared to an air conditioner - which consumes 5 to 7% more energy for each additional degree - by using evaporative cooling instead of or in combination with air conditioning in shaded buildings, a 50% reduction in energy can be achieved. Therefore, a capacity of 1 ton of air-conditioning (1 ton of cooling is 12,000 Btu per hour [3.52 kilowatts]) can be saved in shaded buildings for each 3.5 kW of energy consumption (8-5).

Givoni (1998) reported the study of Parker (1983, 1987, 1 989) on the effect of landscape on the temperature of walls. This study was carried out in Miami, Florida on hot sunny late summer days. The measured data showed that the surface temperature of walls shaded by trees or a combination of tree and shrubs was reduced by 13.5-15.5°C, while wall surface temperature when shaded by climbing vines was reduced by 10°C -12°C. , Another study also, carried by Parker (1983), measured the effect of plants on the cooling energy consumption of the building. This study showed that the cooling energy consumption without shading from plants was 5.56 Kw, while with landscaped shading it was reduced to 2.28 Kw, and the peak load after noon was reduced to 8.65-3.67Kw (8-7).

The study of the effect of landscaping on cooling energy consumption by McPherson et al. (1989), also represented by Givoni (8-7), consisted of three landscape treatments of Bermuda grass around buildings with no shade. Buildings were surrounded either by rock or by shrubs. The surface temperature of grass at noon time was lower by 15°C compared to the rocks and the air temperature above the grass was about 2°C lower than above the rocks. The study carried out in Japan in (1988) by Hoyano (8-7) measured the effect of plants on the surface and air temperature. His result showed that the wall air temperature before the introduction of an ivy screen covering the west wall was 10°C and after covering was reduced to 1°C.

Also, the effect of the reflection from the ground surface is considered as an important factor as the solar heat received on the ground in summer is about twice that received by the east or west walls. Reflected radiation from the ground can heat surrounding surfaces and enter zones through internal openings [(8-9)]. However, through the literatures [(8-9, 8-10, 8-11)] the reflected value from grass surfaces was expressed by generalized estimations ranging between 12-30% as can be seen in Table (8-3). Thus, by covering any exposed ground with grass or other ground cover vegetation, the effects of this radiation can be significantly reduced.

Table (8-3) Some of surfaces reflection in % quoted from some writers.

Reference	Grass	Sand	Water
Watson, D. [(8-9)]	12-30	15-40	3-10
Geiger, R. [(8-10)]	12-30	15-40	3-10
Konya, A. [(8-11)]	20	-	-

8.4.6.3.1.1 Testing Evaporative Cooling and Vegetation

It is not yet possible to fully model the effects of direct or indirect evaporative cooling using a simple thermal model. For this, an iterative process in which the results of a complex air-flow analysis are fed back into a thermal analysis model - which then updates the air-flow model, etc - is required. Currently there are no readily available implementations of computational fluid dynamics that link directly to thermal analysis models and then back again. The COMIS system implemented in EnergyPlus may be considered reasonably close, but it still deals with bulk air-flows and not the detailed geometry required to induce a passive downdraft as required to accurately model a cooling tower.

More importantly, there are virtually no readily available simulation models to predict the transpiration effects of trees and other vegetations. Many researchers have made reference to various rates for different species under very specific conditions, but there are no generally applicable rules that can be applied to dynamic conditions such as those experienced in an enclosed courtyard, etc.

As a result, to design for evaporative cooling, the best approach is simply determine how much cooling is required to reduce internal air temperatures and/or maintain comfort conditions. Once this information is known, the amount of vegetation or the size of the evaporative system to supply that cooling can be set. With modern analysis tools, the process of determining the amount of cooling required can be quite precise, however the process of selecting vegetation or sizing the system is much less precise as the correlation models require significant interpretation and interpolation/extrapolation.

However, it is possible to examine particular aspects of the model which will affect the evaporative cooling potential of a site. This includes looking at air-flow rates within the courtyard when subject to breezes as well as the ability to 'duct' air from beneath the vegetation in the courtyard to particular areas of the dwelling. This can be done using the ECOTECT model and exporting it to a computational fluid dynamic (CFD) model. The programme WinAir4 was used for this analysis as ECOTECT exports models directly to its native file format, allowing for runs to be carried out quite simply and the results loaded back in for visualisation. WinAir4 was developed as part of an ongoing research programme at the Welsh School of Architecture (see section 7.14.1 in Chapter 7 for more information about WinAir4).

8.5 Conclusion

This Chapter reviewed the various passive design techniques that can be applied to the example adobe buildings to improved their internal comfort conditions. Most of these techniques are derived from the climate data analysis in Chapter 2 as well as the known responses of buildings to the climatological characteristics of other regions in Saudi. Obviously the next step is to determine the potential effect of each of these techniques, which is done in the following chapter.

CHAPTER NINE

THERMAL MODELLING

9.1 Introduction

A good thermal model relies not only on the accurate representation of building geometry, but also on accurate usage and environmental parameters. It is relatively simple to compare the accuracy of the geometric representation in the computer model with the actual form of the building itself, even if gross simplifications have been made. However, the accuracy of numeric parameters such as fabric conductance or infiltration rate are usually much more difficult to compare with the existing building without extensive technical measurements.

Thus, whilst Chapter Seven discusses in detail the derivation of these usage and environmental parameters, as well as the basis on which they were selected, it is still necessary to ensure that slight variations between selected and actual values do not invalidate comparative results. Even if the selected values lead to simulation results that closely matched measured conditions, there was still no way of knowing if these judged values were actually accurate. As the means were not available to physically measure these parameters on-site, a simple sensitivity analysis has been conducted to determine just how much any slight variations are likely to affect calculation results. As this was done as a separate process in each analysis tool, it will also indicate how sensitive the different methods and implementations are to each of these parameters.

The aim of this analysis is threefold:

- To provide an indication of likely margins of error in the comparison of internal zone temperatures and heat gains, and to assess just how accurately the judgements for these model parameters matched real conditions;
- To determine which tool or method would most closely correlate with measured values (it is fully understood that any comparison of measured and calculated values raises a number of issues, many of which will be addressed in detail later in this Chapter); and,
- To formally assess the sensitivity of the models to different parameters in order to determine the most potentially effective passive design strategies to implement.

9.2 Modelling Methodology

In term of building simulation, Clarke (2001) points out that ultimately a program's predictive accuracy can only be assessed by comparing its outputs with buildings in use [9-1]. Often this is not possible, especially if the building is in the process of being designed. In such a case, confidence in the predictive accuracy of any simulation process can be increased by comparing the results of more than one simulation tool. If this is not viable to use multiple tools, then another way of checking is to run several simulations in the one tool but using a range of different input parameters to see just how sensitive it is to different user input. As confidence in the simulation process is very important in this study, all three different kinds of comparison techniques have been used:

- **Physical comparison**, in which a comparison is made between the results of a simulation model and actual measured data of thermal performance of the example buildings.
- **Comparative modelling**, in which a building is modelled in more than one simulation program and the result of each is compared.
- **Sensitivity analysis**, in which multiple runs are carried out in each tool, varying a single parameter each time, to see just how sensitive the model is to changes in different user input.

9.3 Physical Comparison

As the main purpose of any simulation process is to model as close as possible a real-world physical situation, it is important to establish first that simulation results from the building models described in Chapter 7 can closely match actual measured results. However, it is also important to first ensure that what is being compared is actually comparable.

The most obvious comparison is between measured internal air temperatures and simulated values within specific zones in each building. This is useful as air temperature is one of the major factors affecting the perception of comfort in any space and is relatively easy to both measure and predict. However, there are many factors to consider in any such comparison:

- Measured values from thermal sensors use to measure the temperature within a space are invariably taken at only a single location. However, simulated values most often represent the average over the entire space. Thus, without a number of sensors in each zone, it is difficult to determine if the measured values contain any localised effects such as a convection current.

- Even with a well protected sensor, it is very difficult to fully exclude radiant effects and measure only the air temperature. Also, the extent of radiant effects cannot be easily controlled or calculated so they are difficult to manually correct for.

- There are inherent error margins in the physical sensors themselves. For the Tiny Tag, Tiny Tag Ultra and Tiny Talk sensors used in this study the manual states that this may be as high as ± 2°C.

- As good quality hourly climate data is very difficult to obtain, particularly in the Middle East, it is almost impossible to consider in the computer model many of the micro-climate effects that may be impacting on the actual building. For example, hourly wind speeds at each window were not measured, so the computer model was based on measured wind speeds at the local weather station. Whilst on-site external temperatures were measured, these too were specific to only one location on the roof of the building.

ventilation rate within the measured zone on day 225 (13th Aug). This is the one time where diurnal variation is clearly apparent in the measurements. Given the diurnal variation present in the predicted temperatures of all the tools, this suggests that ventilation is a sensitive parameter.

The result of the tools prediction in this building show that HTB2 and ECOTECT are generally the closest to the measurements respectively. Their prediction shows good agreement with the measured data. On the other hand, EnergyPlus again showed the greatest variation.

9.5 Parametric Sensitivity Analysis

A sensitivity analysis is described by Saltelli et al. as:

> *"Sensitivity analysis (SA) is the study of how the variation in the output of a model (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of variation, and of how the given model depends upon the information fed into it."* (9-2)

The aim of a sensitivity analysis is to observe the system response following a modification in a given case studies parameter and to determine which input parameter has the greatest effect on the output variable. The main purpose of this analysis is to check the influence of different operative and construction parameters on the thermal performance of the building. Sensitivity analysis of the tools model output is a very important stage in model predictions analysis. It can help increase the reliability of building thermal simulation software. Sensitivity analysis can also help in the improvement and validation of the simulation model. A parametric sensitivity analysis can be used to set up the model predictions uncertainty band associated with the input data. Saltelli et al. also give a list of the pragmatic reasons why modellers conduct sensitivity analysis.

"To determine:

- *if a model resembles the system or processes under study;*
- *the factors that most contribute to the output variability and that require additional research to strengthen the knowledge base;*
- *the model parameters (or parts of the model itself) that are insignificant, and that can be eliminated from the final model;*

- *if there is some region in the space of input factors for which the model variation is maximum;*
- *the optimal regions within the space of the factors for use in a subsequent calibration study;*
- *if and which (group of) factors interact with each other."*

Therefore, a sensitivity analysis was carried out, given a realistic variation in values for a range of parameters in the model.

One of the reasons for conducting a sensitivity analysis in this work was to gain confidence that the parameters used for materials, occupancy, internal gains and ventilation did not skew the analysis or produced unrealistic results. To do this, many runs were performed in which the value of only a single parameter was varied within a realistic range. The following table shows the parameters varied and the range of values used for each.

Table (9-1) Parameters and value ranges used in the sensitivity analysis.

Parameter	Minimum Value	Maximum Value
Infiltration (Ventilation) Rate	0.1 ac/h	4 ac/h
Internal Gains	1 W/m^2	40 W/m^2
Window Shading	0.1	1.0
Wall Reflectance	0.1	0.9
Wall (and Roof) Insulation	0.1 W/m^{2}K	4.0 W/m^{2}K
Orientation	0deg	360deg

9.5.1 Parameters Simulation

A number of simulation runs were carried out to investigate the sensitivity of each tool to changes in the parameters suggested in Table (9-1). There are six main parameters, each having 10 different values, tested for each the four zones of interest using the three analysis tools. The time consumed for each run varied between tools and depended greatly on the capability of the machine doing the calculation. For example in HTB2 and EnergyPlus the times ranged from 25 minutes per parametric run for a well specified 3.0GHz machine to nearly 72 hours for a similar run on a 800MHz P4. More than 3348 runs were required (see Tables (9-19 to 9-24) in Appendix F), generating files of 1.5 Gigabytes in size per parameter range.

From the results, average values for average temperatures and total space loads were calculated for each of the four zones of interest (three zone in building 3), taken over the whole year as well as for just the three months of summer and three months of winter.

9.5.1.2 Surface Colour Simulation

In this test the reflectance properties of the surface colour are simulated and their effects on the internal temperature a ssessed. The suggested reflectance values were 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1, in all the case studies buildings.

Using light coloured walls and roofs affect internal temperature positively a nd can help to improve indoor conditions. As seen in the charts below in Table (9-3), the annual effect of surface colour is to reduce average daily temperatures from 30.5°C at 0.1 Refl. to 28°C at 0.9 Refl. in both HTB2 and EnergyPlus. The effect of this parameter in the summer period also shows a drop in average daily temperature from about 40°C at 0.1 Refl. to 35.2°C at 0.9 Refl. The temperature dropped 3 deg, in winter time from 22°C at 0.1 Refl. to about 19°C at 0.9 Refl., In ECOTECT, this parameter had only the slightest effect temperatures for all periods.

Outer surfaces can help to improve indoor temperature. Using low surface absorptivity has a good effect, especially as it helps to reduce indoor temperatures in summer. With the same effect, it also reduces temperatures in winter. The colour white proved to be the most appropriate for use in this area to help to reduce the impact of solar radiation on exterior wall surfaces. Therefore, applying light colours such as whitewash to reflect larger amounts of solar radiation can be used on external walls, but to remain efficient it should be maintained in a clean condition or renewed annually.

9.5.1.3 Internal Gains

The thermal analysis was undertaken to investigate the effects of internal gains associated with occupancy, lighting, and equipment. In the case studies buildings, 10 different values were used: 1, 2, 3, 4, 5, 7, 10, 15, 20 and 40 W/m^2 floor area.

The results regarding the sensitivity of tools indicated that the warmest indoor conditions would occur when the greatest internal heat was generated. As seen in the chart below in Table (9-4), the annual effect on temperature was to increase it by about 10 deg. For example, in zone 4, it was increased from 27.5°C at 1.0 W/m^2 to 37.7°C at 40.0 W/m^2 in Ecotect. In HTB2 and EnergyPlus were increased from 29.6°C at 1.0 W/m^2 to 36.7°C at 40.0 W/m^2 and from 31.6°C at 1.0 W/m^2 to 39.2°C at 40.0 W/m^2 respectively.

In summer the impact of internal gains on temperature increases about 10 deg., as can be seen in the charts. Increasing the internal gain produced by lighting and other equipment has a significant impact on indoor summer temperatures, thus minimizing all sources of heat gains should be taken into account when designing or modifying such spaces. In winter the indoor climate has also shown an increase in temperature of about 10 deg with the increase in internal gains.

The results from this parameter indicate that reducing internal heat gains by improving the efficiency of lighting and equipment is a very important strategy that should be controlled, especially in summer time. During the summer, this heat increases interior temperatures and adds to the cooling load of a home. Thus, using high efficiency lighting and equipment not only reduces internal heat gains to the spaces, but also reduces the cooling load on any air conditioning systems that are used. Lighting loads can be minimized by designing for maximum use of daylight, and both lighting and equipment loads can be reduced through the use of energy efficient hardware. Daylighting systems can be designed to provide direct solar gains in winter while blocking it when it is not wanted in summer. This provides additional heat in winter while reducing internal heat gain from electric lighting year round.

Also summer cooking outside, for example, not only provides for the immediate pleasure of ventilated cooling away from the hot mass of the house, but also removes heat gains due to people, lights and equipment from the kitchen so that the house will stay cooler.

9.5.1.4 Orientation

The change of orientation between 0 and 360 degrees had negligible effect on the inside temperature and different orientations angles didn't result in valuable differences in summer and in winter as well. The charts in Appendix F showed insignificant effects of changing the orientation for 30° in each of HTB2 and EnergyPlus. In Ecotect, the sensitivity to orientation was tested in 15° increments. The result of this test showed that this did not help to reduce the temperature or improve thermal performance. In respect of heat gains and losses, however, there is some noticeable change in the zones located in the upper floor of building two. This is due to the fact that the walls and roof of rooms on the upper floor are more exposed to the heat of the sun than those on the lower floor which are shaded by the adjacent upper floor and other buildings. Thus, with different orientations, different areas of the wall are exposed to low level east and west sun for longer.

What is significant is that, even with this change in loads, the internal temperatures in these upper floor zones did not change noticeably. This clearly indicates that solar gains through the relatively small windows, and through the walls themselves, are not sufficient to overcome the averaging effects of all the surrounding thermal mass. What seems to be dominant is the daily temperature range, which does not change with orientation.

9.5.1.5 Window Shading

With the relative effect of orientation in mind, the application of shading devices to windows in the model were tested for each of the case study buildings. Increases in the level of shading was simulated be changing the transmission coefficients of the glazing used. In ECOTECT this was the shading co-efficient, which was translated into reduced solar transmissions when exported to HTB2 and EnergyPlus. The shading coefficient values used were: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0.

The application of shading devices to openings did not result in better performance and had a negligible effect. This is consistent with the findings of orientation and indicates that the small size of each window compared to the thickness of the wall is such that they are already well shaded.

Despite these results, excluding shading devices cannot be recommended as the results are quite specific to the buildings actually being studied and not to buildings in general. Even in this study, and through the author's personal experience, the use of shading devices would be recommended for the occupant's visual comfort by avoiding direct solar radiation. Also the most appropriate of shading devices is that provided by the window shutters or formed through manipulating them, being flexible and consequently able to be adjusted to fulfil the opposing requirements of both summer and winter. The test results of this parameter are illustrated in Appendix F.

9.5.1.6 Roof and Wall Insulation

Studying the effects of differing levels of insulation in the walls and roof was relatively simple in Ecotect as the thermal analysis is based in the actual U-value for each material. However, both HTB2 and EnergyPlus calculate their own response factors for each material given the different layers from which they are composed.

In Ecotect, the additional wall and roof U-values tested were: 0.1, 0.2, 0.3, 0.4, 0.5, 0.7, 1, 1.5, 2, and 4 $W/m^2/K$. In HTB2 and EnergyPlus, the values refer to the width of additional expanded polystyrene insulation actually added to the width of each external material, being 10, 20, 30, 50, 75, 100, 150, 200, 300 and 500mm.

The results of the roof and wall insulation tests showed that there was no marked improvement in indoor temperatures and only the slightest effect on overall loads. This suggests that fabric gains from outside do not have significant impact on internal conditions. The test results of this parameter for both roofs and walls are illustrated in Appendix F.

9.5.1.7 Ventilation and Surface Colour

A parametric sensitivity analysis was also performed on the combined effect of adjusting both ventilation and surface colour treatment on the thermal performance of adobe buildings. The results of this combination are illustrated in Table (9-5) below.

In ECOTECT, the annual effect of these parameters is to reduce average daily temperatures from 33°C at 0.1ach/0.1refl to 28°C at 4ach/0.9refl. While in summer the drop in average daily temperature was from about 38°C at 0.1ach/0.1refl to 35°C at 4ach/0.9refl. In the winter period, the drop in average daily temperature was from 20°C at 0.1ach/0.1refl to about 18°C at 4ach/0.9refl. In both EnergyPlus and HTB2 the annual effect of these parameters is also to reduce average daily temperatures from about 32°C 0.1ach/0.1refl to 27.9°C at 4ach/0.9refl. In summer, the effect of this parameter showed a drop in average daily temperature from around to 38.4°C at 0.1ach/0.1refl to 35°C at 4ach/0.9refl. In winter period drop in average daily temperature was from about 21°C at 0.1ach/0.1refl to 18°C at 4ach/0.9refl.

However, in all tools the results showed an agreement that increasing ventilation rates and external surface reflectance produces the same behaviour with relatively similar effects occurring on the daily average temperature for all periods.

9.5.2 Summary of Parameters with the Greatest Effect on Temperatures

From the sensitivity analysis above, it is clear that different parameters affect the internal environment in different amounts. To summarise, there is significant potential for improvement in the indoor temperature by using a combination of all the parameters that had a positive effect, as outlined below.

- Night time ventilation in summer proved to have a significant effect on indoor climate.
- The external low surface absorptivity colour and the texture of the building envelope provide considerably more effective reduction in the inner spaces.
- Reducing internal gains i n the building can play an important role in reducing heat gains and thus saving energy consumption.
- The effect of increasing ventilation rates and the external surface reflectance can help to reduce internal air temperatures.

The Figure below for case study one shows the diurnal temperature variation, basically the difference between maximum and minimum temperature, and the percentage variation between maximum and minimum heat loss. This is shown for each tool over the whole year, as well as summer and winter. The annual run represented the whole year whilst the summer period was assumed to b egin on the 1st of June to the 31st of August (3 months) and the winter period started on the 1st of December to the end of February (3 months).

TEMPERATURE	ECOTECT			HTB2			ENERGYPLUS		
PARAM.	**Annual**	**Winter**	**Summer**	**Annual**	**Winter**	**Summer**	**Annual**	**Winter**	**Summer**
Internal Gain	14.0	14.0	16.0	7.0	6.0	8.0	8.0	6.0	7.0
Ventilation	2.0	4.0	2.0	2.0	2.0	1.0	4.0	4.0	4.0
Insulation	1.5	1.5	1.5	0.0	0.0	0.0	0.0	0.0	0.0
Colour	0.5	0.7	0.5	1.8	3.0	2.1	2.2	3.4	1.6
Orientation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Shading	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

SPACE LOADS	ECOTECT			HTB2			ENERGYPLUS		
PARAM.	**Annual**	**Winter**	**Summer**	**Annual**	**Winter**	**Summer**	**Annual**	**Winter**	**Summer**
Internal Gain	468.46%	420.40%	279.40%	1526.44%	1535.61%	1760.87%	535.75%	435.94%	597.64%
Ventilation	128.13%	130.28%	129.69%	225.68%	232.43%	231.60%	227.00%	224.02%	260.96%
Insulation	100.00%	115.50%	112.82%	0.0	0.0	0.0	0.0	0.0	0.0
Shading	100.02%	100.00%	100.01%	100.09%	100.12%	100.09%			
Colour	100.56%	100.26%	100.41%	117.98%	118.42%	123.09%	107.78%	103.09%	104.07%
Orientation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure (9-14) Greatest effect of the parameters.

The next table ranks the relative effect of each parameter on room temperatures in each tool. There is almost universal agreement between the tools, showing that internal gains has the greatest effect, followed by ventilation, surface colour, shading and orientation.

when the breakup between summer and winter is considered where it is clear that this only applies to the rates of heat loss. In summer, a low air change rate means that daytime internal heat is retained until late in the evenings, resulting in overall daily heat losses close to zero up until the 2ac/h or more. If this information is combined with losses in winter, the annual result is a u-shaped curve. The same overall effect is present in both EnergyPlus and HTB2, but to a much lesser degree.

9.6 Conclusion

The initial comparative analysis in all cases showed reasonable correspondence between the simulated and actual data. In some cases there was variation between the tool and the measured data and between the tools themselves, mainly from the fact that each tool uses a different method to constructed the model and calculate its internal temperatures and loads. However, this comparison shows that the prediction of internal temperatures can be made with a fair degree of confidence and that the selection of parameters for the reference buildings did not have an undue influence.

The climatic analysis carried out in Chapter 2 indicated that the most effective passive design strategies for the Riyadh region were a combination of exposed thermal mass, natural ventilation and both direct and indirect evaporative cooling. Looking at the results of the sensitivity analysis, it is clear in all tools that the critical factors affecting both temperatures and loads in each building are the levels of internal gain and the ventilation rate.

The effect of evaporative cooling is essentially to add a negative sensible heat gain to the space and, with direct evaporative cooling, also a latent gain. Thus, the analysis results compare well with the much simpler climate analysis. Given cost considerations, and the fact that the existing external fabric of each building is already known to work well with significant thermal mass in its 400 mm thick adobe walls, the effect of lesser amounts of thermal mass were not studied.

What does come out of this analysis is just how relatively insensitive the buildings are to solar-related parameters such as shading and orientation. There is some sensitivity to the colour of external surfaces, but it is clear that both direct and indirect gains have only a small influence on overall performance. However, this is not to say that solar radiation is unimportant. Its incidence on surfaces around the buildings and in the courtyard can greatly heat up the surrounding air, contributing to increased ventilation gains which the study shows the buildings are very sensitive to.

Another interesting aspect of the results is the rather complex non-linear relationship between space loads and ventilation. Whilst the absolute values of the loads varied significantly between tools, all tools exhibited some degree on non-linearity. The results suggest that there exists some optimum air change rate below which heat builds up internally and is never able to escape and above which too much hot outside air is introduced. Between the three tools, this lies somewhere between 0.25 and 1.5 ach.

CHAPTER TEN

RECOMMENDED PASSIVE DESIGN STRATEGIES

10.1 Introduction

The aim when refurbishing these adobe buildings is to maximise internal comfort and amenity whilst minimising the use of external and auxiliary energy such as fossil fuels and electricity. This chapter outlines recommendations for the most effective combination of the passive design principles outlined in Chapter 8 and discusses their potential effect on the overall performance of the example adobe buildings.

Obviously the aim in this Chapter is also to quantify these effects as much as possible, however this is not a trivial task. As explained in previous chapters, it is not always possible to simply add the structure of a passive design strategy to a 3D computer model and have a thermal analysis tool calculate the result. This is mainly because the effects of many passive systems are much more complex than a simple assembly of their physical components would suggest. Thus, the use of multiple different analysis tools may be required and, as many of these will not easily or directly exchange data, the user must stand in the middle and take responsibility for interpreting the results of one tool and converting them into valid input for another. This requires a relatively high level of understanding and familiarity with different types of analysis tools. However, in order to maximise/optimise the potential effect of each passive design system, it is argued here that this is often necessary.

Therefore, this chapter will also serve as an explanation of the different approaches to analysis required to accurately model some of the complexities of these passive strategies.

10.2 Outline of Passive Strategies

From the discussions of potential strategies in Chapter 8 and the sensitivity analysis results in Chapter 9, it is clear that to prevent overheating problems, decrease cooling loads and improve indoor thermal comfort conditions, a combination of strategies are required. This really requires a two-pronged approach: the first concentrating on reinforcing the cooling aspects of the existing building and structure, and the second maximising the use of passive sources of energy and cooling in the environment.

On the basis of previous analysis, it is recommended that the adaption of these adobe buildings include the following strategies:

- Evaporative Cooling in the Courtyard
- Ventilation Control
- Courtyard Shading
- Night Purge Ventilation
- Zoning of internal spaces to Reduce Distribution Loads
- Leaving the Floor Exposed as Much as Possible

It is obvious that greater control over both infiltration and ventilation is required in these buildings to prevent unwanted heat exchange with the outside. However, controlled ventilation is the only real passive mechanism for the transport of evaporatively cooled air from the courtyard into spaces within the building.

As it is being recommended that the courtyard be used a source of evaporative cooling, it is therefore also necessary that it be shaded in order not to reduce the effectiveness of the evaporative cooling system by having the cool are pool on surfaces heated by direct solar gains.

Both examples clearly indicate that the design of these systems are highly inter-related and should be carried out with significant care and consideration. However, it is not easy to fully explain how the system works as a whole without dividing it up into its constituent components and describing them individually. Thus, whilst acknowledging that the systems function as part of an inter-related whole, this chapter will discuss each component and explain how they function within that whole.

ensures that, when there is no wind and buoyancy effects prevail, it is easier for cool air from the courtyard to enter the space and warm air inside the space to exhaust through the window.

10.2.3 Ventilation Simulation

Calculating the effects of ventilation is difficult as it is dependant on many different factors. These include the current wind speed and direction, window locations and opening areas as well as the temperatures of all surrounding surfaces. As a result, it is only really possible to solve for one very specific set of conditions.

Figure (10-2) below shows both air temperature (top) and the speed of flow (bottom) taken from a cross section through Building 2 of the example adobe buildings. A representative tree has been located within the courtyard and assigned a relatively cool surface temperature to simulate the effects of transpiration.

Unfortunately, as stated previously, there are no readily available models of the actual cooling effect of vegetation. Thus, to model the tree, a series of intersecting planar surfaces were used. The total area of these surfaces is obviously much less than the sum of the many thousands of leaves present in a real tree, which was compensated for by giving them a low surface temperature - in the case of the images below 24 degC. Obviously this is an arbitrary number, however the aim was not to accurately quantify cooling but to investigate the evaporative cooling effect on air flows so this was considered to be low enough to induce an effect.

In this case, the results of one particular thermal analysis on a hot summer's day has been used to set up the CFD mode, with an average outdoor temperature of 40°C, and average ambient indoor air temperature of 33°C, average internal surface temperatures of 32°C and an average air temperature inside the vegetation of 24°C. Incident solar radiation falling on each surface was used to calculate the sol-air temperature for each external surface based on a direct solar component of 680W/m² and a diffuse component of 280W/m² distributed using a CIE Clear Sky model [(10-3)]. On the selected day and hour of the calculation, the recorded air speed was 2.5m/s flowing from left to right in each image.

temperature between rooms. The amount of such exchanges is controlled by the location of spaces in plan and section, the opening and closing of doors, the thermal properties of the partitions, and the differences in temperature between the spaces. It is best avoided locating and using inflexible partitioning in the north zones of a building as it may affect air movement.

Other factors to consider are:

- Placing living rooms and family areas together on the first level of the building.
- Using flexible partitions between spaces which can be open and closed in summer and winter.
- Placing buffer spaces such as conservatories to protect cooled spaces from the outside.
- Placing similar activity rooms grouped together such as bedroom zone, bathroom zone.
- Kitchens which back onto hallways or other living areas can have their back walls lowered or large openings created in them to let air to flow over the top and through the whole house.
- The major openings of the spaces should face the breeze.
- Open plan interiors between spaces are best for encouraging natural ventilation in hot climates.
- Where possible, the garage, laundry, bathroom and storerooms are best positioned on the western wall of the building as they assist in minimising heat transfer into the living areas

10.2.6 Courtyard Shading

Overhead shading in summer can be achieved through the use of deciduous vines and trees or light partial coverings such as palm fronds or open-weave mats or cloth. The adobe house courtyard during summer can become an active and usable living space when it shaded. It can be shaded by a movable shading device that allows occupants to optimize and control its performance differently during summer and winter. In the hot season of the year the courtyard roof can be shaded by light materials which have the additional benefit of providing easy and simple control from the sun's heat, without negatively affecting the quality of lighting and night ventilation. In the winter time the movable device can be removed when the sun's heat is needed.

10.3 Other Elements

10.3.1 Door and Window Infiltration

As explained in Chapter 9, air infiltration or leaks can have significant impact on building heating and cooling loads. Infiltration results from a pressure difference between inside and outside, forcing air through cracks, holes, and crevices in the home.

The best way to begin reducing air infiltration is by knowing where it may be occurring. In the case study buildings, the outside walls have obvious sources of air leaks, but it is often minor compared to hidden air leaks from the edges of doors and windows after years of use. The recommended strategy to reduce air leakage is as follow:

- Apply tight-fitting rubber gaskets around the doors to seal them when shut.
- Placing weather-stripping to reduce air leakage around windows and all exterior doors.
- Replace old and broken windows with newer, high performance ones such as double glazed windows
- Use caulk and seal air leaks where plumbing, ducts, or electrical wiring go through exterior walls, floors.
- Check for cracks where different types of building materials come together and using both caulking and weather stripping efforts are usually the easiest and cheapest way to reduce air leaks.

The general guidelines for lighting efficiency for the existing adobe buildings are as follows:

1. **Strategies for Interior Lighting**

- It is important to look for all opportunities to exploit the potential of natural light as it is more efficient in terms of the number of lumens per watt of heat. Obviously consideration must also be given to heat losses and gains that might result from the use of windows or skylights.
- Using florescent lights instead of regular incandescent lights will reduce internal heat gains, lessening the amount of work the air conditioner needs to do in order to cool the house.
- Switching the existing incandescent lamps (the type normally used) to compact fluorescent lamps which use less amount of energy and emit less heat for the same amount of light.
- Reorganising room dimensions and surface finishes also affect the required light output and thus the energy consumption of all interior lighting systems.
- Locate activity areas that require more light nearer to windows. For instance, place a hobby or homework table next to a window.
- Using light colour in the internal spaces and external walls will improve the lighting quality.
- Dimmer switches help save energy by reducing the light level in a room to only that which is necessary. They are very popular for dining, living, and family rooms.
- Consider the installation of fluorescent fixtures in kitchens, baths, laundry rooms, etc, and locate switches at exits to rooms/lobbies etc to encourage switching off in unused areas.

2. **Strategies for Exterior Lighting**

- Direct and control light output to locations where it is most needed.
- Use outdoor lights with a photocell unit or a timer so they will turn off during the day.
- Design and install lighting to minimize glare.
- Photocells can be used to save energy by turning lights on and off in response to natural light levels. They can also be used to switch outdoor lights on at dusk and off at dawn, for example.

10.3.2.2 Households Appliances

Household's appliances can generate a lot of heat and thus increase the heat gains and air-conditioner cooling load in spaces. Using new and labelled energy-efficient appliances will help to reduce the internal gains as well as cooling load. However, whilst new appliances may be more energy efficient in operation, they are increasingly utilising stand-by modes in which they actually remain on whilst not in use. This was originally designed to keep circuits warmed up so the device could be switched on quickly. More recently, power consumption-when-off has been used to support remote controls (TVs, VCRs, stereos) and built-in continuous displays (such as found in microwave ovens or on a stereo). Other examples of devices that may consume power when off include AC transformers, rechargeable batteries, or wall power adapters. Since these devices typically spend much more time in stand-by mode that in actual operation, this represents a significant additional electrical and heating load that simply was not there 15 years ago.

Given the relative affluence of typical Saudi families, these devices are in widespread use throughout the home. Examples include answering machines, portable radios, external modems, computer printers, and many other electronic devices. Also, some devices that do not use wall adapters and provide no functionality at all when switched off may consume some of the electrical power, totally unknown to the user. A compact stereo system (one piece) for example, was consumed at 1.2 watts when turned off [10-5]. Other appliance used nowadays in Saudi residential homes such as refrigerators, drainwater and clothes dryers that may cause heat to interior spaces and energy consumption. Reducing the heat generated by these machines in summer will also reduce cooling loads. New units are much more efficient than older ones, which also helps reduce heat loads in summer and would reduce the cost of cooling. The following points are general guidelines for the household's appliances:

- Cooking in the open spaces of the house such as courtyards or in the basement and using microwaves more than gas or electric ovens can reduce heat gains and energy consumption.
- Using energy efficient appliances such as washers, dishwashers and water heaters which can generate less amounts of heat and humidity.
- Sealing the laundry space and water heater from the rest of the building will help to minimize the heat gains to other spaces.

10.3.3 External Landscape

In terms of thermal comfort a carefully considered design of the external environment can be extremely beneficial. This can be help to reduce the effect of solar radiation in the adobe building. Whilst the sensitivity analysis in Chapter 9 showed that incident solar radiation was not a significant source of direct heat gain within the building, its indirect effect is to increase the surface temperature of all the external wall, paths and roofs. This in turn raises local ambient air temperatures which, if the air infiltration rate in the building is high, means that any incoming air will be at a higher temperature.

Appropriate selection and placement of vegetation means considering the shape and character of the plants to be used both in winter and summer, as well as the shape of the shadow it provides. The principal factors to be considered in the selection of deciduous trees are the mature height, growth rate, leaf appearance, fall patterns and distance of branches from the ground. For example, the planting of semi-deciduous/deciduous trees to the south can provide shade in summer and yet still allow sunlight to enter through the windows in winter. Planting moderate size shade trees to the southeast and southwest will assist in providing summer shade to the buildings walls and roof. The functional use of groundcovers as a ground surface layer provides for a visually pleasing environment that effectively reduces ambient air temperatures and unnecessary reflective sunlight and heat. These include the following general guideline to be considered in external shading:

- The appropriate shading of external area with trees and shrubs will help to reduce the albedo effect and providing a more visually pleasing environment.
- Select species suitable to the climate and local rainfall is very essential. In other words, select the right plant for the right location and function.
- Trees with heavy foliage such as palm and *Athel* are very effective in obstructing the sun's rays and casting a dense shadow.
- The roof, walls and windows can be shaded by planting high branching canopy trees
- Tree such as deciduous vines such as ornamental grape or wisteria grown over a pergola is best for north-facing windows to provide horizontal shading
- In summer, vertical shading is best for east and west walls and windows, e.g. screening by dense shrubs, trees, deciduous vines supported on a frame, shrubs used in combination with trees to protect from intense sun at low angles.
- In winter, especially to the north of the building, the use deciduous trees and plants, to allow the access of winter sun to north windows.

- Tall, low-branching of the evergreen trees should be kept at adequate distance from north-facing windows to avoid overshadowing in winter.
- The branches of the evergreen trees should be high enough to permit the entry of as much sunlight as possible in winter.

10.4 Putting it all Together

The potential effects of applying all of these recommendations to the example buildings can be quantified by comparing internal temperatures in each zone of interest with those in the same zones of the reference or base case models. To do this, the parameters of the reference models were altered as follows:

- Internal gains were reduced from 5.0 W/m^2 to 2.5W/m^2 floor area in each zone.
- A night-time ventilation schedule was applied in which the air change rate increases from 0.25 ach during the day (7 am-8 pm) to 5 ach at over night (8 pm-6 am) to simulate relatively still conditions.
- The external surfaces of the building were white-washed to obtain a surface reflectance of 0.9.
- An effect of evaporative cooling was applied as a negative heat load to simulate the effect of vegetation and mist spraying in the courtyard. As the amount of vegetation and misting in the courtyard will vary significantly, calculations were run assuming a range of evaporation rates. Using the air flow rates and cell temperatures calculated in CFD analysis described previously, dividing the vegetation cooling potential by the floor areas of each zone to which it was applied gives average cooling values of ranging between -10W/m^2 and -25W/m^2.

Figures below show the potential change in temperature on the hottest day of the year in Riyadh, assuming the lowest potential evaporative cooling rate. It compares temperatures in the four zones of interest both before the application of the suggested techniques and after (given the–Mod suffix). This clearly shows an average instantaneous temperature reduction of almost 4 degrees, a significant reduction given the thermal mass of the building.

10.5 Conclusion

The analysis of these abode buildings has shown that the application of a range of relatively simple passive design modifications can have a significant effect on internal comfort levels. The most important single modification is the control of ventilation. This has two aspects: maximising night-purge effects to cool the mass overnight, and conditioning any inlet air during the day using natural evaporative cooling effects. Controlling this in a simple yet effective manner is the key, hence the use of a sloped courtyard surface to duct air through low level vents into specific ground floor zones designed for daytime occupation.

Reducing internal gains is also important. This is not because there is an immediate effect on internal temperatures, but because each excessive Watt of internal gains is essentially one less Watt of effective evaporative cooling effect.

CHAPTER ELEVEN

SUMMARY AND CONCLUSIONS

11.1 Introduction

The main focus of this thesis was to investigate the thermal performance of traditional adobe houses in Riyadh City, Saudi Arabia. The analysis has been conducted by applying different techniques to achieve the aim of this study. This Chapter will summarise the main aims, objectives and the development of the thesis as well as the findings. The chapter is structured into four main sections. The first section introduces a summary of the research aim. The second section introduces the conclusions and main findings of the research. The third section covers the general recommendations made as a result of the research and the final section proposes suggestions for future study.

11.2 Summary

Saudi is a hot arid country with a bright sky condition, however, the provision of thermal comfort in residential buildings is becoming increasingly dependant on mechanical cooling and air conditioning. Rapid population growth has increased the demand for new houses, which has in turn increased the demand for energy to cool them, usually provided by fossil fuel generated electricity. This will consume the natural resources of Saudi Arabia and cause air pollution from the burned fossil fuel. The overall aim of the research was ***"to analyse the thermal performance of traditional adobe buildings to develop an understanding of exactly how well these buildings are adapted to local conditions and to quantify how they perform thermally. It will also investigate techniques by which their performance can be improved".*** As mentioned in the research scope and limitation in Chapter One the problem of residential houses in Saudi, and particularly in Riyadh, has many aspects. These include economic, energy consumption and socio-cultural needs. These aspects can not be handled all together in a single piece of research work. Thus, this research concentrated on the analysis the thermal performance of adobe buildings and investigated theoretical means for making them more thermally comfortable and efficient. It did not look at the means by which people can be induced to re-occupy these buildings. Whilst there are obviously social issues that may need to be addressed, if they can be demonstrated as more efficient, then the government can advertise and promote an image change which, combined with the potential savings, can make them attractive.

11.3 Findings

The main finding of this thesis can be summarized in the following three parts:

11.3.1 Review

The literature review of the traditional buildings in this work showed that:

- There are different types of construction methods for Saudi traditional buildings and different techniques in house design to manage and adapt to the local climate of each region, depending on the availability of materials.
- Many techniques were used to adapt to local climate, such as using thick walls and courtyards in the central region, *Mashrabya* and *Badgirr* in coastal regions, and stones or mud in the southern regions.

- It seems obvious that adobe as a material has many advantages, mainly in its neutrality, being a cheap, environmental friendly, local building material and able to be obtained almost anywhere.
- The investigation found that it is very rare for modern buildings to make any use of the traditional methods or strategies for cooling, they rely almost exclusively on mechanical systems and air conditioning.
- In terms of privacy, the traditional courtyard houses represent a particular social status or image, while modern buildings depend on high boundary fences for privacy.
- Traditional buildings were a product of local historical, social, cultural, economic circumstances, and adapted well to local environmental conditions.
- Simple elements and features of traditional houses, such as the inner courtyard, have successfully provided tolerable comfort conditions as well as the socio-cultural need for privacy. This has been replaced in modern house design by outer courtyard which allows daylight from four sides but creates overheating and overview privacy problems.

11.3.2 Field Work

- Field work was conducted to measure the performance of some representative adobe buildings. The measurements were conducted to measure air temperature and globe temperature inside a range of different rooms. Measures of the external temperature and the internal shaded courtyard temperatures were also taken. The following is a brief outline of the progression and achievements in this aspect of the work:
- The measurements of the case studies showed that the internal and external conditions were classified as a hot-arid climate due to the low level of humidity and high temperatures.
- The measurements show that outside air temperatures in summer have an average diurnal range of 13°C.
- The collected results show also that outside air temperatures in summer can range from 30°C at night to well over 45°C during the day. This is clearly showed the importance of applying passive modification to the building.
- The shaded courtyard temperatures varied from of 35°C at night to around 43°C during the day. The high temperature in the courtyard showed that the exposed within the paved tiles emphasises that absorbed heat during the day and returned back to the internal rooms during the night were a measure source of heat gain to the building and the need of shading to the courtyard roof was important.

- The closed rooms averaged temperatures of 36-38°C, even when the outdoor temperature was over 45°C, with barely any noticeable diurnal change and with no auxiliary cooling. This clearly showed the warmest condition inside the rooms because the buildings were not sealed due to the high level of infiltration that cause from cracks in window and doors, so during the hottest times of the day the heat flowed from the external environments to the indoor rooms, was kept inside and increased the temperature. The need to seal the building's cracks and replace the old doors and windows are very important to control ventilation during the day. This sealing increases the efficiency of night purging, when the building is manually opened up for natural ventilation at night.

11.3.3 Tools Simulation

The adobe building models developed in this work have been implemented and tested using three different tools, ***ECOTECT***, ***HTB2*** and ***EnergyPlus***. Three different validation approaches were carried out in this study; physical measurements, comparative modelling and a parametric sensitivity analysis.

These comparisons give a degree of confidence in the accuracy of the results obtained, making it possible to believe in the reliability of the predictions of potential effectiveness of different passive design strategies. However, the creation of building simulation models with advanced simulation programs was not a trivial task. It should be noted here that the analysis of performance predictions obtained from the simulation exercise and the reliable model definition process took some considerable time. Whilst the use more than one simulation program increased confidence in the results, it made the modelling process much more complex. Getting each of the parameters right for each tool and ensuring that nothing had been overlooked or missed out in each of the parametric runs required hundreds of additional individual tests to check and re-check the results. The findings of this comparison are summarised below.

11.3.3.1 Tools Capability

- The ability of ECOTECT to export to different simulation tools was very valuable in reducing what would have been an almost impossible data management task in the creation and modification of building geometry for tools such as HTB2 and EnergyPlus.
- The different tools were shown to work under the specific hot arid climatic conditions of Riyadh.
- There were significant differences in the time requirements for the model creation and the levels of detail in model definition between the tools.
- There are significant differences in the ease of use between the simulation programs used in this study. ECOTECT was the simplest and easiest mainly because the user can actually see the building model and access it parameters directly and, for the most part, visually. The other programs were more difficult to use as checking and re-checking parameters required searching through large text files. In the case of HTB2 this was worse as the information is distributed amongst many different files, each with slightly different formats.

- The model detail in HTB2 was limited. For example, the maximum number of window openings was exceeded in the very first model. This was overcome by amalgamating a small number of windows in the one zone together.
- The capability of EnergyPlus is limited to specific shapes. In terms of openings, it does not appear to handle triangular or non-rectangular shapes. Its four-sided polygon limitation, which is believed to have been removed in the most recent release, also required that the geometric model in ECOTECT be constructed very carefully and took some time to get right.

11.3.3.2 Simulation and Validation Techniques

- **Physical comparison:** Involved the comparison of a model's predictions with the actual measured data of thermal performance of the example buildings. This is one of the most powerful amongst the tools available because it provides a direct measure of the truth of the simulation model against reality. Generally the result of this comparison showed a good agreement between the measurements data of the case studies buildings. There was both under and over prediction of temperatures by all tools, however much of this is a result of differences in the base gains and infiltration in each space and is not significant in the overall analysis.
- **Comparative modelling:** Was the comparison of simulation results of a component or system model run on different programs. However, the comparison between the tools result also shows good agreement, with online slightly variation.
- **Sensitivity analysis:** The sensitivity analysis is carried out in each tool for several runs, where in each run single parameter is changing to find out the sensitive of the model is to changes in different parameters. The results of these test is explained in the next section.

11.3.3.3 Technical Recommendation

It has been shown that there are many different techniques that can be used to achieve not only tolerable internal conditions, but actually a reasonably comfortable environment by applying effective design techniques and managing the occupants use of the space. The efficiency of using each of these techniques can be summarized as follows:

- **Ventilation and infiltration:** This is one of the most difficult variables to measure and the resulting losses are the most difficult to control. It was found through the simulation runs to be the major source of heat gains in the hot summer months. Therefore, careful treatments of cracks and leaks should be implemented and only a minimum infiltration rate should be allowed. Appropriate treatment of infiltration losses through the doors, windows and envelop skin can contribute significantly in energy saving.

- **Internal gains:** Simulations performed in this study found the internal gain of lighting, equipment use and occupancy to be the second most significant source of heat gains in each space. Lighting for example is a major component of this and should be given careful consideration in terms of its operation and management to help reduce electricity use and loads on a cooling system, if used. The use of fluorescent lights in important to minimise heat gains to the spaces. Thermal zoning in the case study building is also an important consideration due to the thermal exchanges through internal spaces (walls, doors and floors). Occupant behaviour inside the spaces, and the use of cooking equipment, is also important sources of internal gains and needs careful design.
- **Night ventilation:** Reducing ventilation during the day and enhancing the ventilation at night is an important strategy to be considered.
  - Controlling the effect of ventilation in all simulation tools was proved to be among the most effective strategies used in this work.
  - Controlled ventilation should be considered in Riyadh climate where out door air can be used for cooling especially at cooling summer nights.
  - Encouraging night ventilation is important for cooling, basically removing the heat stored in building fabric during the hottest part of the day. Therefore, openings should be located in such a way that efficient cross ventilation can be provided, especially for the upper level.
  - During the day, the indoor heat impact should be avoided by closing the doors and windows, especially during the hottest parts of the day.
- **Window shading:** In general, shading windows use has negligible effect on heat gains and building energy performance.
- **Flooring:** Heat losses in summer and gains in winter on the ground floor are significantly stabilised by the exposed. Therefore, consideration should be given to the type of furniture and floor coverings used.
- **Surface colour:** The effect of solar absorption on external surfaces was tested in the simulation tools. The result of the test showed that surface colour is producing effective strategy to the indoor climate. Its collective average temperature effect is dropped by 4-5°C
- **Wall and Roof Insulation:** It was shown at the conclusion that the use of insulation has no any effect.

- **Evaporation:** to provide shade in courtyard by placing internal ponds and water droplet for evaporative cooling. For example, trees, shrubs, and bushes provide natural shade from the sun while giving the courtyard area a pleasing look.
- **Orientation:** the result of this simulation in all tools did not improve the indoor temperature.
- **Combination of Passive Strategies:**
  In general the traditional houses thermal performance can improve better after the building is sealed during the day to reduce the infiltration rate yet allow controlled natural ventilation by occupants at night as well as applying appropriate strategies such as evaporative cooling, white-wash for external surfaces, courtyard shading and landscaping.
- **CFD Ventilation Analysis:**
  In the specific case considered in the CFD study, the suggested cross-ventilation and evaporative cooling strategies proposed here were shown to be effective.

11.4 General Recommendations

Suggested general guidelines for local authorities

Adobe buildings in Riyadh occupy a huge area from the city. In order to adaptively re-use and encourage their effective re-occupation, the active participation of local authorities is required. Therefore, some recommendations may be suggested as follows:

- In these houses infiltration is a major source of heat gain and high temperatures. Therefore, sealing and/or replacing the old window and door openings with more efficient apertures is essential.
- In order to increase the efficiency of building cooling, and avoiding the heat gains from the courtyard, landscaping is a natural and beautiful way for protecting against solar radiation and reducing radiant temperatures. A well placed water pool, native tree, bush or vine that survives with minimal care can also deliver effective shade and generate evaporative cooling.
- Start to use adobe material in some governmental projects as the first step by an authority to encourage and educated propel to re-use these types of building, and highlight this important part of Riyadh's heritage as a solution to current social, cultural, and economic circumstances.

- Place greater emphasis in building design to ensure better performance of buildings in general. For example, the efficiency of night ventilation is important for cooling the building and reducing heat storing in the fabric. Thus, openings should be located in such a way that cross ventilation is promoted.
- The development and adoption of energy codes and thermal guidelines to accommodate traditional adobe as a preferred construction material in buildings to enhance energy efficiency and improve performance. This can lead to an appreciable reduction in energy consumption and associated environment pollutants.
- The government should establish a building manufacturing guideline to include traditional adobe brick and other traditional elements in construction to ensure maximum energy conservation for the new building.
- The government should establish an information database in this area, giving out tools and increasing public and policy-makers' awareness of cost effective energy- efficient building material, methods and designs - as well as benefits of energy efficient measures in buildings.
- Using and highlighting the concepts of passive design in the development of the thermal indoor condition is needed in our architectural education.
- There is an important need to consider the environment and climatic factors in the design of housing and the assessment their performance in hot climates, especially at the early stage of design.

11.5 Suggestions for Future Study

The aims and objectives in this thesis have been achieved, however, throughout this investigation several areas need to be investigated and could well form the basis for future research. These areas are as follows:

- To carry out tests for different materials characteristic and more new constructions related for both traditional and modern use.
- A comprehensive thermal analysis and assessment of the adaptation of adobe traditional building and their cooling systems such as *Mashrabya* and wind catcher or compact planning.
- Questionnaires and surveys on the use of traditional buildings should be conducted to cover all of missing points in this study.
- Conduct a filed measurement for the ventilation rate and its effect in the indoor climate.
- Use different simulation programs for analyses, some other simulation tools can be used to perform the analysis so as to study the characteristics of each tool and the effect on the simulation results.
- Extensive energy survey for buildings should be conducted to serve not only to identify the characteristic of building energy use, but also to find out the energy conservation opportunities.
- Create and update weather data and climate properties related to building energy performance. This can be built up to form a technical base for architects, designers and energy analysts.
- The approach and methodology of this thesis can help to be applied to study and conduct more analysis for different type of buildings and the results can be compared to determine the effect of energy conservation.

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APPENDICES

APPENDIX A

1.1 Hassan Fathi and the Traditional Architecture in Saudi Arabia

Architect Hassan Fathi is one of the pioneers who support the use of mud brick in building construction and the revival of traditional architecture. Fathi was a leader among modern architects in adopting the issues of environmental design and self-help housing propagated by many architects. He went to work in Saudi Arabia as a United Nations expert on housing, where he wrote a report titled *"General Outlines in Executing the First Stage of the Rural Housing Project in the Kingdom of Saudi Arabia"* in 1964 (1384 H). " According to what was stated by the United Nations Regional Office for Social Affairs at Beirut, in cooperation with senior governmental officials, the idea of the project was to establish two prototype villages, one at Algamoom (in Wadi Fatma) and the other at Al-Diriya near Riyadh".

Although it had been intended to use these villages as part of a pilot project for a much more ambitious plan to improve the general standard of living in rural areas of the Kingdom, with a particular emphasis on the recognition, in a modern context, of Arab culture and civilisation, by the time Hassan Fathi arrived to take up his work, the scale of the project had been reduced from two villages to just two prototype houses. He explained that:

Two prototype houses were to be constructed using various types of roofing which can be constructed in the rural areas, among which are domical roofs. The designs of these houses allows for the influence of climatic conditions and the provision of thermal comfort, organizing domestic services and health facilities. This aimed at checking the acceptance of the proposed types of architecture by the people before rushing into constructing the entire villages. [1-27].

These houses were subsequently completed, and two others were redesigned with a view to improving the living standards of the occupants. The following factors have been highly influential in the proposed designs and construction suggested for Al-Diriya:

1. **Construction:**

The buildings were constructed of mud according to local custom and practice, and in line with Hassan Fathi's preference for natural local materials. As this material was readily available, being traditionally found in a nearby valley, it was the obvious choice. Used in a variety of ways, the material created a sense of harmony in buildings and communities and obviated the need for recourse to exported materials.

> *"The normal roof requires cement, concrete and steel or wood, which peasants could not offer and would have to buy for cash money. But we could lessen the construction cost if we apply the idea of giving strength via geometrical shapes*

for constructing roofs or palm-leaf, and wire mesh for constructing corrugated roofs" .

Accordingly, Hassan Fathi proposed the use of domed roofs saying,

> "*There should be some solutions for making roofs without hardship. Domed roofs will give this possibility. It is made of adobe consisting of mud and straw which is available and can be afford by most of the inhabitants*".

Domed roofs were a new element in local construction, as they had not been used before in the Kingdom. In order to build houses with domed roofs, Hassan Fathi suggested employing specialist masons from the Aswan province in Egypt, where there is considerable expertise in this type of construction. It was intended that they should pass on their skills to local people at the same time as constructing domed and vaulted roofs.

2. **Climate:**

Because the temperature is severe, and few people have access to air conditioning or other electronic means of cooling, climate is the paramount consideration in housing design in the rural areas of Saudi Arabia. Hassan Fathi states:

> *So, architectural solutions should be studied for treating climatic conditions by considering first of all the architectural treatments founded by the local inhabitants* "Fathi reported.

Fathi had a wide range of experience and this, combined with the results of his considerable research gave him a comprehensive understanding of local building methods, and the means by which extreme climatic conditions had traditionally been dealt with by "aerodynamics" (1-27).

It was his first instinct to revive traditional building design on the grounds of appropriateness and utility, but he was also motivated by the desire to preserve and perpetuate architectural principles reaching back many centuries, and to revitalise Islamic architecture.

3. **Architectural Style:**

Before beginning work, Fathi made a study of the village houses, and noted their construction and aesthetics in order to make himself thoroughly familiar with local styles and practices. In particular, he studied the houses belonging to Mr. Mohamed Bin Abdulrahman, and another gentleman, who is not named. The houses were generally similar, and he concluded that the most important elements of design were the large courtyard, open to the sky, and the allocation of separate spaces for day or night use. Both houses consisted of a ground floor, with rooms, *maqa'ds,* toilets, kitchen and stores, connected by partially covered passageways and surrounded by sheep pens.

4. Problems and Solutions:

Hassan Fathi studied the living conditions of the people of Al-Diriya in some detail, and discovered that the following problems existed in relation to their living accommodation:

1. Disorder of internal organization of the elements and their interrelationship which led to congestion o f i nternal c irculation s uch a s e ntering r ooms v ia u nroofed p assage a nd t he location of the kitchen away from the rooms it serves.
2. Lack of privacy due to the direct entrance or access to the roof by guests via the family courtyard.
3. Bad sanitary sgeleus, fittings and drainage in toilets and kitchens.
4. Lack of architectural elements that provided a suitable micro-climate inside the house such as "*Malqaf*" and water fountains.
5. Inconsistency in the building materials used in walls and roofs which raised the cost of construction specially the cost of wood for making roofs.
6. Weak foundations since the entire wall save built out of adobe.
7. Use of roof during night time only by family members.

Hassan Fathi set out to resolve these problems by putting his knowledge of climate and construction to use in his redesigning of the two houses of Mohamed Ibn Abdulrahman and Mr. (X), which he had previously studied, the following solution by Hassan Fathi:

1. Solving privacy problems inside the house e.g. bent entrances, and facilitating access to the roof through guest *maq'ad* (guest room) instead of through family courtyard.
2. Solving congested circulation as in circulation inside courtyard through covered arcade and making the kitchen close to the living room and dining room that it serves. Using cut stone in lower parts of the mud wall to strengthen the structure.
3. Using adobe for making domed and vaulted roofs in bathrooms and other rooms.
4. Maintaining the use of roofs for sleeping and increasing the amount of shade on them.
5. Use of "*malqaf*" as an architectural feature in *Al-Maq'ad* to cool the air entering the house by passing over surfaces wet by water.
6. Developing better bathrooms and fittings so that the bathroom consists of two parts, hot and cold.
7. Maintaining the general architectural style represented in the open courtyard "*hawsh*" the high openings, and the use of adobe as construction material.
8. By doing so, Hassan Fathi introduced architectural solutions which met the social, cultural and climatic requirements.

9. In addition to the few above-mentioned examples, Hassan Fathi also presented two models; one has already been constructed in Al-Diriya and the other did not pass the proposal stage.

Model: Built in Al- Diriya

Having worked he two houses previously described, Fathi then proceeded to construct a new house in Al-Diriya, putting into effect the techniques he had already developed. While including the use of adobe, and the interior courtyard or *hawsh*, he introduced technical improvements to alleviate the effects of the climate. He introduced in this model the system of "*qa'a*" and "*Dar qa'a*" to the "*maq'ad*", based on traditional Muslim houses, and the "*malqaf*" to cool the air it intercepts through passing over a water surface so that air becomes humid and consequently its temperature is reduced.

The house is a U shape, with the house constructed around three sides of the *hawsh,* from which it gets light and ventilation. The windows of the kitchen and bathrooms open into the back courtyard. (The "introverted" space type.)The "*malqaf*" *rises* high above the walls to intercepts as much as possible from the wind around the house. And the inside elevations of the "*qa'a*" and "*dar qa'a*" are adorned by decorative shapes in the openings or outlets through which the air enters the rooms from the "*malqaf*".

In building this house, Fathi did not adhere to his original plan to use domed and vaulted roofs, as the technical expertise to do this was not available locally. Instead, the roof was built with "*athil*" tree and palm leaves.

The house is considered as a model to illustrate the possibility of reconsidering the use of mud and other architectural elements for the architecture of today and tomorrow. This type of reviving architecture of the past does not merely stop at reviving shapes and forms of the traditional architecture, but also reviving what comes from the logical use of the building material and the functional use of traditional building material good through ages.

This house is generally regarded as an exemplary project for the use of mud and other traditional building materials and approaches in the Najed region, and demonstrates that traditional approaches can be adapted to meet the housing needs of this and future generations. The use of traditional architectural features should not be restricted to ornament and design, but should include serious consideration of the use of traditional approaches to function, through an awareness of the logic of traditional solutions.

1-2 Mofti's Questionnaire

Evaluation of Modern and Traditional Housing

Mofti's Questionnaires

Mufti, F. A. Urban Housing Design in the context of Saudi Arabia's cultural and physical conditions: Potentials and Constraints. Ph.D. Thesis, Rensselar Polytechnic Institute, Troy, New York, December 1981 (1-29).

The following questions are designed to help evaluate design and to help evaluate traditional housing in Riyadh, Saudi Arabia you will be asked to responded to each question on a scale from zero to ten, The less of an attribute a type of housing has, the smaller the number you should write; the more of an attribute it has, the larger the number you should write. Thus, a higher value indicates greater preference than a lower value. Remember that the distances between any two consecutive numbers are equal intervals. For example, a distance of 4 units is twice as far as distance of 2 unites. Thus, if one type housing is 4 unites is twice as far as distance of 2 unites. Thus, if one type of housing is 4 units on attribute and the other type of housing is 2 units, the first type would have twice as much of the attribute as second. Are there any questions? If not, let's begin. Thank you for your help.

Scale:

0-------1-------2-------3-------4-------5-------6-------7-------8-------9-------10

1. **How adaptable is each housing design concept to changes in the income of the family?**
   - Traditional (inward looking) --------------
   - Modern (outward looking) --------------

2. **How private is each type of housing?**
   - Traditional (inward looking) --------------
   - Modern (outward looking) --------------

3. **How effectively does each provide separate area of circulation for the family and male guests?**

- Traditional (inward looking) --------------
- Modern (outward looking) --------------

4. How successfully does each type of housing provide the transitional spaces necessary for privacy between: public street and entrance to house?

- Traditional (inward looking) --------------
- Modern (outward looking) --------------

5. How well does each satisfy cultural requirements for the following spaces needed by the family?

a. **Eating:** Traditional -------------- Modern ------------

b. **Cooking:** Traditional -------------- Modern ------------

c. **Entertaining:** Traditional -------------- Modern ------------

d. **Sleeping:** Traditional -------------- Modern ------------

6. How well does each type of housing meet changed needs for space due to the family life cycle?

- Traditional (inward looking) --------------
- Modern (outward looking) --------------

7. How effectively does each type of house reduce the effects of the following?

- **Temperature:** Traditional -------------- Modern --------------
- **Solar radiation** Traditional -------------- Modern --------------
- **Light glare** Traditional -------------- Modern --------------
- **Wind** Traditional -------------- Modern --------------
- **Sand storm** Traditional -------------- Modern --------------
- **Low humidity** Traditional -------------- Modern --------------

8. How affordable is each type of housing for a middle-income family?

- **To build** Traditional -------------- Modern --------------
- **To maintain** Traditional -------------- Modern --------------

9. How much of the following qualities or things would each type of house require:

	To build	To maintain
• **Skilled Labor:**	Traditional ---- Modern ---------	Traditional -------- Modern
• **Intensity of Labor:**	Traditional ---- Modern ---------	Traditional -------- Modern
• **Labor Wages:**	Traditional ---- Modern ---------	Traditional -------- Modern
• **Local materials:**	Traditional ---- Modern ---------	Traditional -------- Modern
• **Imported materials:**	Traditional ---- Modern ---------	Traditional -------- Modern

10. How strongly do you endorse each type of construction for use in developing Saudi Arabia?

Traditional ---- Contemporary ---------- High Technology

11. How suitable is each type of cooling for housing in terms of :

	Passive	Mechanical
• **Comfort:**	Traditional --------------	Modern --------------
• **Maintenance Expense:**	Traditional --------------	Modern --------------
• **Materials:**	Traditional --------------	Modern --------------
• **Modern:**	Traditional --------------	Modern --------------
• **Temperature:**	Traditional --------------	Modern --------------

12. Overall, how would you rate the suitability of modern and traditional housing in the four following areas?

- **Culture:** Traditional -------------- Modern --------------
- **Economics:** Traditional -------------- Modern --------------
- **Climate:** Traditional -------------- Modern --------------
- **Technology:** Traditional ------------- Modern -------------

13. Please write further comments.

....

End of Mofti's Questionnaires

APPENDIX B

2.1 Climatic Data for Riyadh on the Mahoney Tables

TABLE 1

Location	Riyadh, Saudi Arabia
Longitude	46.4 E
Latitude	24.4 N
Altitude	600 m

Air temperature: °C

	J	F	M	A	M	J	J	A	S	O	N	D		High / Low	AMT / AMR
Monthly mean max.	20.4	24.2	27.8	33.4	38.3	41	42.6	42.1	40	35	28.1	21.5		42.6	27.5
Monthly mean min.	8.8	10.2	14.8	20.1	24.3	26.4	27.6	27.1	24.2	19.3	14.2	10.2		8.8	33.8
Monthly mean range	11.6	14	13	13.3	14	14.6	15	15	15.8	15.7	13.9	11.3			

Relative humidity: %

Monthly mean max. a.m.	64	56	50.9	40	32	21	20	20.5	24	33	46	62
Monthly mean min. p.m.	33	22.7	25	17	13	9	8.8	10	9.3	13	23	30.3
Average	68.5	39.4	38	28.5	22.5	15	14.4	15.1	16.7	23	34.5	46
Humidity Group	2	2	2	1	1	1	1	1	1	1	2	2

Humidity group: 1	**If average RH: below 30%**
2	**30-50%**
3	**50-70%**
4	**above 70%**

Rain and wind

Rainfall, mm	4.5	4	20	21	12	2.5	0	0	0	0	11	12	87	Total

Wind, prevailing	SE.	SE.	SE.	NE.	NE.	N.	NW.	N.	NW.	NW.	NW.	SE.
Wind, secondary												
	J	F	M	A	M	J	J	A	S	O	N	D

		AMT over 20°C		AMT 15- 20°C		AMT below 20°C	
Comfort limits		Day	Night	Day	Night	Day	Night
Humidity group	1	26-34	17-25	23-32	14-23	21-30	12-21
	2	25-31	17-24	22-30	14-22	20-27	12-20
	3	23-29	17-23	21-28	14-21	19-26	12-19
	4	22-27	17-21	20-25	14-20	18-24	12-18

TABLE 2

Diagnosis: °C	J	F	M	A	M	J	J	A	S	O	N	D		
Monthly mean max.	20.4	24.2	27.8	33.4	38.3	41	42.6	42.1	40	35	28.1	21.5	27.5	AMT
Day comfort: upper	31	31	31	34	34	34	34	34	34	34	31	31		
lower	25	25	25	26	26	26	26	26	26	26	25	25		
Monthly mean min.	8.8	10.2	14.8	20.1	24.3	26.4	27.6	27.1	24.2	19.3	14.2	10.2		
Night comfort: upper	24	24	24	25	25	25	25	25	25	25	24	24		
lower	17	17	17	17	17	17	17	17	17	17	17	17		
Thermal stress: day.	C	C	-	C	H	H	H	H	H	H	-	C		
night	C	C	C	-	-	H	H	H	-	-	C	C		

Indicators

Humid: H1													0	Totals
H2													0	
H3													0	
Arid: A1	√	√	√	√	√	√	√	√	√	√	√	√	12	
A2					√	√	√	√	√				5	
A3	√	√		√								√	4	

Applicable when: Meaning:	Indicator	Thermal stress Day	Thermal stress Night	Rainfall	Humidity group	Monthly mean range
Air movement essential	H1	H			4	
		H			2, 3	Less than 10°
Air movement desirable	H2	O			4	
Rain protection necessary	H3			Over 200 mm		
Thermal capacity necessary	A1				1, 2, 3	More than 10°
Out-door sleeping desirable	A2		H		1, 2	
		H	O		1, 2	More than 10°
Protection from cold	A3	C				

Indicator totals from table 2					
H1	H2	H3	A1	A2	A3
0	0	0	12	5	4

TABLE 3

Recommended specifications

Layout

			0-10				1	Orientation north and south (long axis east-west)
			11,12		5-12	√		
					0-4	√	2	Compact courtyard planning

Spacing

11,12							3	Open spacing for breeze penetration
2-10							4	As 3, but protection from hot and cold wind
0,1						√	5	Compact lay-out of estates

Air movement

3-12							6	Room single banked, permanent provision for air movement
1,2			0-5					
			6-12			√	7	Double banked rooms; temporary provision for air movement
0	2-12							
	0,1					√	8	No air movement required

Openings

			0,1		0		9	Large openings, 40-80%
			11,12		0,1	√	10	Very small openings, 10-20%
Any other conditions							11	Medium openings, 20-40%

Walls

			0-2				12	Light walls, short time-lag
			3-12			√	13	Heavy external and internal walls

Roofs

			0-5				14	Light insulated roofs
			6-12			√	15	Heavy roofs, over 8 h time-lag

Out-door sleeping

				2-12		√	16	Space for out-door sleeping required

Rain protection

		3-12					17	Protection from heavy rain necessary

Indicator totals from table 2					
H1	**H2**	**H3**	**A1**	**A2**	**A3**

TABLE 4

Detail recommendations

Size of opening

			0,1		0		1	Large: 40-80%
					1-12		2	Medium: 25-40%
			2-5					
			6-10				3	Small: 15-25%
			11,12		0-3	√	4	Very small: 10-20%
					4-12		5	Medium: 25-40%

Position of openings

3-12						√	6	In north and south walls at body height on windward side
1-2			0-5					
			6-12			√	7	As above, openings also in internal walls
0	2-12							

Protection of openings

					0-2		8	Exclude direct sunlight
		2-12					9	Provide protection from rain

Walls and floors

			0-2				10	Light, low thermal capacity
			3-12			√	11	Heavy, over 8 h time-lag

Roofs

10-12			0-2				12	Light, reflective surface, cavity
			3-12				13	Light, well insulated
0.9			0-5					
			6-12			√	14	Heavy, over 8 h time-lag

External features

				1-12		√	15	Space for out-door sleeping
		1-12					16	Adequate rainwater damage

APPENDIX C

3.1 Heat Transfer

The human body core temperature has to be maintained at an almost constant 37°C in order to survive, if the human body creates more heat more than it needs, then it has to be loss to the surrounding environment. If this does not happen, the individual may grow ill or die. The heat produced by the human b ody is dependent on its activity level, and must balance with the external environment.

The human body exchanges heat with the environment by a complex combination of radiation, convection, conduction and evaporation as briefly explained below in Figure (3-1).

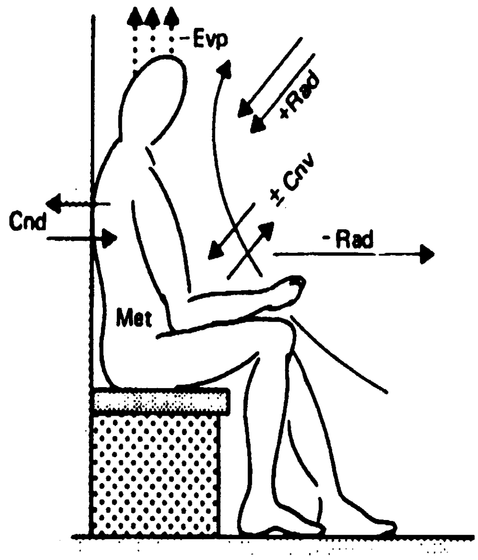


Figure (3-1) Heat transfer process to and from human body, from S. V. Szokolay [3-21].

1. Radiation

Heat exchange is the heat loss by radiation gains from the surface of the human body to its surrounding surfaces without physical contact between the two, when there is different temperature between the two surfaces (bare skin and clothing). The circulation of heat starts by moving from the external surface of the skin to the clothing surface by conduction. After that it moves to air by convection, which is affected by the air speed and radiation. These in turn are affected by the differences between the temperatures of the two surfaces. The rate of the radiant transfer depends on the distance between the two surfaces and the area of the body and the temperature of the environment. It can be calculated as follows:

$$R_e = eh_r \times f_{c1} \times f_{eff} (T_{c1} - T_r) \text{ W/m}^2$$

Where:
e is the emissivity of the clothed/skin surface (generally very close to 1)
h_r is the linear radiation transfer coefficient (W/m^2K)
f_{cl} is the effective clothed area (greater than one because the volume of a clothed body is greater than a nude one)
f_{reff} is the effective radiation area factor (less than one because in some parts - eg under the arms - the body radiates to itself rather than to the environment)
T_{cl} is the clothing surface temperature (deg C)
T_r is the mean radiant temperature (deg C).
as a first approximation:
$f_{cl} = 1 + 0.15\ I_{clo}$ 3.2.2

Where
I_{clo} is the clothing insulation.
$f_{reff} = 0.7$ when seated, 0.72 when standing (Fanger)
$h_r = 4.6\ (1 + 0.01T_r)\ W/m^2K$ 3.2.4

2. Convection

The heat transfers to the surrounding air by contact with the clothing or the skin of the human body. According to Egan, convection takes place between the human body and surrounding air causes heat transfer by motion of heated air (Egan, 1975, pp 47, [3-22]. The amount of convection loss depends on the differences between the skin surface temperature, the air temperature and the air speed. Activities such as walking will add to the effective air movement. It has been put mathematically by McIntyre (1980) as follows: [3-30].

$$C = h_c\ f_{ceff}\ (T_{cl} - T_a) \text{ W/m}^2$$

Where
C is the convective heat loss per square metre of body surface
T_{cl} is the clothing surface temperature (^oC)
T_a is the air temperature (^oC)
h_c is the convective transfer coefficient. in W/m^2K
f_{ceff} is the effective convective area factor
h_c is itself dependent on $T_{cl} - T_a$, and the air velocity (v), but the dependence on temperature is small so that h_c is generally taken to be given by:
$h_c = 4W/m^2K$ for $v < 0.2m/s$ $h_c = 8.3\ v^{0.5}\ W/m^2K$ for $v > 0.2m/s$
the constant value at low air speeds reflects air currents from natural convection

3. Conduction

Conduction is the transfer of heat that occurs through contact between the body and other physical objects such as furniture, floor, etc., or from one location to another within the body. The amount of conduction depends on the difference of temperature between the body surface and the object it touches.

4. Evaporation

As described by Egan (1975) (3-22) evaporation is caused by the change of moisture into vapour. Evaporative cooling helps to cool down the body and takes place when sweat evaporates from the surface skin of the body. This is the only way to lose heat when the body temperature rises. Evaporation occurs when the excess heat loss to the environment can not be lost by convection and radiation alone. The rates of evaporation are dependent on the relative humidity of the surrounding air, air velocity and the amount of moisture available for evaporation. The process of heat loss by evaporation is as follows:

$$\mathbf{E = w\, h_e\, (p_{ssk} - p_a)}$$

Where:
h_e is the evaporative heat transfer coefficient
P_{ssk} the saturated water vapour pressure at skin temperature (mb)
P_a the water vapour pressure of the air (mb)
w is the `skin wettedness' a factor which relates the actual sweating heat loss to the maximum possible
Note: whilst skin wettedness is a factor in the mathematical equation, it will only affect the thermal balance when it implies that the body is having trouble evaporating all the sweat it is producing (though discomfort caused by sweaty skin may also be a problem).
$h_e = 13.7v^{0.5}$ W/m^{2}mb (= $1.65h_c$)

3.2 Clothing Insulation:

Table (3-1) Thermal insulation for individual pieces of garments, after ISO [3-3].

Garment description	Thermal insulation clo	Garment description	Thermal insulation clo
Underwear		**Shirts — Blouses**	
Panties	0.03	Short sleeves	0.15
Underpants with long legs	0.10	light-weight, long sleeves	0.20
Single T-shirt	0.04	Normal, long sleeves	0.25
Shirt with long sleeves	0.09	Flannel shirt, long sleeves	0.30
Panties and bra	0.12	Light-weight blouse, long	0.15
	0.03	sleeves	
Trousers		**Dresses - skirts**	
Shorts	0.06	Light skirts (summer)	0.15
Light-weight	0.20	Heavy skirt (winter)	0.25
Normal	0.25	Light dress, short sleeves	0.20
Flannel	0.28	Winter dress, long sleeves	0.40
		Boiler suit	0.55
Sweaters		**Jackets**	
Sleeveless vest	0.12	Light summer jacket	0.25
Thin sweater	0.20	Jacket	0.35
Sweater	0.28	Smock	0.30
Thick sweater	0.35		
High-insulative, fibre- pelt		**Outdoor clothing**	
Boiler suit		Coat	0.60
Trousers	0.90	Down jacket	0.55
Jacket	0.35	Parka	0.70
Vest	0.40	Fibre-pelt overalls	0.55
	0.20		
Sundries		**Sundries**	
Socks	0.02	Shoes (thin soled)	0.02
Thick, ankle socks	0.05	Shoes (thick soled)	0.04
Thick, long socks	0.10	Boots	0.10
Nylon stockings	0.03	Gloves	0.05

Table (3-2) Thermal insulation for typical combinations of garments, after ISO 7730 (3-3).

Work Clothing	I_{cl} clo	I_{cl} m^2K/W	Daily wear clothing	I_{cl} clo	I_{cl} m^2K/W
U/pants, boiler suit, socks, shoes	0.70	0.110	Panties, T-shirt, shorts, light socks, sandals	0.30	0.050
U/pants, shirt, trousers, socks, shoes	0.75	0.115	Panties, petticoat, stockings, light dress with sleeves, sandals	0.45	0.070
U/pants, shirt, boiler suit, socks, shoes	0.80	0.125	U/pants, short sleeve shirt, light trousers, light socks, shoes	0.50	0.080
U/pants, shirt, trousers, jacket, socks, shoes	0.85	0.135	Panties, stockings, short sleeve shirt, skirt, sandals	0.55	0.085
U/pants, shirt, trousers, smock, socks, shoes	0.90	0.140	U/pants, shirt, light-weight trousers, socks, shoes	0.60	0.095
U/wear (s/sleeves & legs) shirt, trousers, jacket, socks, shoes	1.00	0.155	Panties, petticoat, stockings, dress, shoes	0.70	0.105
U/wear (s/sleeves & legs) shirt, trousers, boiler suit, socks, shoes	1.10	0.170	U/wear, shirt trousers, socks, shoes	0.70	0.110
U/wear (l/sleeves & legs), thermojacket, socks, shoes	1.20	0.185	U/wear, track suit, long socks, runners	0.75	0.115
U/wear (s/sleeves & legs), shirt, trousers, jacket, thermojacket, socks, shoes	1.25	0.190	Panties, petticoat, shirt, skirt, thick knee-socks, shoes	0.80	0.120
U/wear (s/sleeves & legs), boiler suit, thermojacket and trousers, socks, shoes	1.40	0.220	Panties, shirt, skirt, round neck sweater, thick knee-socks, shoes	0.90	0.140
U/wear (s/sleeves & legs), shirt, trousers, jacket, thermojacket & trousers, socks, shoes	1.55	0.225	U/pants, s/sleeve singlet, shirt, trousers, V-neck sweater, socks, shoes	0.95	0.145
U/wear (s/sleeves & legs), shirt, trousers, jacket, heavy quilted outer jacket & overalls, shoes	1.85	0.285	Panties, shirt, trousers, jacket, socks, shoes	1.00	0.155
U/wear (s/sleeves & legs), shirt, trousers, jacket, heavy quilted jacket overalls, socks, shoes, cap, gloves	2.00	0.310	Panties, stockings, shirt, skirt, vest, jacket	1.00	0.155
U/wear (l/sleeves & legs), thermo-jacket & trousers, outer thermo-jacket & trousers, socks, shoes	2.20	0.340	Panties, stockings, blouse, long skirt, jacket, shoes	1.10	0.170
U/wear (l/sleeves & legs), thermo-jacket & trs, quilted parka, quilted overalls, socks, shoes, cap, gloves	2.55	0.395	U/wear, singlet (s/sleeves), shirt, trousers, jacket, socks, shoes	1.10	0.170
			U/wear, singlet (s/sleeves), shirt, trousers, vest, jacket, socks, shoes	1.15	0.180
			U/wear (l/sleeves & legs), shirt, trousers, V-neck sweater, jacket, socks, shoes	1.30	0.200
			U/wear (s/sleeves & legs), shirt, vest trousers, jacket, coat, socks, shoes	1.50	0.230

3.3 Air Velocity

Table (3-3) Associated factors to air temperature factors after Henry J. Cowan [3-31]

	Cause	Associated factors
	Warmth + humid stagnant air	Stuffiness
In door	Coolness + relative dryness + perceptible air movement	Freshness
	Coolness + relative wet + Still air	Dankness
Out door	Hot + humid + windless weather	Sultry
	Extremely hot + windless weather	Sweltering

Table (3-4) The recommended temperatures for different activities after M. David Egan [3-22]

Type of space	Temperature in ° F
Bathrooms, steam and warm-air baths, swimming pools industrial paint shops, special rooms in hospitals, etc.	75 & above
Residences, hotels, motels, apartments, convalescent homes and homes for the aged, etc.	73 to 75
Courtrooms, churches, classrooms, offices, conference rooms, chapels, hospital patient rooms and wards, etc.	72 to 74
Auditoriums, theatres, large meeting rooms, corridors, lobbies, lounges, cafeterias, restaurants, toilets and service rooms, etc.	68 to72
Kitchens, laundries, locker rooms, retail shops and stores, hotel ballrooms, etc.	65 to 70
Gymnasiums, exercise rooms, garages, machinery spaces, foundries, factories, industrial shops, etc.	65 & below

APPENDIX D

The formula of the circle area is as follow:

Area of Circle = πr^2

Where:
$\pi = 3.14$
r^2 = radius of the circle

Therefore, to find the area of the top of the window the following calculation has been done:

Area of Part B:

- **B = 3.14 $(375)^2$ = 441562.5 mm^2**

Area of Part C:

- **C = 38450 / 2 = 220781.25 mm^2**

Area of Part D:

- **D = 220781.25 mm^2**

Length of the heights of the area:

- **L = 220781.25 / 750 = 294.375 mm**

Total length of the heights of the window:

- **Total Length = 294.375 + 1155 = 1404.10 mm**

Area of Circle = πr^2

Where:
$\pi = 3.14$
r^2 = radius of the circle

Therefore, to find the area of the top of the window the following calculation has been done:

Area of the Whole Circle:

- **B = 3.14 $(375)^2$ = 441562.5 mm^2**

Area of Half Circle:

- **C = 38450 / 2 = 220781.25 mm^2**

Area of D

- **D = 220781.25 mm^2**

Length of the heights of the area:

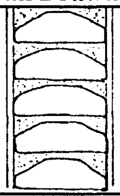
- **L = 220781.25 / 750 = 294.375 mm**

Total length of the heights of the window:

- **Total Length = 294.375 + 1155 = 1404.10 mm**

7.2 Thermal Prosperities of the Adobe Wall

Table (7-1) Thermal properties of the adobe wall.

Thermal Properties of the Adobe Wall	
Wall Drawing	**Wall Detail**
	- 400 mm Adobe Sun Dried Brick. - 30 mm Mud Plaster

Adobe Wall Properties										
Adobe Wall Groups	**U-Val. W/m²K**	**Adm W/m²K**	**S. Abs**	**Tr an**	**Dec**	**Lag (hr)**	**Width (mm)**	**Den s**	**Sp. H**	**Cond**
Adobe Wall Ave	0.9	4.8395			0.2	11	400	1500	845	1.015
Adobe Wall Max	1.1	5.167			0..22	12	400	2000	880	1.28
Adobe Wall Min	0.7	4.512			0.159	10	400	1000	810	0.75

Table (7-2) Adobe wall references.

Thermal Properties of Adobe Sun Dried Brick											
Reference	U-value W/m²K	Admittance W/m²K	Solar Absorption (0-1)	Transparency (0-1)	Decrement (0-1)	Time Lag(hr)	Width (mm)	Weight (kg)	Density Kg/m³.	Specific. Heat J/kg°C	Conductance W/m°C
7-17									1300	0.22	1.4
7-18											
7-19											0.34
7-20	0.7-1.1					12					0.45-1.80
7-21										879	1.28
7-22	0.7-1.1										
7-23										0.2-0.25	
7-24						10					
7-25											0.02
7-26	0.8										
7-27	0.25										
7-28	0.298										
7-29										850	0.46
7-30	1.21						600			810	0.95
7-31	0.0014						254				
	0.001						355				
7-32									1300		0.83
7-33									1730	880	0.75
7-34	1.7					10	304			0.20-0.24	
7-35										0.23	0.17 - 0.58
7-36	0.75	4.512			0.159		400		1730		0.75
	0.75	5.167			0..241		350		1730		0.75
7-37									100-1500		
7-38										0.24	0.75
7-39							500			0.22	1.4
7-40							500			0.22	1.4

7.3 Calculation of Roof Heat Flow:

The materials are evaluated for thermal performance based on measurements known as R-values and U-values. The U-value is the measurement of the thermal conductivity of a material or system of materials measured in W /m2 K. It is the measurement of how much heat will pass through 1m² of a structure when the air temperatures on either side differ by one degree Kelvin. It is used to measure of the thermal efficiency of a building element (i.e. wall, floor, roof, whole building etc). The thermal transmittance is the reciprocal of thermal Resistance (R).

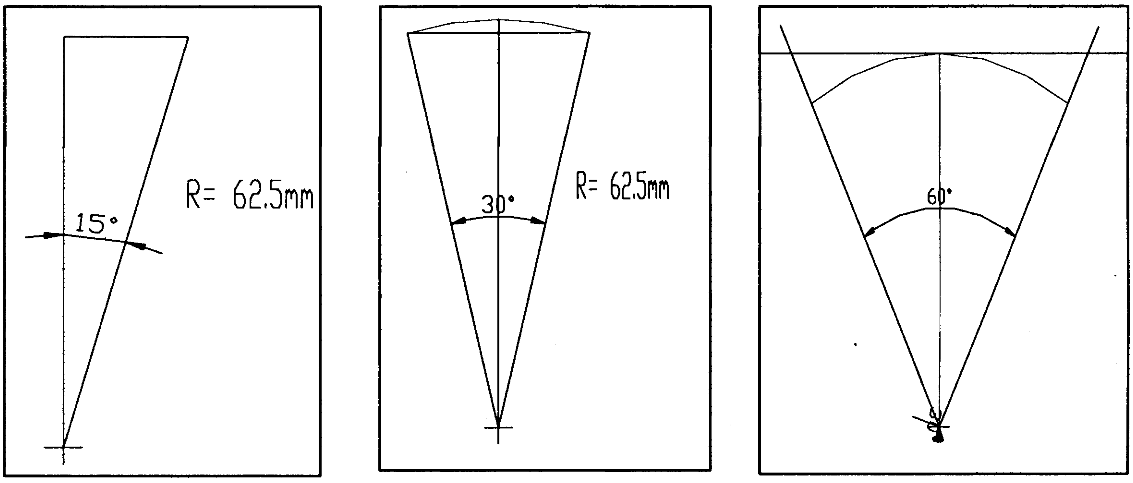
However, the U-value is used to calculate the material properties of the roof layer. In the adobe roof case the heat transfers through the roof layers in two levels (U^A and U^B) as can be seen in Figures (7-5, 7-6). Therefore, the U-values calculation for the two levels is an important element to be taken into account due to the difference on the layer form and on the different level between these layers. The U-value for each part should be calculated separately and then added to the total.

In part U^B the calculation has been made and shown in Table 7-5. In part U^A the calculation of the heat flow in the roof log is calculated in three different angles. The three angels (15°, 30° and 60°) calculation represents the path of the heat flow through the log. The U-value for the three angles calculations will classified into three groups as a maximum, minimum and average, to see if there is difference in the value of thermal transmittance (U) that needs to be modelled.

Table (7-5) U-Value Calculation for Multilayer Roof.

U-Value Calculation for Multilayer Roof					
Layer Name	**Thickness (m) d**	**Conductivity K-value** W/mK	**Resistance R-Value** m²°C/W	**Density** Kg/m³.	**Sp. Heat** J/kg°C
Athel trunk [7-41]	0.125	0.16	0.78	650	1.5
Date palm fronds.	0.03	0.102	0.29	560	-
Soil stabilized layer. [7-44]	0.1	0.75	0.13	1840	850
External Surface resistance	-	-	0.053	-	-
Internal Surface resistance	-	-	0.120	-	-
Clay soil layer. [7-41]	0.1	0.45	0.22	800	800
R-Val. Total for section A	$R^A = 1.593$ m²°C / W				
R-Val. Total for section B	$R^B = 0.813$ m²°C / W				
U-Val. Total for Sec A ,	$U_A = 0.628$ W / m² °K				
U-Val. A+B-1-**Ave**	$U^{A+B} = 1.182$ W / m² °K				
U-Val. A+B-2-**Max**	$U^{A+B} = 1.205$ W / m² °K				
U-Val. A+B-3-**Min**	$U^{A+B} = 1.141$ W / m² °K				

Therefore by using the above formula to calculate the three heat transmittance that flow in each angle of the log, which are 15°, 30° and 60° as seen in Figure below.



Angle 15° **Angle 30°** **Angle 60°**

Figure (7-6) The three angles of heat flow through the roof log.

APPENDIX E

8.2 Exterior and Interior Shading Devices

8.2.1 Exterior Shading Device

a) **Roof overhangs** are particularly effective for the south side of a house, since they allow the winter sun to warm the house while blocking out the high summer sun. The effective design of roof overhangs depends on the latitude of the building site and the times of the year when protection from the sun is needed. Locating the summer and winter path of the sun across the sky will determine the size of overhang necessary to block the sun in the summer but admit it in the winter. Figure (8-3) shows some example of external shading devices.

b) **Awnings** which are attached above and extend down and away from a window, effectively block direct sunlight. A well installed awning can decrease the effect of heat gain up to 65% on southern windows and 77% on eastern windows. Awning colour determines the reflection of heat, so a light coloured an awning helps to increase the reflection of heat. Also, an opening between the top of the awning and the side of the house helps to ventilate the hot air that accumulates. In winter where heat gain is desired, the flexibility of an awning allows it to be rolled up or removed for winter storage.

c) **Shutters** can be made from different materials such as wooden or metal. When they are closed, they cover the windows and prevent sunlight from entering a house. Early builders dealt with their extreme climate by designing windows in two ways:
   - First, the number of window in a building was restricted to those necessary to provide sufficient light and ventilation.
   - Secondly, most of their windows included interior or exterior shelters, such as curtains and drapes or even jars filled with water. These strategies can help to minimize heat gain or loss from windows.

Traditional buildings provide a good example of a wooden shelter or *'Mashrabiyas'* as it called in Arabic, *which* allowed cross ventilation and provided privacy to the occupants of the house. (*see section 4.2.3 Western Region in chapter four for more information*). However, shutters also can be placed outside or on the inside of the window. Besides blocking out the summer heat from the building, shutters also provide privacy, security, and some insulate windows in the winter.

*existing from the evaporative device (dTexit) and the **WBT** depression (dTexit/WBT) is sometimes defined as humidifying efficiency.* Baruch

8.3.2 Cool Tower Work

Cool towers use gravity to move cool air without using any fans due to the difference in the density of air between the inside and outside of the tower which is the main force that drives air in cool towers. Because the inside air is cooler than the outside, its density is higher and the resulting density difference creates its own air flow in a cool tower. This effect translates into the flow of cold air down the tower to the conditioned space. The most common cool towers do this by having a wet pad medium in the top of the tower. Natural down-draft evaporative coolers do not need the blower and require only the re-circulating pump [8-13].

APPENDIX F

BUILDING 1

BUILDING 3

Summary of the Total Simulation Runs

Table (9-19) Summary of HTB2 parameters simulation

HTB2-BUILDING-1

	Internal Gains										Shading										Surface colour										Ventilation									
	1	2	3	4	5	7	10	15	20	40	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2	2.5
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-4	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	40										40										40										40									
	160																																							

HTB2-BUILDING-2

	Internal Gains										Shading										Surface colour										Ventilation									
	1	2	3	4	5	7	10	15	20	40	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2	2.5
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-4	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	40										40										40										40									
	160																																							

HTB2-BUILDING-3

	Internal Gains										Shading										Surface colour										Ventilation									
	1	2	3	4	5	7	10	15	20	40	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2	2.5
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	30										30										30										30									
	120																																							

Total runs =**540**

Table (9-20) Summary of EnergyPlus parameters simulation

	EnergyPlus-BUILDING-1																																							
	Internal Gains										Shading										Surface colour										Ventilation									
	1	2	3	4	5	7	10	15	20	40	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2	2.5
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-4	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	40										40										40										40									
	160																																							
	EnergyPlus-BUILDING-2																																							
	Internal Gains										Shading										Surface colour										Ventilation									
	1	2	3	4	5	7	10	15	20	40	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2	2.5
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-4	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	40										40										40										40									
	160																																							
	EnergyPlus-BUILDING-3																																							
	Internal Gains										Shading										Surface colour										Ventilation									
	1	2	3	4	5	7	10	15	20	40	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2	2.5
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	30										30										30										30									
	120																																							
	Total runs =540																																							

Table (9-21) Summary of ECOTECT parameters simulation

	ECOTECT-BUILDING-1																																							
	Internal Gains										Shading										Surface colour										Ventilation									
	1	2	3	4	5	7	10	15	20	40	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2	2.5
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-4	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	40										40										40										40									
	160																																							
	ECOTECT-BUILDING-2																																							
	Internal Gains										Shading										Surface colour										Ventilation									
	1	2	3	4	5	7	10	15	20	40	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2	2.5
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-4	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	40										40										40										40									
	160																																							
	ECOTECT-BUILDING-3																																							
	Internal Gains										Shading										Surface colour										Ventilation									
	1	2	3	4	5	7	10	15	20	40	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2	2.5
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	30										30										30										30									
	120																																							
	Total runs =540																																							

Table (9-22) Summary of HTB2 parameters simulation

HTB2-BUILDING-1

	Orientation										Insulation										Ventilation and Surface Colour									
	1	2	3	4	5	7	10	15	20	40	10	20	30	50	75	100	150	200	300	500	0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2.5	4
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-4	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	40										40										40									
120																														

HTB2-BUILDING-2

	Orientation										Insulation										Ventilation and Surface Colour									
	1	2	3	4	5	7	10	15	20	40	10	20	30	50	75	100	150	200	300	500	0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2.5	4
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-4	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	40										40										40									
120																														

HTB2-BUILDING-3

	Orientation										Insulation										Ventilation and Surface Colour									
	1	2	3	4	5	7	10	15	20	40	10	20	30	50	75	100	150	200	300	500	0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2.5	4
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	30										30										30									
	90																													
	Total runs =330																													

Table (9-23) Summary of EnergyPlus parameters simulation

EnergyPlus-BUILDING-1																														
	Orientation										Insulation										Ventilation and Surface Colour									
	1	2	3	4	5	7	10	15	20	40	10	20	30	50	75	100	150	200	300	500	0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2.5	4
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-4	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	40										40										40									
120																														
EnergyPlus-BUILDING-2																														
	Orientation										Insulation										Ventilation and Surface Colour									
	1	2	3	4	5	7	10	15	20	40	10	20	30	50	75	100	150	200	300	500	0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2.5	4
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-4	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	40										40										40									
120																														
EnergyPlus-BUILDING-3																														
	Orientation										Insulation										Ventilation and Surface Colour									
	1	2	3	4	5	7	10	15	20	40	10	20	30	50	75	100	150	200	300	500	0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2.5	4
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	30										30										30									
	90																													
	Total runs =330																													

Table (9-24) Summary of ECOTECT parameters simulation

ECOTECT-BUILDING-1

	Orientation										Roof Insulation										Ventilation and Surface Colour										Wall Insulation									
	0	36	72	108	144	180	216	252	288	324	0.1	0.2	0.3	0.4	0.5	7	1	1.5	2	4	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	7	1	1.5	2	4
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-4	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	40										40										40										40									
	160																																							

ECOTECT-BUILDING-2

	Orientation										Roof Insulation										Ventilation and Surface Colour										Wall Insulation									
	0	36	72	108	144	180	216	252	288	324	0.1	0.2	0.3	0.4	0.5	7	1	1.5	2	4	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	7	1	1.5	2	4
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-4	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	40										40										40										40									
	160																																							

ECOTECT-BUILDING-3

	Orientation										Roof Insulation										Ventilation and Surface Colour										Wall Insulation									
	0	36	72	108	144	180	216	252	288	324	0.1	0.2	0.3	0.4	0.5	7	1	1.5	2	4	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3	0.4	0.5	7	1	1.5	2	4
Z-1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Z-3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	30										30										30										30									
	120																																							
	Total runs =540																																							

APPENDIX G

Summary Of Papers Presented In Conferences Based On The Thesis Investigation

1- Fahad Al-Orai'er (2003) **An Analysis Of The Thermal Performance Of Traditional Dwellings In The Hot-Arid Riyadh City.** In the proceeding of The **WAS** Post Graduate Conference 2003. Held in the Welsh School Of Architecture, Cardiff, 10 May 2003.

ABSTRACT
There exist in Riyadh City a large number of traditional dwellings built at the turn of the century that are currently abandoned and unoccupied. Whilst spread out in clusters throughout the city, these account for a significant area in many suburbs. The aim of this PhD study is to investigate ways to make use of these buildings, adapting and refurbishing them to suit the needs of modern city-dwellers. The initial stage of this work has been to analyse the thermal performance of these dwellings relative to more recent buildings using more modern materials and construction techniques. This is of prime importance as thermal comfort is a major factor in the design of buildings throughout Saudi Arabia.
[See the full paper (App G-Paper 1) on the attached CD]

2- Fahad Al-Orai'er (2004) **Climate Consideration in Saudi Arabia Traditional Buildings** In The Proceeding of The First International Conference on Heritage, Globalisation and the Built Environment, Kingdom of Bahrain, 6-8 December 2004.

ABSTRACT
This paper describes the different building traditions of Saudi Arabia in the context of regional climatic variations. Following the discovery of oil, Western building techniques were adopted, which were not always appropriate to the culture and environment. Much recent, Western influenced building is of poor quality. Traditional building methods in each region, from the tents of the Nomads to the reed buildings of the South have evolved to meet human needs and to provide comfort for their inhabitants. A wide variety of building materials, all naturally occurring in the environment, are used and many features of design have been developed to cope with extremes of climate and temperature in a low-impact and environmentally appropriate manner. There has been an interchange of ideas and techniques between Saudi and its neighbours and some influence from the Ottoman Empire.
[See the full paper (App G -Paper 2) on the attached CD]

3- Fahad Al-Orai'er (2005) **An Overview of Riyadh's Traditional Adobe Building: Design Features and Climate Considerations.** Taylor and Francis, Architecture Journal.

ABSTRACT

The traditional adobe building in Riyadh city was developed according to the climatic requirements of the hot-aired dry conditions. The unique features of the adobe building design are based on the internal central courtyard, the thick walls of the building and its minimal openings. An analysis of the traditional urban plan reveals the match to the climatic conditions of Riyadh. The clustered nature of buildings, the attachment of houses and the narrowly bending lanes have contributed to the provision of a cooler environment, adequate shade and reduced impact from sand storms. The mechanisms by which the adobe buildings work to overcome the climatic problems are by providing better heat insulation and higher air circulation through the internal courtyard. The adobe settlement provides a lesson in setting up the urbanisation process without the influence of an urban policy. Nonetheless, the unique features of the traditional adobe houses have been replaced through a rapid urbanisation process with less compatibility to the hot, dry climatic conditions, the social and cultural contexts. This article gives an overview to the adobe building materials, processes and the architecture, as well as appraising the impact of urban modernisation on traditional adobe building and design.

[See the full paper (App G -Paper 3) on the attached CD]

4- Dr. Andrew Marsh and Fahad Al-Orai'er (2005) **A comparative analysis using multiple thermal analysis tools** In The Proceeding of Passive and Low Energy Cooling For The Built Environment Conference. (palenc), Santorini, Greece, 19 - 21 May 2005

ABSTRACT

Recent work has been undertaken to determine the most effective passive cooling strategies to be adopted in the refurbishment of large numbers of traditional adobe dwellings in Riyadh City, Saudi Arabia. To do this, thermal simulation was used to first determine the sensitivity of each building to different design parameters and then assess the potential effectiveness of a range of different passive cooling strategies.

In all aspects of simulation no one algorithm or methodology is perfectly suited to every modelling condition. All have their applications, but some will usually be more appropriate than others under certain circumstances. Given the ramifications of this work in terms of cost, a high level of confidence in the analysis results was very important. Thus, simulations were carried out using multiple thermal analysis tools and their results compared.

This paper outlines the issues associated with creating a base computer model that is fully compatible with multiple tools. It also presents the results of a series of comparative parametric sensitivity studies carried out between the tools and concludes with a summary of the results.

[See the full paper (App G -Paper 4) on the attached CD]