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Impact of Shading Devices on Indoor Sunlight Distribution and Building Energy Performance, *with Reference to Saudi Arabia.*

by

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إهـــــداء

إلى من سهرا من أجل راحتى
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إلى من تحمَّلا غربتى كل هذه السنين

أهدى هذا العمل

إلى أمـــى .... إلى أبـــى

سـهـل

ABSTRACT

Solar shading is one of the cheapest passive cooling techniques employed in hot climates and there is nowadays quite a large number of designs and configurations of shading devices available for architects to use. Considerable work has been done to examine the effect of such shading techniques on space cooling loads. Most published work actually examines the distribution of sunlight on external building surfaces. In regions with both cooling and heating requirements, it becomes important for building designers to understand the impact of solar shading techniques on the thermal performance of buildings throughout the year.

There is an obvious need for reducing the exposure of indoor surfaces to direct sunlight in the cooling season but there is also a need to maximise the exposure of such surfaces to direct sunlight for passive heating in the heating season. A search of the literature has shown a clear need for more comprehensive work to produce useful and more specific data relevant to shading techniques and their impact on indoor sunlight distribution, and consequently on cooling and heating loads, throughout the year. This is the main field for the present research which is partially described in this abstract.

This work evaluates the performance of different shading techniques using a computer program, "SunCast", which is a well-known model developed in the UK as part of a large suite of programs. "SunCast" has already been used for more than a decade by many researchers to investigate the solar performance of building components. Initial experiments were conducted to gain confidence in the "SunCast" model by comparing its results against independent, full-scale tests. The research then examines the criteria and techniques that can be used to evaluate the effects of variables like latitude, orientation and other factors on the distribution of sunlight inside a space. A study was carried out later to evaluate the effect of the indoor sunlit area on the resulting cooling and heating loads, and indoor temperature.

Part of the thesis discusses a thermal simulation for different shading techniques in different climatic zones. Two climatic regions were selected for the experiments: these were Riyadh, Saudi Arabia, representing a hot climate zone; and London, United Kingdom, representing a cold climate zone. The selection of two climatic zones helps to produce a more useful evaluation of the shading techniques. This evaluation also explains the contribution of the selected shading techniques in reducing or increasing heat gain or loss in both climatic zones in summer and winter.

The last part of the thesis presents the main field experiments; these include the physical model and the SunCast model experiments. The experiments were conducted in Jeddah, Saudi Arabia and the efficiency of the selected shading methods were evaluated in this region. The main evaluation reveals that horizontal shading is an efficient shading method which reduces the internal distribution of the sunlit area. Furthermore, reductions in the sunlit area distribution also reduce the required cooling loads, as revealed by the results.

The work which was carried out was as follows:

- The variables that affect the sunlit area inside buildings were specified.
- Using the IES model, the sunlit area was examined as a quantity and as a percentage using different types of shading device.
- Thermal analysis was performed to investigate the contribution of various types of shading device in reducing cooling loads.
- A design guide for shading devices in Saudi Arabia was produced.

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Sahl Waheeb, December 2005

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Nomenclature

θ	the solar altitude angle
$\acute{\alpha}$	the solar azimuth angle
L	the latitude
δ	the declaration angle
G_{sc}	The solar constant (1353W/m^2)
G_{on}	The extraterrestrial radiation
E	The equation of time in minutes
L_{st}	Standard meridian for the local time zone
L_{Loc}	Longitude of the location by degrees west
n	The day of the year
θ	Angle of incidence: the angle of the beam radiation on the surface.
θ_z	Zenith angle
β	Slope: the angle between the surface plane and the horizontal which varies from 0 to 180°.
γ	Surface azimuth angle: the angle on a horizontal plane between the projected solar beam and the projected line which is normal to the surface.
h	Hour angle: the angular at which the earth must turn to bring the local meridian directly under the sun. It is measured on the earth's axis at 15° per hour, with morning being negative and afternoon positive.
R_b	The ratio of the beam radiation on tilted surfaces compared with that on horizontal surfaces.
U	The U-Value of the specified element (W/m^{2}K)
DF	Daylight factor
WFR	Window to floor ratio
QC	Total heat flow in watts
ΔT	The temperature differences
Qs	The total direct solar gain in watts
G	The total solar radiation incident on the window,
sgf	The solar gain factor
SHGC	Solar Heat Gain Coefficient

Abbreviations

HSA	The horizontal shadow angle
VSA	The vertical shadow angle
W	Window without shading devices
H	Horizontal shading devices
V	Vertical shading devices
E	Egg-crate shading devices

CHAPTER 1 INTRODUCTION

1.1. PREFACE

Saudi Arabia is the biggest oil producer in the word, with oil export revenues making up to around 90 – 95 % of the total Saudi earnings from exports. Saudi Arabia's economy is therefore heavily dependent on oil. The Saudi petroleum industry, led by Saudi Aramco, the state's oil company, conducted a study that shows that energy consumption in Saudi Arabia has increased dramatically during the past two decades. Although Saudi Arabia has the biggest oil production capacity, it lacks the ability to develop renewable energy resources. Saudi Arabian science centres have contributed in developing projects to investigate the potential of solar power to be used in green house air-conditioning and desalination plants. However, the potential for collecting renewable solar energy from the Saudi desert is fairly high and, in recent years, saving energy has become a highly desirable approach and is supported by both the people and the government in Saudi Arabia. Electricity bills could be reduced by using energy efficient methods in buildings.

In recent years, modern architecture has developed and focused on natural energy sources. Energy efficient buildings, which mostly use natural energy for their running, use sources like wind power or solar radiation for producing electricity. In hot climates zones much of the energy is consumed to provide huge amounts of cooling loads to provide comfortable temperatures for occupants.

Nevertheless, intensive heat control problems and high temperatures in the hot dry regions have been studied by many researchers. Shading devices have been proven to help decrease the indoor temperature and eliminate the direct solar gain through window openings, especially in hot humid zones. Thus it is important to study other factors which could be useful in eliminating intensive solar radiation through shading devices. There is now much evidence to support the notion of reducing the demand for cooling load through solar control techniques and shading devices.

The majority of the studies on environmental elements and their impact on architecture in hot dry or humid climates has focussed on reducing the undesired sun glare, especially in summer, through shading, enhancing natural ventilation, and using energy efficient materials for thermal insulation in buildings.

However, there are no investigations considering the effect of the distribution of the sunlit area on the space floor, which could be an effective element in reducing cooling loads if this could be minimised in summer using shading devices. Likewise, the distribution of sunlit areas inside the spaces could be useful in winter to enhance the natural heating. It is thus of interest to learn how different effective diameters are related to one another, such as how the sunlit area is related to the thermal performance of the space through the selected shading techniques.

Three main types of shading device were selected for the evaluation. These are: horizontal, vertical and egg-crate shading devices. Other types of shading techniques, for example, light shelves and multi-horizontal louvers, were also used in part of the study.

The present experiments were performed to estimate the magnitude and effectiveness of different types of shading device in reducing the sunlit area and, consequently, temperatures in the hot dry climate of Saudi Arabia, as well as hot climates in general. One of the research aims is also to study the thermal performance of a selected room using these different shading devices. The main tool used for measuring the sunlit areas and thermal performance was the SunCast model.

1.2. AIMS OF THE RESEARCH

These are as follows:

1. To encourage the use of shading techniques, especially in Saudi Arabia, to reduce the required cooling loads.
2. To study the effect of the shading techniques on the penetrated sunlit area which, in turn, affect the required cooling or heating loads. The evaluation is presented through a specific window unit with selected dimensions of shading devices.
3. To provide thermal analysis for the most common shading techniques in hot regions and to study the link for each case with the amount of penetrated sunlit area.
4. To specify the variables that affect the amount of sunlit area distribution. These variables will be very useful for designing appropriate shading techniques.
5. To use the IES (SunCast) model to examine the amount and percentage of the sunlit area by using different types of shading device.
6. To perform thermal analysis to investigate the contribution of various types of shading device in reducing cooling loads.
7. To produce a design guide for shading devices in hot climate zones in general, and with special reference to Saudi Arabia.
8. To recommend an efficient shading method to be used in Saudi Arabia, depending on environmental aspects.
9. To assess various methods to measure the sunlit area on a room's floor. Methods include using computer models and making manual calculations.

10. To conduct a parametrical study which includes a comparison of different types of glazing and shading technique.
11. To investigate different significant factors which highly affect the distribution of the internal sunlit area.
12. To summarize the optimum shading configuration for different shading functions. Results were collected from previous studies and the current study.

1.3. RESEARCH METHODOLOGY

The methodological approach of the thesis can be illustrated in the following points:

- An analysis of the climatic regions in Saudi Arabia and a review of the architectural reactions of each region have been carried out. Special note has been taken of the Jeddah climate and the traditional architecture there. These elements have been presented, with extra emphasis given to natural lighting and shading techniques in the vernacular architecture through the Rowshan.
- Investigations have been made into the previous efforts regarding shading techniques, window functions, natural lighting, and energy saving through shading. Other studies which have a direct relevance to the scope of this research have also been examined, together with the basics of shading principles in buildings.
- The available tools to examine the efficiency of the shading techniques were reviewed; these included computer modelling and physical modelling. The reviewed computer models are:
    - ArchiCAD
    - ECOTECT
    - SunCast, one of the solar IES program packages.

  It has also been noted by previous researchers that physical model experiments are one of the best methods in evaluating the efficiency of shading devices.
- A space unit was designed for the research experiments. This is an average size living space with a window unit facing south, which is the most exposed façade to the sun's radiation the northern hemisphere during winter. In Saudi Arabia during summer, initial experiments revealed that most of the sunlight penetrates the space through the east and west windows.
- The two available evaluation methods, the SunCast model and the scaled physical model, were applied to investigate the distribution of the sunlit area. Moreover, an

examination of the selected room unit with a window was performed using the ArchiCAD model to study the amount of sunlit area penetrating the room's floor through the selected shading techniques, namely the horizontal, vertical and egg-crate shading devices.

- A series of experiments was performed with the SunCast model to study the effect of the selected shading techniques on the amount and percentage of the sunlit area on the internal floor of the room unit. A comparative study was carried out using this model, comparing the efficiency of the shading devices in hot dry climate zones (Riyadh, in Saudi Arabia was selected) and cold climates zones (London, in the United Kingdom was chosen). The thermal simulation comparison was conducted to study the thermal behaviour of the room with the selected shading techniques using the Apachecalc heat gain/loss simulation model in the IES programs package.
- An experiment was also performed using the SunCast model with the same designed room with a window unit in Jeddah, Saudi Arabia, to examine the amount of sunlit area penetrating through the window with each of the selected shading methods. The same experiment was also conducted using the ArchiCAD model. These two experiments were carried out as an appraisal stage for experiments using a scaled physical model in Jeddah.
- A physical model with windows on various orientations was designed and constructed. A model was constructed using the same dimensions as with the SunCast model so the results could be compared. The main aim of these experiments was to examine the distribution of sunlight in various seasons and at various orientations. Consequently, investigations on the required cooling loads could be investigated.
- Design guidelines were drawn up for architects to use for designing shading in Saudi Arabia and in other similar climatic regions. This was achieved by investigating significant factors that affect shading efficiency. Significant factors were investigated to identify the most effective factors in shading design.
- The optimum shading device configurations, orientations and slope angles were investigated. This investigation was conducted by examining recommendations made by different researchers. Various shading functions and aspects were selected for the study.
- Conclusion and recommendations for further research were devised.

1.4. RESEARCH LAYOUT

Chapter One offers a general introduction to the research's scope. A description of the problem upon which the theory is built is given, together with an evaluation of the problem's scale in the architectural approaches in the hot climate regions generally and in Saudi Arabia in particular. The research aims and methodologies are also discussed in this chapter.

Chapter Two is devoted to highlighting the characteristics of the hot climate zones. Furthermore, the architectural response in each region of Saudi Arabia is discussed. This section concentrates on the traditional architectural approaches in the houses in old Jeddah; this illustrates the climatic problems and reflects the bio-climatic requirements, as well as the social desires of occupants. An analysis of the traditional houses of Jeddah is given in this chapter.

Chapter Three illustrates the following factors: window functions, window design methods, natural lighting strategies, and natural ventilation methods. General types of shading device (external and internal) and techniques, and their efficiency in architecture, are also discussed. This discussion includes parameters affecting the effectiveness of shading devices. It is believed that these methods will allow a better understanding of solar control techniques, especially in hot climate zones.

Chapter Four reviews the previous research on window design and shading techniques that is related directly to the scope of this research. Selected research studies have been chosen to be examined and evaluated, which should contribute to a better understanding of shading functions related to window design methods in buildings in hot dry and hot humid regions.

Chapter Five illustrates solar geometry and shading design. Solar radiation characteristics and components are discussed in this chapter, and illustrations of solar charts and sun positions are also provided. Equations for solar altitude and solar azimuth angles were obtained and the effect of solar radiation on buildings is discussed. This chapter also includes a discussion of the horizontal shadow angle and the vertical shadow angle. Examples are provided to calculate the length and width of a horizontal shading device in Jeddah, Saudi Arabia. Furthermore, the overheating period and shading requirements in Riyadh are illustrated.

Chapter Six offers an appraisal of the selected model (SunCast) to evaluate and compare the results achieved using this model with other related research results. It is important to note that the experiments were set up in exactly the same way as the related research experiments so that the results could be compared. The sunlit area through the plain window was investigated using horizontal, vertical and egg-crate shading and a comparison is offered in this chapter between the results concerning shading efficiency in reducing solar radiation achieved in this study and the results achieved in previous research. Moreover, the effect of factors such as latitude and orientation are given at the end of this chapter.

Chapter Seven explores variables affecting the distribution of the sunlit area using different shading techniques. The evaluation was performed using the SunCast model so this chapter also includes a brief description of the abilities of this model. Variables affecting the sunlit area distribution are discussed in detail, together with the effect of summer and winter, to investigate shading efficiency in both seasons. Aspects such as latitude, orientation, shading devices, time and window slope are discussed in detail. Part of the chapter investigates the effect of tilted windows on the required cooling load.

Chapter Eight presents a comparison of the shading devices' performance in two different climatic zones: the cold climate zone represented by London in the United Kingdom and hot dry zones represented by Riyadh, Saudi Arabia. In addition to the study of the sunlit area, a thermal simulation study was performed to evaluate the shading devices' efficiency. Moreover, a sunlit area distribution ratio study was conducted to compare the sunlit penetration ratio in summer to that in winter in Jeddah and Riyadh, Saudi Arabia. The study also investigates the dimensions of shading devices which contribute to reducing the sunlit area by selected sunlit distribution ratios.

Chapter Nine consists of two parts. The first part includes the presentation of the physical model experiment, carried out in Jeddah, Saudi Arabia, on 21 December and in June. Moreover, these experiments were re-conducted in December 2004 for added accuracy. The results of this experiment were compared with other results achieved from the ArchiCAD model and the SunCast model, to evaluate the accuracy level of the results achieved using the physical model. However, the chapter is mainly concerned with discussing and comparing results achieved by the physical model and the SunCast model. The study explores the most efficient shading method in the hot climate with the efficiency of shading devices being measured by their ability to reduce the sunlit area distribution and to decrease the required cooling loads. The second part of the chapter includes parametrical study investigations. These investigations include methods of calculating the internal sunlit area, significant factors related to shading devices, and investigations into various glazing types. One of the main aims of the parametrical study is to explore the most effective factor in the internal distribution of the sunlit area.

Chapter Ten summarises and draws conclusions from the achieved results. Moreover, it illustrates the most effective factors in reducing the internal distribution of the sunlit area. The possibility of reducing cooling loads by reducing the sunlit area is discussed in this chapter. Shading guidelines for Saudi Arabia are presented with recommendations for the best shading methods to use in Saudi Arabia. Illustrations of window ratio, together with the saving in cooling load ratios, are summarized and horizontal shading advantages are also discussed in detail in this chapter. Finally, recommendations for further research are offered.

1.5. THE STRUCTURE OF THE THESIS

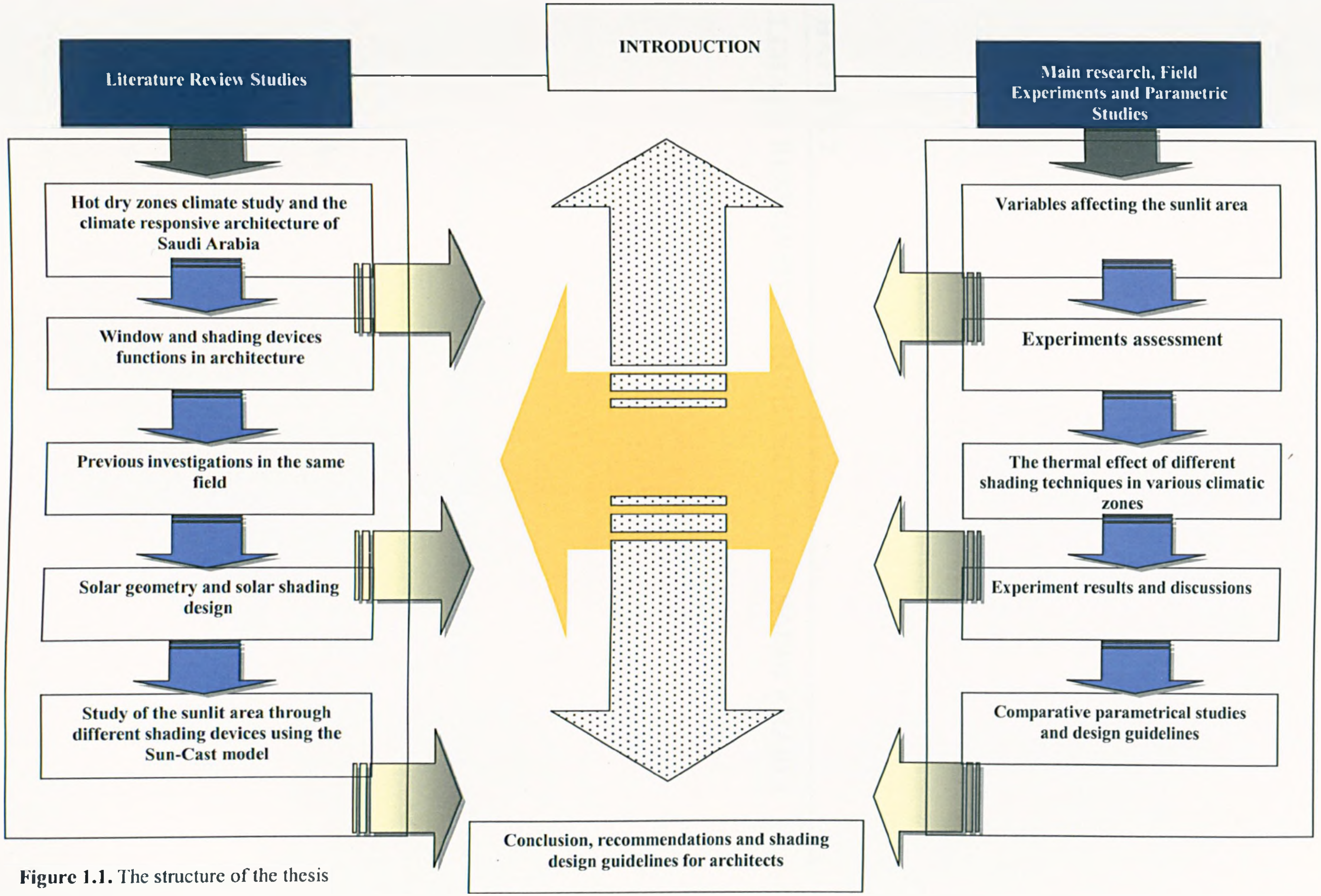


Figure 1.1. The structure of the thesis

CHAPTER 2

CLIMATE RESPONSIVE ARCHITECTURE IN SAUDI ARABIA

2.1. Introduction

Hot climates are generally composed of two main characteristics: 1- the hot dry climate and 2-the hot humid climate. The hot dry climate is characterised by very cool temperatures in winter and very hot temperatures in summer that can reach 40° C to 45°C. The dryness and the high temperatures make the conditions of this climate severe and uncomfortable. One example of the hot dry climate is in the capital city of Saudi Arabia, Riyadh, and in Cairo, the capital of Egypt. The hot humid climate is characterised by high humidity and a high precipitation rate. O.H. Koenigsberger (1974) divided the tropical regions of the earth into three major climatic zones and three sub-groups:

"1-Warm-humid equatorial climate - subgroup: warm-humid island or trade-wind climate
2-Hot-dry desert, or semi-desert climate - subgroup: hot-dry maritime desert climate
3-Composite or monsoon climate (combination of 1 and 2) - subgroup tropical upland climate."

Climatic factors play a decisive role and have a great impact on architectural design and especially on environmental design. These factors include: air temperature, solar radiation, relative humidity, precipitation, and wind speed and direction. Climatic factors can, however, be useful elements in the use of natural energy in buildings. For instance, the sun's heat can be used in heating buildings in cold climate zones and cool winds can ventilate the building spaces in hot humid climate zones where ventilation is essential.

In hot dry and hot humid regions, solar radiation is fairly high; this is why solar radiation control becomes essential. Moreover, the control of the undesirable solar radiation in hot regions can be achieved by the use of shading devices or "solar controls". In the design of the solar shading devices of a window or any opening, a definition and an awareness of the overheated period is required as a first step.

Studying the performance of the devices in terms of shadow angles is essential as only then can the designer proceed to the detailed design of the shading devices. These methods are mentioned by O.H.Koenigsberger (1974). Shading devices come in many forms and shapes. Some are suitable for low sun angles and others are suitable for high sun angles; they can also be fixed externally or internally. Moreover, natural shading devices, such as trees and shrubs, can be efficient shading tools.

The climate in Saudi Arabia has a strong impact on the architecture in different regions of the country. Four main regions are investigated here and the architecture of each region is affected by the local climate and the available materials in the region itself.

2.2. Climate

2.2.1 Climatic Analysis of the Hot Climate

2.2.1.1. Hot Humid Climate

A hot humid climate is characterised by high humidity throughout the year, with a lack of seasonal variation in temperature. Most of the hot humid climates can be found around the Equator and extend to 15° degrees north and south. In such regions, the temperature can reach up to 27°C to 32°C in the shade, and 21°C to 27°C at night. The annual rainfall in a humid climate area can vary from 2000 to 5000mm so vegetation grows quickly due to the effect of continuous rainfall. The sky is always cloudy in this type of climate throughout the year; it can cover up to 60% to 90% of the sky and can be bright, sometimes with a luminance of 7000 cd/m^2. A part of the solar radiation will be reflected, part will be scattered, and part will be diffused when reaching the ground, sometimes causing glare. Wind speeds are generally low in hot humid regions, although high-speed winds up to 30m/s can occur during rain squalls with one or two main directions (Konya, 1980).

2.2.1.1.1. Recommendations for building designs in a hot-humid climate (Konya, 1980):

1- Efficient ventilation is required for this type of climate; also openness and shading should be efficiently designed to provide continuous sun protection and ventilation.
2- Buildings in the layout design should be detached and spread out to allow air movement between them and to provide natural ventilation.
3- The best orientation is north and south, especially for the habitable rooms in order to provide the maximum airflow in the living spaces.
4- Cross ventilation is highly recommended in the hot humid zone. This can be achieved by having two windows in the space: one on the windward side and the other on the leeward or opposite side.
5- Areas surrounding the building should be shaded by vegetation although this vegetation should not block the natural ventilation.
6- Lightweight construction materials with a low thermal capacity should be used. Walls exposed to the solar radiation should be insulated and have a reflective surface on the outside to avoid overheating in summer. For example, light colours could be used on the outer wall surface.

2.2.1.2. Hot Dry Climate

A hot dry climate is characterised by very high temperatures in summer and a cold period in winter. Most of the hot dry sites can be found approximately between latitudes 15° and 30° north and south of the Equator. Temperatures can reach 43°C to 49°C in the daytime and 24°C to 30°C during the night.

The annual rainfall in the hot dry climate is low, reaching only about 50 to 155mm. This affects the growth of vegetation, making it very difficult for plants to survive; low humidity also affects this.

Sky conditions are generally clear and clouds are few, which is another reason for the low humidity. The luminance of the sky is between 1700 to 2500 cd/m² and can fall to 850 cd/m² during sand storms. The solar radiation in this climate is very strong and direct so the glare can be undesirable. Winds are generally hot and sometimes carry dust and sand (Konya, 1980).

2.2.1.2.1. Recommendations for building designs in a hot dry climate (Konya, 1980):

1- Buildings in this type of climate should be protected from the intense solar radiation. This can be achieved by designing the buildings close together so that they can shade each other and provide minimum exposure to the sun.

2- The courtyard design is highly recommended in hot dry climates, especially for large buildings since it provides shading.

3- Large windows should be oriented north and south. Generally, small sized windows are recommended and these should be shaded from the strong glare of the sun.

4- Ventilation is strongly advisable at night-time and should be as low as possible in the daytime.

5- Water features are recommended in the outdoor areas to provide natural cooling.

6- Flat roofs are recommended and light colours for surfaces also are practical.

Konya (1980) noted that white is simple, cheap and very efficient for use in this type of climate. He added that using white is the most efficient technique for making the outer surfaces reflective. However, it needs to be maintained regularly and sometimes this colour can cause glare. In such a case, a light brown colour is recommended.

2.2.2. Climate of Saudi Arabia

2.2.2.1. Geographical location and climatic analysis

Regarding the physical features of Saudi Arabia, structurally, the whole of Arabia is a great platform of ancient rocks which was once joined with north-east Africa. In relatively recent geological times, a series of great fissures opened and, as a result, a large channel or rift valley was formed and was later occupied by the sea, producing the Red Sea and the Gulf of Aden. The Arabian platform is tilted, with its highest part in the farthest west along the Red Sea, sloping gradually down from the west to the east. The Red Sea coast, where the upward tilt is greatest, is often dramatic and mountainous, with peaks of 3,000 metres. Along the Red Sea coast, there is a narrow costal strip (Tihama) which broadens out in the Jeddah area and provides access all the way through the highlands to the interior.

The Kingdom of Saudi Arabia comprises about four-fifths of the Arabian Peninsula, a land mass constituting a separate geographical body, bordered on the south by the Indian Ocean and on the east by the Arabian Gulf. The Kingdom itself, which occupies approximately 2,250,000 square kilometres (868,730 square miles), is bordered on the north by Jordan, Iraq and Kuwait; on the east by the Gulf, Bahrain, Qatar and the United Arab Emirates; on the south by the Sultanate of Oman and Yemen; and on the west by the Red Sea.

Saudi Arabia, one of the world's biggest oil and gas producers and exporters, is one of the Middle-East countries and is located inside the latitudes 16°N to 32°N. Its western border, which is The Red Sea, connects the country to the African, European, North and South American continents. This is the longest border and is approximately 1700km long. Geographically, Saudi Arabia is divided into four major regions, five if the Rub al-Khali ("The Empty-Quarter" or the Saudi desert) is included.

The first major region is the central region, a high country in the heart of the Kingdom. Secondly, there is the western region which lies along the Red Sea coast. The southern region, in the southern Red Sea-Yemen border area, constitutes the third region and fourthly, the Eastern region is the sandy and stormy part of Saudi Arabia; this is the richest of all the regions in petroleum.

The climate of Saudi Arabia varies from one region to another because of its various topographical features. Being under the influence of a sub-tropical high pressure system, the Kingdom is generally hot in summer and cold in winter; its rainfall most often occurs in winter. (SAIR 2002)

The climate in the south-western part of the Kingdom is moderate, with dry hot summers and cold winters in the interior parts, and with high temperatures and humidity in the coastal areas.

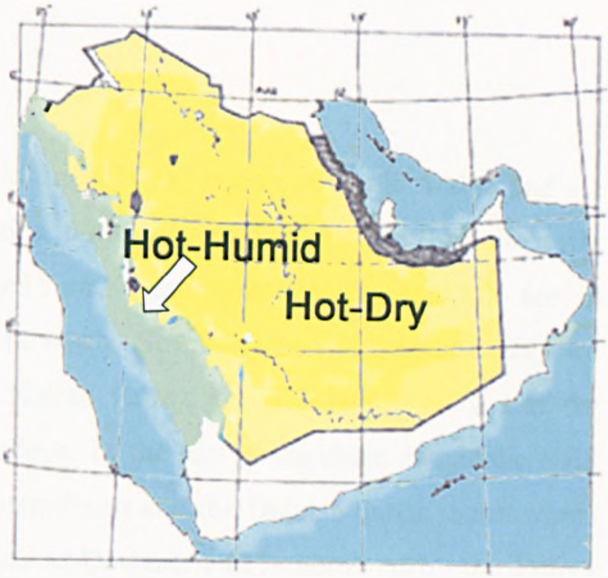


Figure 2.1. Saudi climatic zones, reproduced after Jomah1(1992): (Talib,1984).

Extreme heat and aridity are characteristic of most of Saudi Arabia. The Arabian Peninsula is one of the few places in the world where summer temperatures above 48°C (120°F) are common while, in winter, frost or snow can occur in the interior and on the higher mountains. Precipitation is sparse throughout the country. Annual rainfall in Riyadh, the capital of Saudi Arabia, averages 100 mm (4 in) and falls almost exclusively between January and May; the average in Jeddah is 61 mm (2.4 in) and occurs between November and January. Because of the general aridity, Saudi Arabia has no permanent rivers or lakes.

Jomah (1992) divided the climatic zones in the west of Saudi Arabia into three main zones: 1-The hot humid zone which contains Jeddah and Yandu, 2- The hot dry zone which contains Makkah and Al- Madinah, and 3-The upland zone which contains Taif. The two main zones hot-dry and hot-humid areas can be seen in Figure 2.1.

2.2.2.2. The Hejaz Climate (the Western Region of Saudi Arabia)

The Hejaz region contains some of the major cities in Saudi Arabia, such as Makkah Al Mokaramh, "The Holy City"; Jeddah, a trading city; Madena, the second holy city; and al Taif. The Hejaz climate consists of different climatic zones and each zone has its individual climatic problems. For instance, Makkah and Madena are characterised by a hot dry climate with high temperatures and low humidity for most parts of the year. The winter is cold in Madena while it is warm in Makkah. However, in Jeddah, the climate is hot humid and is characterised by excessive humidity and high temperatures in the hot season; the winter is mostly warm. Maghrabi (2000) described the city of Taif as being in a temperate zone, which is cold in winter and temperate in summer. Problems with humidity do not occur in Jeddah except in rainy periods. Maghrabi also described the whole region of Hejaz as subject to excessive amounts of solar radiation. This also true for the other Saudi Arabian regions.

2.2.2.3. The Sarawat Mountains

The Sarawat Mountains are located in the al Hejaz region in Saudi Arabia and are considered to be the longest chain of mountains in the country. They extend from the north of the country to the south near an area called Asir. These mountains rise to 9,000 feet in the south and gradually fall to 3,000 feet in the north. Several large valleys slope eastward and westward from Sarawat, such as the Najran valley, the Tathleeth valley, and the Bisha, Himdh, Rumah, Yanbu and Fatima valleys. To the east of the chain stands the Najd plateau which extends eastward to the Samman desert and the Dahnaa dunes. Southwards it extends to a region penetrated by the Wadi Al-Dawaser and is bordered by the Empty Quarter. The plateau stretches northward to the Najd Plains, passing through Hoel until it combines with the Great Nefud desert, extending then to the borders of Iraq and Jordan. There are also some mountains on this plateau, such as the Tawabek, Al Aradh, Aja and Salmah mountains. The Empty Quarter is in the south-eastern part of the Kingdom and occupies an estimated area of 640,000 square kilometres. It is composed of sand hills and lava fields. The eastern coastal plain is 610 kilometres long and consists of large sand-covered areas. (SAIR 2002)

2.2.2.4. The Najd Climate (The Middle Region)

In Riyadh, annual rainfall averages 4 inches, with the bulk of it falling from the months of January to May. The Najd region is located in the middle of Saudi Arabia and is characterised by dry, harsh and arid conditions. The middle of the Arabian Peninsula experiences extreme heat and minimal rainfall all year round; rainfall averages less than 5 inches per year. Summers in the Najd region can be remarkably hot because of the inland winds, with temperatures as high as 45°C to 54°C being common. Summer night temperatures are more pleasant, though. Daytime temperatures in winter average around 14°C and, on some nights, the thermometer will plunge occasionally below freezing. Very low humidity in this region is one of the factors that affects the low night temperature.

2.3. The Climatic Environment of the West of Saudi Arabia (Jeddah)

2.3.1. Dry bulb air temperature

In the west of Saudi Arabia, and specifically in the city of Jeddah, the dry bulb temperature reaches up to 38°C in the day time and falls to 26°C at night; this mean maximum temperature is recorded between June and August, the hottest period of the year in Jeddah. In summer, three factors mainly cause discomfort in Jeddah: high humidity, high temperatures and direct solar radiation. Moreover, in winter, the daytime temperature falls to 28°C and nocturnal temperature falls to 18°C. The minimum daily temperatures are found between December and February. As mentioned before, the diurnal temperature range has little variation, unlike the hot dry climate where major variations can be found.

2.3.2. Relative Humidity

Some parts of the western region of Saudi Arabia and Jeddah are exposed to an extremely high humidity level; this is due to the Red Sea that is situated along the west of Saudi Arabia. Relative humidity in Jeddah can reach up to 90%, and occasionally above. Nevertheless, the minimum relative humidity can be around 55%, as shown in Figure 2.3., where the diurnal relative humidity falls to a range of 42% to 92%. During the summer relative humidity is around 90%. These ratios strongly indicate the high humidity rates in Jeddah and in the western region of Saudi Arabia in general. (AL-Lyaly 1990)

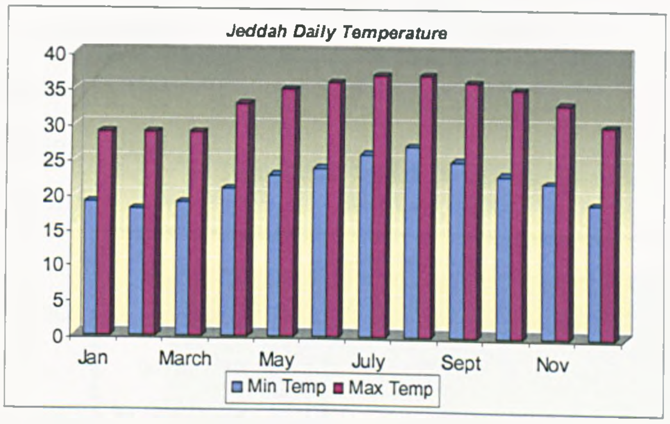


Figure 2.2. Jeddah daily temperatures (AL-Lyaly, 1990).

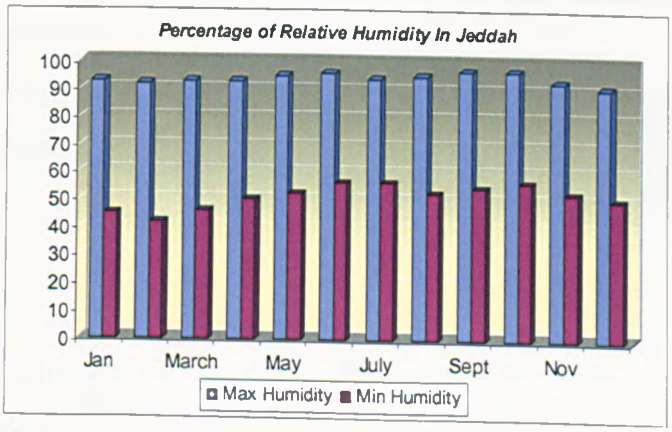


Figure 2.3. Relative humidity in Jeddah (AL-Lyaly, 1990).

2.3.3. Wind speed and direction

Wind and air circulation change from high-pressure zones to low-pressure zones according to seasonal variations. In the spring, a strong wind blows from the "Empty Quarter" desert towards the north west of Saudi Arabia making a low-pressure zone over the Arabian Gulf. In the cool season, the sea breeze in Saudi blows mainly from the northwest and west. However, in warmer seasons, the wind speed in Jeddah reaches 9m/s and is around 6m/s in the cooler seasons. The wind speed is high in the early morning hours, increases, and reach its highest speed at about 3pm. It then starts decreasing, as mentioned by Al-Ansari et al. (1985; AL-Lyaly 1990). The predominant wind in Jeddah blows from the north and northwest of the country, as indicated in the wind rose (Figure 2.4). The prevailing wind directions in Jeddah mainly come from two sides:

1- sea-land breeze from the northwest and west,
2- land-sea breeze, coming from the opposite direction. These occur between the day time and night time cycles. The north wind in Saudi Arabia is usually characterised by high temperature and humidity; such winds blow only occasionally.

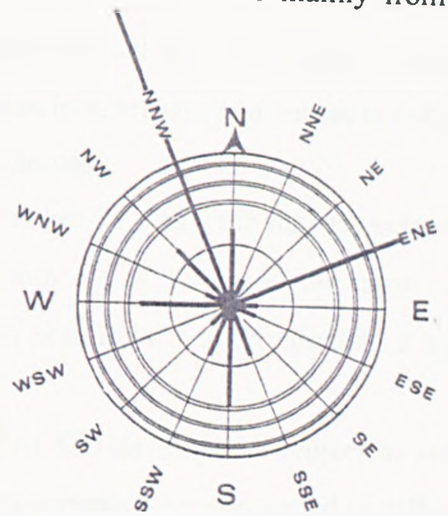


Figure 2.4. Jeddah Wind Rose (Source: Al-Lyaly, 1990).

2.3.4. Precipitation

The Jeddah climate, and generally that of the western part of Saudi Arabia, is hot and humid. Precipitation is very low and, in Jeddah, is irregular; it may even be

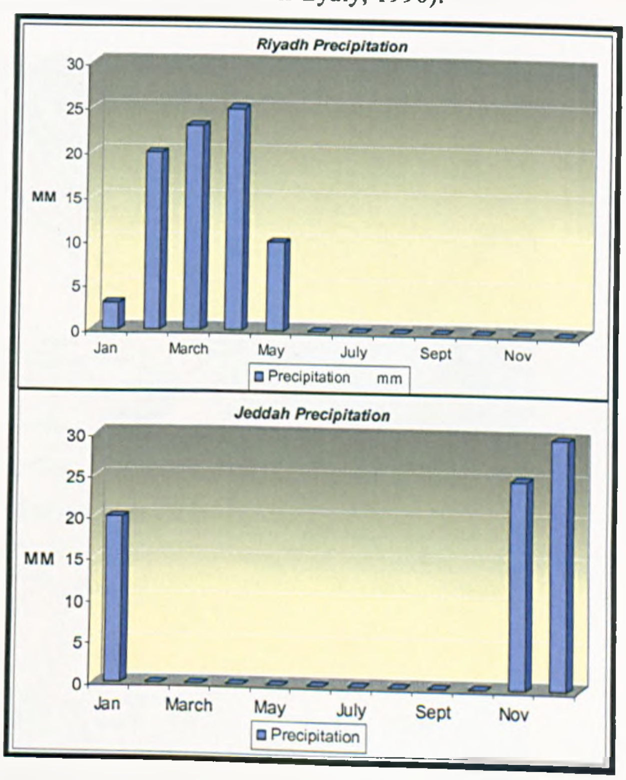


Figure 2.5. Precipitation in Riyadh and Jeddah (Al-Lyaly, 1990).

0mm for the whole year. The maximum precipitation can be found from December to January where it could reach up to 30mm. Figure 2.5 indicates the average monthly precipitation in Riyadh and Jeddah.

2.3.5. Solar radiation

Solar radiation and natural lighting from the sun in the western region is fairly high. The summer solstice occurs on June 21 when the sun's azimuth arc totals 230° (Kukerja, 1978). The noon altitude of the sun is 88° when sunrise is at 5:18am and sunset is 6:42pm, showing that daylight extends up to13 hours and 18 minutes.

The shortest day, the winter solstice, occurs on December 21 when the day extends from 6:36am until 5:24pm; this is where the sun's azimuth arc is 130° and the noon solar altitude is 46°. The difference between the lengths of both days is approximately 2 hours and 30 minutes (Maghrabi, 2000).

King Abdulaziz City for Science and Technology (KACST) developed a project to assess the solar radiation available in Saudi Arabia; these assessments were conducted in different regions of the country. The main aim of the project was to assess the three components of solar radiation: total horizontal, direct beam and diffuse radiation.

Figure 2.6. Map of Saudi Arabia showing the location of Jeddah and Riyadh, (Reproduced from www.lib.utexas.edu/maps/atlas_middle_east/saudi_arabia.jpg)

2.4. The Climate Responsive Architecture in Saudi Arabia

2.4.1. Materials and Construction

Different types of material are used in the traditional architecture of Saudi Arabia. These materials are mainly divided in three groups: stone, wood and mud; the most commonly used material is mud, mostly used as mud bricks. Mud bricks are frequently used in the central region of Saudi Arabia, as well as in the eastern and western regions of the country. The use of materials in the traditional architecture of Saudi Arabia depends on two main factors:1-The availability of the materials in the region and, 2- Climate responsive and environmental necessities.

Stone can be found in the mountainous regions of Hejaz (the western region of Saudi), Asir (the southern region), and formerly in the northern Najed (the central region of the Kingdom). The most common method of construction in the country is using stone slabs laid on rough courses without mortar.

In the Asir region, vernacular buildings are made from layers of projecting flat stones. Flat stones are set into the walls to deflect rainfall away from the outside layer of mud plaster. These stones also protect the mud walls from direct solar radiation in summer.

In the east and west regions of Saudi, coral forms the main building material. Coral could be either fossil or reef coral, depending on the region and its availability. Wood is also an essential component of traditional architecture, with different types of wood being imported from abroad in the past, while now the main source of wood in Saudi is from palm trees; this is used for roofing, lintels (the upper door frame) and wall strengthening. Wood in the traditional architecture of the western region is mainly used to construct doors, windows and decorating façades.

2.4.2. Traditional Materials in the Eastern Region (the Arabian Gulf Coast)

Due to the extreme humidity and hot climate that dominates this region, people here construct buildings by using the limestone that is found in this area while tree trunks are used to construct and support the roofs. A unique feature of the local architectural style is the ventilation tower that is incorporated into the roofs of many buildings on the Arabian Gulf coast. These towers are designed to face the prevailing winds and are constructed to divert the air into the inner spaces of the building. They create an airy and comfortable living environment especially in the hot summers.

2.4.3. Traditional Materials in the Central Region (Najed)

The material most used in this region is the soil or silt collected from the wadis (dry riverbeds) after the seasonal rains, as opposed to the limestone in the eastern region of the Gulf, which is not available here. Straw and other fibres are mixed with water to produce mud bricks which are used in horizontal layers for walls. Windows here are designed to be small in size to provide both privacy and coolness by keeping out the heat. Reducing window size also minimises the entry of the undesired solar radiation. Mud plaster is used to cover the buildings and allows some decorative elements for aesthetic needs. Buildings in this region are structured with practical insulation properties to produce cool living spaces in summer and a warm environment in winter.

2.4.4. Traditional Materials in the Western Region (Hedjaz)

This coastal region is located on a vast layer of coral rock left over from the era when the whole region was below sea level and, because the traditional architecture of the Hedjaz region has been developed through the available local materials, coral and mud blocks are the two main building materials. Mangaby stones are also commonly used in the Hedjaz region. These types of stone are obtained locally from nearby lakes and then sized into cube shapes to be used in buildings (Maghrabi, 2000). Through access to wood imported from India and other sources, the buildings in this region feature highly decorated doors and windows, with windows being carved into screens or Rowshans that allow the passage of air for ventilation while, at the same time, ensuring the privacy of occupants. Screened windows (Rowshans) are also designed as shading devices against the intensive solar radiation. Rowshans are described later on this chapter in more detail.

2.4.5. Traditional Materials in the Southern Region (Asir)

The Asir region is located mainly in the south and southwest of Saudi Arabia between the coastal mountains. The Asir Mountains, which trap the clouds that come from the Red Sea and the Arabian Sea, make mud bricks useless in this wet climate. Instead, the people of this region use stone in the construction of most buildings. The stones, which themselves are found in the Asir region, are often of different colours and sizes, allowing for more decorative alternatives. Houses in the southern region are mainly of two types: town houses and rural houses. Due to the location of this region, the architectural style in Asir is very similar and related to the mountain architecture of Yemen.

2.5. Ventilation and Natural Cooling

Ventilation and natural cooling are essential factors in hot dry and hot humid climates, although the necessity for ventilation is greater in the hot humid zones. In these regions the airflow rate needs to be enhanced to ensure a more comfortable environment for occupants.

The hot humid zones in Saudi Arabia are located in the west region (Hedjaz) where many traditional strategies have been designed to provide efficient ventilation and natural cooling. For instance, Rowshans allow the prevailing wind to ventilate and maximise the air flow rate in the building internal spaces. Another traditional ventilation technique is the use of wind towers which divert the cool air from the upper level to the living zones. Various other factors and strategies can also be found in the traditional architecture of the west region of Saudi (Hedjaz) that can affect and improve the airflow and ventilation. These include building orientation, street orientation and the urban planning of the city.

In terms of the orientation of houses and buildings in Jeddah (the Hedjaz Region) and the efficiency of Rowshans in natural cooling, Maghrabi (2000) noted, in traditional houses in Jeddah, that rooms facing north and west were usually widely opened and facilitated with Rowshans. In more constricted places, houses were also semi-detached (that is, sharing one wall with the neighbouring house). This was essential to enhance the movement of the air between buildings in order to allow moisture to drift away. Consequently, this enhances the house's durability. Maghrabi (2000) also wrote: "*The traditional dwellings therefore faced the seafront. Such orientation is certainly joyful to the occupants who benefit from the continuous breeze*". He also added, regarding the use of urban planning in increasing the efficiency of ventilation, that: "*The distribution of buildings created channels for air to pass*".

The layout of the streets is unequal in width and size. The main streets of old Jeddah radiate from the west which is the waterfront. Moreover, secondary alleyways are arranged along a north-south axis. "*As the sea breeze prevails, the air travelling through the streets tends to generate more speed due to the occurrence of considerable reduction in volume*" (Awbi, 1991; Al-Lyaly, 1990). *The smaller alleys, which are not facing the seafront, on the leeward side would fall under low pressure, which causes airflow through them (Fathy, 1986;* Maghrabi, 2000).

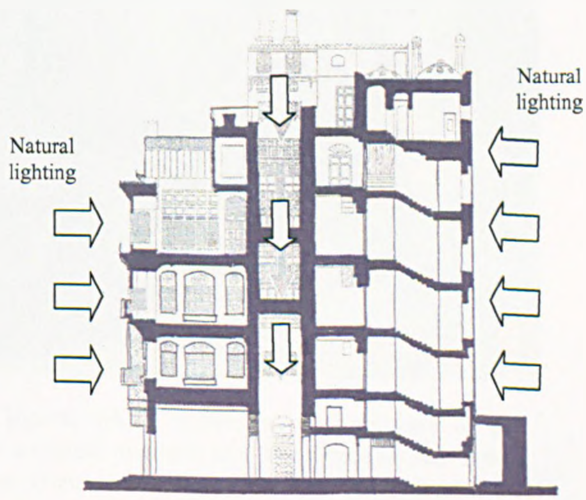
Streets and passageways are always shaded by the surrounding tall buildings. Accordingly, shade will cool the space between the buildings. This efficient method is not theoretical but was confirmed through comparative evaluations and studies of the temperature records of traditional and modern streets in the city of Jeddah.

2.6. Natural Lighting

Throughout the history of architecture, natural light has been considered as the main source of light and so, through studying the availability of natural light, builders and architects have built their dwellings with an appropriate response to this factor. Al-Shareef (1996) observed that windows and openings in regions with high levels of availability of natural lighting should be medium in size and fitted with grilles and translucent or tinted glass for protection against undesired solar radiation.

Al-Shareef (1996) also mentioned that the availability of natural light in a climatic region depends mainly on the amount of solar radiation available in that zone. Moreover, the rotation of the earth about its axis and its revolution about the sun affect natural light availability. Due to the extremely high temperatures, the massive availability of natural light, and the intensive solar radiation in Saudi Arabia, traditional houses, especially in the western region (Hidjaz), are constructed with Rowshans (wooden windows to filter the solar radiation). This traditional element allows a reasonable amount of daylight to penetrate inside the space. Figure 2.7. shows an internal view of the Rowshan. Other strategies to use natural lighting, such as sky light domes, can be found in the traditional houses of Jeddah like those found in Bit Nasef, one of the largest traditional houses in old Jeddah. Some these skylight domes are made of coloured glass to add an aesthetic element to the house. Maghrabi (2000) noted that Khan (1986) indicated that the use of Rowshans reflected the elegance of the house owner.

A



B

Figure 2.7. A. Internal view through a Rowshan and B. cross-section, which shows the penetration of natural light to the internal space (Islamic Architecture: Digital Library).

2.7. The Traditional Houses of Jeddah

2.7.1. Introduction

The traditional houses of Jeddah are generally, as mentioned previously, built from coral which is cut into blocks and mortared together. The mortar mixture could be one of several different types: for example, date pulp, crushed coral and lime, or clay from the bottom of a local lagoon. On the interior and exterior surfaces a smooth plaster made from coral is also used. Wooden beams are used for doors and windows ("Rowshans"), and these are tied to the crossbeams making up the floors. These beams are imported from other countries such as India and Java.

A typical traditional Jeddah house normally consists of 3 to 4 floors (few will extend to 5 floors), depending on the house's location. Jomah (1992) mentioned that in the traditional Hedjazi house: "*Each floor was assigned certain functions suitable to its position in the house and the socio-cultural meaning associated with its spatial organization.*" Maghrabi (2000) also noted social influences on traditional buildings: "*Two dimensions of privacy are found within the traditional house: vertical and horizontal. The social obligations towards guests have created a vertical dimension of privacy between the visitors and the rest of the family.*" The ground floor in houses in Jeddah is the main space for showing hospitality to guests and all other spaces linked with that function are situated there. This is to provide privacy by separating visitors from the family living in the house.

Figure 2.8. Nasef House, which is located in the centre of old Jeddah and which is a typical example of a traditional Jeddah house (Islamic Architecture: Digital Library).

As mentioned earlier, the ground floor is used mainly as a reception area for visitors and is considered to be a semi-private zone in the house. Moreover, the upper floors are normally used for the family members as private zones for living.

Living zones are usually located on the first floor, while the sleeping zones are located on the level above the living zones. Maghrabi (2000) noted that other social behaviours can create different levels of privacy in the growing family structure. For instance, a married son who lives with his parents will usually be provided with his own zone within the house. This private zone is separated from the other house zones to create a specific level of privacy to the son that does not interfere with the daily activities of the other family members. Al-Lyaly (1990) added that this level of privacy is usually achieved by using the upper floor for the parents to live in while the married son will usually use the lower floor.

A horizontal level of privacy is also provided and can be seen in the architectural features of the house. One of these features is that the stairwell in the house is located near the entrance to allow family members, especially women, to move from one floor to another freely without passing by the guests' zone. Also, a degree of privacy can be found in the design of the small stairwell hall which connects the stairwell with some of the house rooms.

Maghrabi (2000) added comments about the privacy afforded by the Rowshan, noting that the privacy achieved by the design of the Rowshan aperture reflects a strong social and cultural impact. The design of the Rowshan, the mashrabiah and the shish are intended to provide a high level of privacy for the occupants while, at the same time, enabling them to observe the activities outdoors. The terrace is an outdoor space with a high level of privacy. This is a room located in the upper level and is open to the sky. Privacy is mainly achieved by the surrounding high parapet which is above the height of the occupants.

2.7.2. Plans of the architectural features

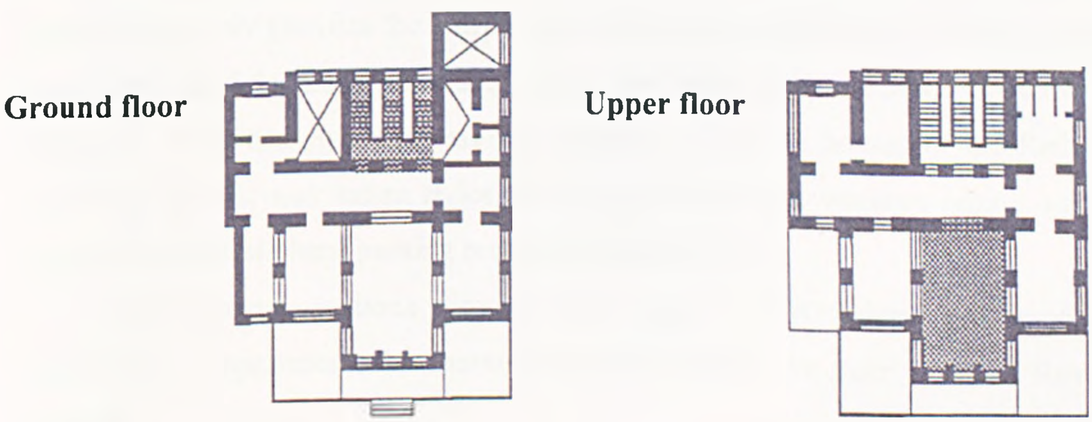


Figure 2.9. A typical traditional Jeddah house: layout of ground and upper floors (Jomah, 1992).

2.7.3. The Rowshan of Jeddah

2.7.3.1. Historical background

Rowshans are considered to be the main window type adopted in Jeddah that provide for the climatic (coolness and ventilation) and social needs (privacy) of occupants inside the dwelling. Jomah (1992) noted that Rowshan is "*a Persian word meaning bright and these structures allow the inner space of the family's living quarters to be extended to the exterior of the house. These Rowshans were elevated seating and sleeping places protruding from the building's façade by means of a latticed, wooden structure. They were the most expensive element of the traditional façade since they were all made of teak. They were decorated with intricately patterned panels, shutters, eaves and cornices.*"

Investigations into Rowshans show that their origins are still arguable. Maghrabi's discussion (2000) suggested that some studies state that their origins go back to ancient castles built thousands of years ago when Rowshans were used merely for defensive purposes, while others studies assert their origins stem from Turkey or India. The most accurate suggestion is probably that made by Khan (1986), who mentioned that the Rowshan is primarily an Islamic technique that has been modified and adapted by many others later.

This argument is also supported by some Islamic literature. Back in 1100AD, the prominent scholar, Ibn Al-Qaim AL-Joziah (1997) cited the word "*Rowzanah*" in one of his books and referred to it as a window. Such an argument could still be debated but what is of more relevance here is the widespread use of this type of window, not only in the Middle East, but world wide, from as far east as India to as far west as South America (Danby, 1980; Greenlaw, 1976; Maghrabi, 2000).

However, Rowshans found elsewhere are much smaller in size and dimensions than those found in the traditional buildings of Jeddah. The projected window bay (the Rowshan) not only glorifies the traditional architecture in Jeddah but is rather a distinctive feature replicated in many structures across the world (Khan, 1986). Greenlaw (1976) mentioned: "The distinguishing external features of the old houses of the Red Sea and some other Islamic and Indian styles are the large casement windows jutting out into the street to catch the slightest passing breeze" (Maghrabi 2000).

The following sections discusses the function of Rowshans and some of their construction components. Also, some information about the main types of Rowshan is provided.

2.7.3.2. Functions of the Rowshan

The main three functions of Rowshans are: 1- ventilation (enhancing airflow); 2- natural lighting; 3- privacy.

Rowshans receive the breeze and prevailing winds from three directions because of their projection and their relatively large size. The Rowshan has the ability to increase airflow and the level of velocity to a desirable level. According to Maghrabi's study (2000), this could be obtained through the use of different types of Rowshan and different sizes of louver aperture.

Al-Lyaly (1990) noted: "*The occupants are cooled through positioning the louver apertures at body level so that even at higher air temperatures there is cooling by sweat evaporation*". Cross ventilation is essential in hot climates, especially in hot humid zones. Rowshans can control the level of humidity in the space through the effect of cross ventilation. Furthermore, Director Arch. Sami Nawar of the Jeddah Historic Area Preservation Department indicated that the Rowshan could reduce humidity and moisture in the passing air through its unique openings.

Direct solar radiation in Jeddah is undesirable, especially in the summer period. This period can extend for more than four months. In turn, shading is essential for such climatic conditions to control the undesirable extensive heat and solar radiation while providing the internal spaces with sufficient daylight. Khan (1986) described the internal penetration of daylight through the Rowshan by the attractive play of light and shadow in the room, the patterns altering throughout the day as they are reflected by louvers and different screen geometries.

The third function of the Rowshan is the provision of privacy. The apertures of the Rowshan allow occupants, especially women, in the house to observe the external view of the street while they remain unseen to people outdoors. One of the factors that enhances this function of privacy is the illumination level which is higher outdoors and lower in the interior. In turn, a desirable level of privacy for the occupants is successfully maintained.

As explained by Al-Lyaly (1990): "*When looking towards the Rowshan from the outside, the solid areas formed by the wooden louvers would be bright and in contrast the gaps in between would be dark prohibiting a view of the interior.*" The Rowshan generally then is an architectural element that can provide the bio-climatic necessities and the social requirements for the occupants. The Rowshan is a very efficient traditional strategy to control the extensive solar radiation.

2.7.3.3. Construction and types of Rowshan

The construction of the Rowshan as an architectural elevation feature reflects the social state of the house owner. This is includes its size and the type of wood used in constructing the Rowshan. Large Rowshans made from high quality wood usually reflect the high social status of the house owner. However, the common type of Rowshan consists of horizontal and vertical patterns extending to cover part of or the whole elevation. According to a previous investigation into traditional houses in Jeddah, the typical Rowshan consist of seven elements, which are:

1- Crown (Taj): located at the top of the top of the Rowshan and consisting of fashionable decoration details. Sometimes this extends beyond the Rowshan's main body.

2- Pearl (Durah): located at the centre of the crown.

3- Upper belt (Hezam Foqani): The horizontal panel that is usually embellished with geometrical patterns. These patterns may sometimes contain porous wooden screens.

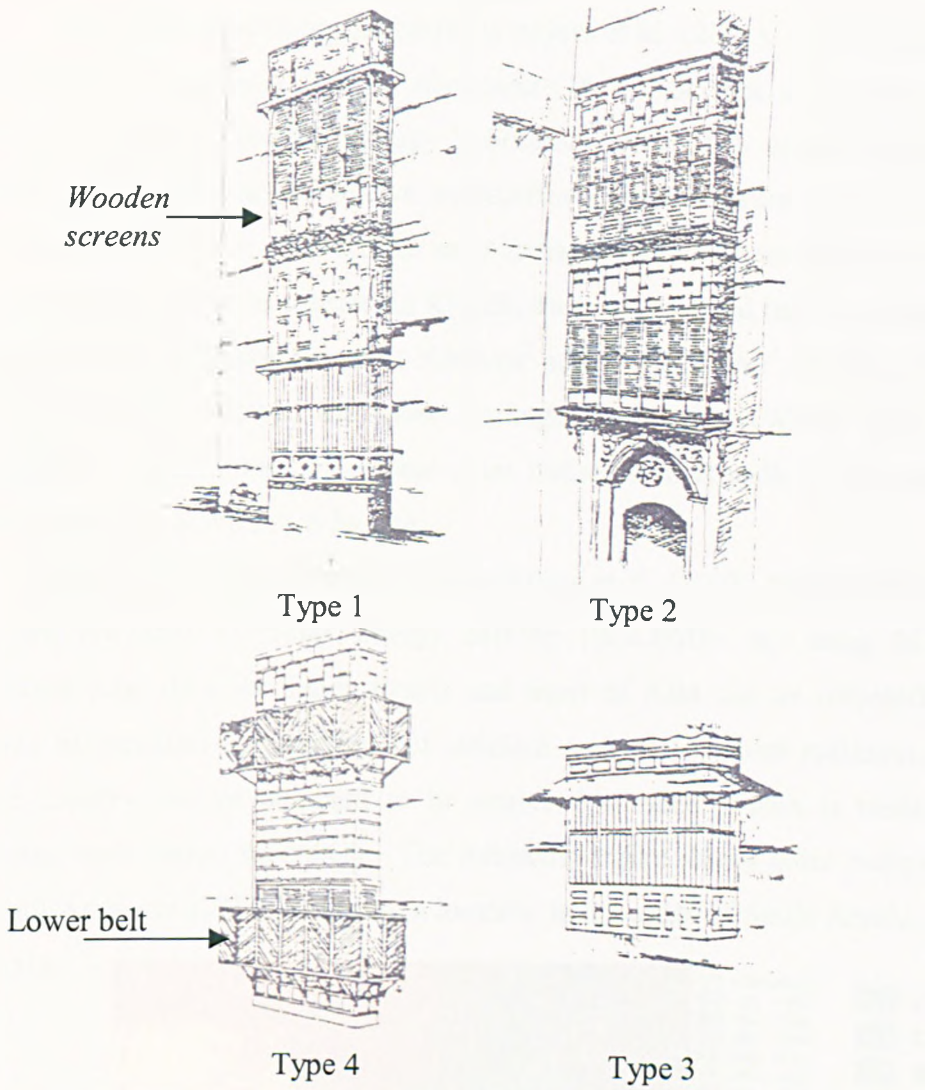
4- The sashes (Deraf): These contain two or more sashes. The upper sashes are fixed and the one underneath moves up and down behind the sash above through side grooves and rests on two hinges leaving a complete aperture. Every sash contains a number of horizontal wooden slats (louver blades). These are movable in a circular manner around their axes. They are called Qalaleeb, referring to the modulated louver windows. Al-Shareef (1996) indicated that every sash contains 12-18 louver blades.

5- Lower belt (Hezam Tahtani): This is wider than the upper belt where its width is normally at a similar height to the inside platform of the Rowshan. The wooden panel is extensively carved with geometrical forms.

6- Brackets (Khradi): These are found at the lowest part of the Rowshan and they act as beams which carry the Rowshan's weight.

7- Wooden screens (Goulah): Lower sashes in some Rowshans are facilitated with wooden screens placed about 0.5m away from the front panel of the sash, leaving a space for water jars (sharbat) to be cooled by cross ventilation. This is illustrated in Figure 2.10, type 4, which illustrates the screen in front of the lower belt.

The following figure, (2.10.), illustrates the different types of Rowshan found in Jeddah according to Khan (1986) and Maghrabi (2000). Several Rowshan elements are demonstrated in this figure. The lower picture in the figure, illustrated by type 5, is a recently built house with all the traditional elements found in the old Jeddah houses.



A

B

Figure 2.10. A. Rowshan types and configurations (Maghrabi, 2000): B. Rowshan photos (Islamic Architecture: Digital Library).

2.8. Solar Radiation Data for Saudi Arabia

According to studies conducted by Myers et al. (2001), an assessment project was performed by researchers at King Abdulaziz City for Science and Technology (KACST) and the National Renewable Energy Laboratory (NREL) to upgrade the available solar radiation in Saudi Arabia. Twelve measurement stations were used to assess the total horizontal, direct beam, and diffuse solar radiation. Measurements were taken on several clear days from sunset to sunrise. In Riyadh, the study showed that the monthly mean daily total direct solar radiation was 8.11 KWh/m^2 and 1.94 KWh/m^2 was the diffused radiation in June while in Jeddah, the same readings were 6.03 KWh/m^2 and 2.23 KWh/m^2 respectively. Furthermore, the global solar radiation in Riyadh in June was 8 KWh/m^2 while it was 7.33 KWh/m^2 in Jeddah.

Based on research conducted by Schilling et al. (2003), high quality solar radiation data are provided by Solar Energy Mining (SOLEMI). By using Metrosat-7, high resolution solar data for Saudi Arabia and most of Asia can be obtained. Satellite data provide information for carrying out efficient analyses of solar radiation and data for a whole country can be obtained to be analysed at once, which is more efficient than analysing each region separately. The following figure shows solar radiation distribution in Saudi Arabia in KWh/m^2. Gizan, a location in the south of Saudi Arabia, is shown as an example.

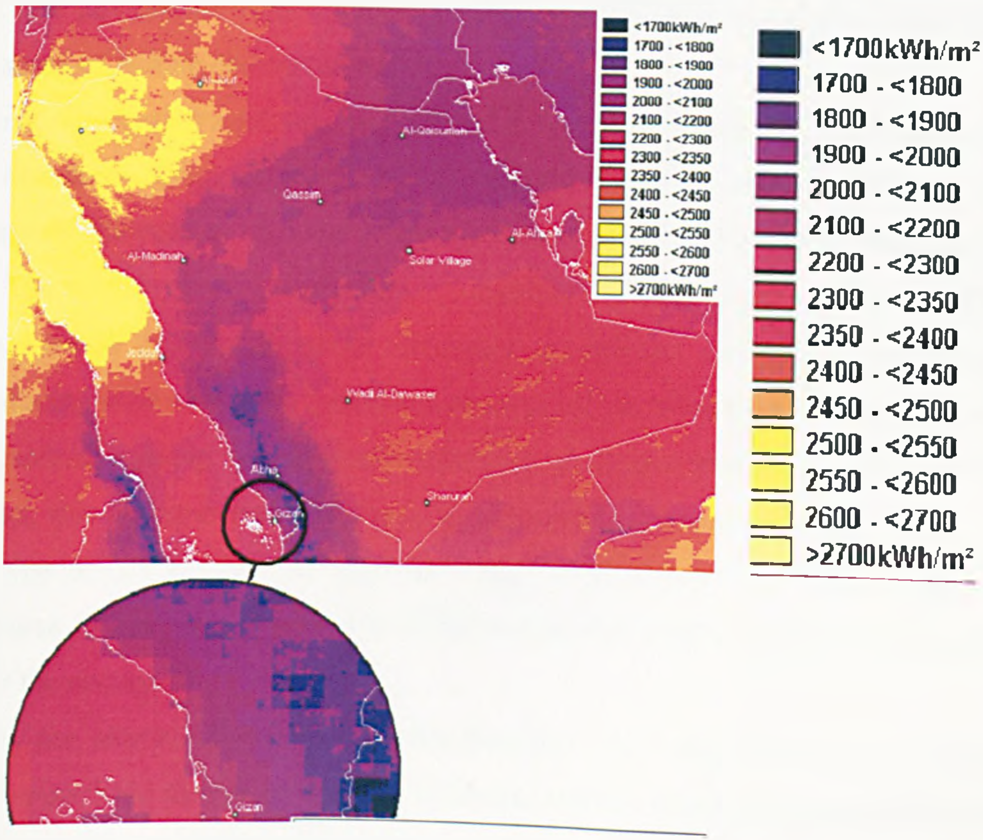


Figure 2.11. Solar radiation data for Saudi Arabia (Schillings et al., 2003).

2.9. Conclusion

Different styles of traditional architecture can be found in Saudi Arabia which reveal specific responses to climatic variations. Variations of style have been created due to three main reasons. These are:

1- The location of Saudi Arabia in a tropical climate zone which includes both hot dry and hot humid climates.
2- The distribution of land and sea masses.
3- The land topographies.

In this chapter the relationship between the architecture and the climate in Saudi Arabia was discussed through an analysis of the climate responsive architecture of the main regions of the country. Each region has its own architectural treatments which have been adapted to respond to the climate through the materials and the construction techniques. Ventilation and natural cooling strategies were also investigated in the vernacular architecture of Saudi Arabia, as well as the natural lighting techniques.

The second part of the chapter investigated the traditional energy efficient techniques used to provide natural lighting and ventilation in the traditional houses of Jeddah in the western region of Saudi Arabia. Existing examples were illustrated by plans and images, as well as the space distributions, and the functions and relationships between these spaces. The last section of the chapter investigated the main elevation structure in the traditional houses of Jeddah (the Rowshan).

An historical background was put forward to include the origin of the Rowshan's name, some discussion about the location of the original Rowshans, and some estimations about the age of Rowshans. A brief discussion showed the three main functions of Rowshans. These are for: 1-ventilation, 2-natural lighting, and 3-privacy. This investigation showed that the Rowshan embodies an efficient strategy for reorienting winds and reducing solar radiation. Rowshans can provide an efficient distribution of both air flow and natural lighting, consequently providing occupants with the desired level of comfort. In fact, this enhances the reduction of energy consumption in buildings.

This type of bay window can provide a high level of privacy for the occupants, especially women. It has been proved that Rowshans provide both the climatic and social necessities for the occupants.

Finally, the articulated elements of the Rowshan were discussed. These are: the crown, pearl, upper belt, sashes, lower belt, brackets, and the wooden screens. Illustrated sketches were presented to show the general types of Rowshan.

CHAPTER 3

THE FUNCTIONS OF WINDOWS AND SHADING DEVICES IN ARCHITECTURE

3.1. Introduction

Windows make us feel and be aware of the world around us through light. Factors affecting windows include their location and design, and not just the aesthetic architectural contribution they make. Other factors that should be considered are the view outside, glare, distribution of daylight and privacy. From the Middle Ages, windows have reflected the social status of the people who lived behind them, and that is also found in old Jeddah where the "Rowshan" gives an indication of the social status of the house owner since the bigger and more articulated the "Rowshan", the higher the social status of the owner.

Windows are the main architectural element in an elevation so when designing elevations, architects are designing the windows and their distribution and proportion in teems of the whole building. Windows have artistic, and also functional and practical features. In practical terms, windows give light, ventilation and a view of the outside while daylighting in buildings can be achieved through windows, sky lights, and by side lighting, which can be direct or indirect. Lighting in buildings can generally be achieved through two direct sources (daylight and artificial light) and one indirect source, which is any surface that can reflect light, for example, light-coloured shelving. It is useful in building design to take daylighting to the highest level possible but, at same time, the problems of glare and overheating must also be considered by the use and design of shading techniques.

Efficient daylighting should penetrate as deeply as possible into the interior so less electric lighting will be required. It is also important to control the brightness and the glare of this daylighting to avoid a reduction in visibility. Daylight controlling devices can orient the daylight where it is needed; they can be dynamic (movable) or static (fixed). The quality and efficiency of the daylight depends on the sky conditions. These conditions are: 1- clear sky, 2- overcast sky, 3- partly cloudy sky. Normally, most daylight can be achieved in the first condition, the clear sky; this is due to the intense direct solar radiation.

This chapter discusses and focuses on two main elements: windows and shading devices. Each part of the discussion includes the main types and functions of both elements. Types of conventional window and the functions of windows in architecture are also discussed. Four main functions of windows are considered: daylighting, ventilation, view to the outside, and privacy. The thermal properties of windows are also a major part of the chapter while the main types of shading device are illustrated using a shading design tool to outline shading efficiency. Three main types of shading device are presented here: natural, external and internal shading devices. Factors affecting shading efficiency are examined in the last part of the chapter.

3.2. Conventional Window Designs

3.2.1. Simple openings

Windows with simple opening are the most commonly used type of window. They can be of any size and depth, and can be used in any type of building, though they are used mainly in residential buildings. Simple openings can be glazed or plain they can be used as decorative elements in the upper part of the building's façade or even in the internal walls of the building.

3.2.2. Glazed wall windows

Glazed wall windows are normally found in offices, institutional buildings or commercial buildings and this type is considered to be one of the most common features of modern architecture. In hot climates, large glass walls in office buildings can cause overheating in the building which will require an extra cooling load. The problem of overheating can be solved, however, through the use of shading devices or tinted glass, which reduces the heat gain through the surface. Joudah (1992) noted that making a proper selection of the glazing type and the shading devices themselves is an important factor in maintaining a comfortable thermal level indoors. This also results in efficient energy consumption in the building. Proper selection of efficient glazing requires an investigation into the properties of the glazing as its ability to reduce solar heat gain depends on the refection, absorption and transmission characteristics of the glazing for the entire wavelength range of the solar spectrum.

3.2.3. Traditional windows

The traditional Arabian window is normally made of wood and projects from the building's external wall with a wooden sunscreen. It is called a "Mashrabiah" in Cairo and a "Rowshan" in Jeddah. This is a distinctive screening device and screens the window completely with a wooden lattice screen system.

Figure 3.1. Traditional windows in houses in Jeddah.

Al-Shareef (1996) mentioned: *"The name of Mashrabiah is used for an opening with a wooden lattice screen composed of small wooden balusters that are circular in section and arranged at specific regular intervals, often in decorative and intricate geometric patterns"*. The Mashrabiah or "Rowshan" has been used as a traditional shading strategy for centuries as it gives daylight, ventilation, view and privacy without glare. The "Rowshan" configuration was discussed in detail in Chapter 2.

3.2.4. Sloped windows

Sloped windows, or the use of sloped glass, is a technique which is normally practical for use in shops and exhibitions as it eliminates reflection on the glass panels. Vertical glass usually reflects the sun's glare on the glass and causes reduced visibility for objects behind the glass. It can also reflect images of dazzlingly lighted objects in or across the street from behind the observer. However, sloped glass has no effect on the level of daylight which penetrates through the glass to the interior. Experiments were conducted in the main study to examine the effect of sloped windows on the internal distribution of sunlight.

3.3. The Function of Windows in Architecture

3.3.1. Daylight and daylighting methods

Daylighting or natural lighting is one of the basic functions of the window. However, the availability of daylight depends on the region's climate and the availability of solar radiation in that region. In the case of Saudi Arabia, for example, daylight from a window can be very practicable and efficient; it can reduce the use of the artificial lighting, consequently reducing the expense of electrical energy during the daytime. The sky's condition varies, however, and this has a significant impact on daylighting. Furthermore, sky conditions are different from one place to another depending on the cloud density and climate type. Fontoynont (1999)

Sky conditions are mainly of three types: 1- The clear sky. In this condition there is strong direct light from the sun and diffuse light from the sky due to the bright horizon. 2- The partly clouded sky. In this case, the percentage of cloud will increase so part of the sunlight will be direct and part will be diffused. 3- The overcast sky condition in which all the sunlight is diffused. Mazria (1979)

3.3.1.1. Top lighting and roof reflectors

Some types of top lighting or skylight, such as coloured skylights, plastic skylights and light pipes, are very useful in reducing heat gain and diffuse light. Skylights can be installed with different types of shading which can effectively protect the skylight from direct sunlight so more efficient daylight enters the spaces. This keeps the heat out in summer and allows the sun to penetrate in winter (Evans, 1981).

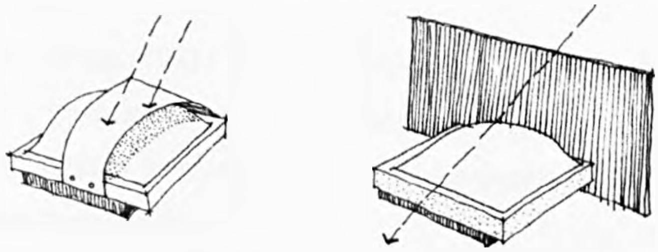


Figure 3.2. Skylight shading (Evans, 1981).

3.3.1.2. Filtering daylight

Daylight can be filtered directly from the skylights to make the natural light more harmonized and uniform inside the space. This can be achieved by surrounding the source of light, the window, skylight or sidelighting, by devices that can filter or reflect the light deep in the space, making it spread and soften. Other aspects, such as using trees or shrubs, light shelves and louvers, can be used to filter the light to make it more efficient and effective when reaching the interior spaces of the building.

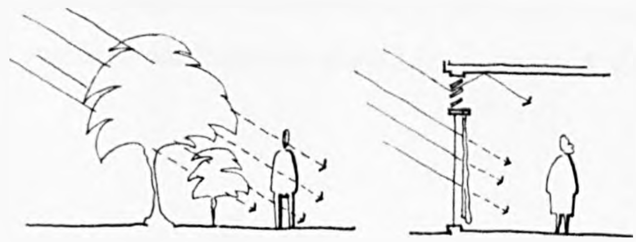


Figure 3.3. Daylight filtering (Evans, 1981).

3.3.1.3. Reflecting blinds, louvers and light shelves

One of the most efficient techniques in daylighting is the use of horizontal Venetian blinds. These can be adjusted to different angles to keep out the direct sunlight and allow a desirable level of daylight to penetrate. This method has the ability to reflect daylight into the ceiling of the space, making the light bounce and distribute itself in the interior areas of the space and, at the same time, allowing the view

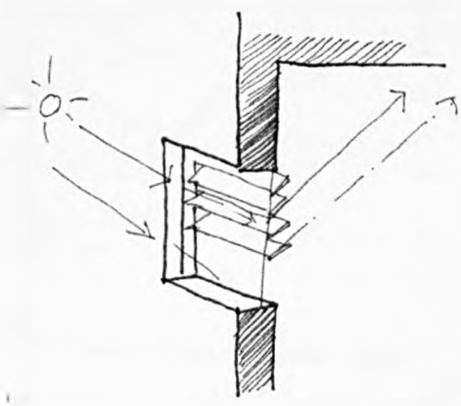


Figure 3.4. Reflected Blinds (Reproduced from Evans, 1981).

outside. They can also be adjusted to a closed position, blocking the view and the daylight completely.

It was mentioned by Benjamin H. Evans (1981) that Venetian blinds also have the ability to be raised or lowered and tilted at the same time to control sun, sky brightness and view. They have great versatility and they tend to increase the ratio of the ground-reflected light as opposed to the light coming direct from the sky.

They also have some disadvantages, however. For them to respond appropriately to changing sky conditions, they must be operated by a human operator with some understanding of the technology who must also have the time and incentive to carry out the task.

3.3.1.4. Environmental Aspects

Other environmental aspects like ventilation, view, artificial lighting and noise should be considered when designing daylighting and shading techniques. All these factors work together to provide the building or the space with the benefits of natural environmental resources. The effectiveness of one factor is likely to affect the efficiency of another. For instance, a window opening for daylighting and ventilation can allow noise to come through the space. Therefore, all environmental aspects should be considered at the same time. Bansal (1994)

3.3.2. Ventilation methods

Ventilation is one of the most useful functions of windows. Ventilation is considered to be a source of natural cooling in hot humid climate zones and efficient ventilation can be achieved through the cross ventilation of wind forces. This is normally achieved by two windows opposite each other.

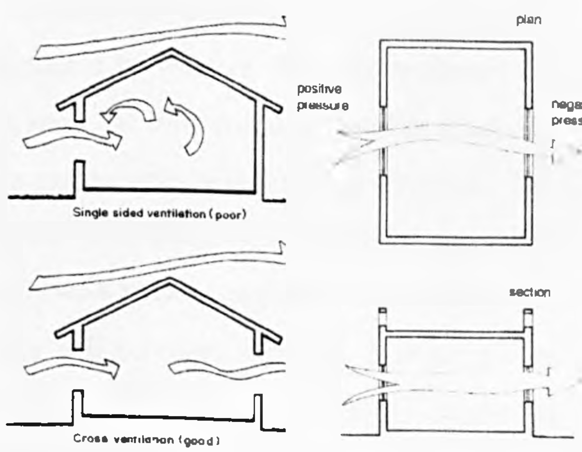


Figure 3.5. Cross ventilation (Bansal, 1994).

Also, there are other factors that can strongly affect the function of the ventilation from a window. These factors are:1-climate.2-wind direction and speed.3-the area and location of the window.4-the volume of the space or room.5-the design of shading devices.

In cross ventilation, the air inside the space is acted upon by two forces: positive pressure and negative pressure, as can be seen in Figure 3.5. Shading devices have a great influence on the pattern of air flow inside the space in terms of their direction and the way they are installed. Louvers and the type of shading device, for example, whether the devices are overhanging, horizontal or vertical, will affect the motion and the speed of the air.

3.3.2.1. Ventilation requirements for hot and cold climate regions

Ventilation is an essential requirement in hot climates in general, and especially in hot humid regions. High relative humidity is a major characteristic of this climate type so ventilation in hot climates is necessary to provide thermal comfort through the air's motion past the body.

Givoni (1976) asserted that the recommended air velocity for efficient ventilation in hot humid zones is 2m/sec (400ft/min) in the surroundings, so prevailing winds and building design details should contribute to achieve this ideal air velocity. Consequently, shading devices can provide both efficient ventilation and protection against the solar radiation. On the other hand, in cold regions, which are characterized by very low outdoor temperatures and low absolute humidity and vapour pressure, it is recommended to keep the ventilation rates as low as possible.

3.3.2.2. Orientation and Ventilation

Window openings should be oriented towards the wind direction to obtain the maximum ventilation. Nevertheless, studies conducted by (Konya 1980) have shown that orienting windows directly to the wind is not always the best solution. Studies have also proved that wind diverted obliquely to windows can be very effective and practical. This method is recommended, especially when efficient ventilation is required for the whole space or area of the room. Study shows that, with two windows opposite to each other and with the wind at a 45° angle, the ventilation rate will be more efficient. The air will be circulated in the space with an increased airflow along the side walls and in the corners. In another study, which had two windows located on nearby walls, better ventilation was achieved when the wind was perpendicular to the inlet window, and not at an oblique angle. Previous research has shown that efficient ventilation can be achieved by the following methods:

1. Changing the airflow direction in the space.

2. When the airflow is direct from inlet to outlet.
3. Orienting the windows so that they are at a 45° angle to the wind.

3.3.3. View Out

Windows link us to the external environment so they create a link between the indoors and the outdoors. This can be strongly affected by the size of the window. For instance, if the whole wall is glass, occupants will be more connected to the outside environment. The function of view becomes more important in deep spaces as this is when the function of daylighting becomes less efficient. However, the external view could be disturbed by the shading devices, especially in hot climate regions, in the attempt to control the climatic problems of solar heat gain and glare. The advantage of a view is mainly psychological, unlike ventilation and daylighting, so the need for a view out of a window cannot be replaced by artificial means. It can be said that a window with a view to the world outside improves the environment of the building as a whole and gives occupants a sense of well being (Tabet-Aoul, 1991).

Tabet-Aoul (1991) summarized the design information of a window's view and discussed the factors that might affect the view. These factors include:

1-View content: this is mainly the nature of the view and determining factors in a window's design for view satisfaction. This also has a strong effect on determining the minimum and preferred window size and shape.

2- Window shape: Tabet-Aoul noted a high concurrence from some experimental studies that the preferred shape for visual requirements is a window with horizontal proportions.

3- Window area: the preferred window area for viewing out varies from 10 % of the wall area up to 80%, depending on the nature of the space, the occupants requirements, and the depth of the space. The study showed that average satisfaction is around 30%, while the percentage of satisfaction increases in deep spaces to reach up to 60% and 80%.

4- Window width and view content: The study stated that window width depends on the observer's distance from the window rather than the viewing angle.

5- Viewing angle or room size: Small windows can be placed in the space so that they can maximise the horizontal viewing.

6- View, shading devices and window design: Some researchers have found that dissatisfaction with divided windows is very high. Kheira (1991) stated that the results of certain studies showed that some windows were felt, for the purposed of viewing outside, to be too small to be of use. The most satisfactory windows are those designed to fit in with certain aspects of the view itself, such as the skyline, for example. It is very difficult to make any precise recommendation concerning a formula for designing a satisfactory window for viewing as many variables exist that have been investigated.

3.3.4. Privacy

Windows can provide privacy to the occupants of the building and the function of the space determines the level of privacy that is required. The traditional wooden windows or "Rowshans" in the old Jeddah houses, present a unique example of windows offering privacy. The attractive articulated wooden screen of the "Rowshan" provides indirect sunlight and privacy for the inhabitants. Maghrabi (2000) observed that the "Rowshan" is a window that projects from the building to the outside and thus provides the inhabitants with a high level of privacy. A platform raised above the floor level can be found behind the "Rowshan" so women can use this seating area to observe activities and daily life in the streets without being seen from the outside.

3.4. Thermal Characteristics of Windows

3.4.1. Heat loss and solar heat gain through windows

From a thermal aspect, windows could be the first source of both undesired heat gain and loss. Heat loss through windows is mainly through conduction while heat gain is mainly through solar radiation. The amount of heat gain via windows depends on factors like window orientation, the season, the time of day, the glazing type and the shading method. Shading methods could include features such as overhangs, other buildings and vegetation. Solar heat gain through the window (the transparent elements) depends on three main factors: the solar gain factor, the global irradiance incident on the surface (W/m^2), and the window area (Szokolay, 2004).

3.4.2. Windows' U-Values

The U-value is the measurement of the rate of heat flow through the window and testing this includes the frame and the glass as a whole unit. Techniques have been devised through many studies to lower the U-values of windows and enhance their thermal performance. Techniques such as using "low E" glass and gas fillers between panes are commonly used in commercial building construction.

Szokolay (2004) noted that the weakest points of buildings are windows. The U-value of a standard single glazed window would be around 5.5-6.5 W/m^{2}K whereas the U-value of a brick wall would be 1.5 W/m^{2}K.

3.5. Main Design Types of Shading Device

3.5.1. Natural shading devices

3.5.1.1. Building Orientation

Studying the sun's behaviour and rotation definitely helps in deciding the best orientation for a building on its site and an appropriate building orientation generally offers two climatic functions. The first function is to minimize the amount of sunlight received by the building's façade. The second function is to avoid reflections from the surrounding buildings, like glazed or shiny façades, that can reflect sunlight and glare onto other buildings. Glazed façades have to be protected from direct sunlight during the hottest period of the day. The maximum amount of solar radiation is usually received by horizontal roofs, followed by the south façade east and west façades, while the minimum solar radiation is received by the north façade.

So, it is most appropriate to have a large glazed area on the north wall of the building and small openings on the east or west walls to protect the building from undesired sunlight. It has been argued that the most significant heat gain occurs between 6:30 h and 10:00 h on the east wall and between 14:00 h and 17:30 h on the west wall when the sun is lower in the sky. The east and west windows are the sources of the greatest solar gains and should therefore either be eliminated or reduced in size. It is also advisable to place unconditioned spaces (garages, closets and other buffer spaces) on the east and west sides. Efficient building orientation should maximize solar exposure in winter (the heating season) and minimise it in summer (the cooling season). Most of the summer heat gain occurs through the east, west, south-east and south-west orientations. Several studies have noted that,

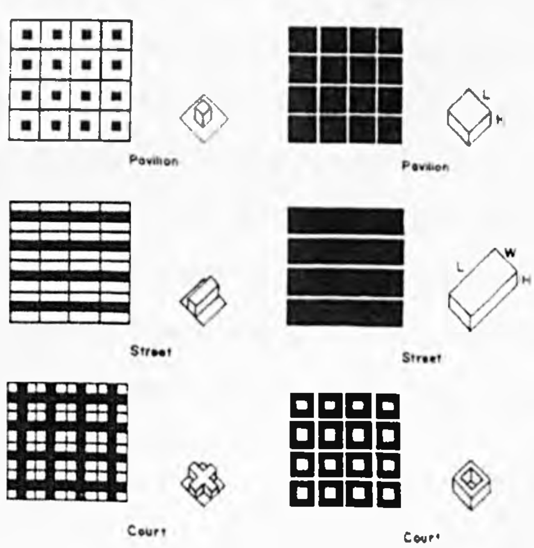


Figure 3.6. Types of shading by neighbouring buildings (Bansal, 1994)

in summer, south facing windows are less exposed to solar radiation due to the high angle of the sun.

3.5.1.2. Shading by neighbouring buildings

The design of the site layout can be very effective in shading the building through the distance between the building and the building's height so they are spaced to shade each other. The efficiency of the shade depends on the type of building group or cluster. Bansal (1994) classified such clusters into three basic types: pavilions, streets and courts. See Figure 3.6. Pavilions are lone buildings, erected singly or in groups; these are surrounded by large open spaces. In street formations, buildings are arranged as blocks in parallel rows separated by the streets themselves while courts are open spaces surrounded by buildings on all sides. To compare the performance of these types of building cluster, it is necessary to refer to building volume and floor area.

3.5.1.3. Shading by Trees and Vegetation

In hot climates, vegetation can be used to shade the buildings. The strategic location of trees can be very effective in shading and therefore saving energy. Low trees or shrubs are suitable when the sun is at a low angle in the morning and evening as they will then cast long shadows against the façades.

The only limitation in gaining shade by using vegetation is that this is only suitable for use with low buildings due to their physical height and the amount of shade they cast. Shade from vegetation is not suitable for high-rise buildings although some architects use vegetation and trees on balconies, in open courts, on terraces, plant boxes and windows of some high-rise buildings to act as shading elements for office spaces. The method of achieving shading and cooling by using vegetation can be effective because the trees' leaves absorb solar radiation for photosynthesis and achieve heat loss by evaporation.

Usually, east and west oriented windows and walls receive about 50% more sunshine than north and south oriented windows. The best location for trees for shading is next to those windows that admit the most sunshine during peak hours so trees should be planted in positions determined by lines drawn from the centres of windows on the west and east façades toward the position of the sun at the selected hour and date.

3.5.2. Internal Shading Devices

3.5.2.1. Venetian Blinds

Venetian blinds usually contain horizontal slats that can be adjusted to let more or less sunlight into the space. The materials usually used for the blinds are metal, timber or plastic. The advantage of Venetian blinds is that they can control the amount of sunlight entering the space. However, they require continuous adjustment and cleaning; they can also be noisy due to the vibration of the slats against the blowing winds. Colour is also effective in the shading properties of Venetian blinds because white blinds give 20% more shade protection than dark blinds. However, Beckett & Godfrey (1974) reported that dark coloured, open-wave blinds are more effective in reducing solar heat gains than light coloured ones. Venetian blinds give very flexible control, both of direct sunlight and the daylight admitted into the space.

3.5.2.2. Curtains

Curtaining is efficient in limiting the amount of solar penetration, heat loss and heat gain through a window. Generally, curtains are more efficient in reducing solar heat gain than reducing the heat loss through windows. However, the efficiency of curtains in reducing heat loss through windows can be improved by increasing their isolation value, by using opaque or metallic fabrics as liners. Efficiency also can be improved by using upholstered cornices to reduce infiltration. Furthermore, curtains can help to reduce acoustic absorption but the material must be of a heavy and dense wave if the contribution is to be significant.

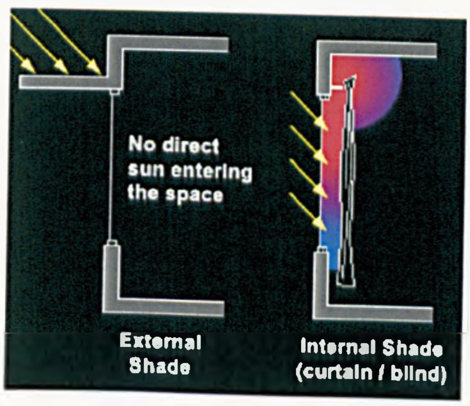


Figure 3.7. Thermal effect on the external and internal shading devices: ECOTECT manual (Marsh, 2004).

3.5.3. External Shading Devices

External shading devices can be fixed or adjustable and are placed on the outdoor side of windows. External shading comes in many forms such as horizontal or vertical devices, exterior roller blinds, and awnings. The efficiency of these types of shading device depends on many factors such as their position, the glass which can be fitted into the external shading, the colour, and ventilation control. The most effective factor is the orientation of the devices, especially if they are fixed because they cannot then be adjusted according to variations in the sun's position and movement and according to the annual and diurnal patterns of the sun's position in the sky. So, devices have to be designed and located in such a way that reduces the interior illumination, thus eliminating solar penetration. One of the most efficient advantages of external shading is that it can exclude solar radiation by blocking it externally before it reaches the internal spaces. This advantage can be seen clearly with horizontal shading which can block out large amounts of solar radiation in summer due to the high angle of the sun.

3.5.3.1. Horizontal Shading Devices

Horizontal shading devices can be in the form of a horizontal overhang on the upper side of a window or in the form of horizontal louvers placed on the whole window from the outside. The horizontal overhangs are usually most effective in the case of high sun positions as compared to when the sun is low. On the other hand, horizontal louvers can be efficient in cases when the sun is low. Generally, a longer depth of projection over the window area would produce a more pronounced shading mask and improve the shading effect. South facing windows are effectively shaded by horizontal projecting planes. Littlefair (2002)

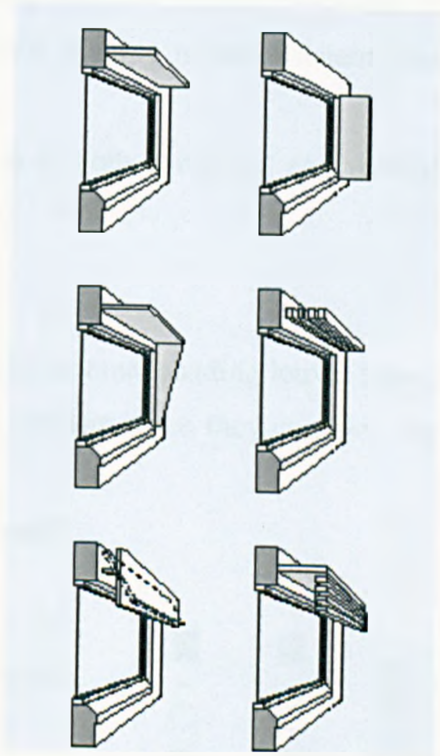


Figure 3.8. Configurations of external shading (A Stack et al., 2005).

The lower the latitude of the building's location, the more significant the shading of east and west facing windows becomes while the shading of south facing windows becomes a less significant factor. It has been argued that the efficiency of the external louvers could be increased if the colour of the inner surface were dark. This reduces the reflection of the sun's radiation through the window. Also, a separation gap between the horizontal devices of the window can be helpful in the mechanism to supply a free circulation of air to ensure heat dissipation. Several studies have suggested that the horizontal shading should be wider than the window so it can efficiently reduce solar penetration.

3.5.3.2. Vertical Shading Devices

Vertical shading devices can come in many architectural forms. They can be placed on the side of the window only or they can cover the whole window; they can also be projected outside the window to give more shade to the space. Vertical shading devices are more efficient on the east and west façades so that they face the low sun in early morning and late evening. They can minimize the penetration of the sun's rays into the space at these times because the rays meet the devices at a suitably oblique angle. Nevertheless, the vertical devices alone cannot work efficiently against solar penetration coming from the high sun because there are no horizontal devices that can be efficient against such conditions. This type of shading is also suitable on building surfaces oriented to the east or west. The literature review shows that, in general, vertical shading is less efficient than horizontal shading.

An efficient method for shading is a combination of both horizontal and vertical shading: this is egg-crate shading.

3.5.3.3. Egg-crate Shading Louvers

Egg-crate shading louvers are the most efficient of the external shading louver types. This is because they can control both the high and the low sun since they combine the characteristics of both horizontal and vertical louvers. Egg-crate shading louvers were used in the old houses of Jeddah, Saudi Arabia. In this shading technique, builders used both vertical and horizontal wooden louvers.

So that they would obtain both indirect sunlight and privacy, they sometimes used angled louvers in the top of the horizontal and vertical louvers so this design would provide more shade from the window and therefore more privacy. The egg-crate louvers, or slats, can project

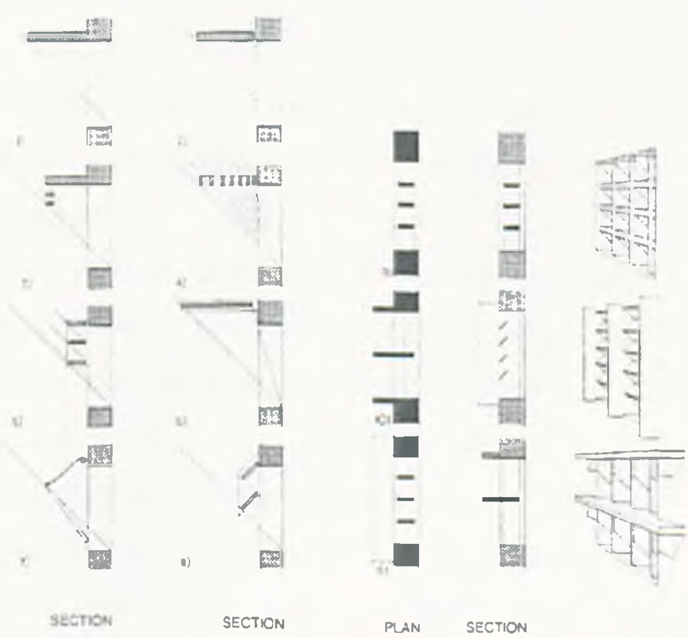


Figure 3.9. Egg-crate shading (Bansal, 1994).

from the window to give more efficient shading or can be flat against the wall. Depending on the shading requirement, the slats of the device can be either slanted or perpendicular to the window area.

3.6. Shading Design Tools

A number of methods exist for evaluating the performance of shading devices. One method is to determine the solar penetration through a fenestration by using solar geometry and the position of the sun through solar altitude and azimuth angle equations (Olgyay & Olgyay, 1957).

The equations are as follows:

$$\mathbf{Sin\ (\theta) = Sin\ (L)\ Sin\ (\delta) + Cos\ (L)\ Cos\ (\delta)\ Cos\ (h)} \qquad \mathbf{3.1}$$

$$\mathbf{Cos\ (\acute{\alpha}) = Sin\ (\delta) - Sin\ (L)\ Sin\ (\theta)\ /\ Cos\ (L)\ Cos\ (\theta)} \qquad \mathbf{3.2}$$

where θ is the solar altitude angle, **L** is the latitude, δ is the declaration angle, **h** is the hour angle, and $\acute{\alpha}$ is the azimuth angle.

Horizontal and vertical shadow angles are also required to determine the sun's position in relation to the façade or window. This can be calculated by plotting the sun patch (the sunlit area) and determining the shading efficiency. More details are given in Chapter Five on solar altitude and azimuth angles.

The second method is to build a model and to test it under artificial or natural sunshine conditions. This method is one of the main tools used in the core study of the current research. Researchers in the field have noted that the physical model is one of the best techniques for measuring shading efficiency.

A third common and more recent method is the use of a computer model. Architects and computer programmers have developed computer models to design shading devices. Most of these models depend mainly on solar geometry. Computer models, such as ECOTECT, designed by A.J Marsh, and SunCast, (part of the IES suite of virtual environment models) show efficient results. The internal penetration of the sunlit area can be calculated in the SunCast model in square metres or percentages for any window in the building and in the desired location. Consequently, shading devices could be designed to prevent the penetration of sunlight in summer. The ECOTECT and SunCast models will represent a major part of the current research.

Shading design tools are available in many types. Depending on the requirements of the environment, the shading tool can be adjusted because each environment requires a different solution. The selection of the most suitable one necessitates careful consideration. Moreover, in most cases, the devices are designed and chosen by examining a combination of two or more considerations.

Another form of shading design is "*Shaviv's Method*" which is concerned with the design of any fixed external solar shading for a specific window area. The fundamental stages of the method include:

- The determination of the necessary depth of the sun-shade for full shading.
- The application of a computer for calculations and the graphical presentation of the results.

3.7. The Efficiency of Shading Devices

Solar shading has many important impacts on a building's energy consumption, the comfort of occupants, and the view out. Shading is also important in the reduction of over heating and glare from the window. Usually, all shading devices will reduce heat gain to some extent but external shading is nearly always better than internal shading. External shading, like overhangs, fixed external shading louvers, and also moveable shading, can be appropriate for many buildings. During the time of peak solar gain, such shading can cut down cooling loads and overheating while the interface of solar radiation by the building is the source of maximum heat gain inside the space. Littlefair (1999)

The natural way to cool a building, therefore, is to minimize the incident solar heat. This can be achieved efficiently by proper orientation of the building, an appropriate layout with respect to other buildings, and by using proper shading devices to help control the incident solar radiation on a building. Efficient shading systems can save up to 10% - 20% of the energy used for cooling the building. Properly designed roof overhangs can provide adequate sun protection, especially for south facing surfaces, while vertical shading devices, such as trees, trellises, shutters, shading screens, awnings and exterior roll blinds, are also effective. These options are recommended for east-facing and west-facing windows and walls. Hassan Fathy (1988) illustrated that shading devices could contribute to reducing the solar heat gain on buildings by a third.

If the ambient temperatures are higher than the room temperature, heat enters the building by convection due to undesirable ventilation; this needs to be reduced to the minimum possible level. Adequate wind shelter and the sealing of windows reduces the infiltration of the air and this requires proper planning and landscaping. An evaluation of the expected performance of a designed shading device and its geometrical characteristics, subsequent to actual construction, is essential for the satisfactory thermal performance of a building. Shading devices can be designed if the position of the sun relative to the building face is known. Allowing privacy is another function of shading devices as adjustable shading devices, such as curtains and movable blinds, allow the occupants to have the degree of privacy they want at any time.

Windows are architectural elements that can be very effective in terms of energy performance in the building when shading systems are used with them. High energy performance of windows can be achieved by using external shading devices which can be considered as a part of the window system itself or as part of the wall or roof systems. Moreover, roof overhangs, louvered sunscreens, blinds or awnings can effectively accomplish efficient shading. Such shading devices can offer secondary energy settlement in addition to their primary function. For example, an external sun screen (fixed or movable), in addition to providing shade in summer, can reduce the heat transfer coefficient at the external surface of the window glass. Consequently, there will be less exposure to wind speed and sky conditions, and reduced winter heat losses. The principal advantage of external shades of all types is that the solar heat absorbed by them dissipates in the open air.

Interior shading devices, like curtains, Venetian blinds or fabric blinds have some advantages over external devices. These interior devices are protected from the weather and are easy to control and maintain. Interior devices reduce heat gain and heat loss through windows and they can shield the occupants of the space from radiant solar heat. However, they are generally less effective than exterior shading devices in minimising solar heat gains because the amount of heat they absorb is released into the room. The shading device has to trap the air between itself and the window to reduce the heat loss effectively if the insulation value is to be at a maximum. Devices should be installed properly to provide a sealed enclosure. Materials should also be selected with proper efficient solar properties so interior devices can improve the energy performance of a window.

In hot humid climates where airflow is desirable, internal devices can seriously impede ventilation. In this case, opaque or translucent blinds could be considered as a means to increase the ventilation rate. Furthermore, in composite climatic conditions, such devices block the undesirable solar radiation very effectively during the summer. Although light-coloured blinds are preferable, dark-coloured blinds absorb solar radiation and transmit it into the room in the form of long wave heat radiation. Overhangs on south oriented windows provide efficient shading from the high sun altitude. Even an extended roof, shading the entire north or south wall, will give effective protection from the noon sun. Richard (2000)

3.7.1. Efficiency of shading by glass

Glass can be very efficient in shading spaces and protecting them from solar radiation. Glass shading is generally used in office buildings to cover large areas of façade. The effectiveness and efficiency of glass shading depend on the type of glass used. Types of glass are divided according to their transmission, absorption and reflection. The basic types of glass are clear glass, heat absorbing glass, and coloured or tinted glass. According to Givoni (1976), in practice, all types of glass absorb and reflect solar radiation but heat-absorbing glasses absorb, and heat-reflecting glasses reflect, infra-red radiation to a greater extent than ordinary clear glass. Grey and coloured (anti-glare) glasses absorb more of the visible part of the solar spectrum and may be grey or coloured, according to the fraction of visible light mostly absorbed. Heat absorbing glass has a great ability to absorb the infra-red segment of the solar spectrum, while allowing a large portion of the visible light to be transmitted.

Givoni (1976) also noted that the solar absorbance of any specific glass is determined by the product of its absorption coefficient and its thickness. Reflectance depends greatly on the angle of incidence of the sun-rays upon the glass (the angle between the rays and the normal to the glass plane); it is lowest when the rays are perpendicular to the glass surface and increases when the rays become more oblique.

Type of glass	Direct transmission	Due to absorbed radiation	Total
Clear glass	74	9	83
Window glass	85	3	88
Light-heat absorbing glass	20	25	45
Grey glass	30	30	60
Lacquered glass	38	17	55

Table 3.1. Heat gain through different types of glass, percentage of radiation at normal incidence (Givoni, 1976).

3.7.2. Efficiency of shading by movable shading devices

The shape and geometrical design of the movable shading device, whether it is horizontal, vertical or egg-crate, and the width of the slits or spacing, do not strongly affect the shading efficiency. Movable shading has the ability to be turned and oriented to the direction of the sun's rays to ward off the undesirable heat and glare. However, the shading efficiency ratios of the movable devices are highly affected by other factors. These factors include their position with respect to the glass, their colour, and the ventilation conditions.

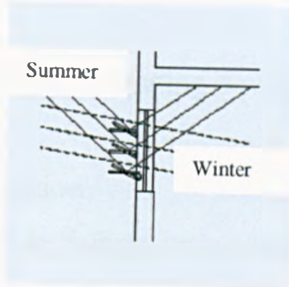


Figure 3.10. Movable shading devices (Stack et al., 2005).

Givoni (1976) used two approaches to study the efficiency of movable shading devices. The first approach involved computing or measuring the "shading factor", which is the ratio of the heat entering the window-shading combination compared to that entering an unshaded window. The second approach involved determining the thermal effect of the shading by comparing the actual indoor temperatures obtained with different types of shading with those obtained without shading. It is also possible to make comparisons in this case, with movable shading, by comparing the different situations with the same shading devices.

3.7.3. Efficiency of shading using fixed shading devices

In the case of fixed shading devices, the geometrical configuration is adjusted to specific settings. Thus, the orientation and profile of these devices cannot be changed according to the sun's movement. Givoni (1976) added that it is not possible to modify fixed shading devices according to environmental needs so they can respond efficiently to the seasons changing. Thus, the efficiency of shading devices in protecting the internal surfaces from the penetration of solar radiation in the overheating periods depends on the relationship between the shading configuration for a specific orientation and the solar geometry. Givoni and Hoffman (1976) studied the effectiveness of different methods of fixed shading devices in various orientations through comparing the following:

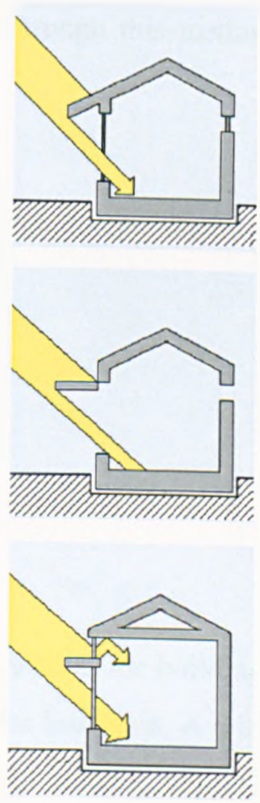


Figure 3.11. Fixed shading devices (Stack et al., 2005).

A. The daily pattern of solar penetration intensity falling on an unshaded window at latitude 32° N.

B. The ratio of the shaded area generated by different types of fixed shading device, as a function of projection depth.

C. The solar radiation intensity on the unshaded part of the window.

Through these experiments, daily curves of solar radiation falling on a window using different types of fixed shading with different orientations in different months were achieved.

According to Stack (2005), in the report on shading systems in European climates, fixed shading is efficient against direct sun radiation and inefficient against diffused or reflected sunlight. The most commonly used type of fixed shading is the horizontal form; it is mainly used on south façades in the northern hemisphere. He recommended that, in the Mediterranean climate, fixed shading should be in the form of louvers so the air can pass freely to achieve increased thermal comfort. Due to the decreased efficiency of fixed horizontal shading against the low sun angle, shrubs and small trees could be planted and carefully placed to control problems associated with the low angle of the sun.

He added that, in fixed shading design, the orientation of the aperture is the most effective factor in shading efficiency. If this is efficiently designed on the south façade, horizontal shading can provide entire shading during midsummer. Through this method, the permeation of solar penetration in winter will also be achieved.

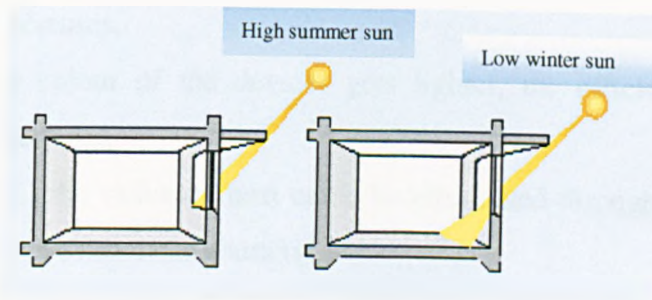


Figure 3.12. Effect of fixed horizontal shading on the high and low angles of the sun (Stack et al., 2005).

3.7.4. Retrofitting and evaluating the shading systems

The retrofitting of shading devices in existing buildings is practical for buildings with large glazed areas and inefficient in isolation systems against solar heat gain. A wide range of shading systems exist to offer specific solutions for a specific building. External and internal shading could be retrofitted into buildings; curtains and blinds are the most typical internal shading systems to be retrofitted. External shading over glazed areas is another efficient solution to improve the thermal performance of a building as indicated by researchers in the field. A shading efficiency evaluation could be assessed by using different methods and three main methods are mentioned by Stack et al. (2005). These are: 1. Methods depending on the calculation of the penetration of the solar heat gain into the space. 2. Methods depending on the calculation of the internal light level. 3. Methods depending on the calculation of the shading coefficient, which is the ratio of the penetrated solar radiation through the glazed shading system to that entering through a single glazed system (Stack et al., 2005).

3.8. Shade Factors of Different Types of Shading Device

Shade factors of different types of both internal and external movable shading device were computed or measured in some research institutions by Givoni (1976). Givoni's study included the following aspects: shading factors of different shading types, two different locations, their relation to the glass, and their colour (expressed in terms of reflectivity). The study results could be summarised as follows:

1- The efficiency of the external shading devices is much higher than the efficiency of internal ones.
2- Darker colour shading increases the difference between the efficiency of external and internal shading.
3- As the colour of the devices gets darker, the efficiency of the external shading increases.
4- As the colour of the devices gets lighter, the efficiency of the internal shading increases.
5- 90% of solar radiation heat could be eliminated through the use of efficient shading such as external shutters.
6- 75% to 80% of the solar heat could penetrate to the internal spaces by using inefficient shading devices such as dark-coloured internal shading.

Givoni added that the increased efficiency of the external shading devices when the colour is dark is applicable only when the window is closed. The efficiency with open windows will vary depending on the window's orientation and the wind direction.

3.9. Parameters Affecting the Effectiveness of Shading Devices

The main parameters that affect the efficiency of the solar shading devices can be described and discussed as follows:

3.9.1. The projection depth of shading devices

The greater the depth and projection of the shading devices, the more efficiently the devices can reduce and cut the solar radiation. Projection and depth are very important factors that affect the efficiency of the devices. Nevertheless, they can also affect the level of illumination inside the space and the external view outside the window so they have to be carefully designed. If the shading devices exceed the desirable level they can be impractical and add an extra financial cost for supplementary materials. The depth of the projection in the shading devices should be designed by examining the capability of the louvers to shade the window area throughout the hottest periods. The depth of the devices can be used to reflect the light deep into the interior spaces. Light shelf shading devices are an example of this method.

3.9.2. The effectiveness of different shading methods

Different types and different sizes of shading device can strongly affect the shading efficiency and the percentage of light transmission inside the space. Furthermore, solar heat gain can also be affected by different shading methods. The best way to study and examine these different shading methods is to measure them and then compare them with each other. The following table, quoted by Jorge (1993), shows the efficiency of each type of shading device arranged according to its shading coefficient.

Type of shading method	Shading coefficient
Venetian Blind	0.75
Roller Shade	0.62 – 0.81
Tinted Glass	0.52 – 0.66
Non-dense Tree	0.50 – 0.60
Insulating Curtain	0.36 – 0.60
Outside Metal Blind	0.28 – 0.43
Coating on Glass Surface	0.20 – 0.50
Dense Tree	0.20 – 0.25
Outside Shade Screen	0.23 – 0.28
Outside Awning	0.25
Outside Fixed Shading Device	0.23 – 0.31
Outside Moveable Shading Device	0.10 – 0.15

Table 3.2. Effectiveness of different shading methods (J.Jorge, et al., 1993).

3.9.3. Effectiveness of the colour and material of shading devices

Light coloured devices have the ability to reflect more solar radiation than dark coloured devices as dark coloured devices will absorb the heat and radiation. Determining the reflectivity of the material and the colour of the shading devices is very important to study the influence of these factors on shading efficiency. This could be achieved by comparing the reflectivity of light coloured material with that of dark coloured material. Researchers agree that light coloured materials have a higher degree of reflectivity as compared to dark coloured surface materials.

A study made by Evans (1980) compared the reflectivity percentage of some colours and materials commonly used for shading devices. The study is shown in Table 3.3. The proportion of the total solar input value is expressed as a percentage. Also, another study, carried out by Olgyay (1969), indicated that different colours of shading materials could result in a different shading coefficient.

The shading coefficient is illustrated as a ratio of the total heat gain through a shaded window. These results are compared to the same total for an unshaded window. This comparative study is exemplified for internal types of shading device in Table 3.4.

Colour and Material	Reflectivity (%)
Glossy white	85
Whitewash	85
Off white	65
Red (light)	35
Red (dark)	10
Black	5
Timber (light)	35
Timber (dark)	20
Concrete (smooth)	30
Concrete (textured)	20

Table 3.3. Reflectivity of some commonly used colours and materials for shading devices (Evans, 1980).

Types of shade	Dark	Medium	Light	Aluminium
Venetian blind	0.75	0.65	0.56	0.45
Roller shade	0.81	0.62	0.41	
Curtain	0.58	0.47	0.4	

Table 3.4. The effect of shading coefficient of colours on types of shading (Olgyay, 1969).

3.10. Conclusion

This chapter sheds light on two main aspects which are strongly related to the scope of this work. These two aspects are windows and shading and, for each aspect, types and functions are discussed. Four main types of window are discussed: these are simple opening, glazed wall windows, traditional windows and sloped windows. Daylighting, ventilation, view out and privacy are the main functions of the window discussed in detail in the chapter, while top lighting, daylight filtering, reflecting blinds, louvers and light shelves are illustrated as daylighting methods. Methods of ventilation through windows that can be achieved through window orientation, cross ventilation and shading devices, are also examined in this chapter. Viewing out is one of the main functions of windows, allowing contact between the living spaces and the outside environment, but privacy is also one of the window's main functions in Saudi Arabia. Providing this aspect of privacy is discussed with regards to the traditional windows of Jeddah (the "Rowshan").

In terms of the thermal aspects of windows, the solar heat gain on the window (the transparent elements) depends on three main factors: solar gain, the global irradiance incident on the surface (W/m^2), and the window area. Glazing techniques exist to lower the window's U-values and, consequently, increase the window's efficiency.

Three main types of shading device are discussed in the chapter. These are natural, internal and external shading devices. Natural shading devices are efficient against low winter sun conditions, as mentioned by many researchers, while internal shading can contribute to reducing solar heat gain. This could be achieved by using curtains or Venetian blinds. Moreover, external fixed shading devices are efficient in reducing solar heat gain from high sun angles in summer. Horizontal, vertical and egg-crate shading devices are the three main external shading methods discussed in the chapter. These three methods are the main shading techniques used in the core study.

Three main shading design tools are illustrated. The first method involves calculating horizontal and vertical shadow angles and locating the sun's position. The second method involves using a physical model and examining the shading devices. The third shading design method uses a computer model which achieves efficient and reliable results. The last two methods are the main tools used in the current research. The shading efficiency of three commonly used shading techniques (glass, movable and fixed shading) is also discussed. The efficiency of glass depends on the glass's transmission, absorption and reflective features, while the efficiency of movable shading devices is achieved by the ability of this shading to turn and orient itself against solar radiation. On the other hand, fixed shading cannot be turned or reoriented according to the sun's movements and therefore, the efficiency of fixed shading depends mainly on the relationship between the shading device's configuration for a specific orientation and solar geometry. Retrofitting of shading is principally useful for buildings with a large glazed area and an inefficient isolation system against solar heat gain. Givoni (1976) summarized the shade factors collected from previous studies. One of these factors is that the efficiency of external shading is much higher than the efficiency of internal shading while darker coloured shading devices increase the difference between the efficiency of external and internal shading. 90% of solar radiation heat could be eliminated by using efficient shading, such as external shutters.

The three main parameters that affect the efficiency of shading devices are discussed. Selected parameters for the investigation are shading projection depth, the shading method used, and the effect of colour and material on shading performance. Extended shading depth is efficient in protecting the internal spaces from direct solar radiation. However, this could affect the desirable solar penetration in winter in cold regions. Different shading methods affect solar heat gain and light transmission inside the spaces.

Shading coefficients are illustrated for the most common used shading methods in Table 3.2. Hassan (1996) noted that light coloured shading devices reflect more solar radiation than dark coloured ones. Shading materials and their colour will increase or decrease shading efficiency, depending on the material's properties. The reflectivity of commonly used materials and colours is illustrated in Table 3.3. White has a reflectivity of 85%, which makes it very efficient colour for use in hot climates. On the other hand, black for example, has a reflectivity of only 5%.

CHAPTER 4

PREVIOUS STUDIES ON SHADING DEVICES (Ph.D. RESEARCHES)

4.1. Introduction

This chapter discusses and analyses previous studies related to window performance on issues such as air flow, daylighting, thermal performance and outward view. These studies examine PhD researches that are related directly or indirectly to the current research. They are discussed in the following order:

1. Airflow characteristics of modulated louvered windows with reference to the "Rowshan" of Jeddah, Saudi Arabia. A. Maghrabi, 2000. (Ph.D. thesis).
2. The application of solar shading devices for buildings in hot humid climates with special reference to Malaysia, KU. Hassan,1996. (Ph.D. thesis).
3. Daylighting and shading for thermal comfort in Malaysian buildings. A. Ahmed. 2000. (Ph.D. thesis).
4. The interaction of view, window design and shading devices. K. Tabet-Aoul, 1991. (Ph.D. thesis).
5. Passive solar energy and buildings, including the shading and climate of Saudi Arabia. N. Joudah, 1992. (Ph.D. thesis).
6. Natural lighting control in Hedjazi architecture: An investigation of the "Rowshan" performance by computer simulation. F. Al Shareef, 1996. (Ph.D. thesis).
7. Evaluation of overheating protection with sun-shading systems. T.Kuhn, C.Buhler, W.Platzer, 2001. (Research paper).

The analysis of each thesis covers the following:

1. Introduction and illustration of the general ideas of the thesis.
2. Research objectives.
3. Main research concept, researcher experiments and solutions.
4. Research results and recommendations.
5. Analysis, general discussion, exploitation and benefits of the thesis.

Priority was given to the thesis or paper concerned with one or more of the following factors, listed in order of relevance to my chosen research area:

1. Solar control and shading techniques.
2. Functions of windows and shading devices.
3. Thermal characteristics of windows and shading.
4. Window and shading design issues in general.

4.2. Airflow Characteristics of Modulated Louvered Windows with Reference to the "Rowshan" of Jeddah, Saudi Arabia. (A. Maghrabi, 2000)

4.2.1. Research structure

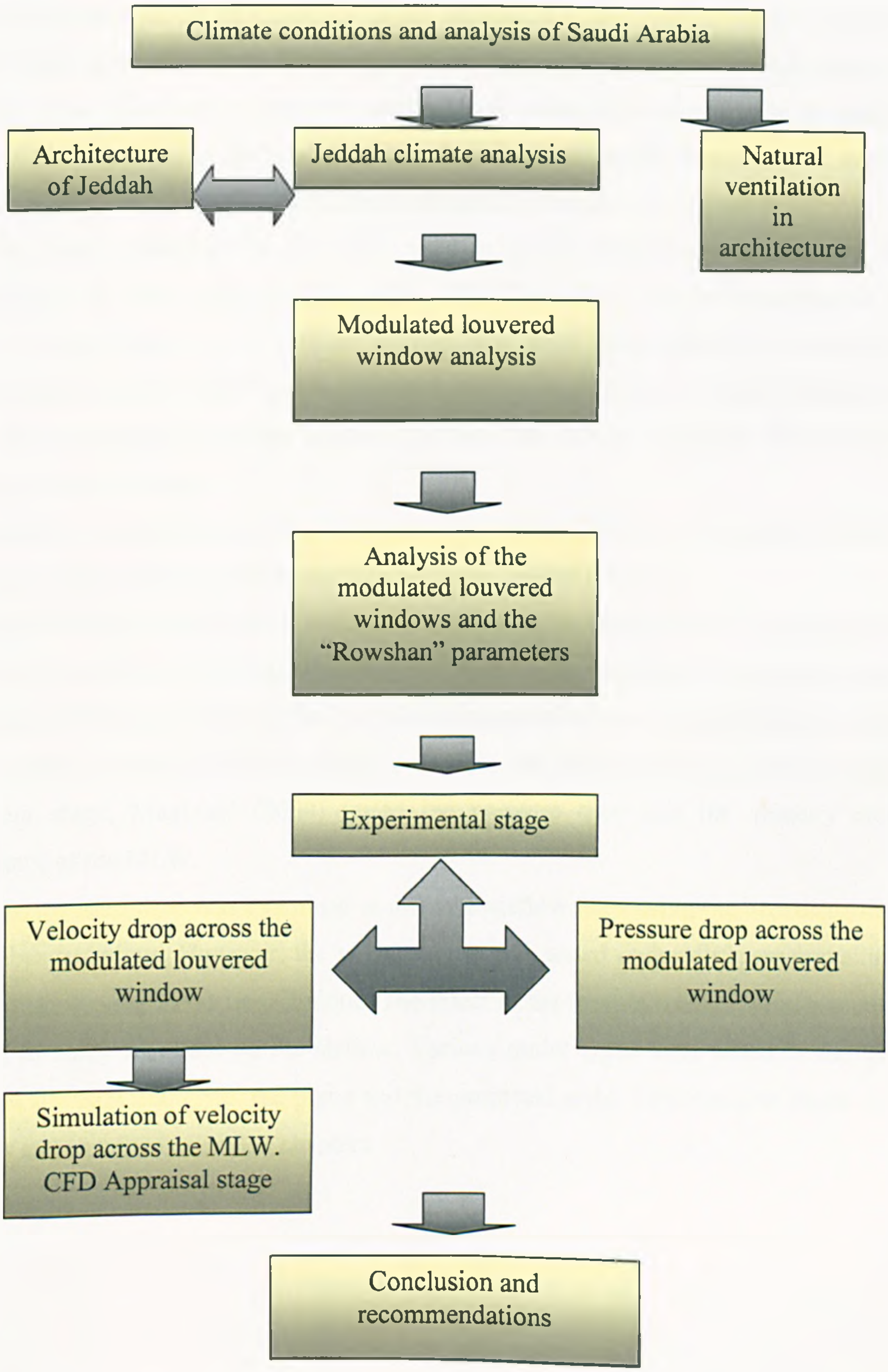


Figure 4.1. Research structure

4.2.2. Introduction and illustration of the general ideas of the thesis

In this case study, the researcher has evaluated the performance of a selected type of traditional Arabian window found in the old city of Jeddah, Saudi Arabia. The evaluation concentrated on the efficiency of the ventilation of this type of window, namely the MLW (Modulated Louvered Window) as the author called it. The author has assessed the ability of the MLW in providing the required level of natural cooling inside the space. He applied his investigation of the MLW to the "Rowshan" of Jeddah, Saudi Arabia; this is the main element in the elevation of houses constructed in the old city of Jeddah.

The name "Rowshan" is commonly used in Saudi Arabia but is also known as "Mashrabiyah" in some other Arabian cities. The "Rowshan" can be described as a wooden window, which can be a plane or projection from the elevation. It consists of horizontal and vertical wooden slats but can also contain angled slats for extra filtration of sunlight and more efficient natural lighting. The functions of the "Rowshan" described in this research are as follows:

1. It provides natural lighting that excludes the sun's glare. 2. It provides natural ventilation. 3. It provides the occupants with a certain level of privacy.

Maghrabi (2000) performed a series of experiments to evaluate and investigate the airflow characteristics of the MLW using two main tools: laboratory experiments and computational fluid dynamics (CFD). The laboratory experiments comprised the basic tool of the research, with a computer program used at the assessment stage. In the main experiment stage, Maghrabi (2000) tested the pressure drop and the velocity drop performance of the MLW.

The pressure drop was examined at different airflow rates using the depressurising test chamber technique. However, the velocity drop was tested under different prevailing wind conditions using the same technique. The effect of the room's configuration was also examined to study its effect on the airflow. Various outlet types were tested in the two main types of "Rowshan", i.e. the plane and the projected style. This research thesis was 295 pages and stretched over nine chapters.

4.2.3. Research Objectives

The main research objective was to evaluate and study the efficiency of the natural ventilation provided by selected MLWs, acting as a cooling source to achieve a desirable level of thermal comfort inside the space for the occupants. The researcher highlighted additional aims for his study. These were:

1. To encourage the use of natural ventilation techniques. This was achieved by studying and reviewing of traditional strategies and techniques to control the natural ventilation in the traditional houses of Jeddah. It is also very important to study the architectural elements that affect the efficiency of natural ventilation in general, and especially cross ventilation in traditional houses. For example, "wind catchers" are one of the techniques used to maximise airflow rates.
2. To study and present a technical investigation of the efficiency of the MLW. This was achieved through carrying out a proper and concerted investigation into the various parameters of MLW and their ability to affect airflow rates inside the space. This takes into account two factors: pressure drop and velocity drop. The investigation also covered the general performance of the MLW related to the integration of all variables. The velocity drop is affected by two factors: prevailing wind conditions and the depth of space behind the louvers.

   One of the researcher's most important objectives underlying this work was to provide architects, environmental designers and engineers with the best possible "Rowshan" configuration in order to provide natural ventilation. This was achieved by studying and investigating the schematic analysis of the airflow pattern inside the space provided by different outlet types. The researcher added the following objectives in the same context because the objectives mentioned above cannot be achieved without a suitable investigation and analysis tool.
3. To analyse the results obtained from the pressure drop assessment phase using the two equations of Power Law and Quadratic Function and, furthermore, to examine the theoretical coefficients embedded in them.
4. To evaluate the performance of CFD in simulating the efficiency of the airflow rates around the reviewed MLW.

4.2.4. The main research concept and the researcher's experiments and solutions

The main research work and experiments are discussed in Chapters Six, Seven and Eight of the thesis. Maghrabi (2000) divided his experimental work among three such chapters as, in Chapter Six, he examined the pressure drop across the MLW. In Chapter Seven, he presented the test velocity drop across the MLW and in Chapter Eight, he discussed the velocity drop simulated across the MLW using computational fluid dynamics, or the "CFD appraisal stage" as he called it.

Generally, Chapter Six investigates the significant angle of the MLW under which maximum airflow decrease will exist. This was achieved by studying the pressure performance through the MLW that was used in Jeddah, the typical "Rowshan" configuration. The researcher found that a considerable pressure drop could be achieved at an angle of ±60° of inclination. At this point, the best resistance to airflow is produced by the MLW. The experimental set-up included a test chamber for pressure recording, a micro-manometer to record the quantity of airflow passing through the sash unit, a laminar volume flow-meter to record the quantity of airflow through the MLW, a fan for depressurisation, pressure tapping to measure pressure, and a data acquisition unit for transferring the data to a computer.

In the second chapter of the experimental study, which is Chapter Seven, the researcher investigated the velocity drop across the MLW; this is involved in and affected by various factors. These factors were given as: louver depths *(L)*, inclination angle *(θ)*, apertures *(d)*, and porosity percentage *(p)* of the MLW. Additional factors that can affect the velocity drop are also noted e.g. room height (R_h) and depth (R_d), as well as prevailing wind conditions, including angle of incidence (w_i) and wind speed (v_e). The analysis of the results is then discussed in three stages:

1. When the velocity drop is affected by wind speed. 2. When the velocity drop is affected by the wind's angle of incidence. 3. When the velocity drop is affected by room geometry (room height and depth).

The experiments indicated that louver angle was the most effective factor in velocity drop, while louver depth was the least effective factor. However, the greatest velocity drop was found when a combination of factors acted together.

Wind (v_e) affects the normalised indoor velocity (v_i/v_e) by a maximum of less than 15%. Also, with apertures of less than 0.05m, the normalised indoor velocity is proportional to the wind speed. Normalised indoor velocity reduces to 20% near the window due to a change in the wind direction of 30° from the perpendicular state. The porosity percentage is an effective element in defining airflow performance. Airflow velocity in a room with an MLW is strongly affected by the interaction of louver geometry, room geometry and prevailing wind conditions.

The third chapter describing the experimental stage is Chapter Eight, which involves an appraisal of the experiments in Chapter Seven using CFD. Maghrabi (2000) decided to evaluate his work on the physical model using CFD. The CFD program had been validated in ventilation research and can reduce the errors that occur when using a physical model. It also reduces the computational timings that could make the results more accurate and comparable.

Maghrabi (2000) noted: "*CFD coding was a reliable tool to examine the velocity components in the room near the MLW. However, CFD results measured away from the MLW were accompanied with a level of error percentage higher than those obtained near the MLW. Nevertheless, within the scope of this study, CFD results are acceptable since the error was less than 20% at the farthest measuring location, i.e. R_d= 1.5m*".

The simulation of the vertical velocity profile within the room is a technique that is used to evaluate the pattern along both dimensions, and some conclusions were derived from this evaluation.

- The presence of steeper louver inclination angles induced a bi-directional flow within the room unlike the horizontal angle inclination. The latter inclination, however, is the optimum when direct ventilation of the occupants' living zone is desired.
- The outlet type used controls the flow behaviour and the percentage of bi-directional flow.
- The plane "Rowshan" is generally a better choice than the projected "Rowshan", yet the same flow in the living zones could be obtained by correctly sizing the projected "Rowshan".

4.2.5. Research results and recommendations

Pressure and velocity drops are the two main factors which have been considered in the study of the characteristics of airflow performance inside the spaces. The study shows that the enhancement in pressure drops could, at a certain point, be a function of certain variables, and that adjustment of louvers to give steeper blade inclination and a reduction in aperture are the main causes of poor ventilation. Maghrabi (2000) studied and discussed some design guidelines which could be very useful to architects and environmental designers. These could be summarised as follows:

1. Window accessory design can be achieved in many forms, while achieving similar ventilation rates. This can support architects by offering more than one solution of the MLW's configuration, maximising the choice of window treatments.

2. Horizontally inclined louvers can provide the maximum ventilation rate for the spaces inside.

3. Efficient ventilation performance can be achieved when the inclination is more than 60°. Inclination of less than 60° is considered the critical MLW geometry and should not be used. Nevertheless, if designers need to use inclinations of less than 60°, employing larger louver apertures becomes necessary.

4. Louver inclinations of less than 30° will result in poor ventilation performance in the living zones, while enhancing it near the ceiling. Enhanced ventilation performance near ground level is possible only if there is a suitable outlet opening.

5. Louver depths for the MLW have no substantial effect on the ventilation performance inside the spaces. However, room depth affects the performance of the ventilation rate inside the spaces.

6. The "Rowshan" configuration is an effective factor in ventilation performance. Maghrabi (2000) found that the plane "Rowshan" achieves higher ventilation rates where they are employed. However, the projected "Rowshan" could improve the airflow in the living zone.

7. Smaller outlets are recommended in the case of bi-directional flow between different heights inside the room.

4.2.6. Analysis, general discussion, exploitation and benefits of the thesis

This thesis presents treatments and solutions for the improvement of the quality of ventilation rates inside the spaces using a traditional architectural element, the "Rowshan". This is a development of a traditional method of enhancing ventilation and airflow that has been used in most hot climate regions. Using a wooden screening system to develop the quality of ventilation is an effective strategy in controlling the environmental conditions, especially in a hot humid climate. Other traditional strategies, such as wind towers, wind catchers and cross ventilation, have also been used in the past to improve airflow rates. These strategies could be developed to produce better treatments for these environmental conditions.

Maghrabi (2000) presented the minimum acceptable inclination angle providing a desirable level of ventilation, which is ± 60°, where the MLW provides significant resistance to airflow. See Figure 4.2. Louver depth also has an effective role to play in ventilation at the steeper inclination only and there is no major difference in the performance of the positive and negative inclinations, as the researcher indicates. The same strategy could be applied to the louver in order to study solar control efficiency. Hence, the inclination angle can be examined in order to produce maximum sun radiation and daylighting inside the space with the elimination of overheating and undesirable sun glare. Efficient ventilation and solar control are two objectives that can be achieved through window louvers. There are factors that can affect the efficiency of both functions, while others affect the ventilation only or the solar control function only. Factors that affect both ventilation and solar control are: 1. Louver inclination angle. 2. Window orientation. 3. Window size. 4. Aperture percentage of the void and solid area in the window.

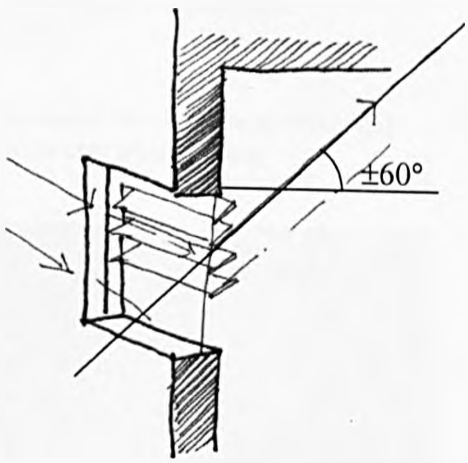


Figure 4.2. Horizontal louvers with 60° inclination (Reproduced from Maghrabi, 2000).

Factors affecting solar control efficiency only could be listed as: 1. Louver depth. 2. Louver colour.

Factors only affecting ventilation efficiency are: 1. Prevailing winds. 2. Space size and depth.

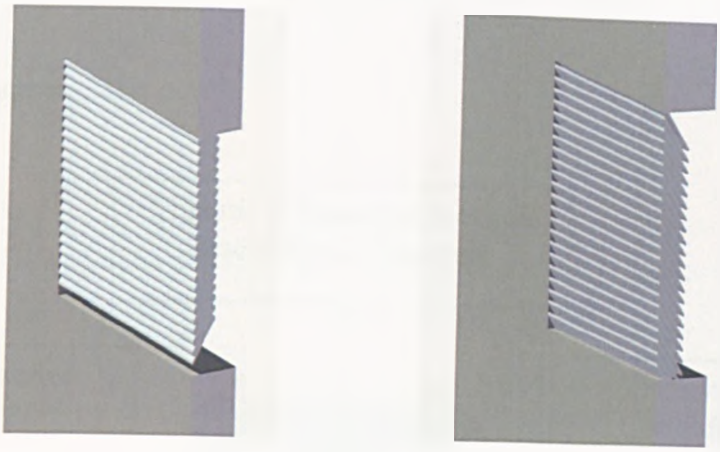


Figure 4.3. 60° inclination angled louver at positive and negative inclinations. Reproduced from (Maghrabi 2000)

Figure 4.4 illustrates the best angle of inclination (i.e. 60°) which achieves a desirable pressure drop inside the space through the MLW, as indicated by Maghrabi (2000). The pressure ratio is shown as the x-axis of the graph and is the ratio of inside pressure to outside pressure. For instance, number 1 in the x-axis indicates that the pressure outside is the same as inside. Figure 4.5 was originally produced by Maghrabi (2000) to illustrate the pressure drop (ΔP) as a function of louver number at a louver inclination of 60°. The researcher noted that there was a gradual increase in the pressure drop (ΔP) proportional to the increase in the louver within the MLW.

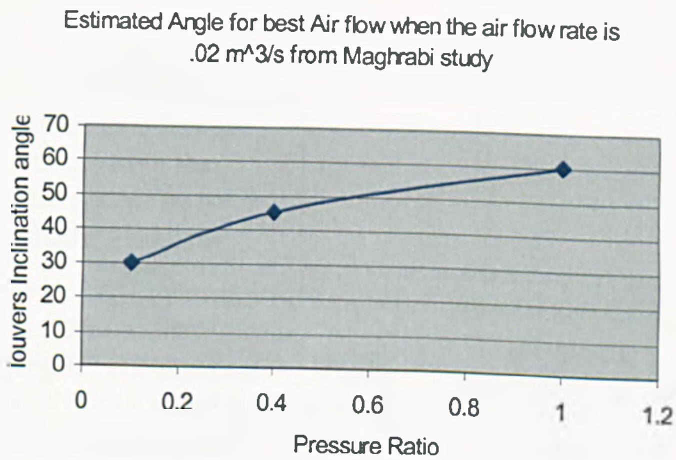


Figure 4.4. Best air flow angle (Maghrabi, 2000).

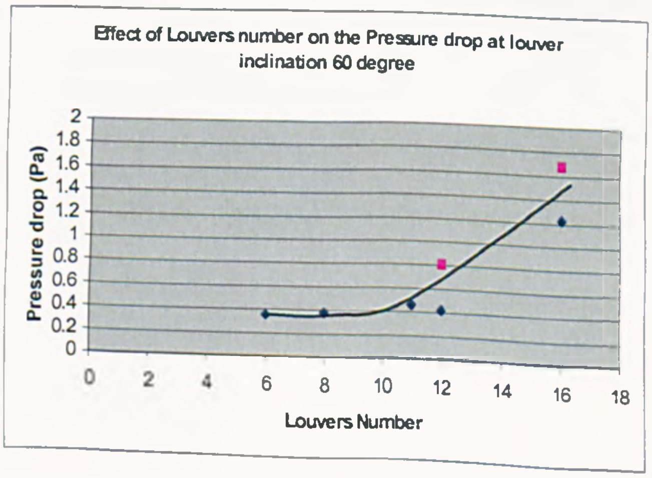


Figure 4.5. Effect of louver number on the pressure drop at a louver inclination of 60 degrees (Maghrabi, 2000).

4.3. The Application of Solar Shading Devices for Buildings in Hot Humid Climates with Special Reference to Malaysia, KU. (Azhar Ku Hassan, 1996)

4.3.1. Research structure

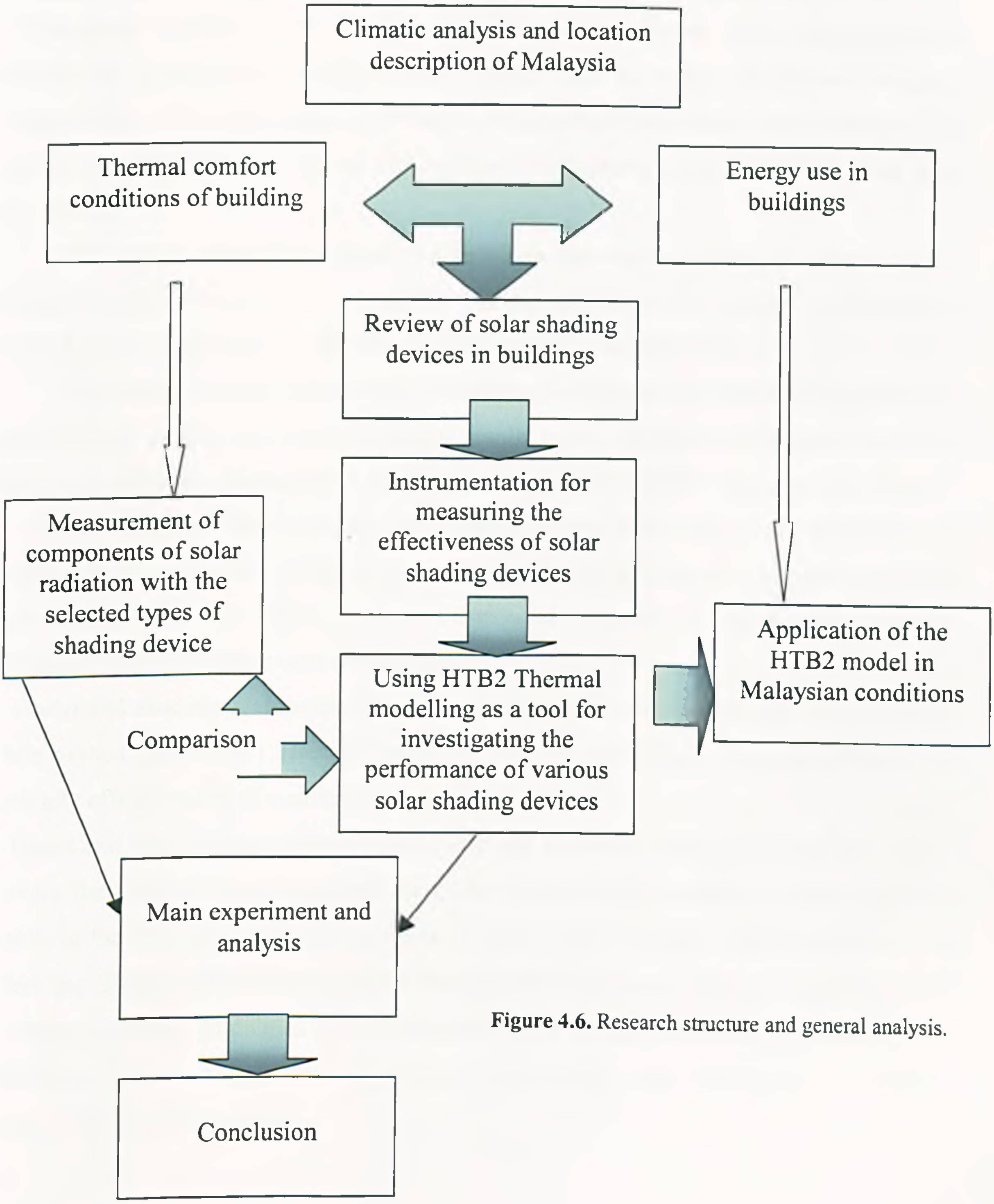


Figure 4.6. Research structure and general analysis.

4.3.2. Introduction and illustration of the general ideas of the thesis

This research study is considered to be the one that is most related study to the current research. The research mainly concentrates and focuses on assessing the performance of selected types of shading device that affect both indoor thermal comfort and the efficient use of energy in buildings. The selected types of shading device are: 1. Horizontal devices. 2. Vertical devices. 3. Egg-crate devices. The assessment also includes the performance of the shading devices under the effect of different window orientations and the components of radiation, which are direct, diffuse and reflected. The research covers 352 pages and is divided into 12 chapters, excluding the abstract and appendices.

The author started his research by shedding light on the following topics: 1. The external climate condition; 2. The desirable thermal conditions for comfort; 3. Energy use in buildings; 4. Solar shading devices; 5. The theory of solar radiation.

The practical side of the assessment consisted of a series of experiments performed under UK sky conditions. The experiments results passed through an appraisal stage and were evaluated using the computer thermal dynamic model *(HTB2)*. The researcher found, in the first appraisal stage, that the experimental results were higher than the computer predictions so he decided to use a better description of shading and a higher value of ground reflectance. The HTB2 model was then used to predict the solar input in the hot climate of Malaysia. The results showed that:

1. Horizontal shading devices are suitable and effective in the case of high sun positions, while vertical devices are effective in cases when the sun is low; egg-crate devices are generally effective in both conditions.
2. Direct and diffuse solar radiation components are generally higher in the case of vertical louvers for west and south orientations while reflected solar radiation components are higher in the horizontal and egg-crate louver cases. There are also other factors that can affect the thermal performance of the shading louvers. These were summarised in the section on design guidelines and recommendations as the following: ground surface materials, colours of the devices, window orientation, and the impact of various components of solar radiation.

4.3.3. Research objectives

The research aims and objectives could be summarised in the following:

1. To investigate conditions of thermal comfort for buildings through analysing the hot humid climate conditions of Malaysia.
2. To review energy consumption methods and strategies in buildings that have been achieved through investigating heat transfer processes through buildings in general and especially through windows.
3. To illustrate the existing types of shading technique that could be used for solar control in buildings, both externally and internally, and to examine their ability and efficiency in producing the required level of shading. It was also essential to study the factors that can affect the efficiency of the shading devices, i.e. maximise or minimise the shading quality and efficiency.
4. To carry out an intensive study of the theory of solar radiation, which comprises: solar movement, solar altitude, solar azimuth and the components of solar radiation. The effect of these factors on different building orientations was also covered.
5. One of the main research objectives was to measure the effectiveness of the selected shading devices. This was achieved through constructing a physical model containing a typical window unit area in order to evaluate the amount of solar radiation under the effect of the three main types of shading device: horizontal, vertical and egg-crate. This could also show the performance of these types of shading device and evaluate the solar radiation components: total, direct, diffuse and reflected. This is shown in Table 4.1.
6. A second appraisal stage was performed in order to have a better understanding of the performance of the shading devices. This was achieved through using *HTB2* thermal modelling.
7. KU Hassan (1996) noted that: "*The main aims of the experiment are to provide measured data in order to validate the computer data of the HTB2 model and test the effectiveness of the selected solar shading devices in UK conditions.*"
8. To use the measured results to validate *HTB2*, which can then be used to predict the efficiency of shading for the Malaysian climate.
9. To study the effect of ground reflectivity and the colours of the shading devices through *HTB2* simulation measurements. The application of *HTB2* was made with regard to two regions: the United Kingdom and Malaysia.

4.3.4. The main research concept and the researcher's experiments and solutions

KU Hussan (1996) performed a series of experiments mainly to assess the performance of selected types of solar shading device, namely, horizontal shading devices, vertical shading devices, and egg-crate shading devices. He started by investigating the instruments for measuring the effectiveness of solar shading devices in order to have a standard window unit to use in most of the experiments and to achieve the following objectives:

1. To evaluate the amount of solar radiation that penetrates through the window.
2. To evaluate the efficiency of different types of shading device.
3. To evaluate the solar radiation components, which include the total, direct, diffuse and reflected radiation.
4. To perform the same measurement procedures under the climate conditions of the UK and to design an appropriate tool that could withstand the external climate conditions.
5. To be able to compute and evaluate the results of the measurements' efficiency.

Instruments for the solar shading test could be described as follows:

1. Solarimeter. 2. Window-unit structure. 3. Data logger. 4. Shading devices with dimensions of 0.5m x 1.2m.

After the assessment of the instruments, KU Hussan (1996) began work on the actual pilot study, which was the second phase of evaluating the performance of the selected shading devices and determining their efficiency. The location of the experiments was Cardiff, in the United Kingdom, at latitude 51° 24N. From the experiment's results, the researcher found that shading devices could contribute to reducing the solar radiation of the four solar radiation components (total, direct, diffuse and reflected). The results are summarised in Table 4.1 below.

Total		Direct		Diffuse		Reflected	
Horizontal	31%	Horizontal	63%	Horizontal	-20%	Horizontal	-50%
Vertical	18%	Vertical	42%	Vertical	0%	Vertical	-90%
Egg-crate	69%	Egg-crate	91%	Egg-crate	60%	Egg-crate	-40%

Table 4.1. Shading contribution in reducing solar radiation components. " The negative results could be due to the ground reflected coming from above solarimeter" (Hassan, 1996).

Hassan (1996) then used the *HTB2* thermal modelling program, which is software developed from the "Heat Transfer in Building" HTB model. He used this model as a prediction tool to examine the simulated results concerning the efficiency of the selected types of shading device (without shading, horizontal, vertical and egg-crate). The test was carried out on the 23rd of June, 1995 and the most important aspect in the simulation was obtaining the respective contribution of solar radiation and its components (direct, diffuse and reflected). The simulation was then performed for a second time using the climate conditions of Malaysia to examine shading efficiency in hot humid regions. The second simulation was considered to be the main experiment in the thesis, which included the following factors, according to the author:

1. The performance of the selected solar shading devices.
2. The effect of the ground surface reflectivity.
3. The effect of colours on the solar shading devices.

Hassan (1996) found that the measured results in the physical model were generally higher than the results obtained from the *HTB2* model for all types of shading device. He mentions two main reasons: 1. The effect of ground reflectance: the grey concrete surface could possibly have caused the higher value of reflection. 2. The effect of experimental errors. The researcher found that the highest contributions accrue in the case of the vertical device, which is 4% of the total value. The following table presents a comparison between the *HTB2* model and the measured results of total daily radiation.

Types of Shading Device	HTB2 Model (Wh/m2)	Measured result (Wh/m2)	Difference (%)
Without shading	3872	3907	1
Horizontal Device	1394	1424	2
Vertical Device	3338	3474	4
Egg-Crate Device	1200	1221	2

Table 4.2. Comparison of the HTB2 results and the measured results. (Hassan, 1996).

4.3.5. Research results and recommendations

The research's main focus is the application of solar shading devices to the hot humid climate of Malaysia. From the experiment's measurements and computer modelling results, the researcher outlined the following:

1. In hot humid climates, the contribution of diffuse and reflected radiation is generally higher and proportionally larger with the respect to the total solar gain.
2. Simple types of shading device can affect the direct solar radiation components. However, the intensity of diffuse and reflected solar radiation components could still affect the thermal atmosphere of the buildings in hot humid climates.
3. The effect of solar heat gain from the reflected radiation can be increased in the case of shaded windows. Extra care should be taken when commencing work on the shading design by selecting suitable types of shading device and the type of ground surface.
4. To perform the thermal simulation, a suitable model of shading is required and also a reasonable value for ground reflectance should be used.
5. Horizontal shading devices are mostly efficient against the high sun for east -west building orientations.
6. Vertical shading devices are mostly efficient for south oriented buildings.
7. Egg-crate shading devices are mostly efficient for all building orientations.

Hassan (1996) pointed out some additional design guidelines and recommendations. These could be summarised as follows:

1. The selection of the type of shading device should be made according to their best performance. For example, horizontal devices have performed efficiently with most window orientations. On the other hand, vertical devices are less effective in most window orientations.
2. Ground surface materials should be also carefully selected. Dark and dense surface materials have more ability to absorb solar heat and reduce the effect of reflected radiation in the building. Light and polished ground surfaces, however, can increase the effect of reflected radiation on the building.
3. Colour can affect the efficiency of the shading devices. The amount of solar radiation entering the building will be affected and could be reduced to a certain extent in the internal spaces.

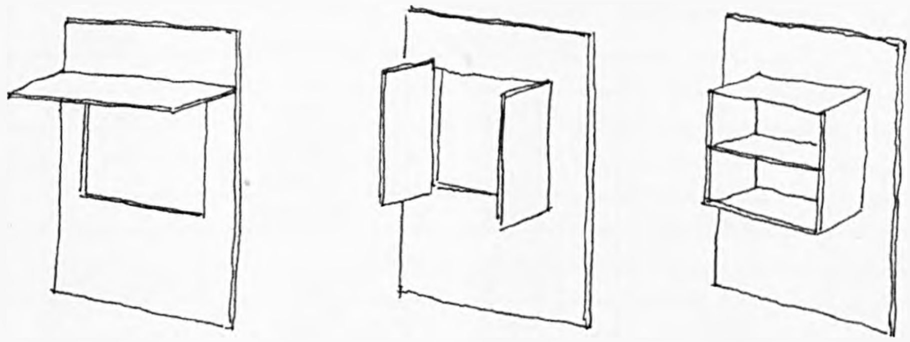
4.3.6. Analysis, general discussion, exploitation and benefits from the thesis

This research involved four main procedures, which can be described in the following:

1. An analysis of initial factors, which were: climate conditions, thermal comfort requirements, energy use in buildings, shading devices and solar radiation.
2. A study of the efficiency of selected types of shading device carried out through a series of experiments in two stages: 1. Using a physical model and suitable instruments, and obtaining measured results. 2. Completing an assessment stage which was achieved by using a computer thermal dynamic model (*HTB2*).
3. The third stage, considered as the main part of the work, comprised the experiment. This investigated the measurements of solar radiation, including tests of other factors: A. The performance of the selected shading devices. B. The effect of ground surface reflectivity. C. The effect of colours on the solar shading devices was also examined. A comparison was performed between the measured efficiency of selected shading devices and the simulated result returned by *HTB2*. The researcher found that the measured results were generally higher than the simulated results given by *HTB2* and reasoned that this could be due to the high ground surface reflectivity.
4. In the fourth stage, the *HTB2* model was applied to Malaysian climatic conditions to assess the efficiency of the shading devices in a hot humid climate. The assessment also evaluated the effect of hourly variations, daily variations, different shading methods and ground reflectance values. The following table illustrates the percentages of solar radiation components on the south orientation elevation.

Shading Device	% Difference Direct	% Difference Diffuse	% Difference Reflected
Without Shading	0.8	0.8	60
Horizontal	-7.5	3.8	60
Vertical	-10.6	6.2	60
Egg-Crate	0	4.8	60

Table 4.3. Solar radiation components: percentage differences at the south orientation (Hassan, 1996).



Single overhang louver Double vertical louver Double egg-crate louver

Figure 4.7. Fixed shading devices.

The research discussed and reviewed a number of selected types of solar shading device used in buildings and also investigated the factors affecting their effectiveness. The devices were horizontal, vertical and egg-crate shading devices. The types of device used in the study were of the fixed louver type with a single or double louver, as shown in Figure 4.7.

By increasing the number of shading louvers, the efficiency of the louvers might be increased but this will affect the view-out function of the window. If the louvers installed were movable, this could help the view function, increase the shading efficiency, and help the ventilation performance as well. Tinted glass can block a reasonable amount of sun glare, especially in hot climate conditions; it can be integrated into the shading devices. Tinted glass is generally used in a large proportion of elevations to eliminate sun heat. The research investigated factors that can affect shading performance but there is an essential topic which should be highlighted at this stage: how shading devices affect the environmental conditions which makes them highly recommended in regions that require shading through the whole year. This could be illustrated by the following:

1. Shading in hot regions reduces the sun's glare and the sunlit area that penetrates inside the spaces through the windows.
2. Shading can affect the environmental conditions by reducing the required cooling load inside buildings.

The performance of the egg-crate shading device is summarised and illustrated in the following table.

Time	Component of radiation	Proportion of unshaded ref	Ratio normalised to 1	Solar radiation (W/m2)
900-1000	total	0.074	1	88
	direct	0.004	0.05	4
	diffuse	0.007	0.1	9
	reflected	0.063	0.85	75
1000-1100	total	0.113	1	116
	direct	0.007	0.06	7
	diffuse	0.011	0.1	12
	reflected	0.095	0.84	97
1100-1200	total	0.122	1	134
	direct	0.007	0.06	8
	diffuse	0.011	0.09	12
	reflected	0.104	0.85	114
1200-1300	total	0.134	1	156
	direct	0.005	0.04	6
	diffuse	0.008	0.06	9
	reflected	0.121	0.9	140
1300-1400	total	0.136	1	170
	direct	0.005	0.04	7
	diffuse	0.008	0.06	10
	reflected	0.123	0.9	153
1400-1500	total	0.135	1	163
	direct	0.005	0.03	5
	diffuse	0.008	0.06	10
	reflected	0.122	0.91	148
1500-1600	total	0.13	1	158
	direct	0.004	0.03	5
	diffuse	0.008	0.06	9
	reflected	0.118	0.91	144
1600-1700	total	0.094	1	133
	direct	0.002	0.02	3
	diffuse	0.005	0.05	7
	reflected	0.087	0.93	123
1700-1800	total	0.089	1	108
	direct	0.001	0.01	1
	diffuse	0.005	0.06	7
	reflected	0.083	0.93	100

Table 4.4. Egg-Crate Device Performance (Hassan, 1996).

4.4. Daylighting and Shading for Thermal Comfort in Malaysian Buildings. (Ahmed, 2000)

4.4.1. Research structure

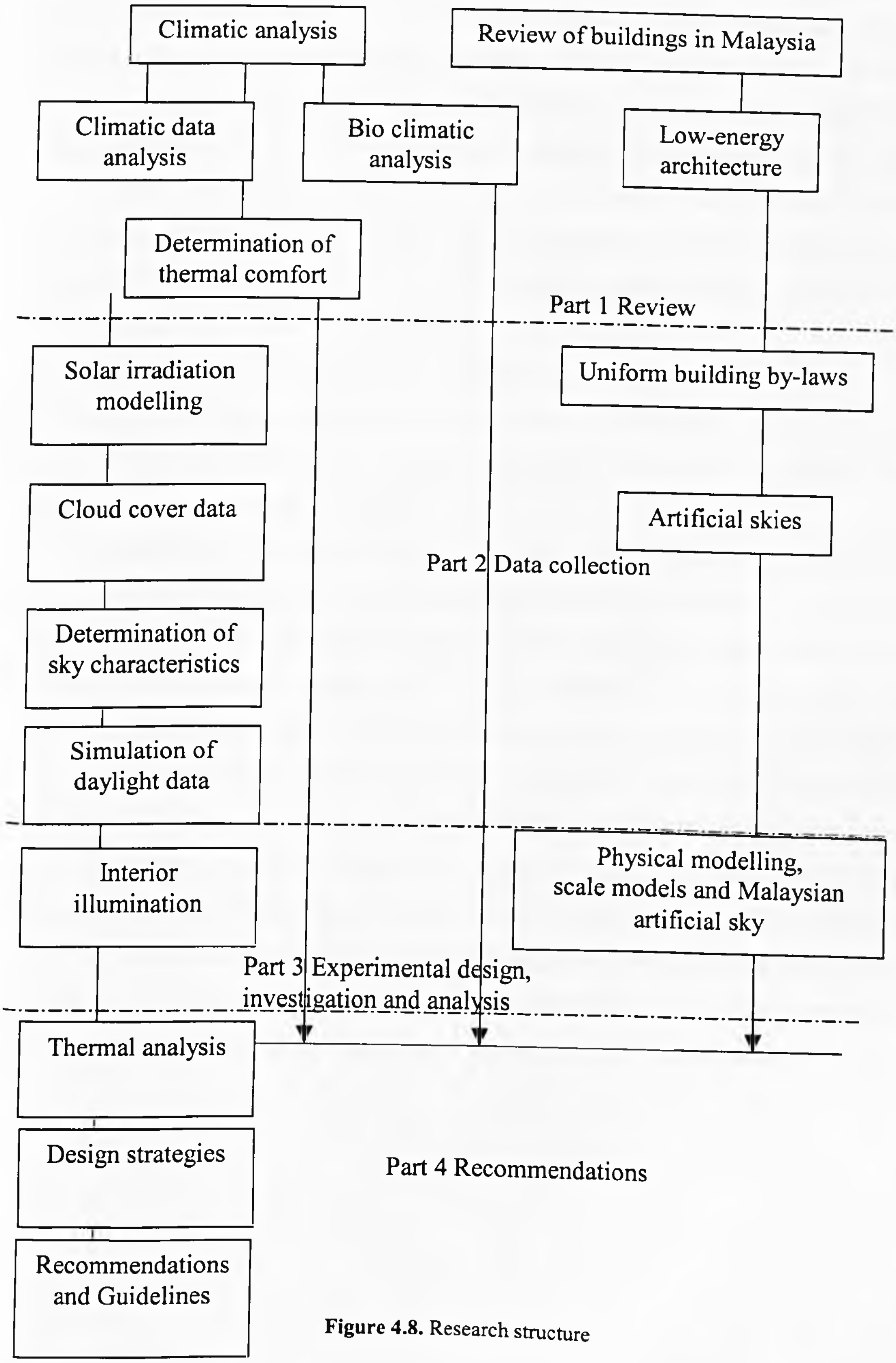


Figure 4.8. Research structure

4.4.2. Introduction and illustration of the general ideas of the thesis

In this study, Ahmed (2000) examined the possibility of natural indoor daylighting in Malaysian buildings through factors which strongly affect the efficiency of natural lighting. These factors are: 1. The Malaysian climate. 2. The traditional and modern buildings of Malaysia and the traditional cooling and daylighting strategies that have been used in Malaysian architecture. 3. The passive cooling approach. 4. The potential of solar radiation and daylighting. 5. The interaction of daylighting and energy-efficient buildings.

Natural daylighting is one aspect of low-energy and thermally comfortable buildings in hot humid regions. In this study, the integration and design of daylighting was investigated by considering the size of the window opening and the types of shading device. Three main studies were carried out to achieve this:

1. Identifying old and new daylighting techniques and strategies.
2. Carrying out statistical analyses for a model climate for one year.
3. Conducting a field study to determine conditions for the thermal comfort of young people in a normal working environment.

Ahmed (2000) illustrated daylighting design in the building process by offering a simple diagram in Chapter One. This diagram presents three main stages: 1. The predesign stage, which is affected by daylight data, daylight availability, energy considerations and the site. 2. The schematic design stage, which is affected by daylight geometry and the illumination inside the building. Then the concept moves on to systems. 3. The final design stage, which is affected by energy analysis and integration with other systems. The thesis extends to 291 pages and is divided into eight chapters excluding the appendices.

The thesis in general consists of four main parts: the first part is a general discussion of daylight strategies and climatic conditions; Part Two involves a mathematical modelling technique and the results of the investigation into daylighting; the construction and design of the physical model are placed in the third section of the thesis while the fourth part contains the thermal analysis, the conclusion and recommendations.

4.4.3. Research Objectives

The main aim of the thesis was to investigate the possibility of daylighting as a source of natural indoor lighting in Malaysia. The research also aimed to provide a solid foundation for knowledge about daylight and the development of design tools and strategies for buildings in hot humid climates. Ahmed (2000) outlined the research objectives as follows:

1. To observe and analyse the daylighting strategies in vernacular and selected modern buildings in Malaysia.
2. To analyse the Malaysian climate parameters most pertinent to climate-responsive design.
3. To study the acceptable human comfort level of Malaysians.
4. To determine the typical Malaysian sky type from climate data.
5. To build a suitable modelling technique that can simulate the Malaysian sky's luminance.
6. To predict the level of illumination on the ground caused by the sky.
7. To study the distribution of illumination caused by different types of fenestration.
8. To produce a simple daylighting design aid suitable for the Malaysian sky.
9. To predict energy saving by the use of daylighting instead of artificial lighting.

The field study was performed to define the thermal comfort conditions of young people of 21 years of age in a normal working environment. This thermal analysis aimed to provide essential data on the desirable indoor comfort conditions that could be used for assessing building performance. Utilising climatic data, a bioclimatic analysis was carried out to help in identifying the fundamental strategies in designing energy efficient buildings. Due to the lack of daylight data on Malaysia, there was a need to model daylight availability. This is very important for improving the design of energy efficient building elements, but especially energy efficient windows. Modelling techniques for producing daylight data require that the sky for the type of location is determined, i.e. in this case, the conditions of the Malaysian sky. Some studies have observed that artificial lighting in tropical buildings has not yet developed a "new vernacular", as building designs have been borrowed from those in the temperate climates. In this study, the ultimate objective was to determine the energy saved by using daylighting strategies in simple buildings.

4.4.4. The main research concept and the researcher's experiments and solutions

Ahmed (2000) illustrated the research ideas in a research design and process chart, consisting of four main parts. The first part is a general review, sub-divided into two main parts: climatic analysis and a review of building in Malaysia. The climatic analysis is further subdivided into three parts:

1. Climatic data analysis. 2. Bioclimatic analysis. 3. Determination of thermal comfort. Studying low-energy architecture was the next step after reviewing the environmental characteristics of buildings in Malaysia. The second part of the thesis contains supportive data. From the climate data analysis, Ahmed (2000) achieved the following: solar irradiation modelling, cloud cover data, determination of the sky characteristics, and simulation of daylight data. After reviewing low-energy architecture, two main factors were studied in the second part of the thesis: building law and artificial skies.

The third part of the study consists of the experimental design, investigation and analysis. After a simulation of daylight data, the researcher studied two factors: interior illumination and thermal analysis, through physical modelling. This section was entitled, "Scale Models and Malaysian Artificial Sky". The daylighting system analysis was carried out to fulfil the following objectives:

1. To analyse the performance characteristics analysis of lighting or lighting energy use.
2. To perform a trade-off analysis of lighting, heating and cooling energy use.
3. To carry out a cost analysis.
4. To perform a human comfort analysis.

The focus of this part of the study is on daylighting strategies, daylighting analysis methods to evaluate interior illuminances, the modelling technique to determine the daylighting efficiency of building spaces under the Malaysian sky, and the development of a daylighting design tool suitable for the Malaysian sky. The study also included the following: daylight design concepts, side lighting, top lighting, atria, direct beams, and indirect beams.

The final part of the thesis (the fourth) contains design strategies, recommendations and guidelines. The thesis recommended changing the existing window and shading device designs.

4.4.5. Research results and recommendations

The research results were produced in the form of graphical methods and tables to aid the design process of designing daylighting in buildings. The bioclimatic study showed that dehumidification and cooling are two important passive design strategies. In vernacular buildings, shading is also a major feature.

Shade cooling was therefore included in daylighting design by the use of sloped shading devices. Five types of shading device were tested in the study for visual performance, which included traditional and modern forms: louvers, horizontal overhang, sloped overhang, the modern light shelf and a new design of sloped overhang. The most efficient shading design was found to be the light shelf with a sloped overhang. This type of shading allows the interior illuminates to be above 5%DF. The optimum slope of the overhang was found to be an angle of 45°.

The thesis showed that 10% of instantaneous energy could be saved using daylighting strategies for glazed, unshaded windows. Moreover, savings could be made if a device shaded the windows. It was found that a shading device, made up of a combined horizontal light shelf and a sloped overhang, can reduce the interior illumination near the window by 60%, while maintaining a daylight factor of at least 5%.

The author made a list of recommendations based on the experiment results for the daylighting design of buildings in Malaysia. These are listed below:

- The window–to–floor ratio and window–to–wall ratio must be at least 25% for a fully daylit room.
- A shading device made of a horizontal light shelf up to 0.5m, and a 0.5m sloped overhang of 45° to the horizontal, is recommended for large windows.
- Windows need not face any particular orientation for maximum daylight penetration.
- The daylight design value should be 1,000 lux.
- The design aids (daylight footprints, contour maps and look-up tables) produced by the work are to be included in any daylight design process.
- The model year climate model must be used in any mathematical modelling that requires climate data as input parameters for best accuracy.

4.4.6. Analysis, general discussion, exploitation and benefits from the thesis

The impact of window opening size on interior natural lighting (illuminance) in this work was limited to 10% to 40% WFR. More experiments could be performed on different WFR percentages to obtain the most efficient window and to achieve the maximum energy saving. Different types of louver could be applied in the experiments to study the effect of louvers on window performance. Also, various surface reflectances could be added to maximise the efficiency. The experiments in this work are limited to interior natural lighting without external obstruction; this could affect the indoor lighting. For example, trees and nearby buildings will play a significant role in a window's efficiency and this is why they should be included in the study.

The model that was used in this study to investigate the daylight behaviour inside the space represented a basic room of 4m in length, 3m in depth and 3m in height, with a total floor area of $12m^2$. Various models were used in the experiment with different openings, sizes and directions of window. The model was also used to evaluate the performance of five types of shading device through a window with 40% WFR, to investigate the effect of various types of shading device on daylight efficiency. From the test results, Ahmed (2000) found that the optimum window size is 25% window-to-wall ratio; this provides a minimum 5% daylight factor within the room. From the shading devices used in the investigation, the author found that the best shading device performance-wise was the light shelf with the sloped overhang, as shown in Figure 4.9. This type of shading has the ability to reduce, by a large amount, the sunlight near the window and yet is able to maintain a daylight factor of at least 5% all round the room. Passive design strategies for hot humid climate zones were identified by the bioclimatic analyses aimed to develop energy efficient buildings in these regions. The research also indicated that fenestration design in buildings could affect the energy consumption through windows and shading devices, as mentioned in the case of the light shelf with the sloped overhang. Other types of shading device could be examined to study the effect of various shading methods on internal natural lighting and solar radiation.

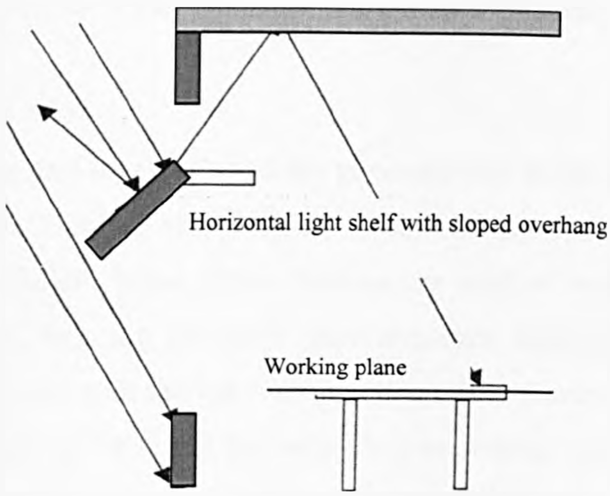


Figure 4.9. Shading and reflection by light shelves, reproduced after Ahmed (2000).

4.4.6.1. Daylight demand in spaces

The thesis indicates that if 40% WFR (Window-to-Floor ratio) glazing had been used, no artificial lighting would be required at all, at any time. An investigation was carried out to evaluate daylight demand presented in WWR values, and the simulation of artificial lighting in term of numbers of lamps and WWR values ranging from 10% to 100%. The study is illustrated in Table 4.5. The simulation was performed in March at 13:00, with a south-west window orientation; this is the condition of peak solar irradiation and temperature. This study showed that the ideal window opening size for receiving daylight should be 25% WWR. If the size of the window exceeds this ratio, the thermal gain will be increased and affect the thermal comfort of the occupants. This problem could be avoided by the use of shading devices. The recommended type in this study is the light shelf with sloped overhangs, as mentioned previously. This can reduce indoor illumination by 60%.

WWR (%)	10	15	20	25	30	35
No of lamps	12	8	4	0	0	0

Table 4.5. Number of lamps required per room (Ahmed, 2000).

4.5. The Interaction of View, Window Design and Shading Devices. (K. Tabt-aoul 1991)

4.5.1. Introduction and illustration of the general ideas of the thesis

The outside external view can be obstructed by the use of shading devices, especially in hot climate zones. These devices are used to control other environmental needs: for instance, reducing the sun's glare and solar heat gain. This research mainly investigates satisfaction with the view-out function of the window. Since the evaluation of view-out quality should be tested by people's preferences, and be based on observers' judgments, Tabt-Aoul (1991) used a scale model and observers from different backgrounds (in terms of climate and culture) to investigate the possibility of improving the view-out of the window and to assess the minimum acceptable window size for viewing. Following the assessment, an investigation was carried out on the thermal and daylight performance of the minimum acceptable view-window as a requirement for sun control devices. This idea is suggested as an alternative to large windows obstructed by shading devices. The researcher decided to conduct the investigation using people from different backgrounds to gather a variety of preferences and opinions on the greatest satisfaction with view-out, hence increasing the chance of reaching the best view-out for most people.

Using the same experimental setting, the potential of optimisation of view and shading device combinations through window design was studied. An evaluation was conducted on various types of shading device to study the effect of these devices on window view-out. The evaluation involved three main aspects: satisfaction, clarity and enclosure-spaciousness. These investigations were implemented using two groups of observers.

Tabt-Aoul (1991) highlighted, in her research, various solutions for window design using different types of shading device in providing the best shading device configuration for view optimisation. This research covered 219 pages and was divided into 10 chapters, excluding the abstract and appendices.

4.5.2. Research Objectives

The main objective of this study was to evaluate the view-out function through windows designed to incorporate solar control shading devices. In the evaluation, the researcher took into account the observers' backgrounds (climatic and cultural) which could affect the results of the experiments. The researcher also discussed the existing types of window and their functions to illustrate the significance of the view function.

The experimental method selected used a scale model and a real building to simulate the view from the window. An appraisal was carried out to determine the experimental requirements with a view to selecting an appropriate scale model, then the experimental procedure proceeded. Two main window design concepts were examined in detail. These were: 1. Minimum acceptable window size for view-out. 2. Optimum window size for view-out.

The window design concepts were suggested as replacements for large windows obstructed by solar shading devices. The effect of the climatic and cultural backgrounds of the observers was also added to the assessment of window view and these factors were evaluated in the study. The investigation was followed by an evaluation of two environmental factors: 1. Thermal performance. 2. Daylight performance of the view window.

General results showed that there is a need for shading devices, even with the minimum acceptable window size. An experimental evaluation was carried out to find the best view-out performance from a window combined with solar shading devices, again using two groups of observers. The research objectives can be summarised as follows:

1. Shading studies concentrated on the function of the view-out of the window and the elements that could affect this function.

2. Detailed investigations were carried out on the influence of the solar control shading devices which can affect both the view-out and the thermal performance of the window.

3. Two main window design concepts were studied: (a) The minimum acceptable window size for view; (b) The optimum window size for view.

4. The effect of the climatic and cultural backgrounds of observers on the evaluation of the view-out function was studied.

5. An evaluation was conducted into the thermal and daylight properties of the view-window (or the outlook window).

4.5.3. The main research concept and the researcher's experiments and solutions

Tabt-Aoul (1991) drew a structured outline of the research which illustrates the general ideas of the thesis. The following diagram demonstrates the outlines of the study.

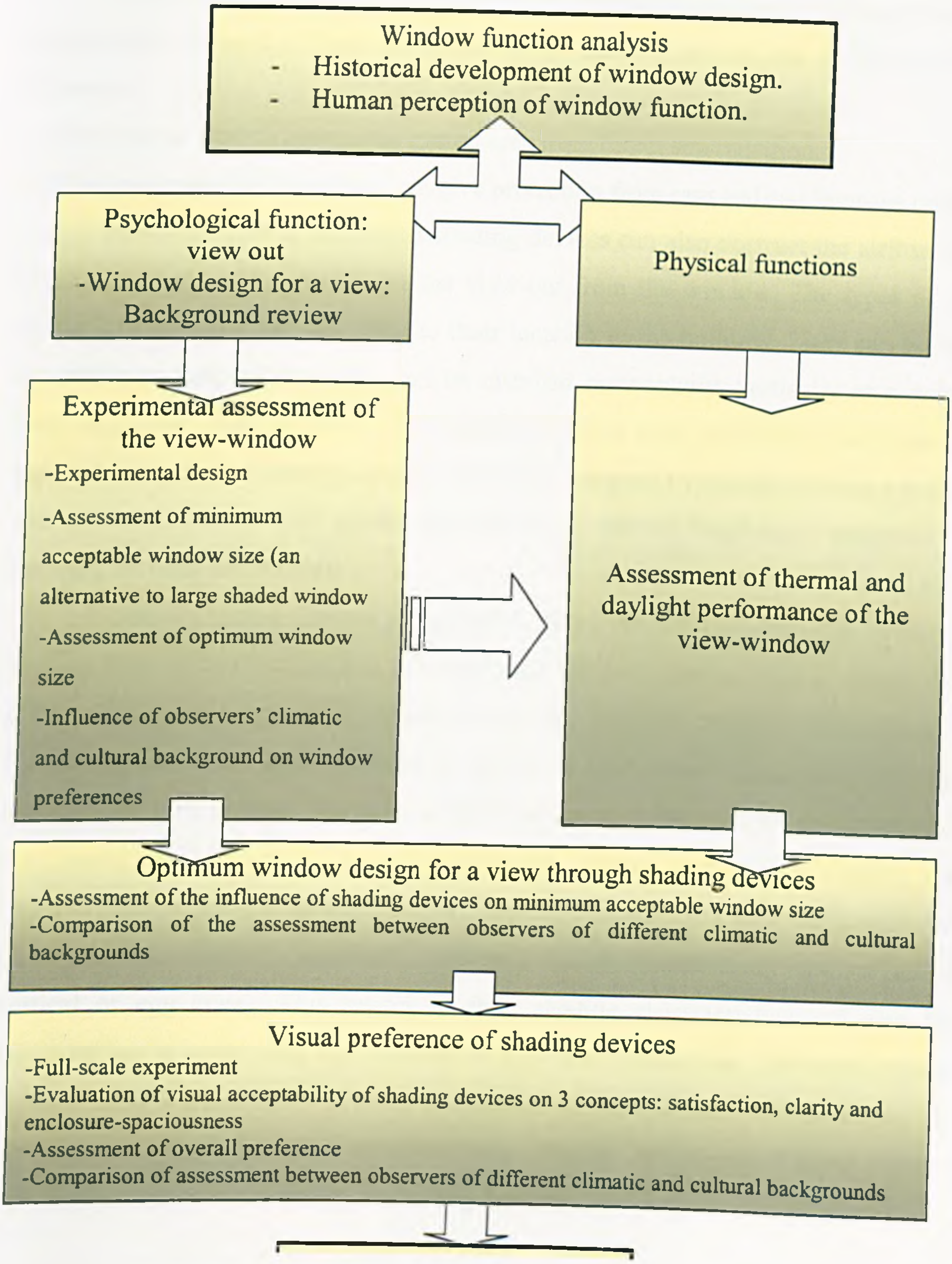


Figure 4.10. Structure of the research (Tabt-Aoul, 1991).

Tabt-Aoul (1991) noted that, in the experiments, the observers' responses might have been affected by certain factors: the use of a scale model, size, furnishing, layout, the viewing distance, the types of view, and the possible conditioning of the observers by their everyday environment, for example.

The researcher offered a summary of the types of solar control shading device, their functions and materials. Practical aspects of the shading devices can be illustrated in the following:

1. They can be used to protect the glazed area from direct sun radiation.
2. Shading devices reduce glare, can give protection from rain and can improve privacy.

Tabt-Aoul (1991) added that shading devices can also obstruct the airflow patterns inside the space and can obstruct the view-out from the window. The types of shading device can be classified according to their location in the building. They can be installed externally or internally; or they can be installed horizontally, vertically or a mixture of both (egg-crate shading devices). Tabt-Aoul (1991) also mentioned that Danz (1967) asserted that external shading devices have been designed in various of ways including the use of the floor, as roof protection, balconies, and as small-scale structural shades (louvers, screens and blinds).

External shading devices are generally fixed but can be adjustable while internal shading devices use vertical and /or horizontal blinds (Venetian blinds, vertical louvers, curtains etc.); these are usually adjustable (i.e. can be lifted, rolled or drawn back). Also, there are some types that use shading similar to the internal type; these may be used between multiple glazing. As well as these two main types (external and internal), there also exists "sun protection glass" (translucent, tinted glass). Such shading devices, however, do not provide total protection; they only transmit less solar radiation than other types of glass. Another classification is based on the orientation of devices (horizontal, vertical or egg crate). This relates to their shading characteristics and also to their effectiveness in controlling the radiation in different orientations. The main objective of these shading studies is to develop a methodological approach for estimating shading performance. The researcher illustrated the Olgyay & Olgyay shading methods in subsequent studies in the design of shading devices.

4.5.4. Research results and recommendations

From the experiments and investigations into climatic and cultural preferences in window design for view-out, the researcher drew the following conclusions:

1. The content of the view has a determinant effect on the shape, design and location of the window and, subsequently, on people's satisfaction with their view.
2. The two concepts, minimum acceptable window size (MAWS) and optimum window size (OWS), significantly influence the assessment of the window, with the OWS almost twice as large as the MAWS. This was mainly due to an increase in the window's width.
3. The researcher found that the best view-out from the window is through horizontal apertures with a width occupying a minimum of 35% to 40% of the wall width and an optimum of 45 to 60%. Bigger apertures are better for distant views.
4. The best glazed to wall ratios were found to range from 12% to 17% for the MAWS and 21% to 30% for the OWS. The study found that the two main factors affecting the window design parameters are window shape and location. Tabt-Aoul (1991) added that: "*the nature of the view affected by the dimension of the window with the height of the skyline influencing the head height, the visibility of the ground affecting the setting of the window sill, while the distance or proximity of the view affected the preferred window width.*"
5. The most significant parameters in the design of windows are the head and the sill.
6. For a better view, the window height should be set at 1.5 to 2 times the eye level for higher and lower floors respectively to include the skyline whenever it is visible.
7. The windowsill height is governed by the nature of the view and the degree of overlooking, also by the cultural background of the observers. The research results showed that views at ground level required higher sills (0.60-0.80m), while low windowsills were preferred at high levels (0.40-0.55m).
8. The apparent view from the window depends mainly on the eye level and distance of the observer from the window. Further research should examine the change in window requirements at different distances from the window.

4.5.5. Analysis, general discussion, exploitation and benefits from the thesis

The most important subject in the study relevant to this work is on shading devices. This topic was discussed in the thesis from the perspective of window view-out. In the main body of the research, the author discussed shading devices in general, their design and constraints. The researcher started her investigation by discussing the types of shading device in general, where they could be used, and their orientation and location. She then proceeded to examine the shading design methods of Olgyay & Olgyay (1957), and then considered subsequent studies based on the same approach. The methods of Olgyay & Olgyay (1957) of shading device design could be summarised in three main steps:

1. First, it has to be determined when shading is required, considering 21°C as the lower limit for overheating.
2. Second, by using a sun path diagram, the sun has to be located at times when shading is required. Sun path diagrams show the sky-vault projected on the horizontal plane. The sun's position is plotted over the overheated period.
3. The third step is to determine the type of shading device (horizontal, vertical or a combination of both, i.e. egg-crate). The position of the shading devices which meet the requirements are then located. From the shading mask, the size and angle of the shading devices can be defined. The device angle identifies the ratio of the depth of the shading and the dimension of the opening.

After designing the window configuration and size with an appropriate view requirement, the window orientation can then be chosen. After these two main steps, the detailed design of the shading device can be determined; this can be made by the use of a shadow angle projector. In the research, the analysis of the window protection requirements are illustrated by Figure 4.11. The vertical shadow angle is illustrated by the curved lines, while the vertical lines give the horizontal shadow angle. Tabt-Aoul (1991) noted also, that if the shadow angles are the same in the shading devices, the scale will not affect the features of the shading devices and they can be classified according to their shading masks. For instance, Venetian blinds and a balcony can be classified as the same type because they have the same shading mask (the same angle). Consequently, this gives a technically accurate solution for each situation.

Other considerations affecting the choice of shading device are aesthetics, ventilation, daylighting or view-out.

Tabt-Aoul (1991) also discussed the factors which can be restricted by the shading devices. These are:

1. The level of daylight.
2. The most efficient amount of ventilation and airflow pattern (especially on non-conditioned buildings).
3. The level of satisfactory view-out from the building.

In the investigation into the optimum window design of a shaded view, the researcher examined the effect of using different combinations of shading devices and views on the minimum acceptable window size (MAWS) in order to produce an acceptable view-out. In this experiment, Tabt-Aoul (1991) used eight types of shading device: four horizontal and four vertical. The total area of the window obstructed by the shading devices was 12%. The shading devices were classified according to the features of the elements contained in them: number, thickness and orientation. This is illustrated by Figure 4.12. The observers in the experiment were divided into two groups: the hot climate group (Hc) and the temperate climate group (Tc). One of the experiment results is that the view content and the different climatic and cultural backgrounds of the observers had the greatest influence on the evaluation of the view-shadings.

In the last part of the study, Tabt-Aoul (1991) presented some useful information regarding the comfort of the visual environment, given the incompatible needs of providing a view out and sun control. Three concepts were used to evaluate the subjective responses of the users to the screened view. These were: satisfaction, clarity and enclosure-spaciousness.

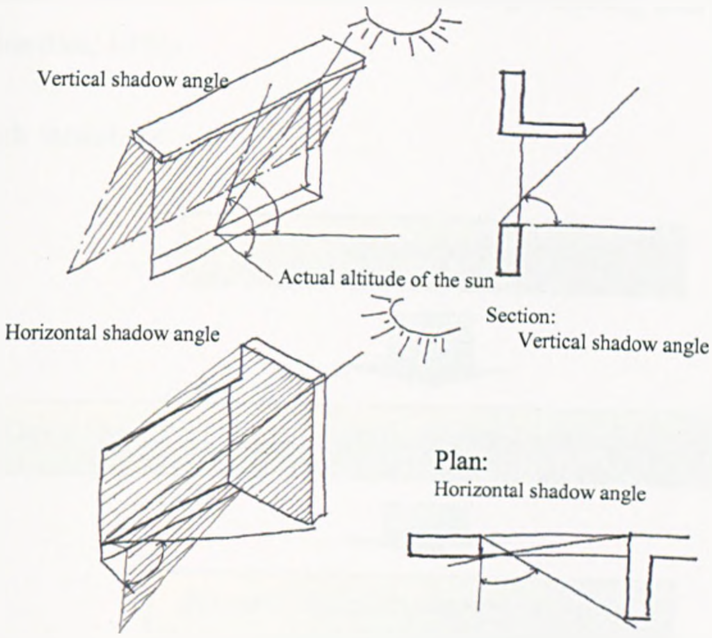
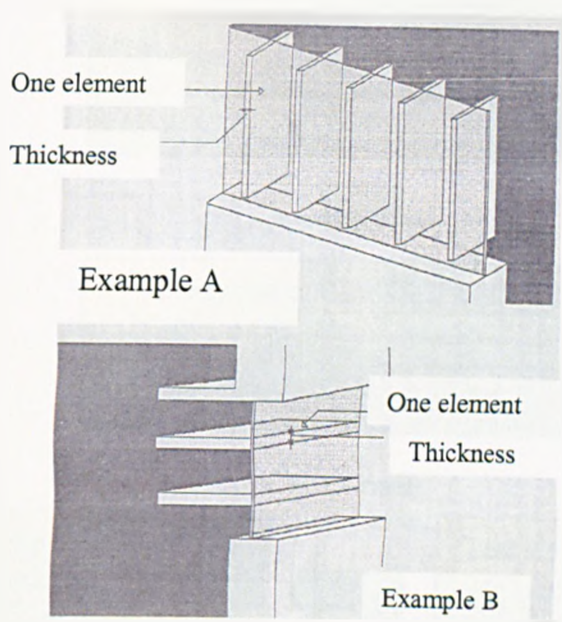


Figure 4.11. Vertical and horizontal shadow angle (Tabt-Aoul, 1991).



	No of Elements	Thickness	Orientation
Example A	5	X	Vertical
Example B	3	2X	Horizontal

Figure 4.12. Description and classification of the shading devices: original source (Tabt-Aoul, 1991).

4.6. Passive Solar Energy and Building: Including Shading and the Climate of Saudi Arabia. (N. Joudah, 1992)

4.6.1. Research structure

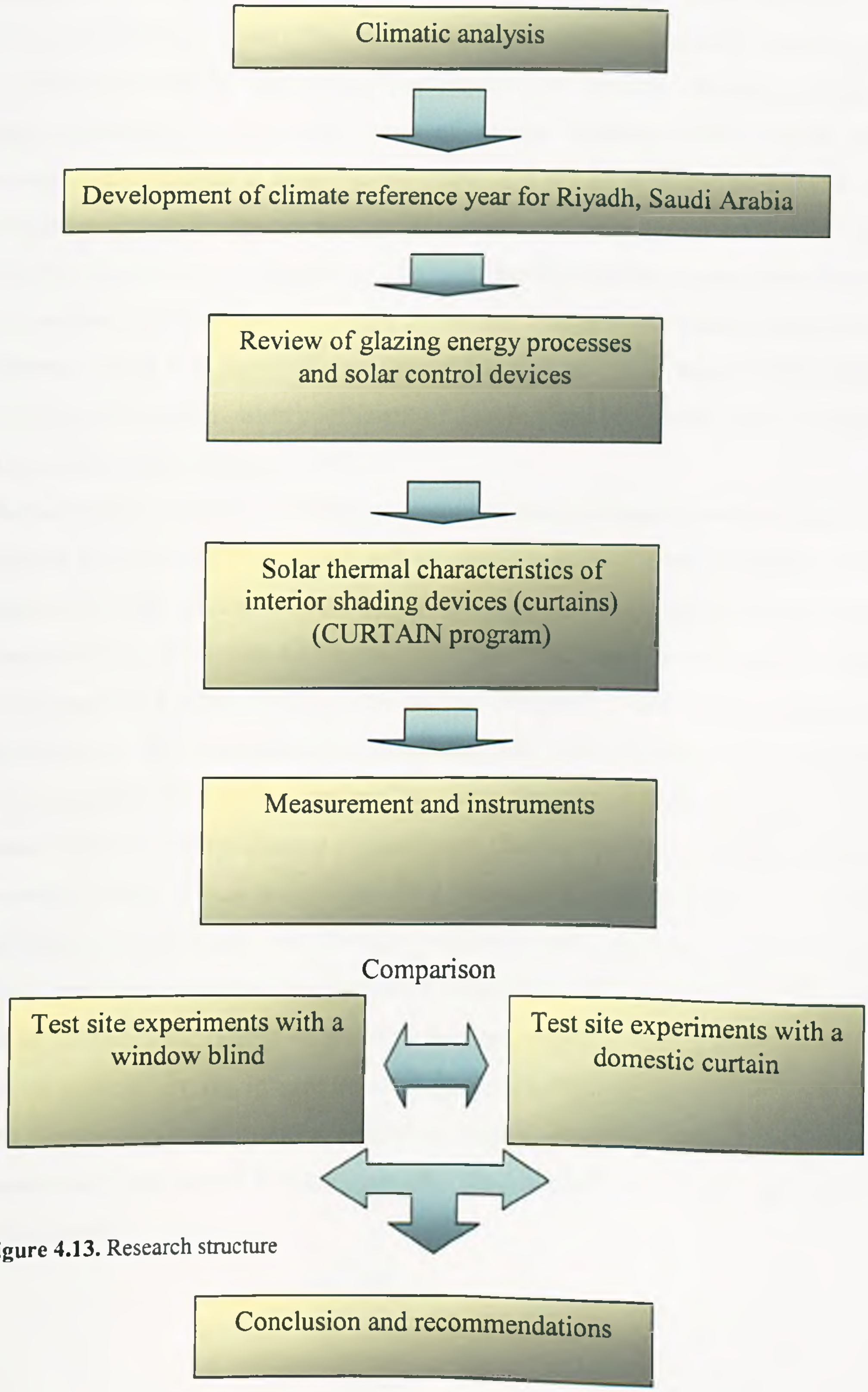


Figure 4.13. Research structure

4.6.2. Introduction and illustration of the general ideas of thesis

Simulating the energy performance of building designs is one of the major issues in producing an energy efficient building that faces designers, architects and engineers in Saudi Arabia. The author of this study aimed to produce useful information and simulation results for the building industry the context of Saudi Arabia. The main concern of the research was investigating the energy performance of internal shading devices. The researcher concentrated on two main types of internal shading device, namely internal curtains and internal blinds. A study of the effect of these types of shading device on the energy consumption inside spaces was performed by carrying out an investigation into the required level of comfort for occupants. The experimental measurements were researched using the outdoor test room at the PASSYS test site. The general results showed that the use of internal blinds was more efficient than using curtains. The author indicated that the blind can reduce the transmission coefficient of double glazed fenestration by 11% and can reduce the solar heat gain factor by 34%.

In the literature review, the researcher studied the relationship between climate data and buildings at different design stages and reviewed some mathematical models. He also investigated different calculation methods for the convective and radiative heat transfer at glazing surfaces. He developed a computer program to calculate the maximum solar heat gain flux through clear window glass in the climate of Riyadh, Saudi Arabia, and discussed some design tools for solar control, incorporating the effect of the angular relationship between the sun and the shading device. The study also included an investigation of the performance of solar control glazing and different shading devices, external and internal. The theoretical bases which were used to determine the effectiveness of curtains in reducing heat gain and heat loss through windows were provided, together with the classification and thermophysical properties of curtain fabrics. The research also examined the effect of the geometric configuration of curtain properties.

In the main study, the researcher investigated the thermal performance of a pleated metallised fabric blind with a low emissivity, on a double-glazed window from the experiments conducted on the PASSYS test site. This research covers nine chapters and is 191 pages in length.

4.6.3. Research Objectives

The main research objective was to study and investigate the energy performance of two types of internal shading device, namely curtains and blinds, which are common features in residential living spaces. The study also aimed to investigate the effect of these devices on the efficient use of energy in the internal spaces of the building and the comfort of occupants. These investigations were to be used in the assessment of the design tools developed in the study. The research also aimed to produce a significant climatic variable database for use in simulation programs for Saudi Arabia and other regions with similar climatic conditions, (i.e. hot dry zones). Joudah (1992) also summarised the research objectives to be achieved through the study as:

1. Building up a representative climatic data reference year for Riyadh, Saudi Arabia, to include the climatic parameters required in order to assess building energy simulation programs but which would also be useful for other hot dry zones.
2. Developing and presenting appraisals, to a high standard, of the solar and thermal properties of textile fabric internal shading devices. These would fulfil the need for a database in this field and be useful to further research.
3. Developing and providing architects and engineers with a simple design tool for modelling the thermal energy performance of curtains and blinds, which are used in shading fenestration under the influence of real climatic conditions. These would be validated through experiment.
4. Determining the thermal influence of curtain- and blind-shaded fenestration installed in real building components through the experimental study. The experiments were intended to illustrate the performance characteristics of these components and confirm the simulated results given by the "Curtain" program. The study also offered a comparison between the transmitted coefficient of double glazed fenestration and the reduced solar heat gain factor percentages for both curtains and blinds. This comparison was achieved using the simulation programs "ESP" and "Curtain", which were compared using some measured parameters.

4.6.4. The main research concept and the researcher's experiments and solutions

After reviewing the climatic conditions and the climate reference year which represents hot dry regions, Joudah (1992) started to investigate different calculation procedures for convective heat transfer at glazed surfaces. Then he developed computer software to calculate the maximum solar heat gain flux through clear window glass in the climate of Riyadh, Saudi Arabia. An examination of the efficiency of some types of shading devices was performed with both types of exterior and internal shading device. The researcher then examined and investigated the solar and thermal characteristics of the selected internal shading devices (curtains). A classification of types of curtain was provided with the thermophysical properties of these types of curtain fabric. The author also focused on the following: the solar properties of curtains (measurements and results), the effect of geometric configuration on curtain properties, and modelling the heat transfer through curtain-shaded windows.

A review was performed on different instruments for measuring: temperature, relative humidity, wind speed and direction, and insolation, concentrating on the measurement mechanism and the accuracy of the instruments. The researcher described and then developed a computer model, "Dtclm.bas", to process the logged data. Then an experimental study was performed to assess the thermal performance of a pleated metallised fabric blind with a low emissivity on a double-glazed window. In this experiment, the researcher examined the heat transmission coefficient and the solar heat gain factor. The test was performed in the PASSYS test site, which was located on the campus of Strathclyde University. The experiment results showed that the heat transmission coefficient of the blind-shaded fenestration is lower than the unshaded glazing. Moreover, the unshaded fenestration has a vertical solar aperture which is 0.17 (m^2) greater than the blind-shaded fenestration. In the next stage, the author examined internal domestic curtains using the same experimental methods. Experiments were performed to examine the thermal performance characteristics of the "reference wall", with and without a curtain. The main characteristics of these components were the heat loss coefficient and the solar aperture.

4.6.5. Research results and recommendations

The study examined different types of shading device and various properties related to curtain fabric and curtain-glass fenestration as a means of solar control (shading). The advantages of internal shading devices were given: for example, they are easy to reach and control for maintenance. Furthermore, they can reduce heat gain and heat loss through windows. However, they are less effective than external shades in minimising solar heat gain.

The curtain modelling software, which was developed by Joudah (1992) in this research, calculated the fenestration temperatures and energy flows associated with curtain-shaded single or double glazed windows affected by real climatic conditions. This model could be used in other assessments of energy performance of different types of internal shading device. In the experiments, a set of measurements of different indoor window coverings on passive building performance was developed using real building elements.

The experiment results showed that the curtain-shaded window could reduce the daily average heat transmission coefficient by 8% as compared with an unshaded window. Curtains can also reduce the solar aperture of the fenestration by 29%. On the other hand, blind-shaded fenestration resulted in 11% and 34% reductions in heat transmission and solar aperture respectively. The results show that the thermal performance of the PASSYS blind is better than the curtains. Joudah (1992) noted: "*Clearly the parameters measured in these tests relate only to the particular samples of interior shading devices tests (i.e. the "PASSYS" blind and the domestic curtain), operating under the conditions of the tests. Variables which might lead to different results for other types of textile-based interior shading devices, or for the same samples in different conditions, include: Fabric types and geometric configuration.*"

He also added: "*The outcome of experiments also showed confidence in the computer modelling of the energy performance of passive solar components. The simulation results of the "Curtains" program have shown good agreement with measured temperatures of the fenestration layers*".

4.6.6. Analysis, general discussion, exploitation and benefits from the thesis

The study gives an explanation for the efficiency of the shading devices and this could be the most important part of the thesis related to the scope of the current main research. From the study of the efficiency of shading devices, it can be found that the energy performance of a window could be highly improved by using external shading devices (i.e. louvered sun screens, blinds, awnings and roof overhangs).

The study gives examples of internal shading devices that could be used for solar control and for increasing the efficiency of the space. These include (Venetian blinds, vertical louver systems, fabric blinds of various kinds, and curtains). It has been shown that there are advantages to internal shading devices over external shading devices, in that they are protected against the weather and are easy to get at for control and maintenance. The research also offers a brief discussion and explanation of most shading device types used both externally and internally. External shading devices discussed in the study were: sun screens, exterior shutters, exterior roller blinds, architectural projections and awnings. Interior shading devices discussed in the study were: internal Venetian blinds, internal roller shades, curtains and insulated shutters.

The study also illustrated the characteristics of solar control glazing which could act as an efficient heat filter with some effect on the other functions of windows and facades. These include view and the provision of sufficient daylight. Solar control glazing could be classified according to specification, which could be summarised as the following: heat absorbing, heat reflecting, photo chromatic and applied films. Various types of glazing could be installed and integrated with the windows to maximize the efficiency of the space and the shading devices. The protection of the interior space from solar heat and undesired sun glare will thus be increased. It was argued in the study that the size and physical make-up of shading devices will sometimes not affect the devices' performance. Figure 4.14. shows different devices with the same performance.

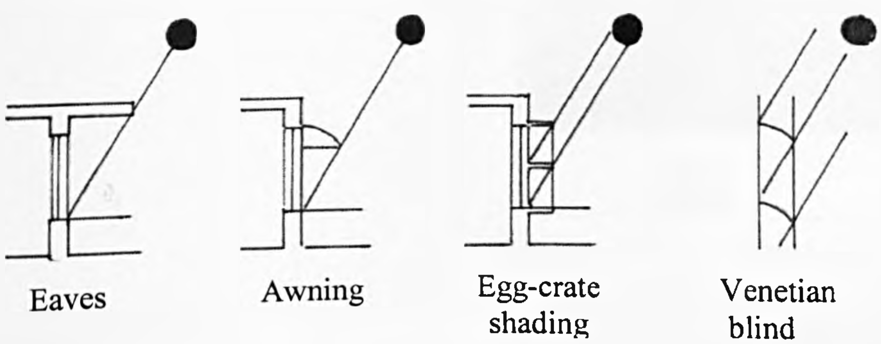


Figure 4.14. Various shading devices for a set performance at a vertical shading angle of 60°' (Joudah, 1992).

4.7. Natural Light Control in Hedjazi Architecture: An Investigation of the "Rowshan" Performance by Computer Simulation. (F.M. Al-Shareef, 1996)

4.7.1. Research structure

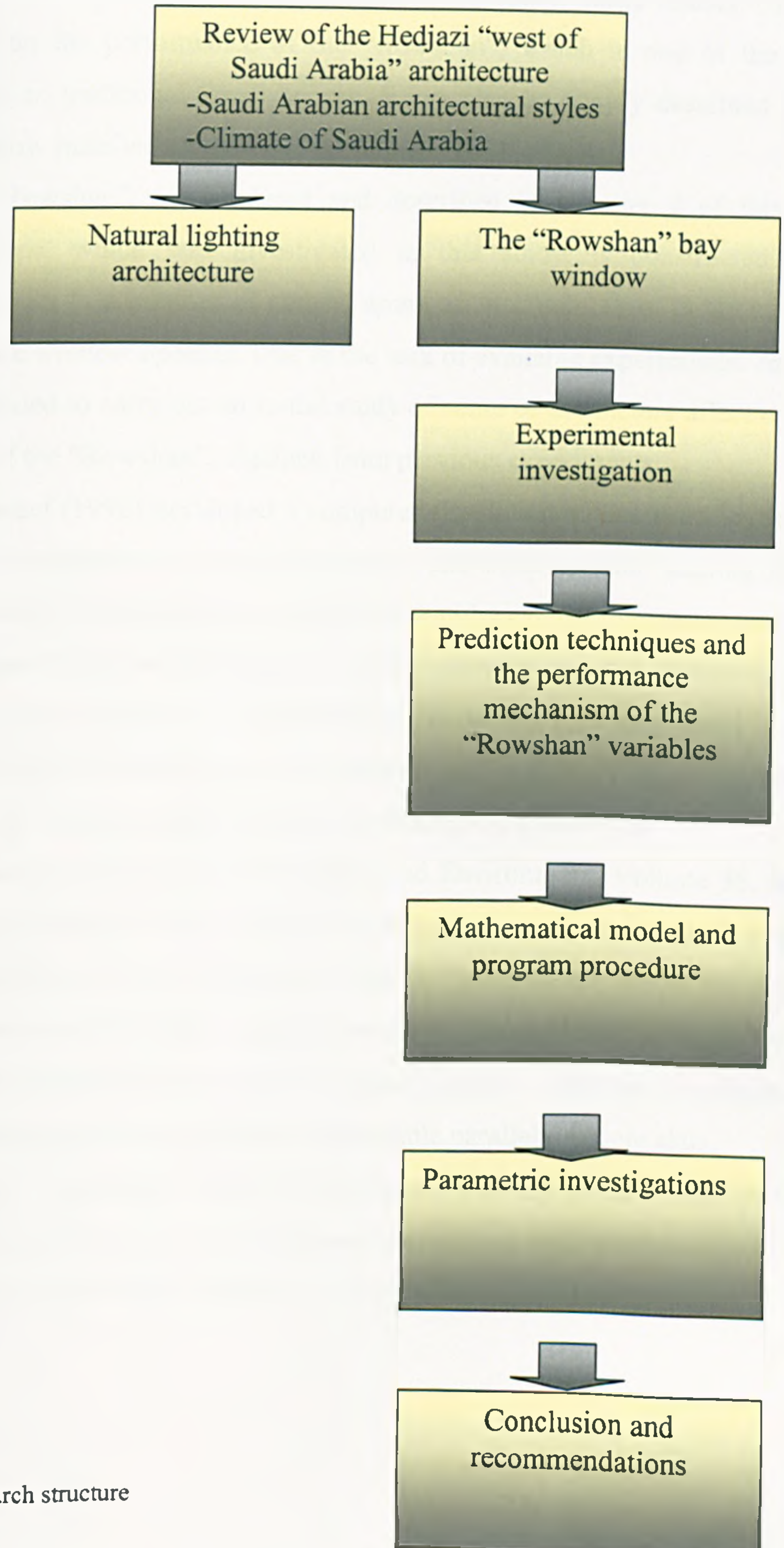


Figure 4.15. Research structure

4.7.2. Introduction and illustration of the general ideas of the thesis

This study mainly investigates the methods which are used in controlling natural light, with an approach for energy-saving methods in hot humid climate conditions, with special reference to the Hedjazi region, located in Western Saudi Arabia. The research is concentrated on the performance of the "Rowshan", which is one of the architectural elements used in traditional Saudi houses. It can also be simply described as a wooden screened window installed on the building façade.

The "Rowshan" was analysed and described in Chapter 2 of this thesis. The "Rowshan" type, which was investigated in this study, is constructed of movable horizontal louvers in a number of sashes, arranged in a number of columns and rows to cover the whole window opening. Due to the lack of available experimental equipment, the researcher decided to carry out an initial study of some of the factors affecting the general performance of the "Rowshan", obtained from previous experiments.

Al-Shareef (1996) developed a computer simulation model as an investigation tool to assess the performance of the "Rowshan" and other similar shading devices with sufficient accuracy. This investigation was followed by extensive experiments to study the effect of various "Rowshan" parameters. Each parameter was then discussed and defined with respect to the functions of the "Rowshan" in natural lighting control in the internal spaces under the climatic conditions of Western Saudi Arabia's Hedjazi region. The study stretched over 10 chapters with 377 pages, excluding the appendices.

This paper was published in Building and Environment, Volume 36, Issue 5, June 2000 by F. M. Al-Shareef, D. J. Oldham and D. J. Carter and was presented as an extended research on the same topic. The article's title is: *"A computer model for predicting the daylight performance of complex parallel shading systems"*. This study is also discussed here, as well the thesis, as one unit. The paper aimed to develop a computer model to investigate shading systems consisting of adjustable parallel multiple slats.

A model was defined for the "Rowshan" shading system used in the Hedjazi architecture of Saudi Arabia. The study was carried out with reference to tropical areas where the elimination of solar heat from buildings is a major consideration.

4.7.3. Research Objectives

The main aim of the thesis was to investigate the techniques which are used to control natural lighting as a means of energy saving in tropical climatic conditions, with special reference to the Hedjazi architecture in Saudi Arabia. The concept of energy conservation is one of the main objectives in both of the studies. This results from the increased demand for using natural daylighting instead of artificial lighting.

From this approach, the researcher found that it was essential to develop many of the traditional techniques to create new systems and materials for fenestration. In both hot dry and humid regions, it is very important to eliminate the solar heat gain and sun glare from the internal spaces in buildings. The traditional methods have been developed to allow the shading of direct solar radiation whilst allowing some penetration of daylight and visual communication between the interior and the exterior.

Shading devices in the traditional architecture may take many forms. For instance, these include overhang structures; deep windows, which allow an extra depth for solar shading; and louvers and blinds systems for both approaches, externally and internally. Al-Shareef's paper assessed the objective of louvers and blind-shading systems, that is, blocking direct sunlight whilst allowing daylight to enter the internal space. Moreover, most traditional Arabian shading systems are designed with parallel multiple slats that can be adjusted to any declination angle of the sun.

Al-Shareef (2000), in the published paper, added: "*Such traditional methods have largely stood the test of time but reappraisal of them may now be necessary. For example, traditional materials may no longer be available (e.g. some types of hardwood) or the basic design of the devices may need to be adapted to be used as part of modern buildings. To enable such changes to be made efficiently, the traditional techniques must be understood in a quantitative manner.*"

4.7.4. The main research concept and the researcher's experiments and solutions

The paper investigates, in the main, the lack of daylight illuminance modelling; it also discusses the development of a computer-based model for the analysis of the general case of parallel shading louver systems. The application of the model is demonstrated with reference to the "Rowshan" shading system used in Western Saudi Arabia's Hedjazi region. The computer model in this study has the capability of simulating daylight performance for compound shading systems. Moreover, the concept of the model technique lies in calculating the illuminance at any point in the interior of the room. External daylight sources have been classified in the paper as:

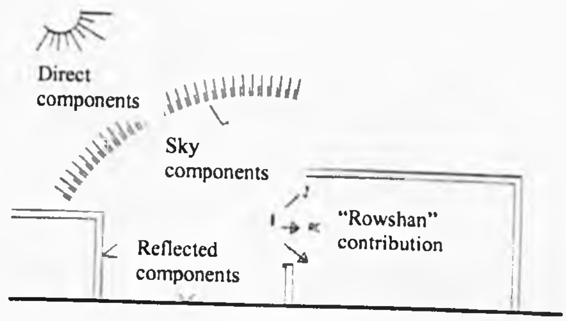


Figure 4.16. Daylight components. Original Source: Al-Shareef (2000).

1. Sunlight (direct sun light), 2. Sky component (light from the sky), 3. External reflected component (light reflected off the ground and external surfaces). See Figure 4.16. External daylight sources constitute one of the principles underlying the computer model. Another principle mentioned in the paper is the influence of the shading system on the interior illuminance. A station point is the point that light reaches inside the space from the daylight penetrating through the window slats, which is the main possible source of illumination. See Figure 4.17. Other factors that also affect the influence of the shading system on the interior illuminance are: 1. Light penetration through gaps between slats. 2. Inter-reflection between slats. 3. The position and geometric relationship of the station point.

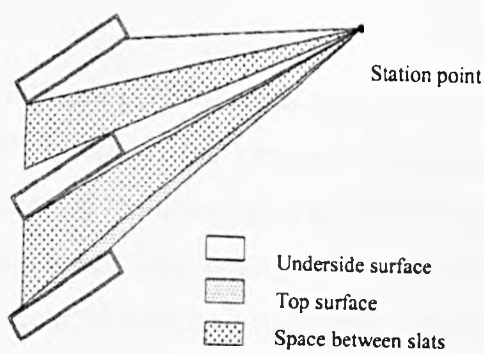


Figure 4.17. Daylight penetration through or reflected from window "Rowshan" slats (Al-Shareef, 2000).

The model application then proceeded to consider the "Rowshan" configuration and the researcher calculated the daylight received on a slat surface from a combination of sources.

In the investigation, the researcher used three common cases of the projected "Rowshan" on the solar-elevation azimuth angle and studied their effect on the contribution of the front or side "Rowshan" sashes. See Figure 4.18. Al-Shareef (2000) mentions: "*Inter-reflection between the facing surface of slats can be an important factor in determining the ultimate contribution from a slat surface to a station point. The program calculates the exitance of the slat top surface as a result of the sun and sky components and the inter-reflections between slats, and the exitance of the slat's underside surface as a result of the external reflected component and the inter-reflections exitance*". The paper also included a validation of the computer model and a parametric study of the daylight behaviour through slats, the direct sunlight component and other components.

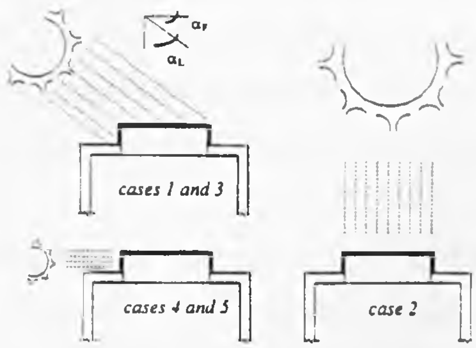


Figure 4.18. The common cases of the solar-elevation azimuth angle and its effect on the contribution of the front or side "Rowshan" sashes (Al-Shareef, 2000).

4.7.5. Research results and recommendations

In the conclusion of the research paper, Al-Shareef (2000) mentioned that this type of shading system, the "parallel shading system", is one of the vernacular strategies in controlling daylight in various regions. He also stressed the importance of being aware of the daylight transmission methods and techniques through these devices so that they could be redesigned and installed in buildings in tropical areas, hence developing new technology and energy-saving methods. Al-Shareef (2000) also added: "*The passage of light from natural sources through parallel shading devices has been shown to be a complex process. Unfortunately, this cannot easily be modelled using conventional methods. The validation exercise indicates that the model described in this work is robust and has considerable potential as a reliable method of quantitative understanding daylight penetration through a parallel shading system and the subsequent light distribution within a room*".

4.7.6. Analysis, general discussion, exploitation and benefits from the thesis

In his thesis, Al-Shareef (1996) discussed natural light availability and noted that the availability of natural light depends on the amount of solar radiation. Also, he observed that other factors could affect the availability of natural lighting, like the effect of the rotation of the Earth about its axis and its revolution about the sun. After a process of investigation of the atmosphere and the climatic conditions, and an analysis of the natural light, it was found that natural lighting is mainly composed of two types of component: direct light and indirect light.

The daylight availability and the effect of the sun were also discussed in the thesis. Al-Shareef (1996) noted that the position of the sun with respect to any point on the Earth's surface is expressed in terms of two angles: 1. the solar altitude angle, which is the vertical angle of the sun above the horizon, and 2. the solar azimuth angle, which is the horizontal angle of the sun from due south in the Northern hemisphere.

One of the most important topics in the thesis is solar control and shading. Strategies of solar control are important in resolving the problems of sun glare and undesired direct sunlight inside the space. Shading devices and tinted glass could be used to solve these problems. However, tinted glass is not recommended in tropical regions, due to the thermal properties of the glass. Direct sun glare cannot easily be avoided by using tinted low-transmission glass. The level of transmittance should be less than 0.05 so it is better to use other methods to reduce glare. Shading devices can be installed in a building externally, internally, or between double-glazing. They can be fixed or movable and could be of different architectural shapes and geometric configurations.

The thermal performance of shading devices is dependent on various factors, for instance, shading type and climatic conditions. Al-Shareef (1996) illustrated the functional Olgyay & Olgyay shading methods, which divide shading devices into three main types: vertical, horizontal and egg-crate. Each type will affect the window by what is called a shading mask or shaded area. The shading effect from any vertical object is generally indicated by radial lines emanating from the reference point. On the other hand, horizontal objects are indicated by a semi-circular segment. The effect of the egg-crate will be a combination of those represented by vertical and horizontal elements. See Figure 4.19.

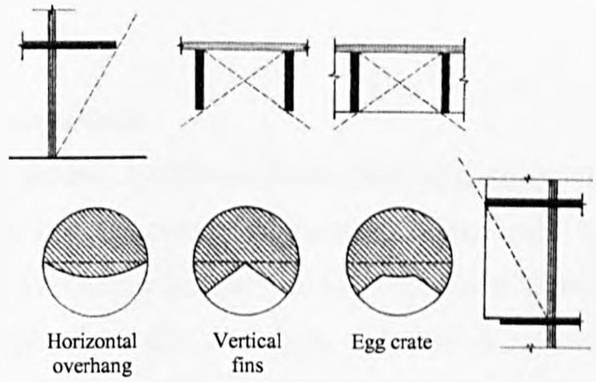


Figure 4.19. Shading masks of fixed shading devices (Givoni, 1976).

Al-Shareef (1996) noted that it was argued by Givoni (1976), regarding the thermal effect of shading, that it is more efficient to use an adjustable type of shading device and that this could also be efficient in most types of climatic conditions and in various situations due to the fact that they could be moved and controlled to cut the sun's rays. The efficiency of these types of shading device is greatly affected by their position, the size and percentage of the aperture, and their colour. Givoni (1976) noted also that external shading devices are generally more efficient than internal ones. He observed that an increase in the darkness of the colour would cause a decrease in reflectance which, in turn, leads to an increase in the efficiency of the shading device. For external devices, the level of darkness of the device's colour will affect the efficiency: "*The darker the colour, the more efficient the devices*".

4.8. Evaluation of Overheating Protection with Sun-Shading Systems. (T.kuhn, C.buhler, W. Platzer, 2001)

4.8.1. Introduction and research paper objectives

This research paper deals with the general functions of sun-shading systems. These systems mainly provide thermal and visual comfort consistently and cost-effectively. They should also prevent undesirable solar gain in summer and provide high solar gain in winter. The paper also investigates and develops a strategy to assess overheating protection through the use of various types of shading device systems applied together.

The main objective of the selected shading methods is to provide an efficient and reliable approach to assess the performance of a combination of three shading methods: 1. internal shading devices, 2. external shading devices, 3. glazing, regardless of the type of building. The selected new method consists of the angle-dependent determination of the total solar energy transmittance, based on ray-tracing methods, which were evaluated through calorimetric measurements. The researchers used the annual irradiance distribution to evaluate various control strategies and demonstrated that this is essential for reliably calculating cooling and heating loads. Furthermore, they noted that the calculation should be based on a control strategy, which represents the building users' priorities. The paper demonstrated that there are no efficient methods to assess the performance of sun-shading systems. This means that architects and designers have to make their own choice on the methodology of shading strategies. The researchers aimed to develop and investigate a methodology to evaluate the performance of sun shading devices, together with a connected control strategy. The methodology was designed and validated for internal and external Venetian blinds, supplied by the company "Huppe form" of Germany.

The research paper started by explaining the users' requirements, which were divided into two main groups. These are illustrated in Figures 4.20. and 4.21. The first figure illustrates the requirements for sun-shading while the second figure illustrates both the thermal and visual comfort requirements. The paper also maintained that it is impossible to optimise all factors at the same time. For instance, good visual contact to the exterior could be achieved only with reduced protection against overheating and glare.

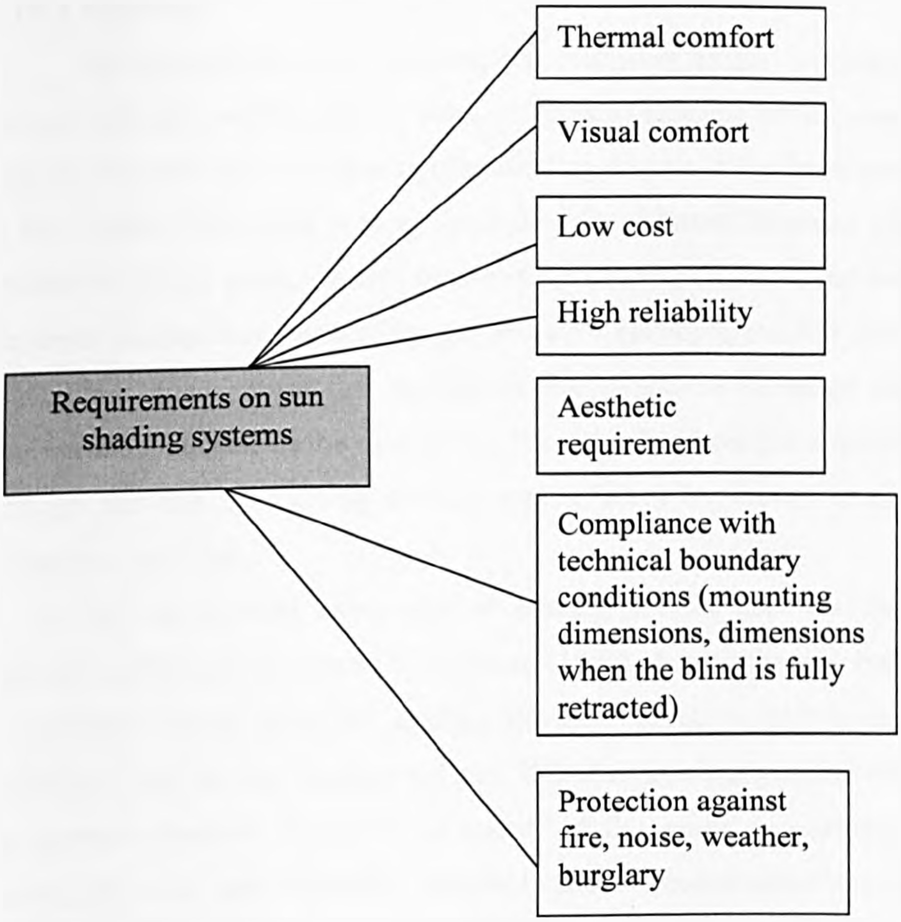


Figure 4.20. Requirements of sun shading systems (W. Platzer, 2001).

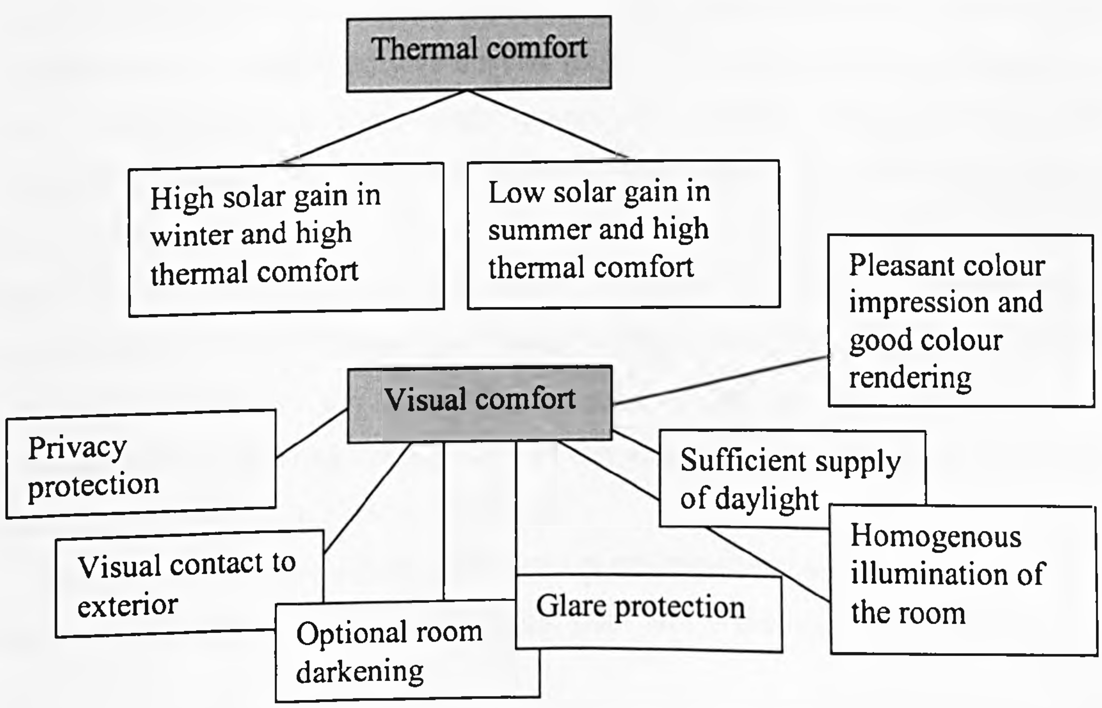


Figure 4.21. Daylight and thermal requirements for sun shading systems (W. Platzer, 2001).

4.10. Conclusion

Six research studies, covering the following topics: ventilation through shading devices; thermal performance of selected types of shading device; natural lighting through shading devices; and view through the shading devices, have been reviewed and presented in this chapter. This work is an evaluation of the different functions of shading devices and an analysis of the general performance of the shading devices. The structure of each study has been illustrated in terms of the general work elements, and the tools and methodologies used. It has been proved that ventilation rates could be increased through using shading devices. This is clear in the case of the "Rowshan", where the enhancement of ventilation through the use of shading devices was affected by factors such as the inclination, orientation and size.

On the thermal assessment of shading devices and how they affect the indoor thermal comfort of occupants, KU Hassan (1996) showed that the best performance could be achieved using egg-crate shading devices, which consist mainly of a mixture of horizontal and vertical shading devices. KU Hassan's study is the most relevant study to the current research. Some of the results of this study concerning the contribution of shading in solar gain reduction are used later for comparison with the current research results as a validation assessment. Some of the research studies presented here consisted of two parts: an experimental part, which evaluated the performance of the selected function of the shading devices, and an appraisal, which assessed and evaluated the results of the experiments, in order to achieve the best results and obtain a good understanding of the topic. This resulted in some useful points and excellent design guidelines for environmental designers and architects to use in the production of energy efficient buildings. KU Hassan's study is entitled *"The Application of Solar Shading Devices for Building in a Hot Humid Climate with Special Reference to Malaysia"*. This produced design guidelines for the performance of shading devices and for the selection of suitable types of device to achieve the best and most efficient use of these shading devices. However, the types of shading device tested in this study were very simple and designed with a basic configuration, as shown in Figure 4.7.

Shading devices have a strong effect on the environmental conditions, especially in hot regions, which require shading for the whole year. This is pointed out in the following:

1. Shading devices in hot zones reduce the sun's glare and the sunlit area that penetrates into the spaces inside through the window.

2. Shading devices can affect environmental conditions by reducing the required cooling load inside buildings.

In this chapter, some of the original results of these researches were reproduced to offer a detailed examination and illustrate the aims and objectives of the researchers. The climatic conditions in most of the studies applied to hot regions. This shows that solar shading devices are essential elements in such climatic conditions for reflecting heat, reducing cooling loads, and for achieving comfort for the occupants.

Investigations concerning daylighting through shading devices were also widely discussed in *"Daylighting and Shading for Thermal Comfort in Malaysian Buildings"*. The researcher found that the best performance and the most efficient shading design for daylighting by windows is through the light shelf with a sloped overhang, which allows a sufficient level of daylight to penetrate through it. Moreover, the optimum slope of the overhang was found to be at an angle of 45°. Shading devices were recommended in this research in the investigation of the "WWR" (the window to wall ratio). The researcher found that the best WWR percentage is 25%. However, if the window exceeds this percentage, the installation of a solar shading device becomes essential for reducing undesirable glare.

View-out is one of the window's functions that is affected by shading devices. This function was discussed intensively in *"The Interaction of View, Window Design and Shading Devices"* by K.Tabt-Aoul (1991). This study closely examined two main window design concepts: the minimum acceptable window size for view-out (MAWS) and optimum the window size for view-out (OWS). The investigation results showed that there is a need for shading devices, even with the minimum acceptable window size. It was also proved that the best view-out from the window is through horizontal apertures with a width which occupies a minimum of 35% to 40% of the wall width, and an optimum of 45% to 60%. Another study, *"Passive Solar Energy and Building; Including Shading and Climate of Saudi Arabia"*, which concentrated on the performance of internal shading devices, showed that blind-shaded fenestration could achieve from 11% up to 34% reductions in heat transmission in buildings.

Investigating the previous efforts in the field will result in a better understanding of shading types and functions. The current research should present a continuation of the chain of previous studies.

CHAPTER 5

SOLAR GEOMETRY AND SOLAR SHADING DESIGN

5.1. Introduction

The sun is the main source of radiation which gives us energy for heating and lighting. It also provides the human body with vitamin D, which is a very important element in the body building process. With the huge advances in technology, the sun has become more important and has become a source of electricity through the use of PV cells. Nevertheless, there is still a great deal of research being done on how to get electrical energy from the sun and there is an expectation that, in a short time, the sun's radiation will be the most important source of energy on earth (Bin Oaf, 1994).

A firm knowledge of the sun's movement in the sky is very important for designing shading devices. The behaviour of solar radiation and its components is also fundamental in the knowledge of heat gain and loss in buildings.

This chapter sheds light on three main topics. Solar geometry and the earth's movements constitute the first topic while the second topic covers shading design and shading periods and requirements. The third topic is an introduction to the parametric study and illustrates the experiments' concepts and aims. The first part of this section includes a brief explanation of the earth's movements, its tilt axis and the nature and components of solar radiation. A description of the effect of a building's orientation on the amount of the received solar radiation has been obtained through initial experiments.

Shading design using solar charts is discussed by illustrating the shading design process. This includes an example of designing a horizontal overhang shading to shade a window in Jeddah, Saudi Arabia. A general discussion is offered concerning the internal exposure of the indoor surfaces to the solar radiation. This discussion includes the effect of shading devices, the internal sunlit area, and the thermal performance of the shading devices. Shading requirements and periods for Riyadh, Saudi Arabia, are also explained, as well as the overheating and underheating periods in Riyadh that are also illustrated in the study.

The last part of the chapter gives a brief idea of the research's parametric study approach and the aims of the conducted experiments. Experiments in the research were conducted using two main methods. The first method involves the use of computer software models (SunCast and ECOTECT) and experiments using these models were conducted in different latitudes and climatic zones. This included the selected latitudes of London, in the UK; Riyadh, in Saudi Arabia; and Jeddah, also in Saudi Arabia. The second experiment method uses a scaled physical model. This method was used only in

Jeddah, Saudi Arabia to predict the penetrated sunlit area on the internal surfaces in both the summer and winter seasons.

5.2. Solar Geometry

5.2.1. The earth's movements

There are two main earth movements: the earth's rotation (around it own axis) and the earth's revolution (around the sun). The earth travels in an almost circular orbit around the sun, as indicated diagrammatically in Figure 5.1. This rotation is completed in 365 days. The main cause of this rotation is the sun's gravity. The earth rotates around its own axis (N, S) at the rate of one revolution per day (24 hours). This is known also as the **mean solar day**.

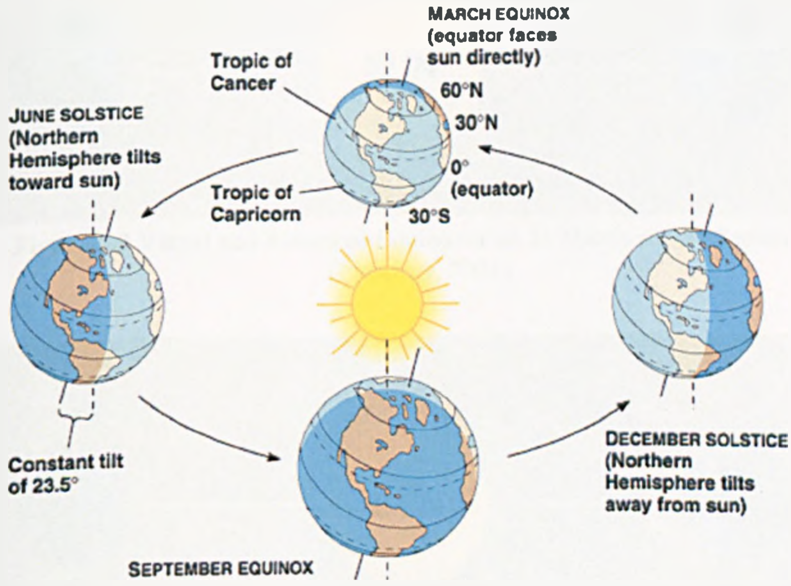


Figure.5.1 Movement of the earth around the sun and around it own axis. (www.bio.miami.edu/dana/160/globalseasons.jpg)

5.2.2. Tilt of the earth's axis

The earth's axis (N, S) is not perpendicular to the plan of its orbit (called ecliptic) but is inclined at an angle of 23° 27′ (practically taken at 23 1/2°) so that, when the sun is at the date point around December 21 and the north pole is inclined directly away from the sun, the latter appears to be at a declination of -23 1/2°. A quarter of a year later, when the earth reaches the date-point around March 21, the sun's declination will be zero. Three months later still, when the earth passes through the date point on June 21, it will be +23 1/2°, while on the date point at about Sept 21 it will again be zero.

The direction of the sun's rays in relation to the earth varies on different dates. For the northern hemisphere, the date at which there is extreme declination is called the winter solstice; this is around December 21. The vernal and autumnal equinoxes are around March 21 and Sept 21 respectively and the summer solstice is on June 21 (Olgyay, 1957).

The annual variation in the sun's height above the horizon results from the movement of the earth around the sun and the changing positions of the earth's axis to the sun. The changing of the seasons also results from the intensity and duration of the solar radiation received by specific locations on the earth (Pidwirny, 2004).

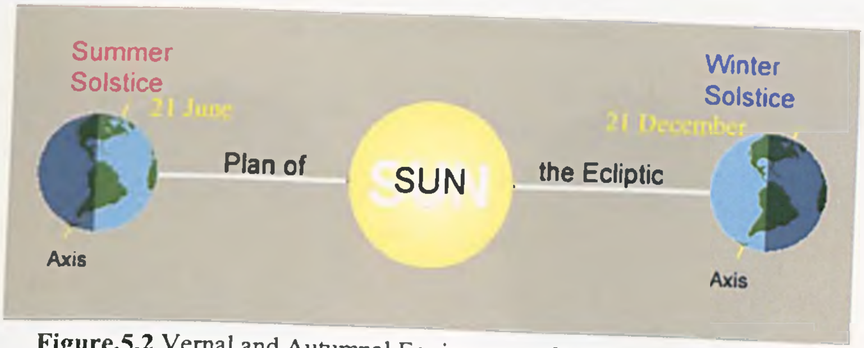


Figure.5.2 Vernal and Autumnal Equinoxes on 21 March and 21 September (Pidwirny, 2004).

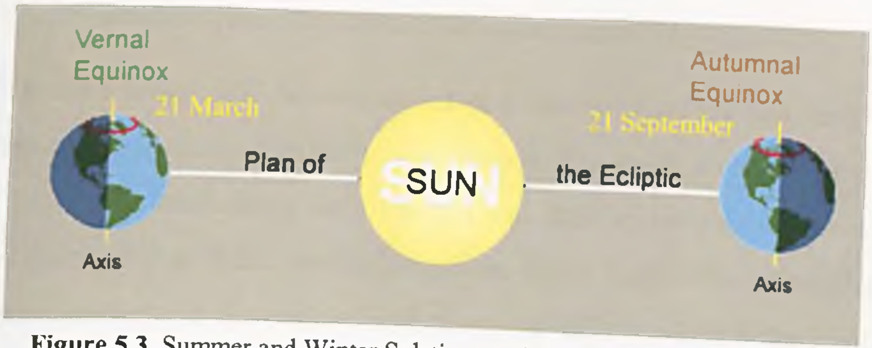


Figure.5.3 Summer and Winter Solstices on 21 June and 21 December (Pidwirny, 2004).

5.2.3. Solar altitude and axis tilt

According to Pidwirny (2004), solar altitude is the vertical height of the sun from the horizon. As mentioned earlier, the annual changing in the position of the earth's axis in relationship to the sun results in variations in the height of the sun (solar altitude). The maximum total variation in the solar altitude is 47° (23.5x2) for any location on the earth over a one-year period. For example, in a 50° N location, the solar altitude values vary from 63.5° in summer to 16.5° in winter. At the equator, the solar altitude is 66.5° above the northern end of the horizon in summer and in winter the solar altitude is 66.5° above the southern end of the horizon. In the case of the equator, the solar altitude at the horizon is 90°, as shown in Figure 5.4.

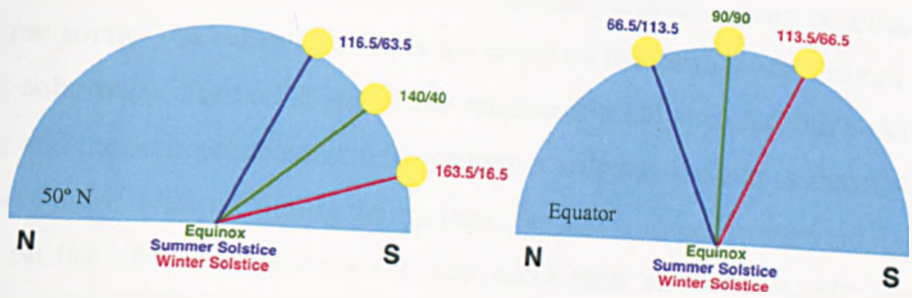


Figure 5.4. Solar altitude angle variation in the sky at solar noon at 50N° and at the equator (Pidwirny, 2004).

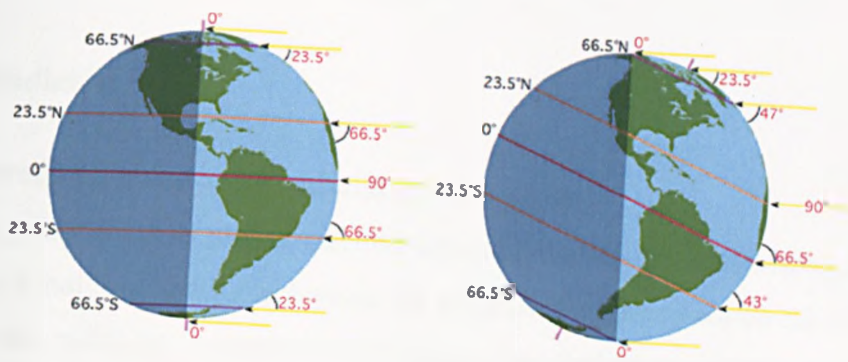


Figure.5.5 Equinox (left) and summer solstice (right) (Pidwirny, 2004).

The earth's orbit could be considered as a circle around the sun, with the sun at the centre of this orbit; in detail this orbit is an ellipse. The earth's rotational speed varies in this orbit; it is faster when away from the sun and then it slows as it moves closer to the sun. This should give a better perception of the sun's angles for principles of building design. These variations in the earth's orbit cause the differences in *solar time*, which is the sun's position in the sky, and the *standard time*, which is the time showing on our clocks. Differences in these two times could be illustrated by the following equation:

$$\textbf{Solar time} - \textbf{standard time} = 4(L_{st} - L_{Loc}) + E \qquad \textbf{5. 1}$$

L_{st} is the standard meridian for the local time zone

L_{Loc} is the longitude of the location by degrees west

E is the equation of time in minutes.

The annual solar energy variation received by the earth from the sun mainly depends on the earth's position and its tilt on the orbit around the sun. It is very important to understand the sun-earth relationship in order to produce energy efficient solar control design in buildings. There are two main methods for solar control. These are:

1. Reducing solar heat gain in the overheating periods to provide natural cooling.
2. Maximizing solar heat gain in the underheating periods to provide natural heating.

Solar noon is known as the time during the day where the sun is allied with true north and true south. The subsolar point is the point on the earth when the sun is directly overhead at solar noon. Figure 5.5 shows the relationship between the sun's radiation and the equinox and the summer solstice. In the summer solstice, the sun is directly overhead the Tropic of Cancer whereas, during the equinox, the sun is directly overhead the Equator. Red angles on the right side illustrate the maximum solar altitudes at solar noon while black angles on the left side illustrate the Equator, the Tropic of Cancer, the Tropic of Capricorn and the Arctic Circle (Pidwirny, 2004).

5.3. Solar Radiation

5.3.1. Solar radiation and solar radiation components

Solar radiation is largely an electromagnetic radiation that emits from the sun and is the fuel source that provides a mechanism for all biological processes on earth. Direct solar radiation is the radiation received by the earth's atmosphere or earth's surface without being scattered in the atmosphere.

There are three main components of solar radiation. These components are: 1- Direct solar radiation. 2- Diffuse solar radiation. 3- Reflected solar radiation. Direct solar radiation is largely the radiation received without it changing its direction. The amounts of solar radiation received by the ground depend on the sky conditions. The percentage of dust particles, ozone content, water vapour and solar altitude are all factors that affect the intensity of solar radiation. Diffused radiation is mainly caused by the dispersal of components of air molecules, water vapour and dust particles in the sky. Diffused solar radiation is normally greater in the higher latitudes and smaller in the lower latitudes. Diffused radiation makes up about 20% to 30% of the total radiation received on the horizontal plane in lower latitudes. However, in higher latitudes, it is about 30% to 40%. Reflected radiation is mainly caused by surrounding surfaces and ground. The properties and reflectivity of these surroundings strongly affect the amount of reflected radiation (Hassan,1996).

Solar radiation and daylight are essential to all forms of life. Solar radiation is a fundamental energy for survival and the development of living things. Daylight to humans *is important in that it is necessary for visual comfort and providing for psychological needs (Muneer, 1997).*

Muneer (2000) defined the solar day as the interval of time between two successive returns of the sun to the local meridian. The time required for the earth to make a full rotation is less than a solar day by four minutes. He also defined solar radiation (W/m^2) as the energy emanating from the sun. Luminance is the energy contained within the visible part of the solar radiation.

5.3.2. Transmission of solar radiation

Solar radiation is transmitted into buildings through their transparent external surfaces. Efficient solar design of buildings aims to provide an amount of energy sufficient to be used for heating in cold climate zones. Transparent materials like plastic and glass are widely used in modern architecture. These materials provide protection from unwanted climatic elements like cold and hot winds, dust and snow. At the same time they provide natural lighting and link visually the internal spaces with the exterior environment.

Incident radiation on the transparent surfaces is divided to three main parts: 1. that which is reflected to the exterior. 2. that which is absorbed by the glass. 3. that which is transparent from the exterior to interior through the transparent surface. This is shown in Figure 5.6. The percentage of the reflected incidence of solar radiation on normal glass depends on the angle of solar radiation incidence on the glass surface. Studies have proved that, as the angle of incidence increases, the rate of reflection achieved becomes greater (Bin Oaf, 1994).

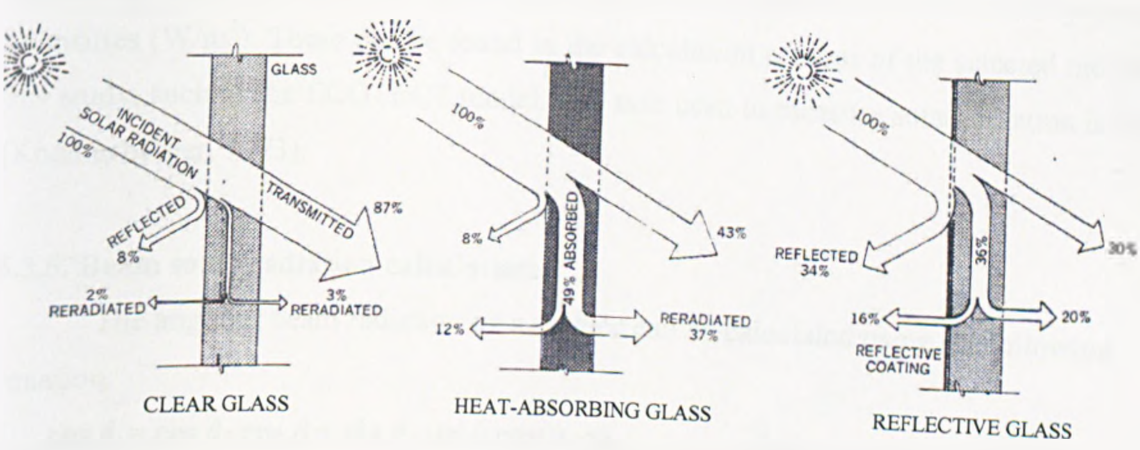


Figure.5.6 Solar radiation transfer through the glass surfaces (Norbet, 1991).

5.3.3. Solar constant and extraterrestrial radiation

As stated by Duffie and Beckman (1991), the solar constant (G_{sc}) is the amount of energy from the sun received by a surface perpendicular to the direction of the propagation radiation per unit of area, per unit of time. A study by Johnson (1954) evaluated the solar constant value of 1395 W/m^2. Extraterrestrial radiation is the radiation received in the absence of the atmosphere and can be calculated through the following equation:

$$G_{on} = G_{sc}(1+0.033\cos 360n/365) \quad 5.2$$

where G_{sc} is the solar constant and G_{on} is the extraterrestrial radiation, measured on the normal plan of the radiation on the nth day of the year.

Variations in extraterrestrial radiation are affected by two major factors. The first factor is the radiation emitted by the sun. The second variation factor is variations in the earth-sun distance. Goswami (2000)

5.3.4. Measurements and predictions of solar radiation

In order better to understand climate change, it is necessary to know how much energy is entering the earth's atmosphere. Methods used to measure solar radiation are made by using the available instruments. These instruments, such as the solarimeter, heliometer, actinometer and pyranometer, are used to evaluate the quantity of solar radiation. General climatic conditions for a region can be predicted from the amount of solar radiation. This will include the average daily maximum and minimum solar radiation for each month. In the process of designing an energy efficient building, general knowledge must be obtained about the hourly total (MJ/m^{2}h) or the hourly average intensities (W/m^2). These can be found in the calculation process of the selected models in this study, such as the ECOTECT model. The unit used to measure solar radiation is W/m^2 (Koenigsberger, 1973).

5.3.5. Beam solar radiation calculations

The angle of beam radiation on a surface can be calculated using the following equation:

$$\cos\theta = \cos\theta_z \cos\beta + \sin\theta_z \sin\beta \cos(\acute{\alpha} - \gamma) \quad 5.3$$

ere,

Angle of incidence, the angle of the beam radiation on the surface.

θ_z = Zenith angle, the angle between the vertical and the line to the sun, complement to any solar altitude angle.

β = Slope, the angle between the surface plane and the horizontal which varies from 0 to 180°.

ά = Solar azimuth angle, the angle on the horizontal surface between the projected solar beam and the line which points to true south.

γ = Surface azimuth angle, the angle on a horizontal plane between the projected solar beam and the projected line which is normal to the surface.

For the horizontal surfaces, the angle of incidence is the zenith angle of the sun (θ_z)

$$\cos \theta_z = \cos L \cos \delta \cos h + \sin L \sin \delta \qquad 5.4$$

where,

L = Latitude, the location on the north or south of the equator; north positive and south negative varies from -90° to 90°.

h = Hour angle, the angular at which the earth must turn to bring the local meridian directly under the sun. It is measured on the earth's axis at 15° per hour, with morning being negative and afternoon positive.

δ = Declination, the angular distance of the sun north or south of the earth's equator, with north being positive, and varying from -23.45° to 23.45°.

Beckman (1991) pointed out that in solar methods design and performance calculations, it is important to calculate the hourly data for radiation on tilted surfaces from measurements or estimations of solar radiation on the horizontal surface. The available data are mainly for hourly or daily total radiation on a horizontal surface.

Figure 5.7. shows the angles of solar beam radiation on horizontal and tilted surfaces. For calculating the ratio of the beam radiation on tilted surfaces compared with that on horizontal surfaces, the following equation could be used:

$$R_b = \cos \theta / \cos \theta_z \qquad 5.5$$

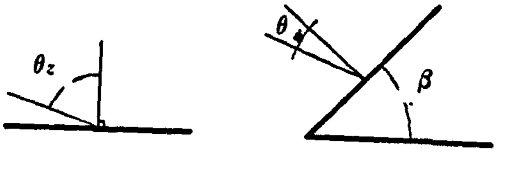


Figure 5.7. Beam radiation on both horizontal and tilted surfaces (reproduced after Beckman, 1991).

5.4. Solar Charts and Locating the Sun's Position

5.4.1. Solar charts

The position of the sun in the sky can be determined by several methods. One of the most common methods is the two-dimensional solar chart or the sun path diagram. Two main angles in this chart are used to find the sun's position, that is, the solar azimuth angle and the solar altitude angle (θ). In a typical solar chart the radiating lines indicate the azimuth angle (ά), which is 0° in the south, while it is 90° on either side in the east and west. Concentric circles show altitude angles, which vary from 0° to 90°. Sun charts can be used to assess shading on the building façades due to geographical characteristics, surrounding buildings, façade projections and local landscape features. This assessment is achieved via the solar altitude angle which shows the angle of the sun radiation incidence on the building's façade. In this way, the shading devices can be designed. Shading should protect buildings from the penetration of sunlight in summer and allow this penetration to occur in winter for natural heating.

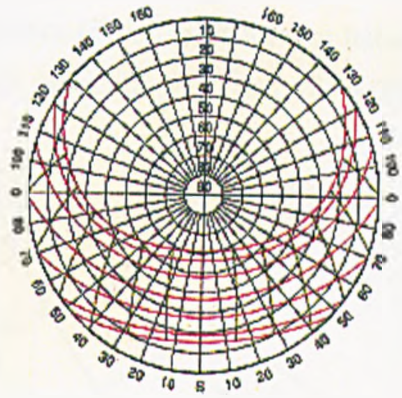


Figure 5.8 Solar chart: the concentric lines are the altitude angles; the red radiating lines are the azimuth angle. (http://www.esru.strath.ac.uk/Courseware/Design_tools/Sun_chart/sun-chart.htm)

5.4.2. Solar altitude and solar azimuth angles

The solar altitude angle (θ) is defined as the angular height of the sun measured between the horizontal plane and the line connecting the sun to the observer. The solar altitude angle varies from 0° to 90°.

The solar azimuth angle (ά) is defined as the horizontal angle measured at the horizontal plane between the north and the vertical plane including the sun. The solar azimuth angle varies from 0° to 360°.

The azimuth angle is measured clockwise from the north and therefore:

North direction (ά) = 0° or 360°
East direction (ά) = 90°
South direction (ά) = 180°
West direction (ά) = 270°

Calculating the solar altitude (θ) and the azimuth angle ($\acute{\alpha}$) can be achieved through the following factors: solar declination angle (δ), hour angle (h), and the latitude of the observer (L). The following equation can be used to find these two angles:

Solar altitude Sin (θ) = Sin (L) Sin (δ) + Cos (L) Cos (δ) Cos (h) **5. 6**

Solar azimuth Cos ($\acute{\alpha}$) = Sin (δ) - Sin (L) Sin (θ) / Cos (L) Cos (θ) **5. 7**

The solar declination angle or the angle of incidence (δ) is the difference between the solar azimuth and the wall azimuth. Thus, if the wall is facing west, then (δ) = 270 – the azimuth angle.

The wall solar azimuth angle is defined as the horizontal angle measured between the vertical plane and the perpendicular to the wall.

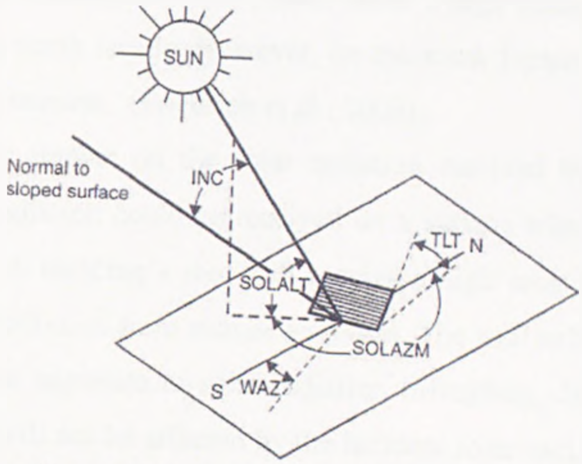


Figure 5.9. Solar altitude, solar azimuth, inclination, and wall azimuth angles (Muneer, 2000).

5.4.3. The process of locating the sun's position by calculating the azimuth and altitude angles

Locating the sun's position, the altitude and azimuth angles, for a specific location at a certain month at a certain time, can be achieved by using solar charts. This can be illustrated as the following:

- Selecting the location's solar chart.
- Locating the selected date curve in the chart, for example, 21 December.
- Finding the intersection between the date curve and the selected time line, for example, at 9 h.
- Drawing a straight line from the centre of the chart through the marked hour and date intersection and through the perimeter circle. The azimuth angle can then be read from the perimeter circle.
- On the same drawn line, the distance between the perimeter circle and the marked point illustrates the altitude angle of the sun.

5.5. Effect of Solar Radiation on Buildings

5.5.1. Building Orientation

When producing a building design form that is energy efficient and whose orientation is determined by climatic factors, such as the solar radiation of the surroundings, knowledge of the solar radiation distribution on different building orientations is essential for producing energy efficient façades. This is useful for the reduction of thermal radiation loads, as well as glare, through shading systems. Friedrich et al. (2003) performed an experimental study to evaluate the monthly diffuse and direct radiation on vertical façades on different orientations. The results show a high amount of solar radiation in summer months on the north façade. However, on the south façade high solar radiation is found during the winter seasons (Friedrich et al., 2003).

Building orientation has a strong impact on the solar radiation received by the building surfaces. The maximum solar radiation could be received on a surface when the solar azimuth is equal to wall azimuth. A building's roof will receive a high amount of solar radiation due to its exposure to the radiation from sunrise to sunset. The wall azimuth is the main factor that affects the surface exposure to solar radiation (Mingfang, 2002). Internal heat gain in a building normally will not be affected by the incident solar radiation because of the well-insulated opaque surfaces. Energy efficient materials will absorb the heat from the solar radiation and this will be re-radiated internally later.

This can be observed in the traditionally built walls in old Jeddah. The walls are thick to absorb cool air at night; they then re-radiate this coolness during the day time. Solar radiation falls on building surfaces in two main ways during the day: by direct and indirect radiation. Direct radiation is the incident radiation coming directly from the sun through the atmosphere. Indirect radiation is the radiation scattered in the atmosphere or reflected from other objects like nearby buildings. Incident direct radiation on surfaces is highly dependent on surface orientation. However, indirect radiation is independent of surface orientation.

By using the SunCast model, a primary study was conducted to assess the behaviour of solar radiation on different façade orientations. The study was performed in summer and winter in order to achieve an efficient evaluation. This study is described in Chapter Six.

5.5.2. Initial experiments on solar radiation on different orientations and climatic zones

The main aim of this study is to evaluate the solar radiation exposure on the four main elevations (N, S, E and W) in Riyadh (a hot climate) and in London (a cold climate). The evaluation was carried out by using the ECOTECT model simulation. A simple 6m (width) x 6m (length) x 3m (height) room unit was designed for the evaluation. The exposed examination wall area therefore was 18 m^2. The results show that the maximum solar radiation exposure occurs on the south and east walls in Riyadh (the hot climate). The maximum solar radiation exposure in London (the cold climate is on the south facing wall, as can be seen in Table 5.1. and Figure 5.10). Results show the monthly average radiation. From these study results it can be concluded that a south orientation is the most useful for investigation. (A complete set of study results appears in the Appendices.)

Average solar radiation on different orientations for different climatic zones				
Orientation	N	S	E	W
Riyadh (Hot climate)	26568 Wh	47439 Wh	48374 Wh	42137 Wh
London (Cold climate)	10460 Wh	18041 Wh	15453 Wh	13600 Wh

Table 5.1. Solar radiation exposure in the four main elevations in both hot and cold climatic zones.

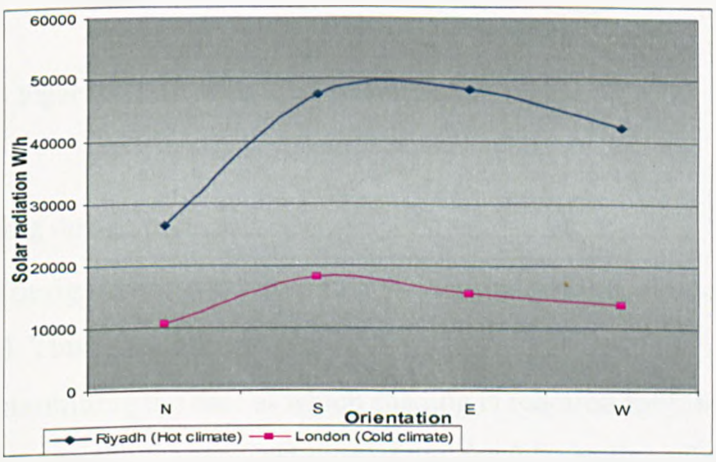


Figure 5.10. Graph showing the various solar radiation values on different orientations for both cold and hot climate zones.

5.6. Solar Radiation Control Methods

5.6.1. Shading design from solar charts

The dimensions of shading devices can be calculated by using solar charts to examine the horizontal shadow angle (HSA) and the vertical shadow angle (VSA). The

HSA is the angle between the solar azimuth and the wall azimuth while the VSA is the vertical angle including the bottom two points of the window and the sun, as shown in Figure 5.11.

HSA = azimuth – orientation **5. 8**

VSA= atan[tan(altitude)/cos (HSA)] **5. 9**

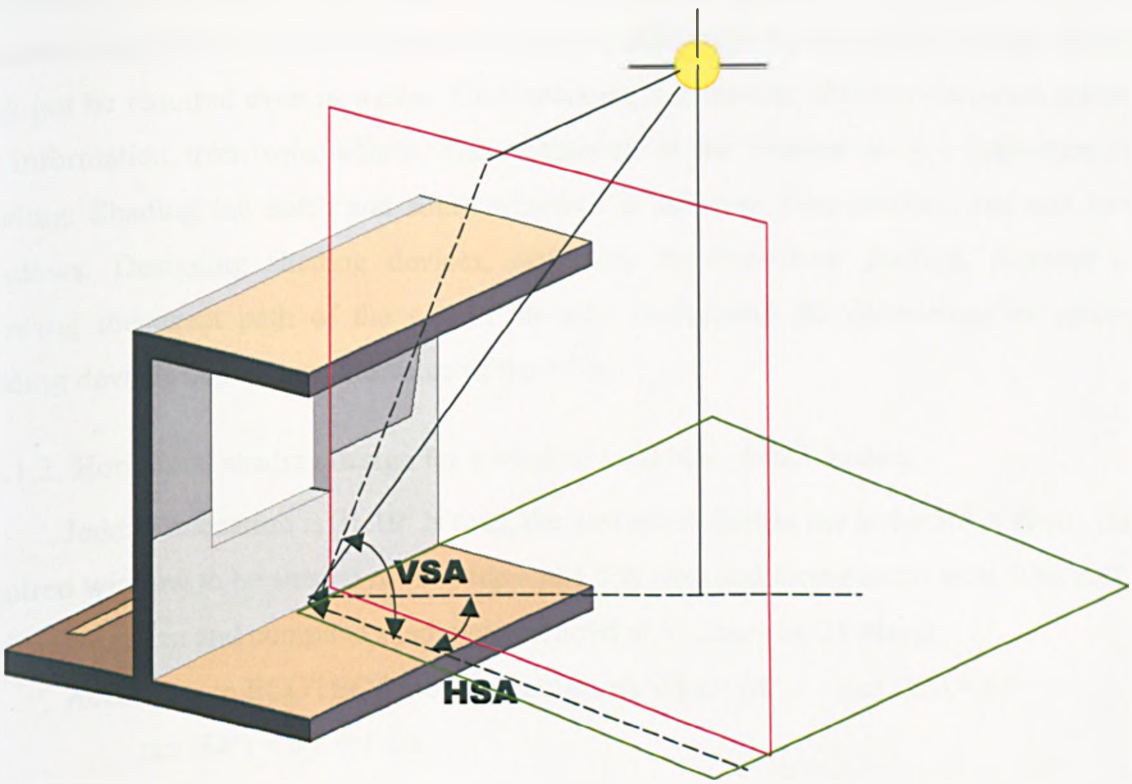


Figure 5.11. Horizontal and vertical shadow angles.

5.6.1.1. The shading design process

There is a design process to determine the horizontal shading according to the ECOTECT model. This is as follows:

- Determining the date at which shading is required for the window.
- Determining the required time of day for full shading of the window.
- Studying the sun's position at the location from the related solar charts. This will help to calculate the solar azimuth and solar altitude angle for the required shading time.
- Obtaining the horizontal and vertical shadow angles (HSA and VSA).
- Calculating the width and depth of the horizontal shading using the equations below:

$$\textit{Depth} = \textit{height} / \tan(\textit{VSA}) \qquad 5.10$$

$$\textit{Width} = \textit{depth} \times \tan(\textit{HAS}) \qquad 5.11$$

These methods should provide efficient shading for the required periods. However, it is very important to know how much sunlight will penetrate in winter. In winter, the penetration of sunlight may be desirable, especially in cold climate zones. In a very hot climate zone, however, penetration of sunlight in winter may not be useful because heating may not be required even in winter. Understanding the shading efficiency depends mainly on information from solar charts. The orientation of the window is very important for shading. Shading the north and south windows is different from shading east and west windows. Designing shading devices, especially for horizontal shading, depends on knowing the exact path of the sun in the sky. Calculating the dimensions of vertical shading devices depends on the value of the VSA.

5.6.1.2. Horizontal shading design for a window in Jeddah, Saudi Arabia.

Jeddah's location is 21.19° N thus, the best solar chart to use is the 20° N chart. The required window to be shaded is 1m wide and 1.5 m high and facing south-west. The wall thickness is .2 m and complete shading is required at 13 hours on 21 March.

According to ECOTECT model calculations VSA= 64° and HSA= 10°

$\tan(64°) = b/a = 1.5/a$

$2.050 = 1.5/a \qquad a = 0.731$

b= the window height and a= length of the horizontal shading.

The horizontal shading projection will be 0.731 - 0.2, which is the wall's thickness. The result is 0.531, as shown in Figure 5.12. There is an unshaded triangle in the window's side. To shade this triangle, an HSA of 10° could be used so an extra length needs to be added to shade this triangle. According to Harkness (1978), this extension could be calculated through (*e*)

$e = 0.531 \tan(\text{HSA}) = 0.531 \tan 10 = 0.093$

by applying Equation 5.1 which is

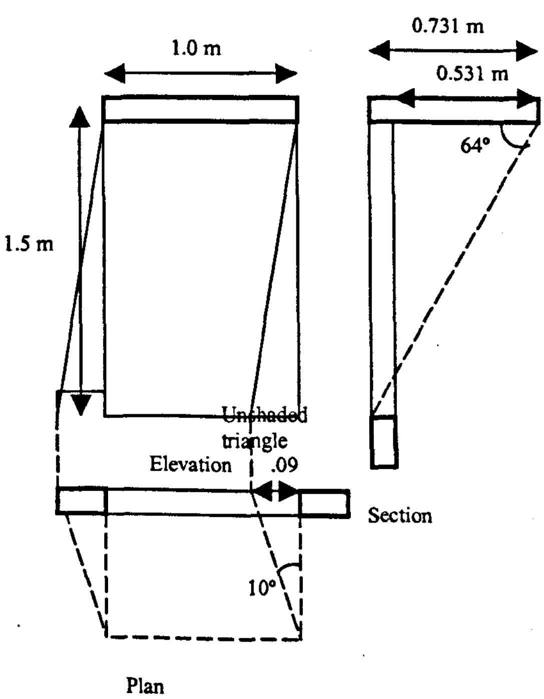


Figure 5.12. Shading device design illustration.

Depth = height / tan(VSA)

Depth = 1.5 / tan 64 = 0.731 m. This gives the same result.

5.7. Exposure of Indoor Surfaces to Direct Solar Radiation

5.7.1. Shading analysis

According to Jorge (1993), shading analysis can be achieved through three existing methods. The first method is by using a graphic tool, the second method uses manual calculation and the third employs a scale model. An analytical model can offer a sufficiently accurate prediction of the desired amount of shading. Shading will be achieved under different conditions such as location, orientation, time, etc.

Shading devices are used in many forms in different buildings and locations. Nowadays, shading device configurations are increasing and they are varied in design, shape, material and location related to the shaded surface. Subsequently, they have different abilities, levels of efficiency and performance (EL-Refaie, 1987).

5.7.2. Internal sunlit analysis

One of the most important aspects in building design is the internal sun lighting. Penetration of natural sunlight not only reduces the demand for artificial lighting, but also can be a decorative element in the interior. Internal sunlit penetration connects the exterior and the interior environments. This is by giving the occupants a feeling of being closer to nature (info.tuwien.ac.at 2004). Sun lighting should be integrated into the overall objectives and aesthetics of the architectural design. Nevertheless, direct sun on the interior could produce undesirable glare, especially when the internal direct radiation reaches desks or computer screens (Gon Kim, 2003).

5.7.3. Thermal analysis

Within the scope of the main work, simulation will investigate the thermal performance of the shading devices which affect the required cooling or heating loads. Room comfort temperature is also another aspect which will be investigated in a different study of the effect of the internal sunlit area on the thermal performance of the shading. In the IES "SunCast" model, the default setting of the room data for the maximum summer design temperature is 23 °C, and the minimum summer design temperature is 19 °C for the heating setting. In the cool setting, the winter design room temperature is 19 °C. This setting is changeable according to the most desirable temperature in summer and winter, and the general climatic conditions.

Using a computer model, like SunCast, has a several advantages. These are as follows. It is: 1. A simple and fast simulation tool. 2. Any desirable shading configuration and orientation could be simulated. 3. It is an efficient tool to understand the relationship between the solar geometry and shading (Capeluto, 2003). Achieving an efficient assessment of shading devices depends on the performance of shading in both the overheating and underheating periods. Consequently, an annual shading evaluation should be achieved (Olgyay, 1957). According to this, the evaluation of shading efficiency will be performed in summer and winter. Previous investigations proved that external shading could reduce a tremendous amount of heat gain, especially in buildings with large fenestrations (EL-Refaie, 1987).

5.8. Shading Periods and Building Types

Shading is always required in the overheating periods of the year. Norbert (1991) noted that shading is required as both a function of climate and building type. He also divided the buildings into two groups and mentioned that, from an energy point of view, buildings can be divided into two main types: *envelope-dominated* and *internally dominated*. The envelope-dominated building is very much affected by the climate because it has a large surface area-to-volume ratio and because it has only modest internal heat sources. The internally dominated building, on the other hand, tends to have a small surface area-to-volume ratio and large internal heat gains from sources such as machines, lights and people. Norbert (1991) added to the study a comparison table of the two types of building.

He also classified buildings through the *balance point temperature (BPT)*. This method depends on the outdoor temperature and the building's internal temperature. He defined the balance point temperature as that outdoor temperature below which heating is required. He added that buildings do not need heating when the outdoor temperature is only slightly below the comfort zone because there are internal heat sources (lights, people, machines, etc) and because the skin of the building slows the loss of heat. Thus, the greater the internal heat sources and the more effectively the building skin can retain heat, the lower the outdoor temperature will be before heating is required. The balance point temperature for a typical internally dominated building is about 50°F (10° C) and, for a typical envelope-dominated building, it is about 60°F (15.5° C).

Since the comfort zone has a range of about 10°F (68 to 78°F), the overheated period of the year starts at about 10°F above the balance point temperature of any building.

For example, for an internally dominated building (BPT=50°F), the overheated period would start when the average daily outdoor temperature reached about 60°F. Consequently, the lower the balance point temperature of a particular building, the shorter will be the under heating periods (heating season) and the longer will be its overheating period (cooling season) during which time shading is required. Norbert (1991) also included two tables to show the under heating periods and the overheating periods throughout the whole year for both an envelope-dominated building and an internally dominated building. The study was carried out in different regions in the U.S.A. with a reference for each region by a particular city. The study shows that much shorter overheating periods are found with the envelope-dominated building compared with the internally dominated building.

Characteristic	Envelope Dominated Buildings	Internally Dominated Buildings
Balance point temperature	60°F=15.5°C	50°F=10°C or less
Building form	Spread out	Compact
Surface area-to-volume ratio	High	Low
Internal heat gain	Low	High
Internal rooms	Very few	Many
Number of exterior walls of typical rooms	2 to 3	0 to 1
Use of passive solar heating	Yes, except in a very hot climate	No, except in a very cold climate
Typical examples	Residences, small office buildings, some small schools	Large offices and school buildings, auditoriums, theatres, factories

Table.5.2. Comparison of two building types, rearranged by the researcher after Norbert (1991).

Other shading studies presented by Norbert (1991) illustrate methods as shading design guidelines in the forementioned regions of the U.S.A. which could be useful in the shading study and the design of shading in Saudi Arabia. For example, for shading design for a south window, he stated the rules for selecting a south-shading strategy. These are: 1. If shading is the main concern and passive heating is not required, then a fixed overhang may be used. (This would apply to the climate of Jeddah, Saudi Arabia). 2. If both passive heating and shading are important (for long over-and. under-heating periods), then a movable overhang should be used. (This would apply to the climate of Riyadh, Saudi Arabia.)

Also, he stated other design guidelines for fixed south overhangs, shading for east and west windows, designs for east and west horizontal overhangs, a design for slanted vertical fins, a design for fins on north windows, and design guidelines for egg-crate shading devices. Other special shading strategies were illustrated, such as a design for shading to surround the building and the exterior building parts, such as balconies and outdoor areas extending from the living room and used for sitting or dining. This shading envelope provides the building with cool shaded outdoor spaces and such a strategy could be very effective in hot climate zones. This idea was designed and applied to a residence by MLTW/Turnbull Assoc. in Virginia, U.S.A. where the building was placed inside a separate structure made of redwood lattice walls.

5.8.1. Overheating periods in Riyadh, Saudi Arabia

To achieve an efficient design for shading devices, overheating periods must be located. These periods are the times when total protection from direct solar radiation is required, thus preventing the sun's rays from penetrating into the internal spaces. The basic factor to identify these periods is the average temperature, which represents the minimum human comfort zone (Koenigsberger, 1973). Complete shading and protecting the internal spaces of the building from the penetration of solar radiation is required when the external temperature is equal or higher than the thermal rate that represents the minimum comfort zone level. In hot dry and hot humid zones, overheating periods could be most days of the year. However, night temperatures could decrease to reach below the minimum comfort temperature in Riyadh.

In cold climate zones, temperatures are always below the minimum comfort temperature, which requires the penetration of solar radiation for natural heating. Therefore there is no shading required for windows and openings.

The most efficient technique to use to identify the overheating periods is by drawing the temperature contour lines on a diagram that has day hours on its vertical axis and months on its horizontal axis. Average temperatures for each month are then distributed between these two axes so a contour line can be drawn, as shown in Figure 5.14. (Said, 1991; Bin Oaf ,1994).

If the average daily temperature is not available it can be assumed that the highest average monthly temperature represents the highest daily temperature (which is normally observed from 14:00 h to 15:00 h). Also, the average minimum monthly temperature can represent the minimum daily temperature, which is normally observed from 5:00h to 6:00h (Bin Oaf ,1994).

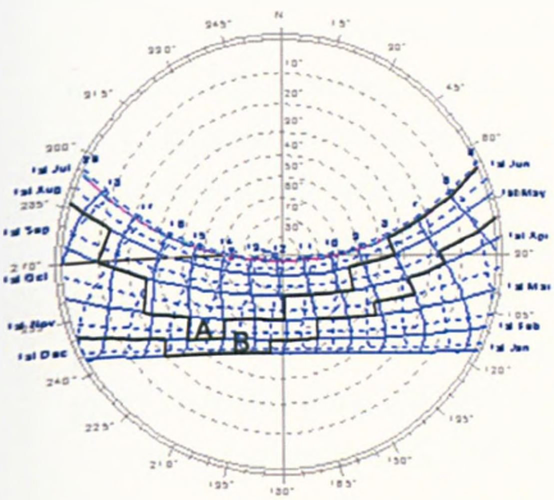


Figure.5.13. Shading requirements for Riyadh, reproduced after Bin Oaf, 1994.

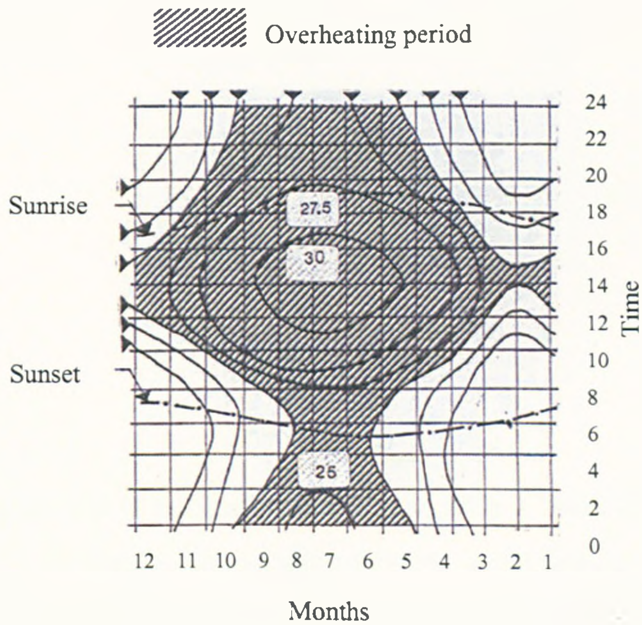


Figure.5.14. Contour lines for temperature in Riyadh (Bin Oaf, 1994).

5.9. Shading Requirements for Riyadh, Saudi Arabia, as noted by Bin Oaf, (1994).

The most important design requirement, which should be included in the basic design criteria of the hot climate zones, is to protect the building generally and the openings especially from direct solar radiation in summer. To achieve the best available alternatives to protect the building from solar heat gain, it is essential to study the solar geometry and locate the shading angles. The table to plot the solar geometry for the sun in Riyadh was designed according to the methods of Bin Oaf (1994). In this study, Bin Oaf found the vertical shadow angle (VSA) and the horizontal shadow angle (HSA) for the different openings; these assist in designing efficient shading devices. Figure 5.14 shows the contour lines for the temperatures in Riyadh. In the following section, the overheating periods, during which protection from the sun's radiation is required, and radiation, which must be prevented from penetrating to the internal space, are presented. This is noted by Bin Oaf (1994) after Said (1991) and Koenigsberger (1973).

5.9.1. Periods when shading is required

1. 28 January from 14:00 to 15:00.
2. 28 February from 12:00 to 15:15.
3. 21 March from 10:30 to 17:30.
4. 15 April from 9:30 to sunset.
5. 15 May from 8:20 to sunset.
6. 22 June from sunrise to sunset.
7. 30 July from sunrise to sunset.
8. 30 August from sunrise to sunset.
9. 23 September from 8:00 to sunset.
10. 15 October from 9:15 to sunset.
11. 15 November from 11:00 to sunset.
12. 22 December from 12:00 to 15:30.

The first alternative for a shading device is the horizontal device with a vertical shading angle of 15°, as shown in Figure 5.16. Using such shading devices, windows can be protected from the solar radiation in the overheating periods. Horizontal shading devices will prevent the solar radiation from penetrating to the internal spaces also in the winter when shading is not required. However, solar radiation is important in winter for natural heating. Bin Oaf (1994) identified the following periods when heating is required:

1. January from 7:20 to 11:00.
2. February from 6:30 to 9:15.
3. March from sunrise to 8:00.
4. September from sunrise to 9:30.
5. October from 6:30 to 10:30.
6. November from 7:20 to 13:00.
7. December from 7:30 to 12:30 and from 15:30 to 16:45.

The second alternative for shading is using egg-crate shading devices. In this case the vertical shading angle is 40° and the horizontal shading angle is 45°, as shown in Figure 5.17. By using this type of shading, complete shading for the window can be achieved as the double action of both horizontal and vertical devices prevents the sunlight from penetrating to the internal spaces in winter periods, which is essential for heating. These periods are the under heating periods and can be outlined as the following:

1. January from 9:15 to 11:00.
2. February from 7:20 to 9:30.
3. March from sunrise to 8:00.
4. September from sunrise to 9:30.
5. October from 7:00 to 10:30.
6. November from 8:30 to 13:00.
7. December from 10:00 to 12:30 and from 15:30 to sunset. Figure 5.15 shows the recommended shading angles for the north windows in Riyadh, Saudi Arabia. furthermore, figure 5.18 illustrates the under-heating periods in Riyadh by using both horizontal and egg-crate shading devices.

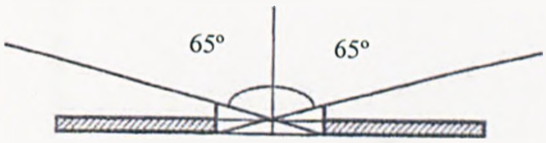


Figure 5.15. Shading the north windows in Riyadh (Bin Oaf, 1994).

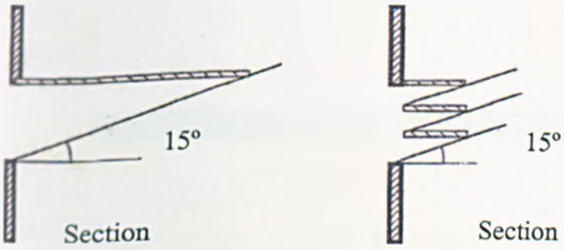


Figure 5.16. Shading the south windows with horizontal devices in Riyadh (Bin Oaf, 1994).

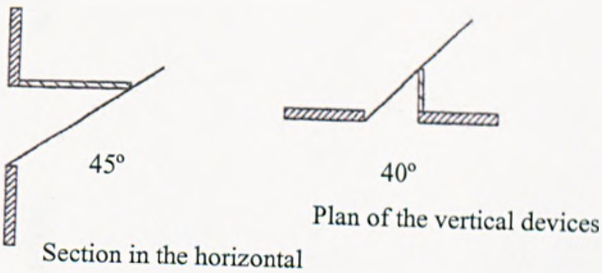


Figure 5.17. Shading the south windows with egg-crate devices in Riyadh (Bin Oaf, 1994).

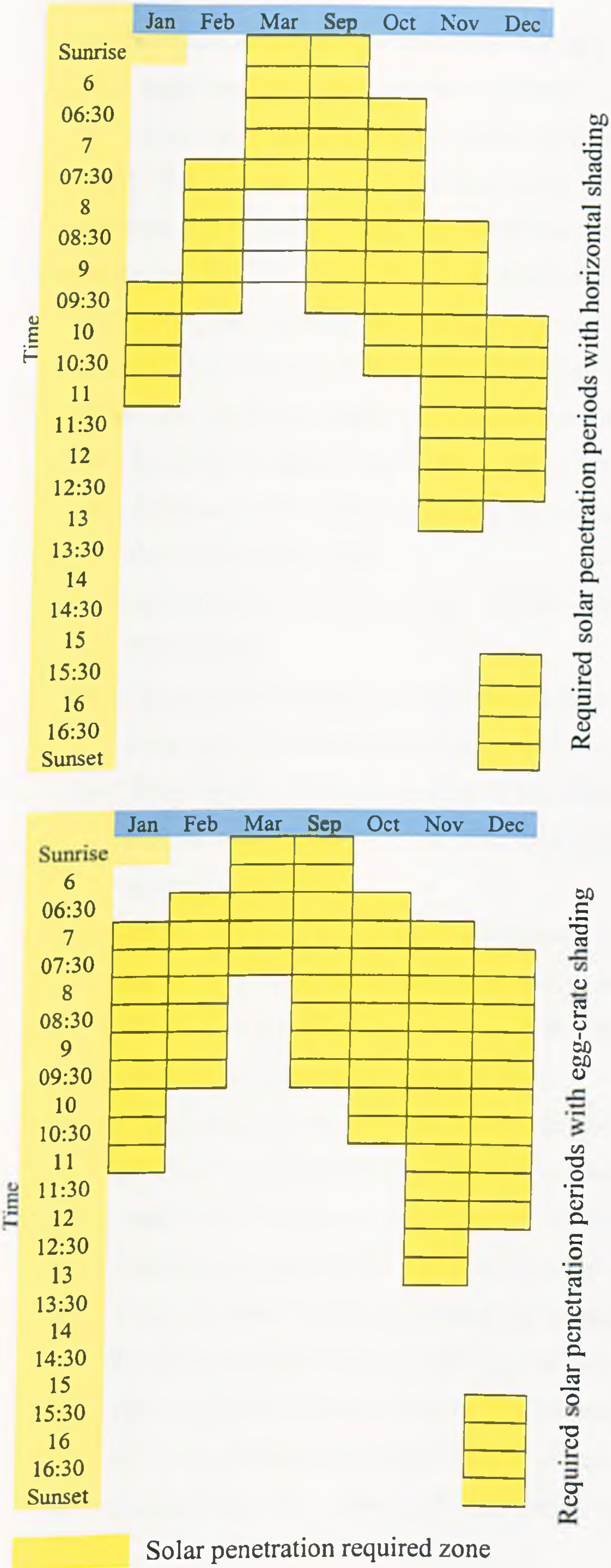


Figure 5.18.Required solar radiation penetration zone for natural heating. Reproduced from (Bin Oaf, 1994).

5.10. Introduction to the Parametric Study and Field Experiments

5.10.1. Introduction to the parametric study

After understanding the solar geometry, an outline of the parametric study is now offered. The main aim of the experiments is to evaluate the internal distribution of the sunlit area. This internal sunlit area distribution mainly depends on the solar altitude and azimuth angles. The evaluation was performed on various types of shading and the efficiency of the shading devices in reducing the penetration of solar radiation was evaluated. This was also achieved by examining the thermal performance of the selected devices. Outlines of the parametric study can be illustrated in the following:

- Revision of the solar geometry in Saudi Arabia and in other climatic zones.
- Revision of the available shading techniques and the most commonly used shading devices in Saudi Arabia.
- Investigation of the ability of the available prediction models (SunCast-ECOTECT).
- Investigation of the variables that affect the internal distribution of the solar radiation in buildings, including the effect of tilted wall windows.
- Investigation of the penetration of solar radiation in two main climatic zones (a hot climate and a cold climate). The investigation was performed by using different shading techniques.
- Investigation of the internal distribution of solar radiation by a using physical model. The experiment was performed in Jeddah, Saudi Arabia. Different shading device configurations were used in the model. Sunlit area measurements were obtained over a selected period of time.
- Comparison to compare the results achieved in the current research with other previous investigations in the field. The study mainly investigates the effect of the shading configuration on different window functions. Selected functions are ventilation, daylighting, view out, privacy and solar penetration in summer and winter for both cooling in summer and heating in winter.
- Obtaining shading design guidelines with special reference to Saudi Arabia. These can also be used for hot climate regions in general. The design guide recommends the most efficient shading techniques in terms of energy performance for reducing cooling loads. Also, other social necessities were considered, such as privacy.

5.10.2. Experiments' aims

The aims of the experiments could be expressed in the following points:

- To understand the solar geometry using the selected computer models. These models are SunCast and ECOTECT. The SunCast model illustrates the parts of the building exposed to direct solar radiation. Solar radiation transmitted into the building through windows and openings could be one of the model's outputs. The ECOTECT model is more useful in understanding solar movements. Daily and annual sun paths can be displayed in this model. The sun's location over the building is clearly shown and can easily be controlled according to the required time of the day and the year.
- Using the ECOTECT model, the shading device's dimensions can be predicted. This includes overhangs and vertical shading. The evaluation was carried out in different climatic zones to gain a better understanding of the solar radiation penetration into buildings, and the sun's angles.
- The general behaviour of the transmitted sunlit area was studied. This was performed in different latitudes and orientations.
- The results achieved were compared with previous full-scale experiments, to gain confidence in the tool used.
- Various factors that could affect the penetration of the sunlit area were studied. These included factors such as orientation, latitude, shading device types and depths, window slope, time of day, and the effect of the seasons (summer and winter).
- The investigation focused on the distribution of the sunlit area through the tilted windows. Angles included in the study are: 90° (which is the normal wall), 80°, 70°, 60°, 50° and 40°.
- The distribution of the sunlit area through different shading techniques was compared in different climatic zones: namely, in Riyadh, Saudi Arabia (a hot climate zone) and London in the United Kingdom, (a cold climate zone).
- The internal sunlit area distribution results, achieved from the SunCast model, were compared with the same results achieved from the physical model. The experiments were performed in Jeddah with the same experiment set up in both cases. Conducting such experiments will help in building guidelines for shading in Saudi

Arabia. Furthermore, this is a step forward to assess the potential for reducing cooling loads in buildings.

5.11. Conclusion

This chapter covers three main aspects: solar geometry, shading requirements in Saudi Arabia, and an introduction to the parametric study. Understanding the solar geometry is very important in the design of shading systems. The following chart exemplifies areas covered by this chapter.

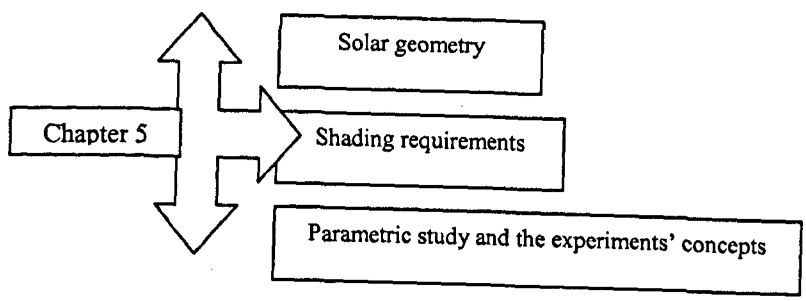


Figure 5.19. Diagram showing the components of Chapter 5

The earth has two movements around its own axis: rotation and revolution around the sun. The earth's axis is inclined at an angle of $23^{\circ}\frac{1}{2}$. The relationship between the solar altitude and the earth's tilt is explained here together with a brief discussion of solar radiation and the components of solar radiation. The effect of solar radiation on buildings is described with an initial study of the effect of a building's orientation on the received solar radiation. The study consists of an experiment using the ECOTECT model. The results show the amount of solar radiation received on the four main elevations. They also indicate that a south-facing façade receives most of the solar radiation.

Locating the sun's position via the solar charts is described with the identification of the solar and shading angles. The processes involved in locating the sun's position through the azimuth and altitude angles are also discussed in this chapter. These processes are essential for shading design. The design of shading devices is presented for horizontal shading for a typical window size facing south-west in Jeddah. The design was arrived at by using the VSA and HSA, which was calculated using the solar chart for Jeddah.

A brief discussion of the exposure of the indoor surfaces to direct solar radiation was carried out with three main factors: shading, the internal sunlit area and thermal analysis. The internal exposure of solar radiation is affected by these selected factors. Moreover, these factors could also be affected by the internal solar exposure. An interaction of both elements can then be obtained. For example, shading devices affect the internal distribution of solar radiation. On the other hand, internal exposure of surfaces to solar radiation could affect the thermal behaviour of the building.

To design effective shading it is very important to locate the overheating and the underheating periods in the selected design region. Overheating periods can be located through studying temperature variations. A study performed by Bin Oaf (1994) shows the overheating and underheating periods in Riyadh. The study results indicate that shading is required on most days of the year in this hot dry region.

The last part of the chapter is an introduction to the parametric study. This section is divided into two main parts. The first part is a general introduction to the parametric study and the second part is an illustration of the experiments' aims. The main aim of the research is to investigate the penetration of the sunlit area through selected window units. The window size and orientation are selected according to analytical investigations. Several types of shading device were selected for the investigation including horizontal, vertical and egg-crate shading. Periods of investigation were selected to be the peak of summer (21 June) and the peak of winter (21 December).

Another important aspect of the investigation is to study the effect of various factors on the distribution of sunlit area through windows. These factors are orientation, latitude, the types and depths of shading devices, window slope, time of day, and the effect of seasons (summer and winter).

The investigations were carried out using two main methods. The first method was the experimental investigation using computers models. Two main models were selected: SunCast and ECOTECT. The second selected method for the investigation was carried out using a scaled physical model constructed and examined in Jeddah, Saudi Arabia. The model was constructed for experiments in winter then modified to examine sunlit area distribution in summer by using various shading methods.

CHAPTER 6

STUDY OF THE SUNLIT AREA THROUGH DIFFERENT SHADING DEVICES, USING THE SUN-CAST MODEL

6.1. Introduction

This chapter is constructed to include the general simulation of the sunlit area. The distribution of the sunlight which penetrates into the internal surfaces was evaluated by using different shading methods. A room with dimensions of 6m x 6m and 3m in height was constructed in the Modelbuilder (one of the IES models) to examine the distribution of the sunlit area. A 1.6m x 1.6m double glazed window was also added to the south wall of the model. This chapter discusses two main aspects which affect the distribution of the sunlit area on the internal surfaces. The first aspect is the effect of different shading techniques on the sunlit area distribution. Horizontal (overhangs), vertical and egg-crate shading devices were selected for this study and a plain window (without shading) was also included so the shading performance of the selected shading methods in this study could be compared with other studies. This is useful in judging the selection of a shading method at an early design stage.

The second aspect of the chapter involves different parameters which affect the intensity of the penetrated sunlit area. Three main parameters were evaluated: 1. Sunlit area distribution as a function of time. This was studied in two different latitudes, 50°N and 30°N. Experiments of this kind need to illustrate the time of the day when shading is most wanted; this is most likely to be during the overheating period. 2. Sunlit area behaviour as a function of latitude. This included the study of a range of latitudes (20°N, 30°N, 40°N, 50°N, and 60°N). The evaluation was intended mainly to predict the distribution of the sunlit area in different locations. 3. Sunlit area distribution as a function of orientation. The orientations selected for the study were N, NE, E, SE, S, SW, W, and NW. This study was conducted to examine the effect of the orientation on the penetrated sunlit area. All the selected latitudes were included in the orientation study. It was expected that the south orientation would receive the most solar radiation during the daytime. Experiments also were conducted in summer and winter to examine the difference in sunlit area distribution internally.

As a part of this chapter, a comparison study was conducted to compare the results achieved by this research, which were achieved using the SunCast model, with other results achieved by experiments conducted by Hassan's PhD research (1996). The main comparative study involves evaluating the efficiency of the selected shading methods. The shading techniques used were the same in both studies. These were horizontal, vertical and egg-crate shading. Also, the same experiment setup, in terms of location, was used so the results could be comparable. The efficiency of the selected shading devices is expressed by the percentage of saving in cooling loads when compared with the case of a window without shading.

6.2. The Performance and Ability of the Sun-Cast Model

SunCast enables the researcher to perform shading and solar insolation analysis studies and can generate images and animations quickly and easily. SunCast can be used at any stage of the design process and creates solar shading and insolation information from a model created by the IES ModelBuilder or from 2D or 3D CAD data.

SunCast can be used to investigate:

1. The external obstruction and self-shading of a building;
2. Solar mapping through windows and openings;
3. The effects of changing the orientation of a building.

SunCast generates shadows and internal solar insolation from any sun position defined by date, time, orientation, site latitude and longitude. This shadow information can be stored for subsequent analysis by:

1. Viewing shadows from any eye position;
2. Animating the solar analyses by generating a sequence of images and creating an avi movie which is useful for demonstration;
3. Making opaque surfaces "transparent" to permit the user better to view the solar insolation on internal surfaces e.g. “removing” roofs or surfaces to identify internal solar insolation paths;
4. Displaying solar surface shading/insolation statistics.

SunCast can be used in a variety of studies including passive solar design and is essential at the planning stage to visualise the effect of the building on surrounding buildings. SunCast has also been used to study problems such as grass growth in sports stadia and ‘right of light’ issues. In addition, because it is possible to remove surfaces to investigate solar penetration, SunCast can be used to investigate internal design issues from office layouts to the positioning of art in museums.

6.3. Prediction of the Sunlit Area using the Sun-Cast Model

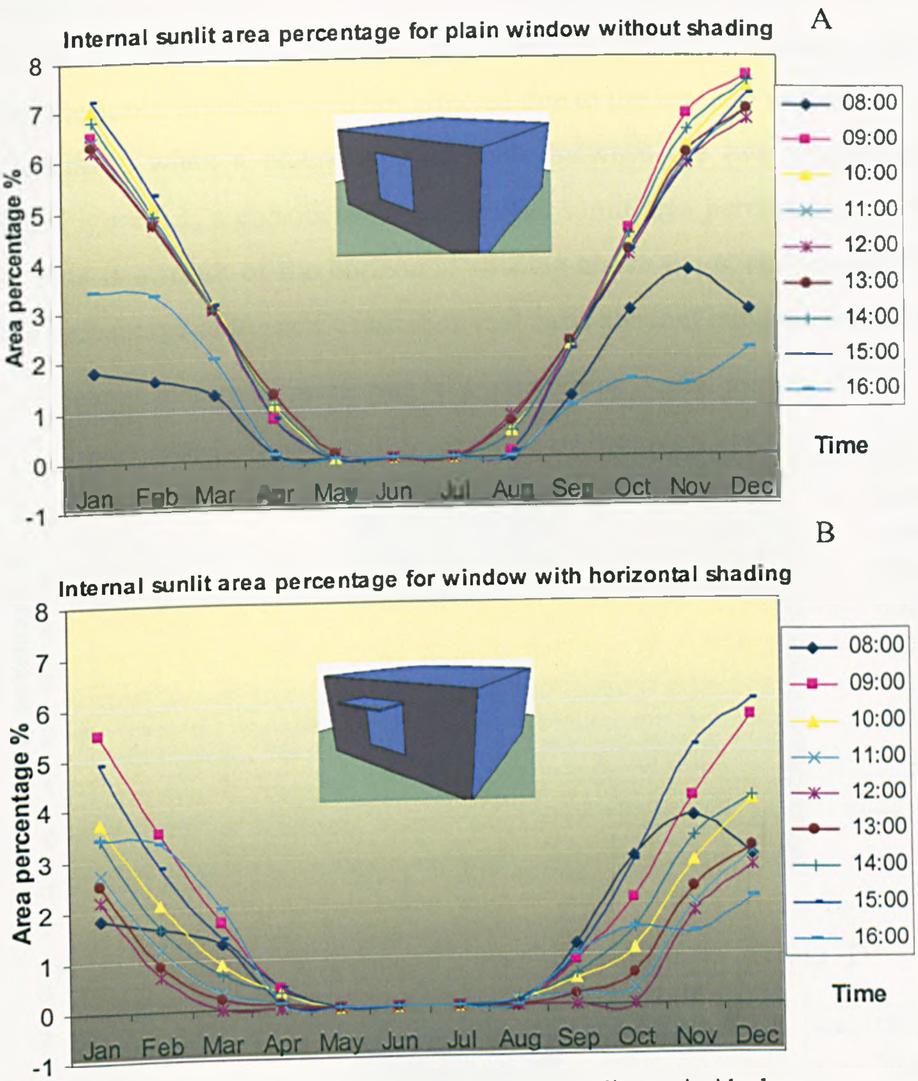
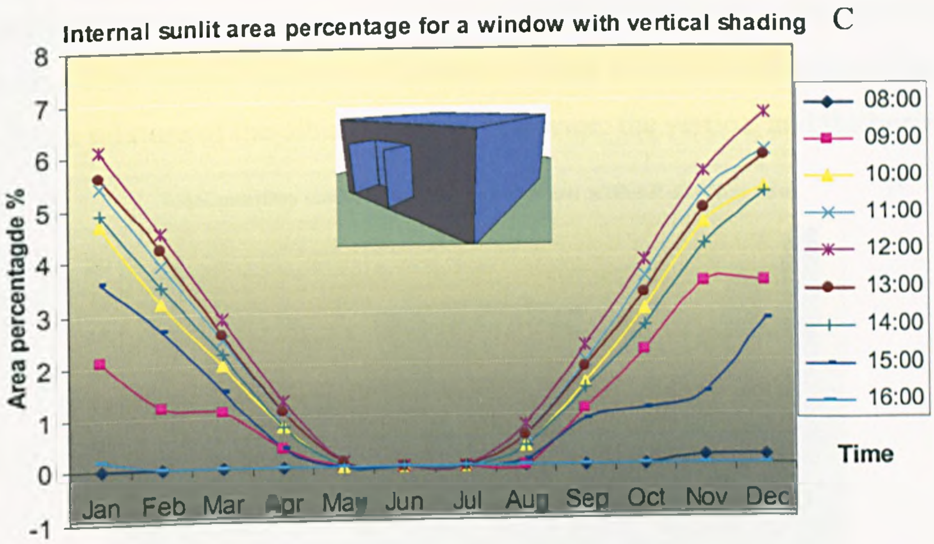


Figure 6.1. Effect of shading devices shape type on the sunlit area inside the space according to sunlit area percentages

The presented graphs show the direct sun "sunlit area" percentage variation at different times during the day from 8:00 am to 4:00 pm; the test was carried out on the 15th of each month. The selected location of the experiments was latitude 20°N, which is located in a hot dry zone. As noted by Hyde (2000), the hot dry climate zones are located between 15 to 30 degrees north and south of the Equator. From the graphs as a general results, it can be seen that the maximum sunlit area penetrates between November and February. In the first graph (Graph A in Figure 6.1.), which illustrates the plain window case, that is one without shading devices, it was found that the maximum sunlit area percentage on the floor was around 7 and 8 % in winter during the morning hours. Moreover, the low sun angle in the morning and late afternoon hours causes a lower sunlit distribution percentage In the second graph, Graph B, which illustrates the case of the window with horizontal shading, the maximum sunlit area percentage is 6 % in December at 15h. A reduction in the sunlit area is clearly shown in August, September and October as an effect of the horizontal shading. However, in January, February, November and December, the sunlit distribution is not affected due to the low sun angle.

Generally, when a comparison is made between the two graphs, Graph A and Graph B in Figure 6.1, a considerable drop in the sunlit area percentage can be noticed in Graph B. This is a result of the horizontal shading above the window which blocks out a reasonable percentage of the sun's radiation that casts shadow into the internal space.



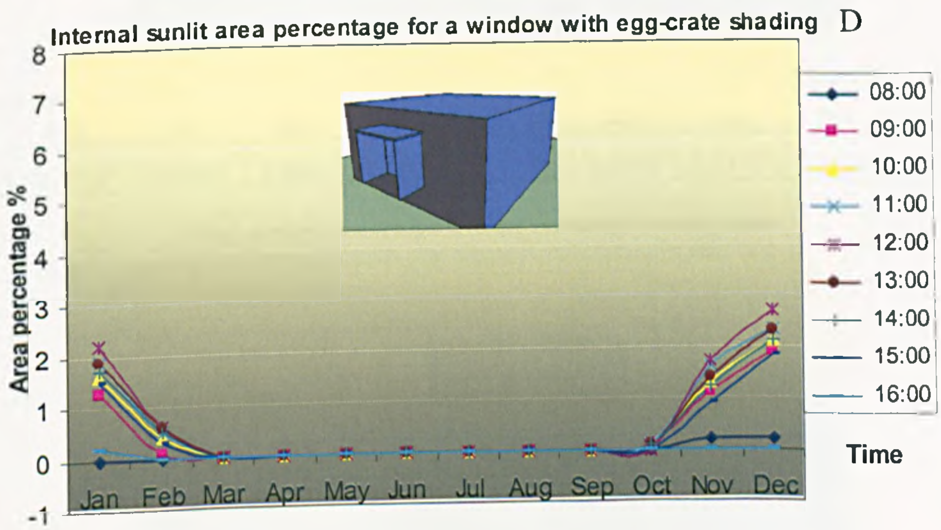
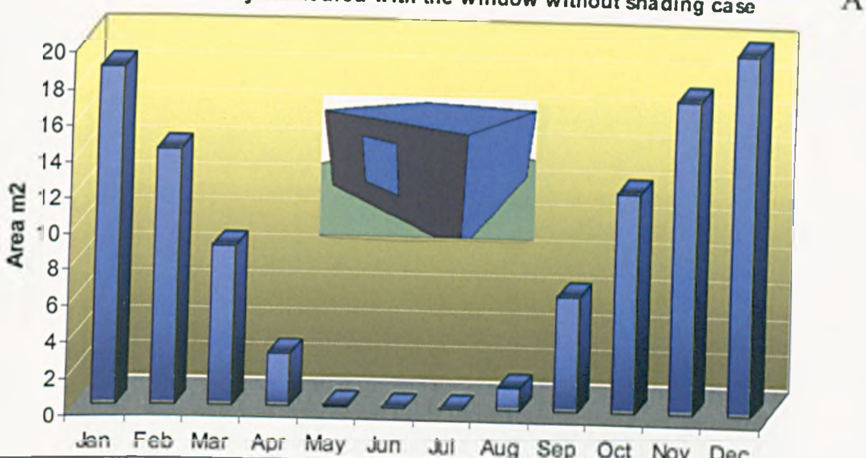


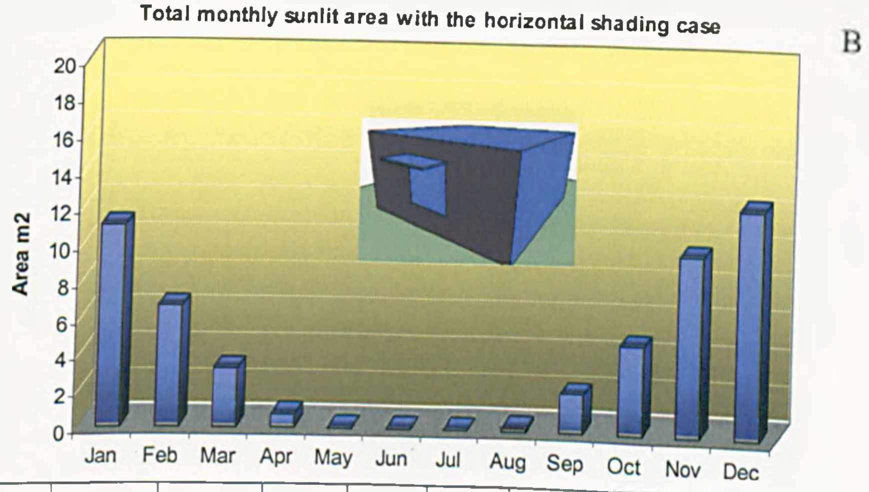
Figure 6.2. Effect of shading devices shape type on the sunlit area distribution inside the space according to sunlit area percentages

In Graph C, which shows the efficiency of the vertical shading devices, the sunlit area shows little difference when compared with Graph B which considers the case of horizontal shading. However, the general results from the two graphs show that more sunlit area penetrates in the case using vertical shading, shown in Graph C. This could be due to the configuration of the shading devices. There are two vertical louvers on both sides of the window in the example of vertical shading whereas there is one horizontal louver in the horizontal shading case on the top of the window. The shape of this device is shown in Figure 6.7. This shows that horizontal louvers are more effective and efficient in such conditions. It has been proved in these two cases that the horizontal shading device could block out more solar radiation in this location (latitude 20°N) as a result of the sun's angle.

In the fourth case, the egg-crate device illustrated in Graph D, the graph shows the minimum sunlit area distribution compared with the previous three cases. The maximum sunlit area percentage in this case was around 2-3% and this occurred only in December and January. This makes this type of shading device the most efficient of the four cases because it is a mixture of the other two types of device: the vertical and the horizontal.



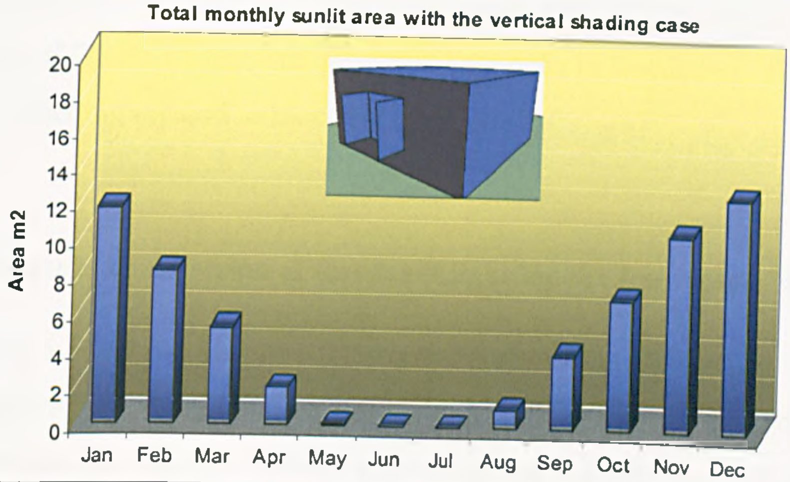
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
18.65m^2	14.15m^2	8.81m^2	2.92m^2	0.1m^2	0	0	1.23m^2	6.37m^2	12.2m^2	17m^2	19.9m^2



Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
11.04m^2	6.62m^2	3.21m^2	0.69m^2	0	0	0	0.17m^2	2.15m^2	4.88m^2	9.8m^2	12.4m^2

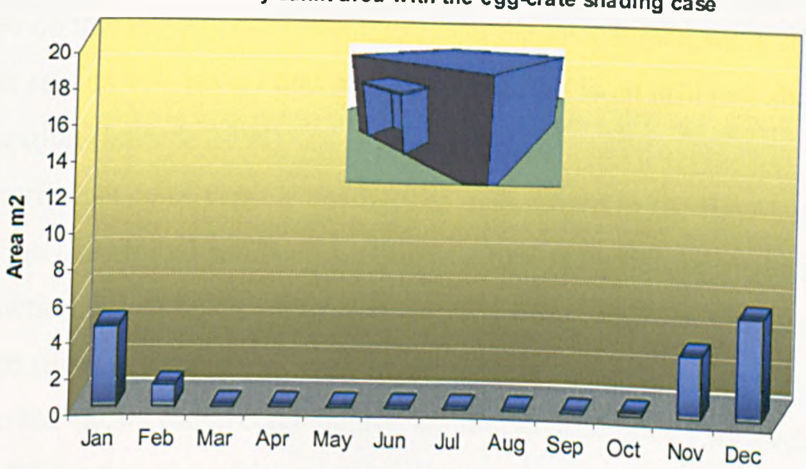
Figure 6.3. Graphs and tables showing the amount of the sunlit area distributed through the window without shading and with horizontal shading.

Figure 6.3 shows the monthly amounts of the penetrated sunlit area for the plain window without shading and the horizontal device. The monthly sunlit area is the average of the present of sunlit area and day for the whole month. The reduction of the sunlit area is clear when using the horizontal shading. Graph A (Figure 6.3) shows the full possible monthly distribution of the sunlit area through the selected window with the maximum distribution, which is 19.9m^2, being found in December. The second graph in this phase, (Graph B Figure 6.3), represents the analysis of the case of the horizontal shading devices. When the two graphs are compared, the remarkable drop in the total sunlit area in most of the months can be noted in this graph due to the horizontal shading. The maximum distribution, which is 12.4m^2 , is found in December. A simple calculation shows that the percentage reduction in the sunlit area is 37.6% when using the horizontal shading in December.



A

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
11.7m^2	8.3m^2	5.3m^2	2.1m^2	0.1m^2	0	0	1.04m^2	4.06m^2	7.15m^2	11m^2	12.8m^2



B

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
4.43m^2	1.13m^2	0	0	0	0	0	0	0	0.16m^2	3.4m^2	5.5m^2

Figure 6.4. Graphs and tables showing the amount of the sunlit area penetrated using vertical and egg-crate shading devices

In Graph A, (shown in Figure 6.4), which presents the performance of the vertical louver, the maximum monthly sunlit area distribution is 12.8m^2 in December. The reduction of the sunlit area by using this shading method is not as efficient as that achieved with the horizontal shading. The relative low efficiency of these types of device could be due to their location on the sides of the window; this affects the window's protection from direct sunlight. O.H.Koenigsberger (1974) noted that vertical shading is mostly effective for the east and west elevations: "*A vertical device to be effective when the sun is opposite to the wall considered*".

As the last graph, which stands for the performance of the egg-crate shading devices, shows, the minimum average percentage of sunlit area for the four cases was obtained with this type of shading device. The high level of efficiency in this case is generally due to the mixture of two types of device, the horizontal and the vertical, that protect the window. The maximum sunlit area was found to be 5.5 m^2 in December, which is a reduction of 72.3% of the total penetrated sunlight in December. This shows the high ability of this shading method to block solar radiation.

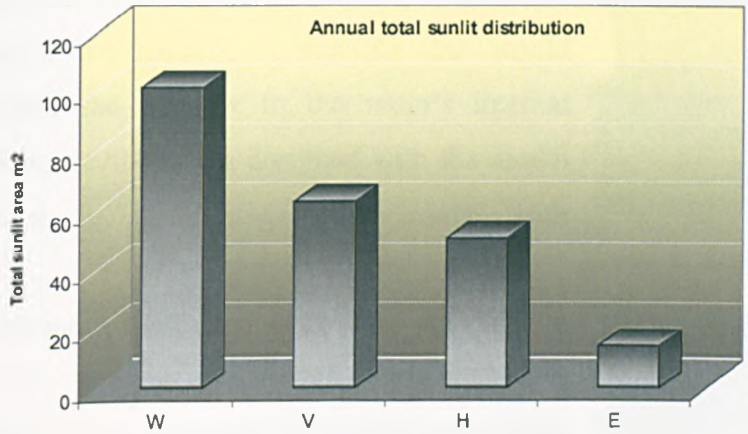
6.3.1. Total annual distribution of direct sunlight for the four cases: W, H, V and E.

Figures 6.5 and 6.6 illustrate the general study of the distribution of the sunlit area. Figure 6.5 shows the annual distribution of sunlit area by using the selected three shading types. The results for egg-crate shading demonstrate the lowest sunlit area distribution. This figure also includes the case of a plain window so the efficiency of the shading methods could be measured. Calculations are based on measurements of the distribution of the sunlit area on the 15th day of each month, then the total annual sunlit distribution can be obtained. The results also reveal that horizontal shading is an efficient shading method for use in this location (latitude 20°N).

The performance of vertical shading, as also shown in the figure, represents a 37% reduction of the distributed sunlit area. This is a low reduction rate when compared with the 50% reduction achieved by using horizontal shading while the highest reduction was achieved when using egg-crate shading where the reduction percentage was 85%.

Figure 6.6 shows the average hourly sunlit area distribution for each month. During May, June and July, due to the high sun position in this latitude, there will be no sunlit area penetration. The lowest sunlit area distribution is achieved by using egg-crate shading as can be seen in the lowest line in the graph in the figure which illustrates the performance of this shading method. Horizontal shading also demonstrates a reasonable reduction in the sunlit area. This shading method will also allow sunlit area penetration during the heating periods. As shown in the graph, sufficient sunlit area will penetrate during November, December, January and February. The performance of vertical shading in terms of the hourly average is similar to the performance of the horizontal shading.

Generally, shading devices will contribute to reducing the distribution of the sunlit area. This can be clearly seen in Figure 6.6 when comparing the plain window curve with the curves of the other shading methods.



W	Window without shading
H	Horizontal shading
V	Vertical shading
E	Egg-crate shading

Figure 6.5. The total annual sunlit area distribution using the selected shading methods

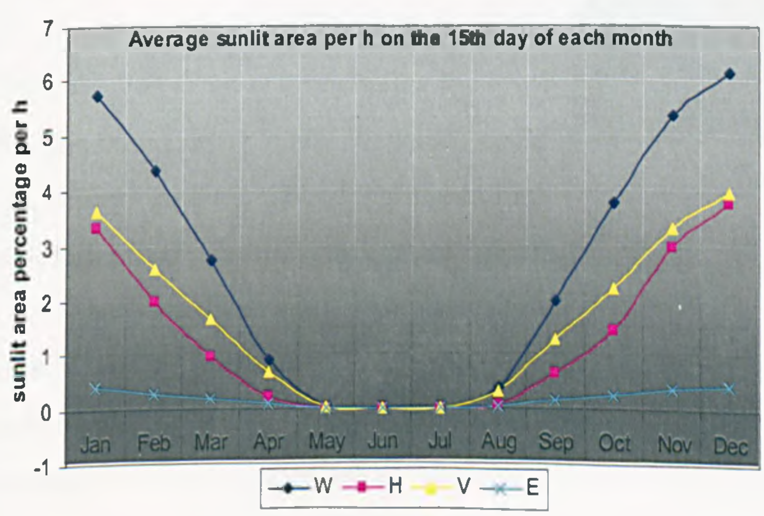


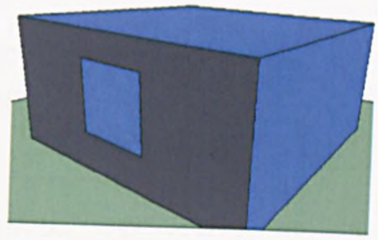
Figure 6.6. The average sunlit area per hour on the 15th day of each month using the selected shading methods

6.3.2. Room, window and shading device configurations

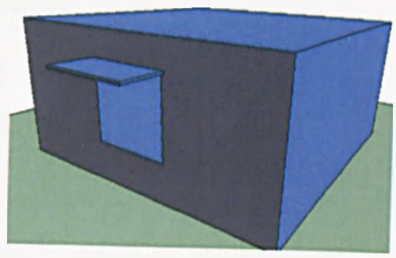
An evaluation of shading efficiency was carried out using the SunCast model. A room with dimensions of 6m x 6m and 3m in height (36m² room area) was designed with a window unit. The window unit was 1.6m x 1.6m, at height of .8m from the ground and oriented at 180° , facing south.

The window was a hole in the wall and had no glazing; this was to test the efficiency of the shading devices and the variations in the amount of sunlight that would penetrate through the window to the room's internal surfaces. Shading devices were designed with the model and constructed in three ways: 1.horizontal with overhang, 2.vertical louvers, 3. egg-crate louvers. In cases 2 and 3 the horizontal and vertical louver dimensions were 1.8m x .9m, and, in the latter case of the egg-crate louvers, these were designed with the same dimensions as the horizontal and vertical louvers.

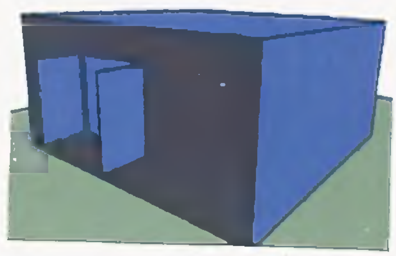
Moreover, in Case 1, the window was constructed without shading devices to test the full distribution of the sunlight. The original amount of sunlight penetrated inside the space so an evaluation of the effect of the configuration of the shading devices on reducing the level of direct sunlight (the sunlit area) inside the space could be calculated. Different shading device configurations showed a significant effect on the amount of direct sunlight inside the space which, in turn, will also affect the required levels of cooling and heating loads. These initial experiments were conducted on the 15th of each month.



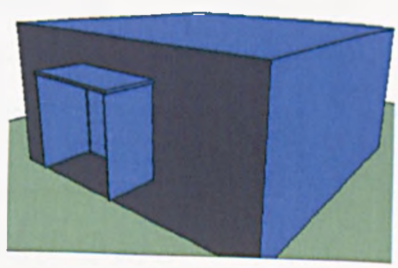
Case 1.W



Case 2.H



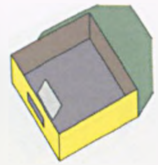
Case 3.V



Case 4.E

Figure.6.7. Shading device configurations considered in this study.

The following section includes tables showing the amounts and percentages of sunlit area distribution by using the selected shading methods including the case of the plain window.



6.3.3. Calculation tables

Case 1. Window without a shading device.

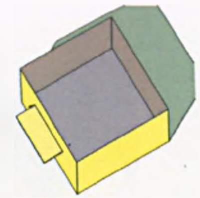
Direct sunlit areas in m²

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
08:00	1.8	1.6	1.3	0.1	0	0	0	0	1.2	2.9	3.7	2.9
09:00	6.5	4.8	3	0.8	0	0	0	0.1	2.2	4.5	6.8	7.6
10:00	7	5.1	3.1	1.1	0	0	0	0.5	2.2	4.2	6.2	7.4
11:00	6.4	4.8	3	1.3	0.1	0	0	0.7	2.3	4.1	5.9	6.9
12:00	6.2	4.7	3	1.3	0.1	0	0	0.8	2.3	4	5.8	6.7
13:00	6.3	4.7	3	1.3	0.1	0	0	0.7	2.3	4.1	6	6.9
14:00	6.8	4.9	3	1.1	0	0	0	0.5	2.2	4.4	6.5	7.5
15:00	7.2	5.3	3.1	0.8	0	0	0	0.1	2.1	4.1	5.8	7.2
16:00	3.4	3.3	2	0.1	0	0	0	0	1	1.5	1.4	2.1
Total	51.6	39.2	24.5	7.9	0.3	0	0	3.4	17.8	33.8	48.1	55.2

Direct sunlit percentage %

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
08:00	0.64	0.58	0.48	0.05	0	0	0	0	0.44	1.05	1.34	1.04
09:00	2.35	1.74	1.07	0.3	0	0	0	0.02	0.77	1.62	2.43	2.73
10:00	2.54	1.85	1.1	0.41	0	0	0	0.18	0.81	1.52	2.24	2.68
11:00	2.32	1.73	1.08	0.46	0.03	0	0	0.25	0.82	1.46	2.11	2.47
12:00	2.25	1.68	1.08	0.48	0.05	0	0	0.28	0.82	1.46	2.09	2.42
13:00	2.29	1.7	1.08	0.46	0.02	0	0	0.26	0.82	1.49	2.16	2.49
14:00	2.45	1.78	1.1	0.41	0	0	0	0.19	0.8	1.57	2.36	2.72
15:00	2.6	1.92	1.12	0.3	0	0	0	0.05	0.75	1.49	2.1	2.6
16:00	1.21	1.17	0.7	0.05	0	0	0	0	0.34	0.55	0.52	0.77

Table 6.1 Calculation of the sunlit area for the plain window (without shading).



Case 2. Overhang or horizontal shading device

Direct sunlit areas in m^2

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
08:00	1.8	1.6	1.3	0.1	0	0	0	0	1.2	2.9	3.7	2.9
09:00	5.5	3.5	1.7	0.4	0	0	0	0	0.9	2.1	4.1	5.7
10:00	3.7	2.1	0.9	0.3	0	0	0	0.1	0.5	1.1	2.8	4
11:00	2.7	1.2	0.3	0.1	0	0	0	0.1	0.2	0.3	2	3
12:00	2.2	0.7	0	0	0	0	0	0	0	0	1.8	2.7
13:00	2.5	0.9	0.2	0.1	0	0	0	0	0.2	0.6	2.3	3.1
14:00	3.4	1.6	0.7	0.3	0	0	0	0.1	0.6	1.5	3.3	4.1
15:00	4.9	2.8	1.4	0.4	0	0	0	0.1	1	2.8	5.1	6
16:00	3.4	3.3	2	0.1	0	0	0	0	1	1.5	1.4	2.1
Total	30.1	17.7	8.5	1.8	0	0	0	0.4	5.6	12.8	26.5	33.6

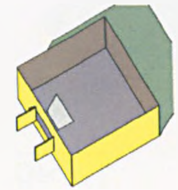
Direct sunlit percentage %

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
08:00	0.64	0.58	0.48	0.05	0	0	0	0	0.44	1.05	1.34	1.04
09:00	2.04	1.32	0.64	0.14	0	0	0	0.01	0.36	0.8	1.52	2.11
10:00	1.38	0.81	0.35	0.11	0	0	0	0.05	0.21	0.42	1.04	1.47
11:00	1.01	0.48	0.15	0.05	0	0	0	0.03	0.08	0.14	0.75	1.12
12:00	0.81	0.25	0	0	0	0	0	0	0	0.03	0.65	0.98
13:00	0.92	0.35	0.09	0.05	0	0	0	0.02	0.1	0.26	0.87	1.15
14:00	1.24	0.63	0.27	0.1	0	0	0	0.04	0.23	0.58	1.23	1.52
15:00	1.79	1.03	0.53	0.14	0	0	0	0.02	0.39	1.05	1.87	2.2
16:00	1.21	1.17	0.7	0.05	0	0	0	0	0.34	0.55	0.52	0.77

Table 6.2 Calculation of the sunlit area for the horizontal shading device.

Case 3. Vertical shading device

Direct sunlit area in m^2

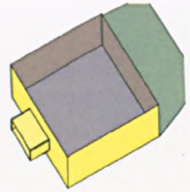


Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
08:00	0	0	0	0	0	0	0	0	0	0	0.2	0.2
09:00	2.1	1.2	1.1	0.4	0	0	0	0	1.1	2.2	3.5	3.5
10:00	4.7	3.2	2	0.8	0	0	0	0.4	1.6	3	4.6	5.3
11:00	5.4	3.9	2.5	1.1	0.1	0	0	0.6	2	3.6	5.2	6
12:00	6.1	4.5	2.9	1.3	0.1	0	0	0.8	2.3	3.9	5.6	6.7
13:00	5.6	4.2	2.6	1.1	0.1	0	0	0.6	1.9	3.3	4.9	5.9
14:00	4.9	3.5	2.2	0.8	0	0	0	0.4	1.5	2.7	4.2	5.2
15:00	3.6	2.7	1.5	0.4	0	0	0	0.1	0.9	1.1	1.4	2.8
16:00	0.2	0	0	0	0	0	0	0	0	0	0	0
Total	32.6	23.2	14.8	5.9	0.3	0	0	2.9	11.3	19.8	29.6	35.6

Direct sunlit percentage %

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
08:00	0	0	0	0	0	0	0	0	0	0	0.06	0.05
09:00	0.74	0.42	0.4	0.15	0	0	0	0.01	0.39	0.8	1.27	1.26
10:00	1.7	1.15	0.72	0.29	0	0	0	0.13	0.58	1.09	1.64	1.92
11:00	1.93	1.4	0.9	0.4	0.03	0	0	0.22	0.71	1.3	1.88	2.15
12:00	2.2	1.62	1.05	0.48	0.05	0	0	0.28	0.81	1.4	2.01	2.39
13:00	2.01	1.5	0.95	0.4	0.02	0	0	0.23	0.69	1.2	1.76	2.11
14:00	1.77	1.28	0.79	0.29	0	0	0	0.14	0.55	0.97	1.52	1.89
15:00	1.29	0.96	0.55	0.15	0	0	0	0.03	0.33	0.39	0.5	1
16:00	0.07	0	0	0	0	0	0	0	0	0	0	0.01

Table 6.3 Calculation of the sunlit area for the vertical shading device.



Case 4. Egg-crate shading device

Direct sunlit areas in m^2

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
08:00	0	0	0	0	0	0	0	0	0	0	0.2	0.2
09:00	1.3	0.1	0	0	0	0	0	0	0	0.1	1.1	1.9
10:00	1.6	0.4	0	0	0	0	0	0	0	0.1	1.3	2.1
11:00	1.9	0.5	0	0	0	0	0	0	0	0.1	1.6	2.3
12:00	2.2	0.6	0	0	0	0	0	0	0	0	1.7	2.7
13:00	1.9	0.6	0	0	0	0	0	0	0	0.1	1.4	2.3
14:00	1.7	0.5	0	0	0	0	0	0	0	0.1	1.2	2.1
15:00	1.5	0.3	0	0	0	0	0	0	0	0	0.9	1.8
16:00	0.2	0	0	0	0	0	0	0	0	0	0	0
Total	12.3	3	0	0	0	0	0	0	0	0.5	9.4	15.4

Direct sunlit percentages %

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
08:00	0	0	0	0	0	0	0	0	0	0	0.06	0.05
09:00	0.48	0.04	0	0	0	0	0	0	0	0.02	0.4	0.69
10:00	0.59	0.16	0	0	0	0	0	0	0	0.04	0.48	0.76
11:00	0.67	0.19	0	0	0	0	0	0	0	0.02	0.56	0.84
12:00	0.78	0.23	0	0	0	0	0	0	0	0.01	0.61	0.96
13:00	0.7	0.21	0	0	0	0	0	0	0	0.03	0.52	0.83
14:00	0.61	0.18	0	0	0	0	0	0	0	0.04	0.45	0.75
15:00	0.53	0.12	0	0	0	0	0	0	0	0	0.31	0.66
16:00	0.07	0	0	0	0	0	0	0	0	0	0	0.01

Table 6.4 Calculation of the sunlit area for the egg-crate shading device.

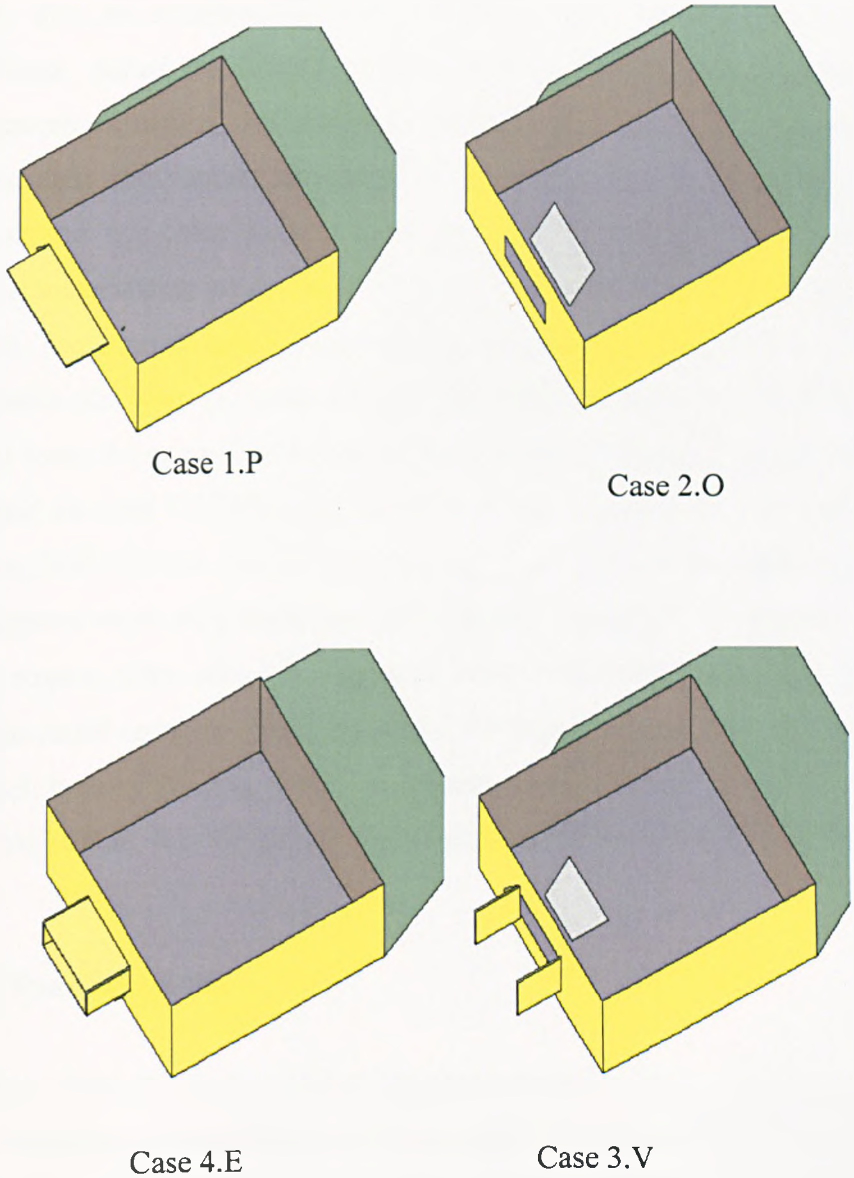


Figure 6.8 Axonometric views of the four selected shading techniques (Produced from the SunCast model)

6.4. Comparison Evaluation of the Shading Contribution

This study aims to evaluate the results obtained from the SunCast model by comparing the results gained by Hassan (1996); these were discussed in Chapter 4. Hassan's work comprised mainly the evaluation of the efficiency of selected types of shading device and their contribution towards reducing solar radiation. These types were horizontal, vertical and egg-crate shading devices. In order to carry out an efficient evaluation, SunCast experiments were set up to mirror Hassan's experiments so the results could be compared. The window unit was .8m x .8m and faced south at 180°. Also, all the shading device dimensions were the same for the three cases (horizontal, vertical and egg-crate) which made them the same dimensions as the devices in Hassan's experiment. The location was Cardiff (latitude 51° 24N) and the date and time chosen for the experiments were 27 September,1995 at 14:00 hours. The measurements of the solar radiation used in the SunCast experiment were taken from the CIBSE guide. This gives the amount of solar radiation on each square metre for each degree of latitude on every hour; then, the sun-exposed area is calculated using the SunCast model. Consequently, an examination of the contribution of each type of shading device in reducing solar radiation can be predicted. The following table (Table 6.5) illustrates the shading contribution results achieved by both experiments.

6.4.1. Analysis of SunCast results

The SunCast model is able to calculate the area exposed to direct sunlight. This can then be used to calculate the percentage of the reduction in solar radiation by using different types of shading device with the assistance of the CIBSE guide. This guide presents the amount of direct solar irradiance for each of the five latitudes (in this case, the nearest latitude is latitude 50N°), each orientation, and during the whole year hour by hour. From the table of latitude for 50N°, the solar irradiance at 14:00 hours on 27 September was found to be 515 W/m². After building the model in SunCast, the direct distribution of sunlight to the internal surfaces can be calculated. Each type of shading device was examined in this experiment, including a plain window area (that is, without a shading device) which is 0.8m x 0.8m in area and facing south. The calculation processes for each shading case can be illustrated as the following:

For the plain window (without shading) 0.8m x 0.8m = 0.64m exposed area.

$0.64\text{m} \times 515\text{W/m}^2 = 329.6$ W.

In the second case, using a horizontal device, the exposed area calculated by the SunCast is .35m². The calculation used is 0.35 x 515W/m² =180.25 W. To calculate the percentage reduction in the solar heat gain we divide the 180.25 W / (329.6 W is the plain window case). The result is then multiplied by 100 to obtain the percentage heat gain, then -100 to arrive at the percentage reduction in solar heat gain.

180.25 W / 329.6 W = 0.5468

0.5468 x 100 - 100 = 45.4 % which is the percentage reduction achieved using the horizontal shading device.

The exposed area in the case of the vertical device is 0.37m²

0.37m²x 515W/m²= 190.55W

190.55W / 329.6W = 0.5781

0.5781 x 100 - 100 = 42.2 % which is the percentage reduction achieved using the vertical shading device.

The exposed area in the case of the egg-crate device case is 0.03m²

0.03m² x 515W/m²=15.45W

15.45 / 329.6W = 0.0468

0.0468 x 100 - 100 = 95.31 % which is the percentage reduction achieved using the egg-crate shading device.

Sun-Cast Results		**Hassan's Results**	
Horizontal shading	45%	Horizontal shading	63%
Vertical shading	42%	Vertical shading	42%
Egg-crate shading	95%	Egg-crate shading	91%

Table 6.5. Comparison of the results of Sun-Cast and Hassan regarding solar radiation and shading contribution.

It could be observed from the results achieved in both models that a general agreement obtained in both models results. However, different in results between the two studies could be mainly revealed in the horizontal shading case, this could be due to the environmental conditions which may not be the same.

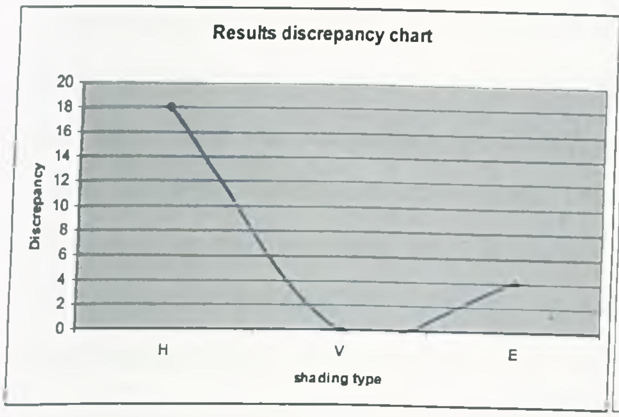


Figure 6.9. Sun-Cast and Hassan: results discrepancy chart

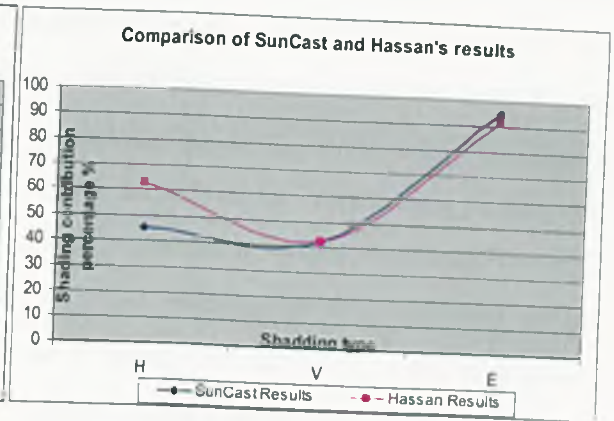


Figure 6.10. Sun-Cast and Hassan: results comparison.

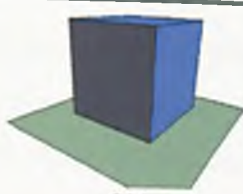
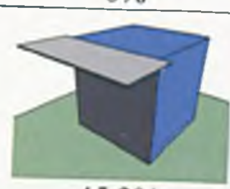
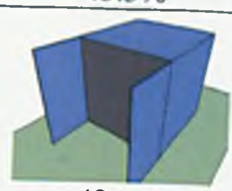
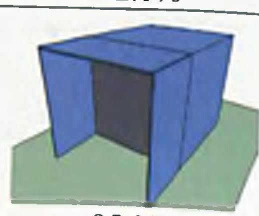
Shading type	Exposed area	Percentage of solar radiation reduction by shading device
Plain window without shading	0.64m²	 0%
Horizontal	0.35m²	 45.3%
Vertical	0.37m²	 42.1%
Egg-crate	0.03m²	 95.3%

Table 6.6 Selected shading devices including plain window (without shading).

6.5. Solar Radiation Behaviour as a Function of Time, Latitude and Orientation

6.5.1. Radiation behaviour as a function of time in different latitudes

Two different latitudes were selected for this study: 30 N° and 50 N°. The periods selected for the investigation were 21 June (summer) and 21 December (winter). In the following graphs, which demonstrate the performance of the solar radiation on the horizontal surface, it can be noticed that the highest radiation rates occur between 10 am and 2pm. This was the period considered in the assessment of the sunlit area distribution using different shading device systems. This period, as well as the overheating period, can be viewed as the time most likely to require an efficient shading system to reduce the sun's glare and the demand for cooling, especially in hot climates. The assessment of the overheating period was carried out in two different latitudes in order to assess the radiation behaviour as a function of time in different climatic zones, making the test more efficient and suitable for different regions. At latitude 30 N°, solar radiation can reach up to 915 W/m^2 at noon in summer on the horizontal surface and up to 475 W/m^2 in winter. This shows the high amount of solar radiation in this period of time. At latitude 50 N °, solar radiation can reach up to 805 W/m^2 at noon on the horizontal surface in summer and up to 155 W/m^2 at the same time and on the same surface in winter. The assessments showed that the overheating period, which receives the highest level of solar radiation in all latitudes on the horizontal surface, is from 10am to 2pm. All calculations in this study are based on the CIBSE guide.

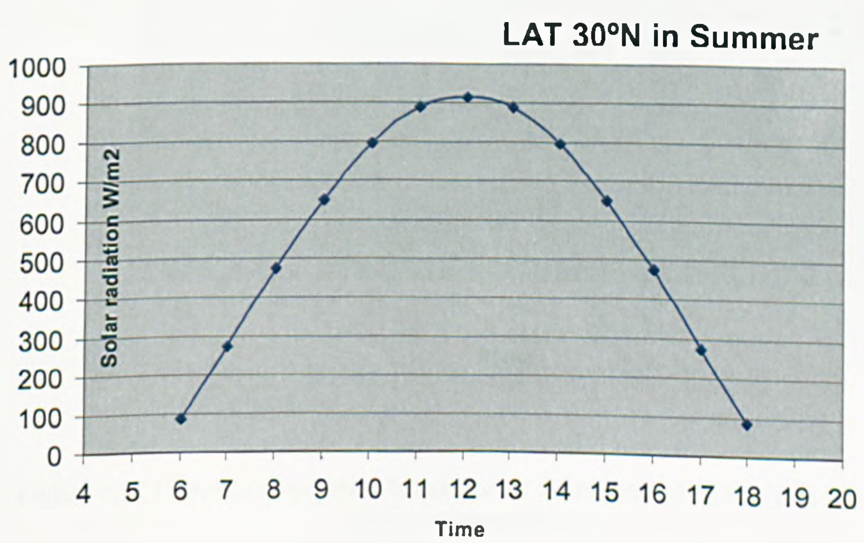


Figure 6.11 Direct solar radiation behaviour on the horizontal surface as a function of time in latitude 30° N in summer.

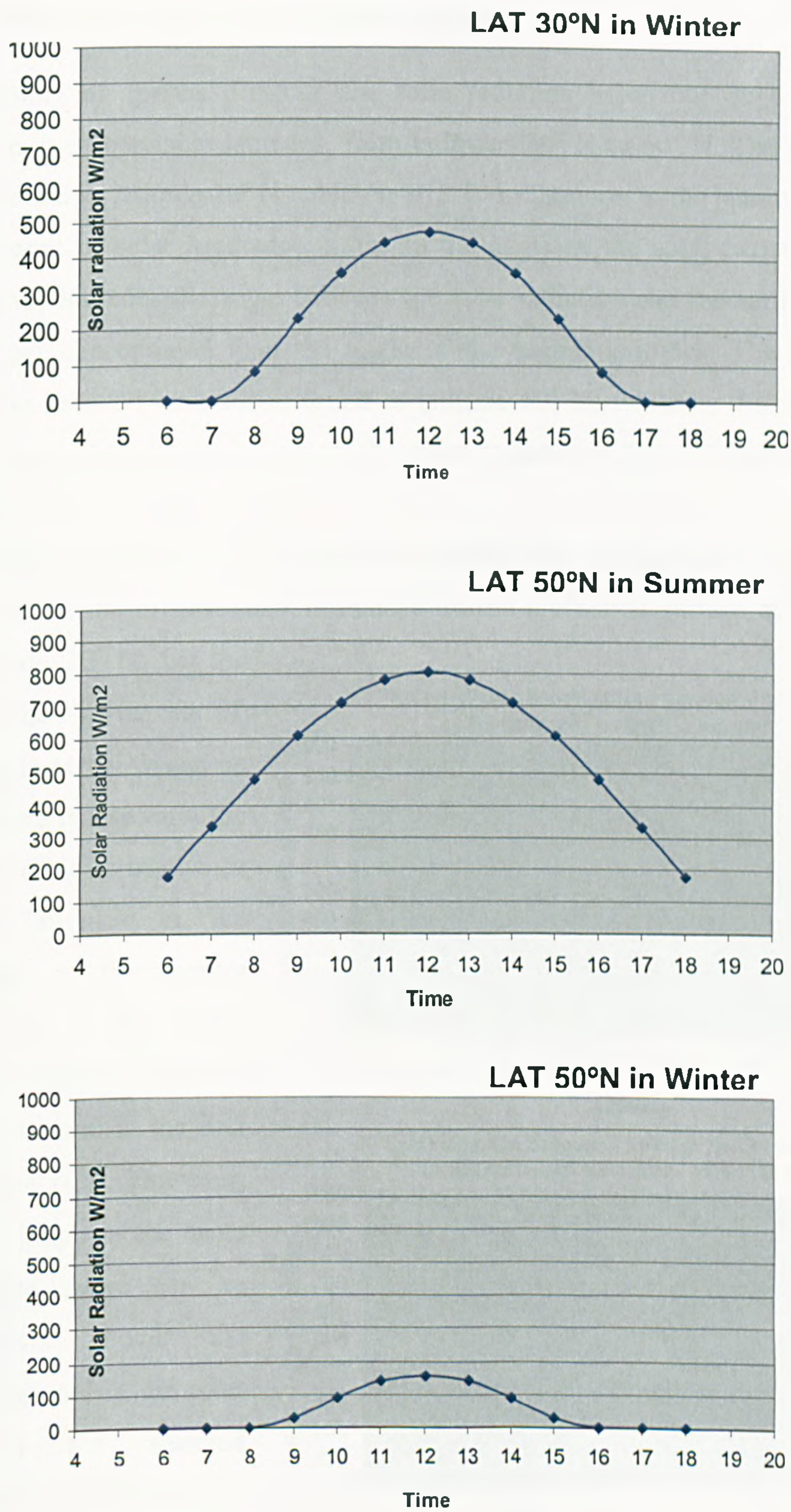


Figure 6.12 Direct solar radiation behaviour on the horizontal surface as a function of time in different latitudes.

6.5.2. Solar radiation behaviour in different latitudes

The following graphs illustrate the solar radiation behaviour on the horizontal surfaces in the most habitable latitudes, from latitudes 20° N to 60° N. The highest solar irradiance is found in latitude 20° N, which is 915 W/m² at noon in the summer (21 June). This high amount of solar irradiance is due to the angle of the solar radiation with the surface. In lower latitudes the angle between the solar radiation and the earth's surface is more direct and concentrated than the angle in the higher latitudes. The lowest solar radiation in the selected latitudes is found at latitude 60° N, which is 700 W/m² in the summer (21 June). Moreover, in winter, the solar radiation will be different due to the sun's position.

In the second graph, which illustrates the behaviour of solar radiation in different latitudes in winter, the highest solar irradiance on the horizontal surface at noon is 615 W/m² at latitude 20° N. On the other hand, the lowest is 30 W/m² at latitude 60° N. It can be noticed that there is less variation in the amount of solar irradiance in different latitudes in the summer graph as this ranges from 700 W/m² to 915 W/m². Thus, in turn, leads to a smooth curve, as can be seen in the first graph in Figure 6.13. However, in the second graph in the same figure, a sharp curve can be observed. This shows the significant difference in the solar irradiance in the selected latitudes which ranged from 30 W/m² up to 615 W/m² in winter, (21 December).

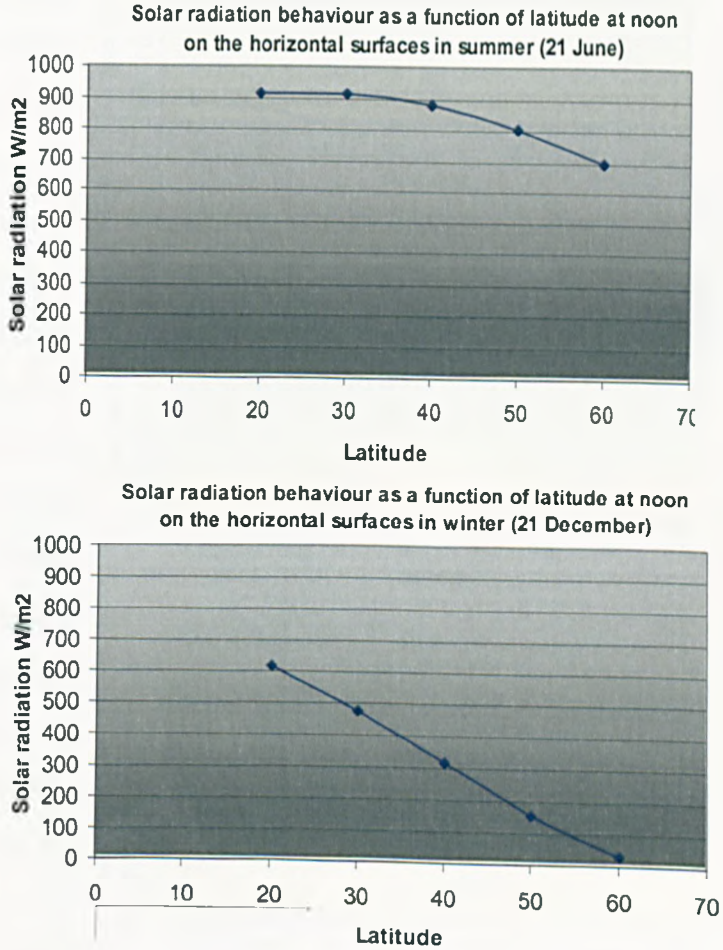


Figure. 6.13 Direct radiation behaviour in different latitudes.

6.5.3. Solar radiation behaviour in different latitudes and orientations

In the evaluation of the radiation's behaviour in the selected latitudes as a function of orientation, the assessment procedures were conducted both in summer and winter in order to make the evaluation more efficient and accurate. As an overall result, the south orientation was found to receive the maximum amount of solar radiation compared with the other orientations. However, in the second graph in Figure 6.14, which shows the radiation behaviour at latitude 20°N in summer, the solar irradiance from the south is 0. This is the only case with a radiation of 0 from the selected latitudes in both seasons, summer and winter. Also, as a general result, solar radiation is usually higher in winter than in summer, except in the case of latitude 60° N, which has more solar radiation in summer than in winter. As this latitude, radiation in summer can reach 520 W/m² from the south while, in winter, radiation can reach 270 W/m² from the same orientation. The maximum solar radiation from the south in the selected latitudes can be found in the third graph in Figure 6.14. This shows the solar irradiance at latitude 30°N in winter. Radiation in this case can reach up to 640 W/m² from the south.

It is clear from the graphs that, although the maximum solar radiation comes from the south, two other

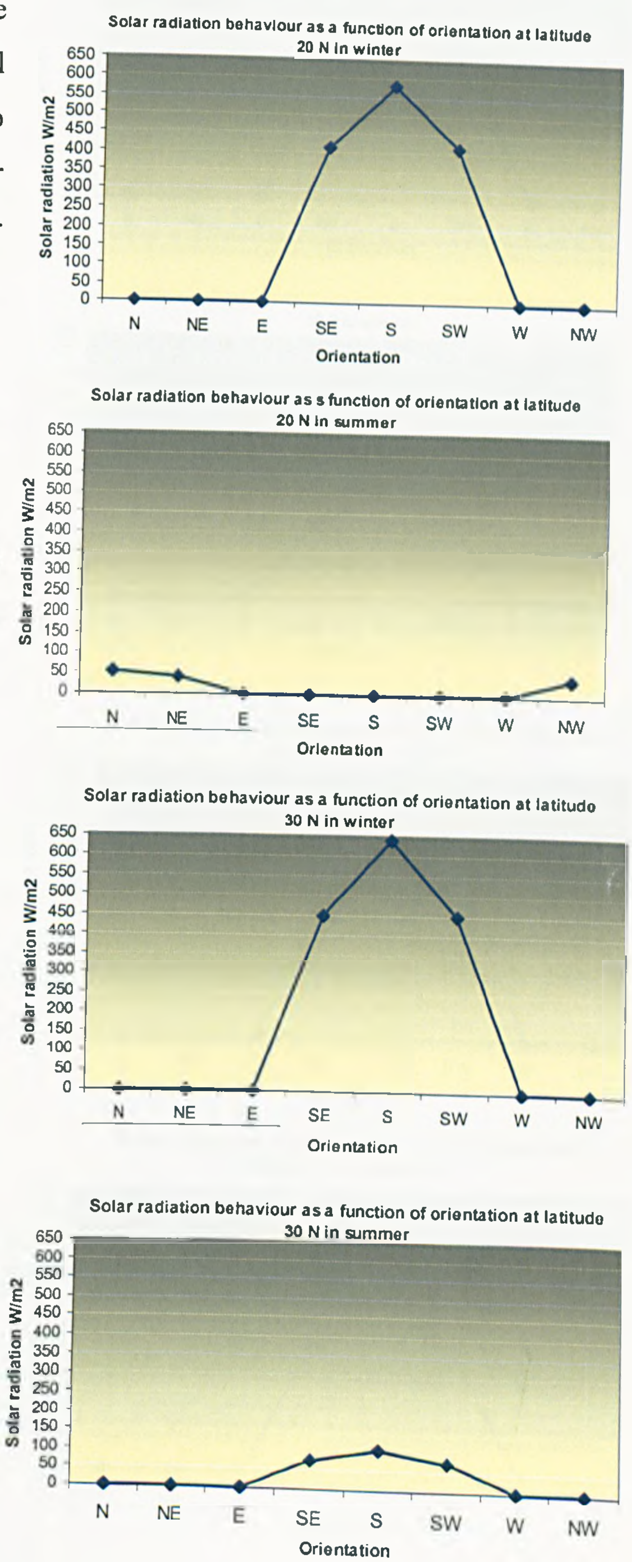


Figure 6.14 Radiation behaviour in different orientations at latitudes 20°N and 30°N.

orientations could be considered as major sources of solar radiation after the south orientation. The orientations with the next highest intensity of solar radiation are the south-east (SE) and south-west (SW) orientations. These two receive more solar radiation than the other orientations due to their location close to the south since they are considered to be part of the south orientation. Radiation from other orientations, such as the east, west, north-west and north east orientations, are always 0, except in the summer simulation graph for latitude 20° N. The solar radiation from the north, north-east and north-west was found to be, in the case of the north, 55 W/m²; for the north-east it was 40 W/m²; and for the north-west, 40 W/m². In winter there is high solar irradiance in lower latitudes (for example, latitude 20° N and latitude 30° N), and low irradiance in summer. A remarkable difference can also be noticed in the simulation graphs between the summer and winter curves in these two latitudes (20 N° and 30 N°) while, in higher latitudes, there is no such difference in the summer and winter curves. This is made clear in the simulation graphs for latitude 50°N.

Koenigsberger, Ingersoll, Mayhew and Szokolay (1973) in

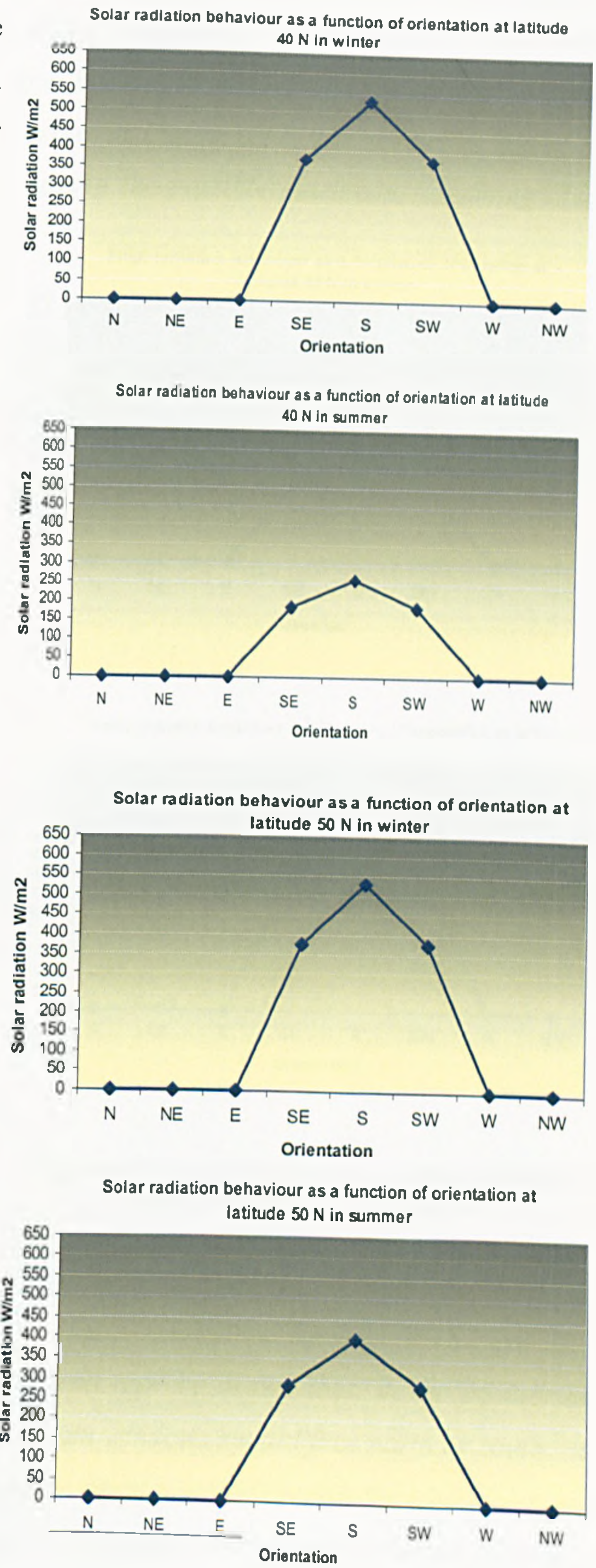


Figure 6.15 Radiation behaviour in different orientations at latitudes 40°N and 50°N.

"Manual of Tropical Housing and Building" carried out a study on the effect of orientation in two locations: latitude 1° S and latitude 33° S. They noted: *"It is useful to compare the variations of solar radiation intensities on a horizontal surface and on vertical walls of different orientations in graph form, as shown in Figure 6.17. The former is based on measured values, the latter is calculated, giving the possible maximum (assuming clear skies). Irregularities in the former are the effects of clouds."*

From graphs shown in Figures 6.17 and 6.18, the authors drew the following facts:

1. In both locations, but especially near the equator, the horizontal surface receives the greatest intensity of solar radiation.
2. At the higher latitude, the wall facing the equator receives the next highest intensity in winter (when the sun is low) but receives very little in summer.
3. In the equatorial location, north and south walls receive the least intensity and that for only short periods of the year.
4. East and west facing walls receive the second highest intensities in the equatorial location and consistently large intensities even at higher latitudes.

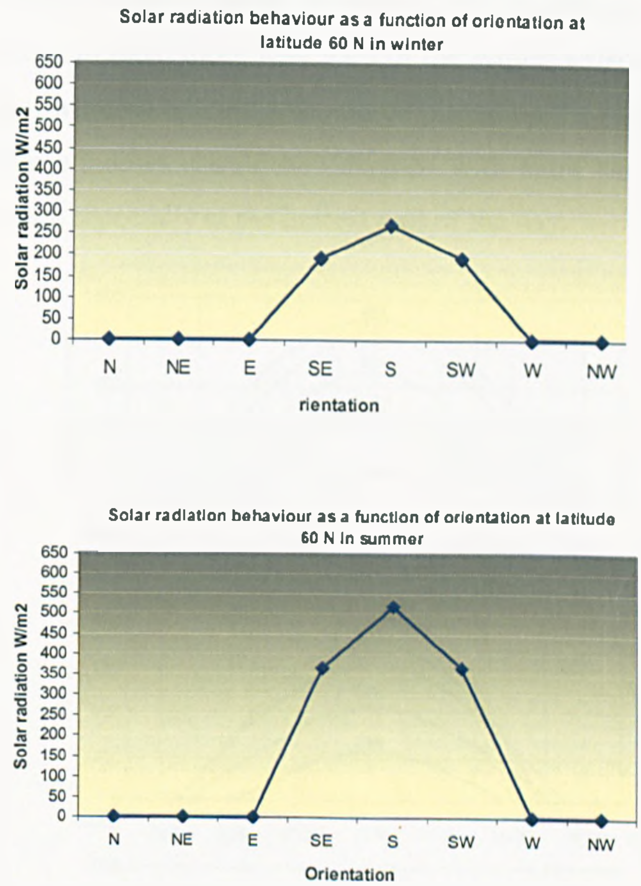


Figure 6.16 Radiation behaviour in different latitudes and orientations at latitude 60°N.

The researchers also added: *"The conclusion can now be drawn that, in the equatorial location, if solar heat gain is be avoided, the main windows should face north or south. At the higher latitude, an orientation away from the equator would receive the least sunshine, but here it may be desirable to have some solar heat gain in winter, when the sun is low-so an orientation towards the equator may be preferable.*

In both locations only minor openings of unimportant rooms should be placed on the east and west sides. Solar heat gain on the west side can be particularly troublesome as its maximum intensity coincides with the hottest part of the day" (Koenigsberger et al., 1973).

These studies prove that it is preferable to avoid heat gains in lower latitudes and that large areas of glass in windows should face north or south. However, in high latitudes, which are away from the equator, it is better to have more heat gain in the winter season when the sun angle is low. Small and minor window openings should be placed on the east and west side in most latitudes. West side windows should be designed with extra care because solar heat gain could be troublesome, especially at the hottest part of the day.

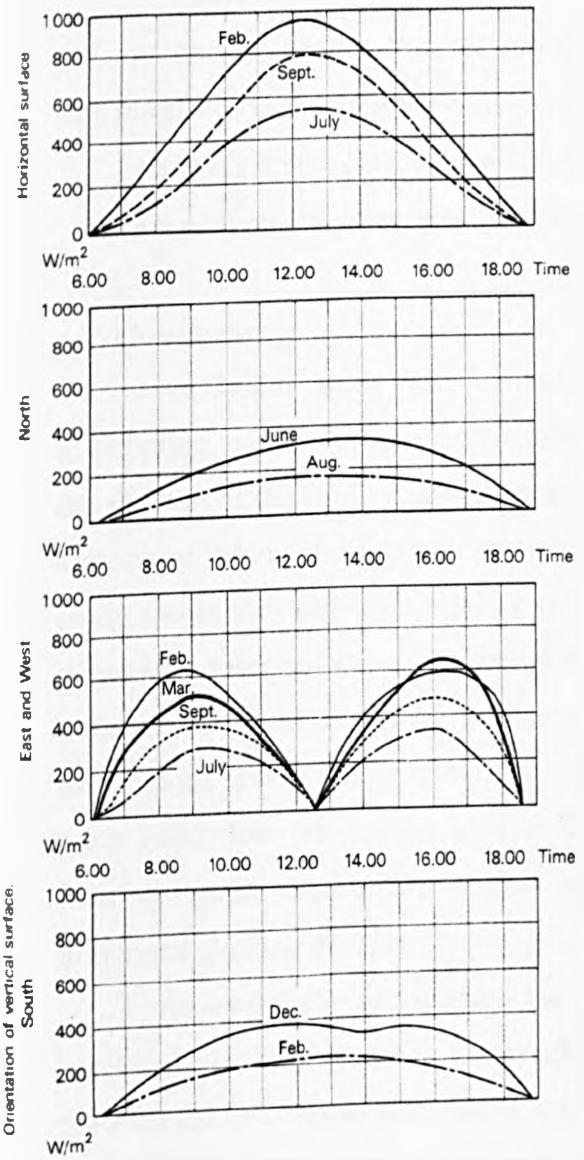


Figure 6.17. Solar radiation intensities for latitude 1° S (Nairobi): measured values (Koenigsberger, 1973).

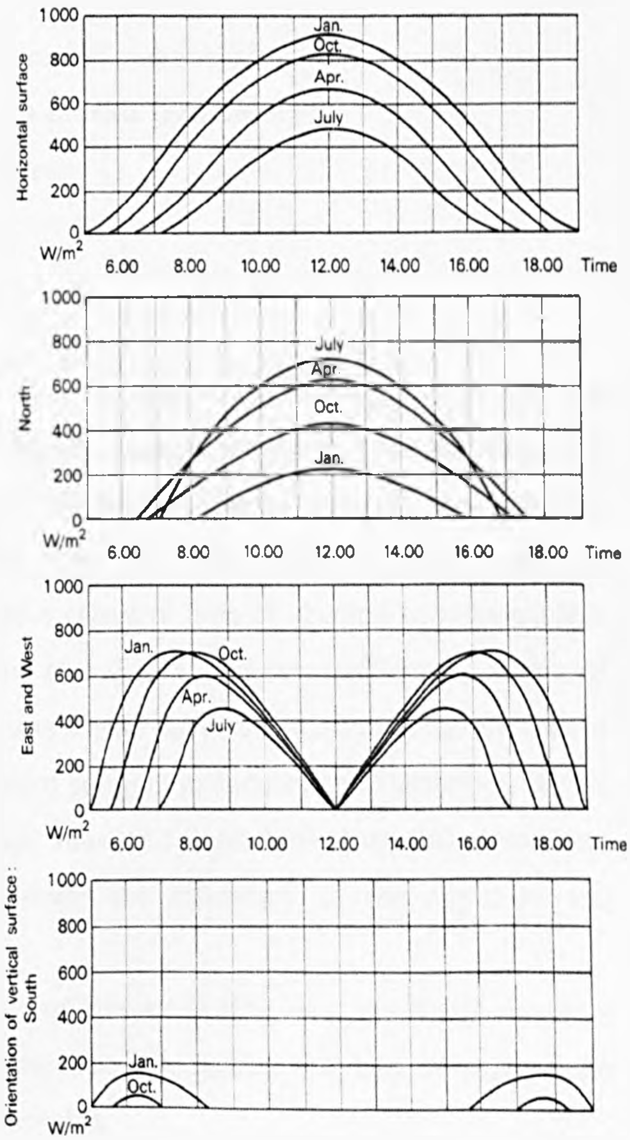


Figure 6.18. Solar radiation intensities for latitude 33° S (Sydney): calculated values (Koenigsberger, 1973).

6.6. Apache Thermal Analysis

Apache is the name given to the thermal analysis programs in the Virtual Environment. The Apache view provides facilities for:

- The preparation of input data for the thermal analysis programs Part L and APcalc, Apsim.
- Calculations and simulations using APcalc, APsim, APhvac and MacroFlo and Part L.

The preparation of thermal input data consists of three main tasks:

- The specification of the building location and weather data
- The specification of data for the building elements (properties of the building fabric)
- The specification of room data (conditions in each room).

The interfaces to the thermal analysis programs provide facilities for:

- Setting up the calculations and simulations
- Specifying the results to be recorded.

6.7. Conclusion

An initial study was carried out in this chapter to investigate the general distribution of the internal sunlit area. Different parameters which strongly affect the distribution of the sunlit area were selected for the study. Different types of shading device are one of the most effective parameters that affect the penetrated solar radiation and the study shows that egg-crate shading is the most effective type of shading in reducing this penetrated solar radiation. Horizontal shading also shows significant efficiency compared with vertical types. The study, performed to investigate the distribution of the sunlit area in each month, shows a high level of penetration of sunlight in January and December. On the other hand, low penetration appears in May, June and July. Moreover, the annual and monthly sunlit distribution studies demonstrate the efficiency of the egg-crate and horizontal shading devices.

An evaluation to compare the results of Hassan (1996) with the SunCast model results shows confidence in the results of the SunCast model; discrepancy percentages between the two results were found to be acceptable.

Three parameters which strongly affect the solar radiation penetration were selected for this study. These were time, location and orientation. The investigation's results for two locations, latitude 30N° and latitude 50N°, show that the overheating period that most requires shading is from 10 am to 2 pm. According to the CIBSE guide and the related graphs, during this period, surfaces are exposed to high amounts of solar radiation. For the second of the parameters, (the location studies), it can be seen that lower latitudes receive the highest amounts of solar radiation. However, the variation in the amounts of solar radiation received by the horizontal surface in summer is much less than it is in winter, as shown in Figure 6.13. The difference in the received solar radiation in winter between latitude 20°N and 60°N is around 550W/h. On the other hand, in summer, the difference is only 200W/h.

Studies into the effect of orientation on the solar radiation penetration indicate that south-facing windows receive most sunlight. Investigation also reveals that south-west and south-east windows could allow a significant amount of solar radiation to penetrate the interior in most latitudes. However, north, north-east and north-west windows offer the minimum penetration of solar radiation.

CHAPTER 7

VARIABLES AFFECTING THE SUNLIT AREA

7.1. Introduction

This chapter will shed light on the variables that affect the distribution of the sunlit area which penetrates into the internal surfaces (mainly the floor in this study) through a 1m x 1m window unit in a 5m x 5m room with 3m high walls. This size could be used as a guide for other windows sizes in real buildings. A group of variables which affect the sunlit area were selected. These variables include the following:

- Location (latitude)
- Types of shading device (horizontal-vertical-egg-crate)
- Time during the day
- Summer and winter (sun's altitude)
- Window orientation
- Window slopes (the window's vertical angle).

Each variable has a significant effect on the sunlit area. The location, for instance, will play a significant role in increasing or decreasing the solar penetration due to the sun's altitude (the solar altitude angle) at each latitude. Solar penetration through windows will increase in higher latitudes and decrease in lower ones. Different types of shading device affect the variation in the distribution of the sunlit area. It has been argued that horizontal devices are effective with a high sun angle and that vertical devices are effective with a low sun angle, with egg-crate devices being effective in both cases.

A period of time (from 10 am to 2 pm) was selected to examine the internal distribution of the sunlit area. It was discussed in the previous chapter why this period of time was chosen and this discussion placed emphasis on the graphs which illustrate the behaviour of solar radiation on the horizontal surfaces as a function of time in different latitudes. One of the main variables which has a significant effect on this study is the summer and winter seasons. Two days were therefore selected to make the evaluation: 21 June which represents the summer period and 21 December which represents the winter. The next variable to be investigated was the window orientation. Orientations vary from one to another in terms of the infiltration process of the solar radiation into the internal surfaces. Some will allow more than others as an effect of the sun's location from this orientation. Windows with a south orientation in the north hemisphere are exposed to high amounts of solar radiation, especially in winter.

The dimensions of shading devices were also considered in this study as the depth of devices affects the internal sunlit area distribution. Devices with depths of .25m, .5m,

.75m, and 1m were selected to be investigated with the three selected shading methods: horizontal, vertical and egg-crate shading devices.

The last part of this chapter contains a comparative study which discusses the different distribution of the sunlit area with different window tilt angles. The vertical window angles selected were 90°, 80°, 70°, 60°, 50° and 40°. This section is followed by a initial thermal evaluation to examine the effect of the tilted window on the required cooling loads in summer.

The following table demonstrates the variables which were evaluated in the current study:

	1	2	3	4	5
Latitude	20°	30°	40°	50°	60°
H Devices	0.25m	0.50m	0.75m	1m	1.25m
V Devices	0.25m	0.50m	0.75m	1m	1.25m
E Devices	0.25m	0.50m	0.75m	1m	1.25m
Time	10	11	12	13	14
Month	21 Jun			21 December	
Orientation	0	90	180	270	
Slope	40°	50°	60°	70°	80°

Table 7.1 Variables affecting the penetration of the sunlit area.

7.2. Summer and winter simulation

7.2.1. Summer simulation

7.2.1.1. The effect of latitude on the sunlit area distribution

In this section of the study, the orientation of the window was 180° and the depth of the shading devices was 0.6m. The following graphs illustrate the effect of latitude on the internal distribution of the sunlit area. Three curves, which represent the selected shading methods, are shown in each graph. H is the horizontal, V is the vertical and E is the egg-crate shading curve.

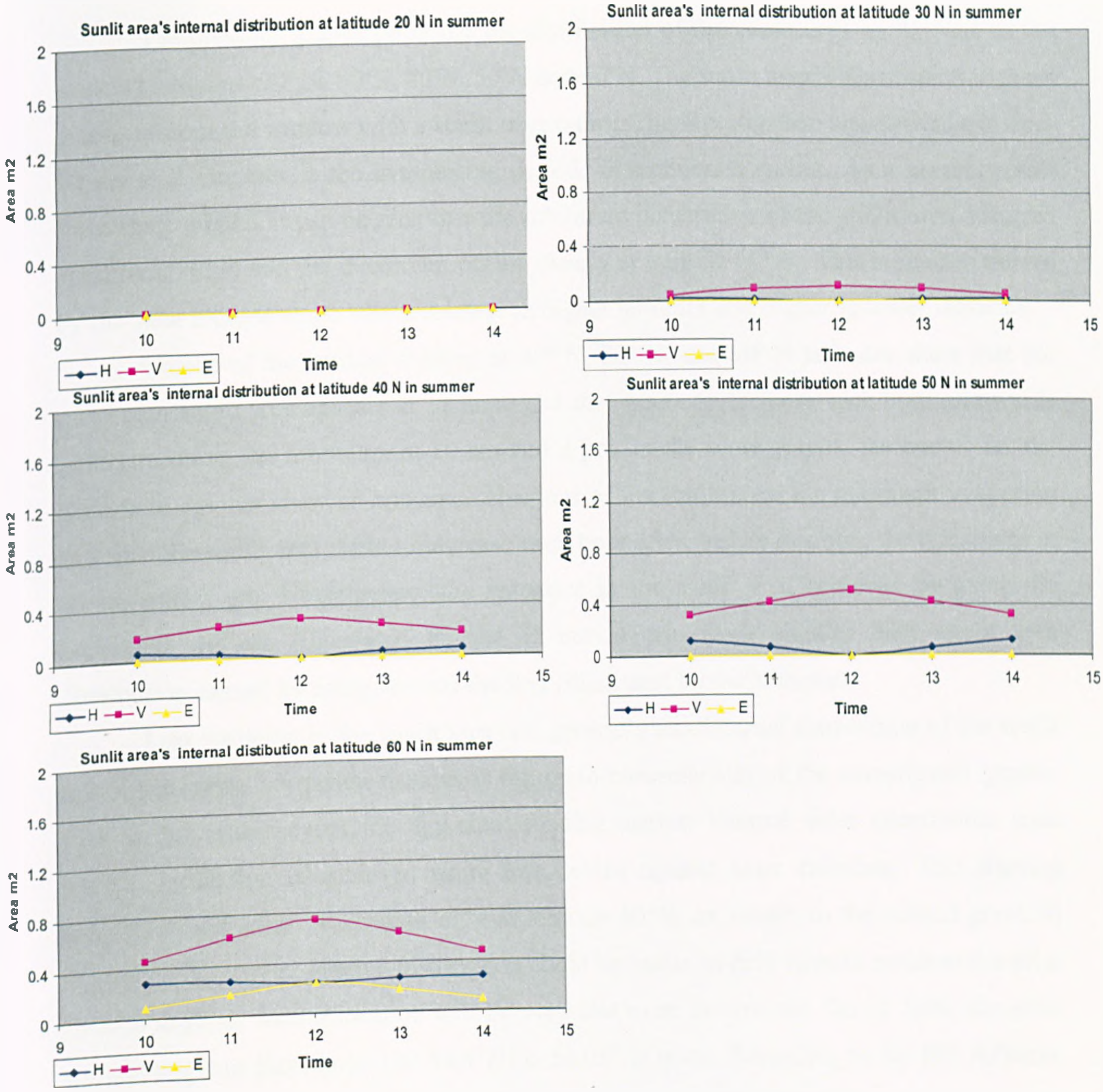


Figure 7.1 The impact of latitude on the internal sunlit area distribution in summer.

The previous graphs point out the distribution of the sunlit area on 21 June in the selected latitudes: 20° N, 30°N, 40°N, 50°N and 60°N. The sunlit area's distribution in these graphs is from the window with a south orientation. The investigation was carried out from 10 am to 2 pm; this is the overheating period, as mentioned earlier. As a general result from these graphs, it can be seen that the minimum penetration of the sunlit area occurred at latitude 20° N and the maximum occurs clearly at latitude 60° N. This is mainly caused by the solar altitude angle which is lower in higher latitudes and higher in lower latitudes.

Graphs of the vertical shading at 40° N, 50° N, and 60° N latitudes show that the maximum sunlit area appears at 12 noon and then starts to decrease each hour afterwards before reaching the minimum at 10 am and 2 pm. In the same graphs, the curves for the horizontal devices show an opposite behaviour of the sunlit area: the minimum is at noon and then the sunlit area starts to increase each hour after, before reaching the maximum at 10 am and 2 pm. Nevertheless, the increases in the sunlit area achieved by using the horizontal devices (illustrated by the H curve) are much smaller than sunlit area distribution caused by using vertical shading (illustrated by the V curve).

Less variation in the sunlit area and generally less internal distribution of the sunlit area when using horizontal devices is the main characteristic of the investigated graphs. Due to the efficiency of the egg-crate shading against internal solar penetration, total internal protection is achieved using this device against solar radiation. This shading method allows solar penetration only at latitude 60°N, as shown in the related graph in Figure 7.1. However, internal distribution could be useful in cold climate zones as the solar altitude angle at such a location will be very low even in summer. On 21 June, the solar altitude angle in Stockholm (lat 59.4°N) is 54.05° at noon. According to the IES APlocat, this is the highest solar altitude angle at this latitude at this time of the year. A low solar altitude angle will indicate penetration of the sunlight on the room's walls. Deep penetration of the sunlit area is due to the low solar altitude angle and this is the main factor that explains the increased sunlit area distribution, even when using the egg-crate shading at latitude 60°N. In higher latitudes, an increased sunlit area is expected even with egg-crate shading. Vertical or horizontal louvers in this case will be identical in their ability to reduce the penetrated solar radiation. The angles of incidence and location are the two main factors affecting the distribution sunlit area, as shown in the previous graphs. Low angles of incidence occur mainly at lower latitudes; this results in deep penetration of the sunlit area. In this case, a different method of shading is required to eradicate problems with undesired solar penetration problems. Various studies have indicated that cloudiness and atmospheric pollution will affect the solar penetration. These two factors could significantly reduce the intensity of the solar radiation.

7.2.1.2. The effect of orientation on the sunlit area distribution

In this study the location is latitude 20 N° and the depth of the shading devices is 0.6m

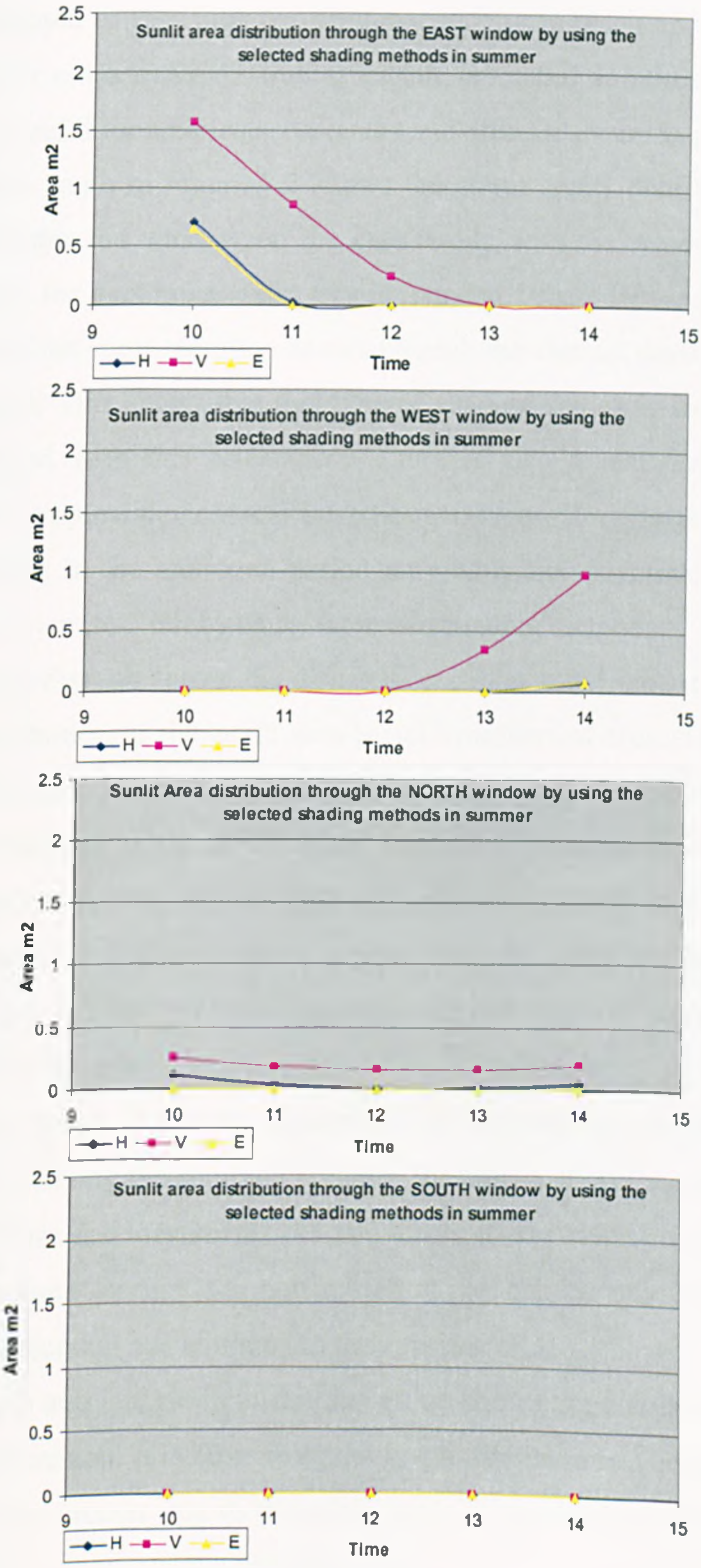


Figure 7.2 The impact of orientation on the internal sunlit area distribution in summer.

This test assessed the effect of orientation on the sunlit area and the evaluation includes the four main orientations: 360° N, W 270°, S 180° and E 90°. The assessment period in this evaluation was 21 June while the selected time of day was from 10 am to 2 pm. The depth of the shading device was .6m in this test and latitude 20° N was the location. This was for two main reasons: 1. Latitude 20° N is considered to be in a hot dry zone and is exposed to very high temperatures which can reach up to 45° C in summer. 2. One of the major cities in Saudi Arabia, Jeddah, is located at latitude 21° N, which makes this study very useful for architects, designers and urban planners in this region.

The first graph in Figure 7.2 shows the sunlit area's distribution when the sun's radiation penetrates the window on the east façade with the window oriented at 90°. In these conditions, the maximum sunlit area is found at 10 am. However, the highest amount of penetration of the sun's radiation occurs through the vertical devices, as can be see from the related graph. This shows that this type of shading device is inefficient and therefore not recommended with this orientation. There is also a remarkable difference in the efficiency of the vertical devices and the other two types. Horizontal and egg-crate devices are more efficient in the afternoon period only with this orientation. Total protection is provided from 11 am to 2 pm by using these two shading methods.

The second graph shows the distribution of the sunlit area in the west orientation. Firstly, the distribution of the sunlit area is not symmetrical around noon-time in the east and west orientations. Later studies show that this is mainly because the solar noon angle at this location does not occur at 12 noon. Moreover, there is no such variation in the performance of the shading devices with this orientation. The sunlit area is generally low with an increased area of penetration when using the vertical devices while increased shading efficiency is achieved by using horizontal and egg-crate shading due to the lower level of sunlit distribution.

The third graph shows the distribution of the sunlit area through a north window orientation. By studying the sun-path diagram for this location (latitude 20°N) in summer, it can be seen that the location of the sun shifts to the north in June. This will allow sunlight to penetrate through the north window, as can be observed in the graph. The related sun-path diagram can be found in the appendices.

The fourth and last graph in this test group shows the distribution of the sunlit area for the south orientation. It is clear from the graph that there is a complete blocking of the sun's radiation in summer due to the sun's angle. Later studies will show that the solar altitude angle at noon in Jeddah (21°N) is 84° on 21 June. Such a high solar angle will prevent any penetration of sunlight.

7.2.1.3. The effect of the depth of devices on the sunlit area distribution

In this study the location is latitude 40 N° and the orientation is 180°

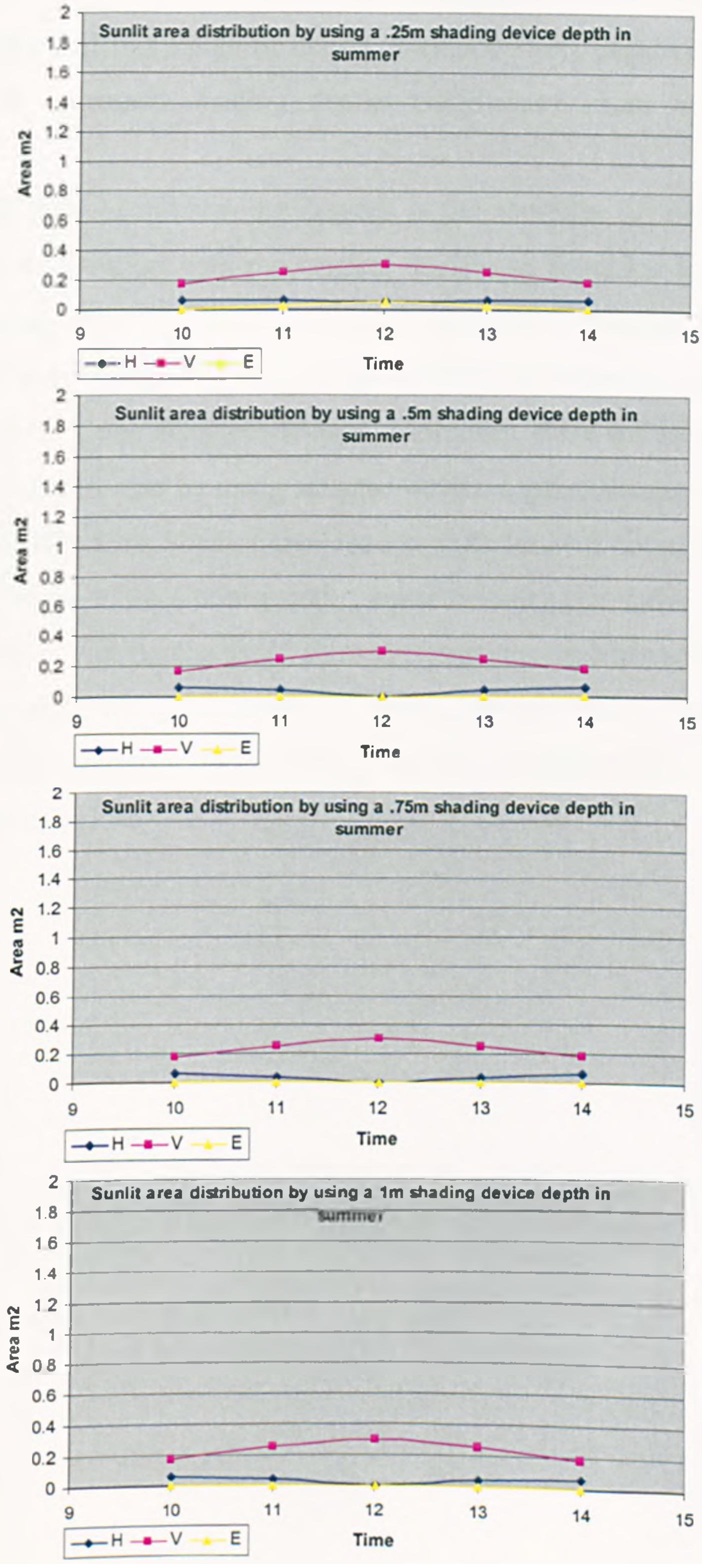


Figure 7.3 The impact of the depth of shading devices on the internal sunlit area distribution in summer.

This study is involves assessing the effect of shading depth on the penetration of the sunlit area's internal distribution. Shading devices with depths of 0.25m, 0.5m, 0.75m and 1m were selected for the evaluation while the selected orientation was south, at a location of 40° N. In order to cover and study various locations and latitudes, different latitudes were selected. It can be observed from the related graphs in Figure 7.3 that variations in the behaviour of the curves are very similar in the four graphs. This shows that shading devices of this range of depths does not affect the distribution of the sunlit area in summer. Increased shading depths could have more effect on sunlit area distribution.

The efficiency of the shading devices is the same for all device depths: there is more sunlit area distribution with the vertical device, so these are less efficient; but less sunlit area with the horizontal devices, making these more efficient. The minimum sunlit area distribution can be achieved using egg-crate devices which are considered to be the most efficient of the three selected devices. Moreover, different latitudes can affect the distribution of the sunlit area by using selected device depths. Winter studies show similar behaviour of the sunlit area. Shading devices less than 1m will not affect the internal solar distribution at latitude 40°N. Consequently, lower latitudes (i.e. latitude 20°N) will not be affected. The same device depths could show different results when using different shading methods. For instance, using horizontal or vertical blinds with a depth of 0.25m could result in considerable variation in the internal solar penetration when compared to using a blind with a depth of 0.75m.

7.2.2. Winter simulation (21 December)

7.2.2.1. The effect of latitude on the sunlit area distribution

In this study, the orientation of the window is 180° and the depth of the shading devices is 0.6m.

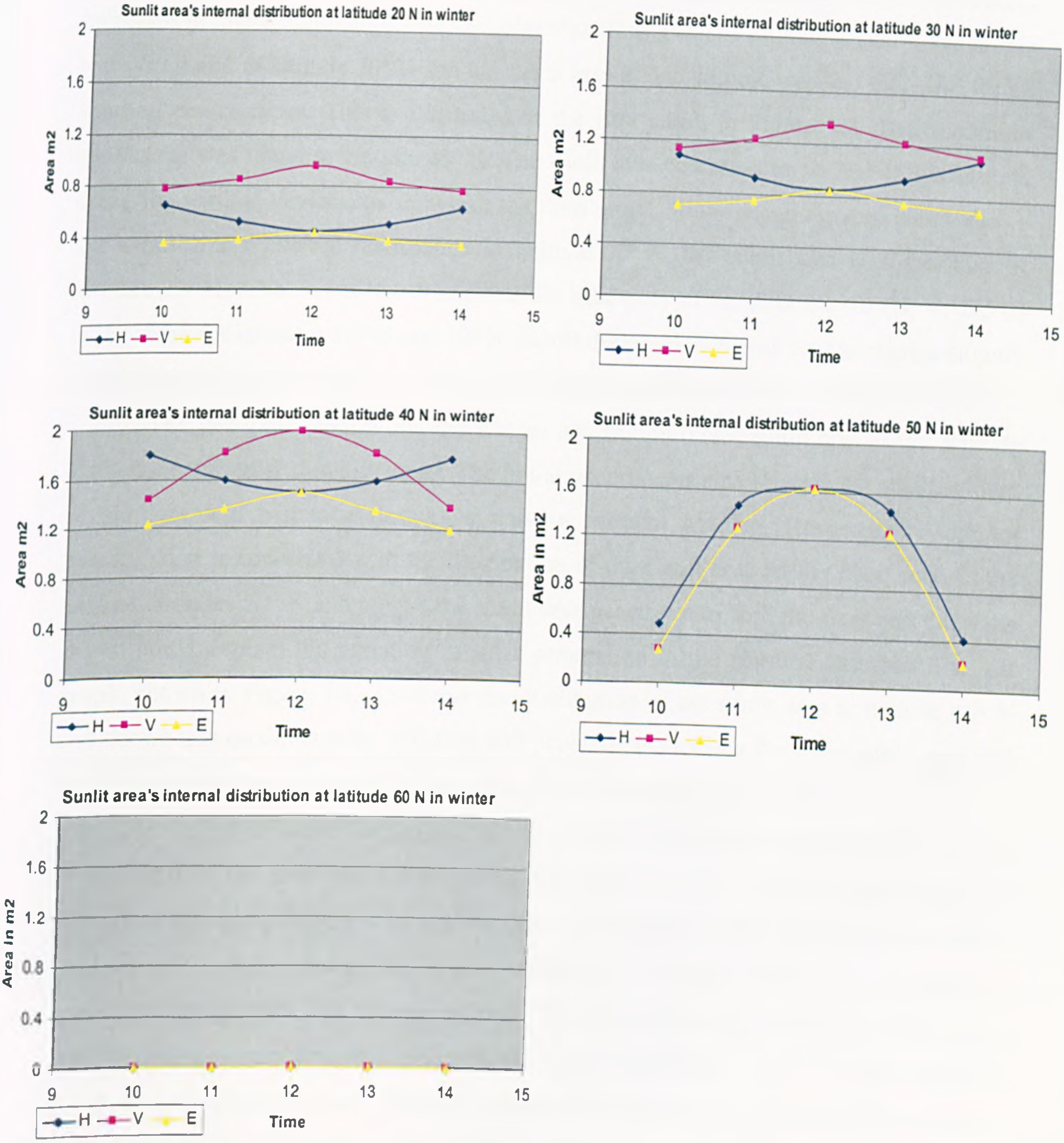


Figure 7.4 The impact of latitude on the internal sunlit area distribution in winter.

Graphs in Figure 7.4 demonstrate the distribution of the internal sunlit area in winter (21 December) in the same previously investigated latitudes: 20° N, 30° N, 40° N, 50° N and 60° N. The sunlit area shown in these graphs penetrates the window with the south orientation. The test was carried out from 10 am to 2 pm. As a general result, the sunlit area distribution in winter is higher than in summer. Internal solar penetration increases in higher latitudes due to the solar altitude angle. The minimum sunlit area in this test was found at latitude 20° N and the sunlit area at this latitude was less than $1m^2$ for all shading device types. This is illustrated in the first graph in Figure 7.4. The maximum sunlit area was found at latitude 40° N. The sunlit area can reach up to $2m^2$ at this latitude using the vertical devices, as shown in the third graph. In the second graph, which shows the sunlit area's internal distribution at latitude 30° N, the sunlit area is higher than at latitude 20° N. Also, it can be noticed that the behaviour of the three curves (H, V, and E) is the same for latitudes 20° N and 30° N. Sunlit distribution curves start to change slightly at latitude 40° N, then higher variations can be seen for latitude 50° N in the fourth graph.

The last graph shows that there is no penetration of the sunlit area at this latitude using the selected shading methods. The initial experiments also show that a small amount of sunlight will penetrate through a window without shading. However, the current investigation is concerned with the distribution of the sunlit area on the floor only. In the case of latitudes 50° N and 60° N, the sunlit area penetrates to both the floor and the walls which could explain the variation in solar penetration in the selected latitudes. The last graph, shown in Figure 7.4, illustrates the distribution of the sunlit area at latitude 60° N and shows that no direct solar radiation will penetrate the room's floor; the sunlit area will mostly occur on the room's walls due to the low altitude angle of the sun.

In the fourth graph, for latitude 50° N, the sunlit area, using the horizontal devices, is greater than the area found when using the vertical devices in the morning and the afternoon. At noon, however, a similar area of sunlight is achieved by both shading methods. This demonstrates the higher efficiency of vertical shading as opposed to horizontal shading for this precise latitude. Similar efficiency is achieved when using vertical and egg-crate devices at this latitude. The increased efficiency of vertical devices at this latitude is mainly due to the solar geometry. Vertical shading is an efficient shading method against low sun angles while the effect of horizontal shading against low angles of the sun will be negligible in this case. At latitude 40° N, it can be observed from the graph that less sunlight will penetrate during the morning and the afternoon, after which the area starts to increase each hour after 10 am and before 2 pm, reaching the maximum at noon when using vertical devices. Using horizontal devices, the opposite effect is achieved. The minimum sunlit area will penetrate at noon; this then increases each hour before and after to reach the maximum in the morning and afternoon.

It can be observed, comparing this study with graphs and results achieved from the previous summer's investigations, that the sunlit area penetrates more in winter due to the sun's latitude and the azimuth angle. Solar penetration is very useful in cold climate zones or in high latitudes, for heat gain and for reducing the heating load in the winter months. This investigation reveals that horizontal shading is an efficient shading method when compared with vertical devices in latitudes 20° N, 30° N and 40° N. At latitude 50° N, the efficiency of horizontal and vertical shading is similar. However, vertical shading is slightly more efficient when compared with horizontal shading. At the same latitude, the efficiency of egg-crate shading is fairly similar to that of horizontal devices. Nevertheless, egg-crate shading is the most efficient of the selected shading methods. At latitude 60° N, shading devices will be less effective due to the solar altitude angles at this location, as can be observed in the related graph. Low sun angles will allow more penetration of the sunlit area onto the walls of the room and less on the floor. Other shading methods are more useful in this case. Shading that covers a greater area of the window is recommended in this case.

7.2.2.2. The effect of orientation on the sunlit area distribution

In this study the location is latitude 20 N° while the depth of the shading devices is 0.6m

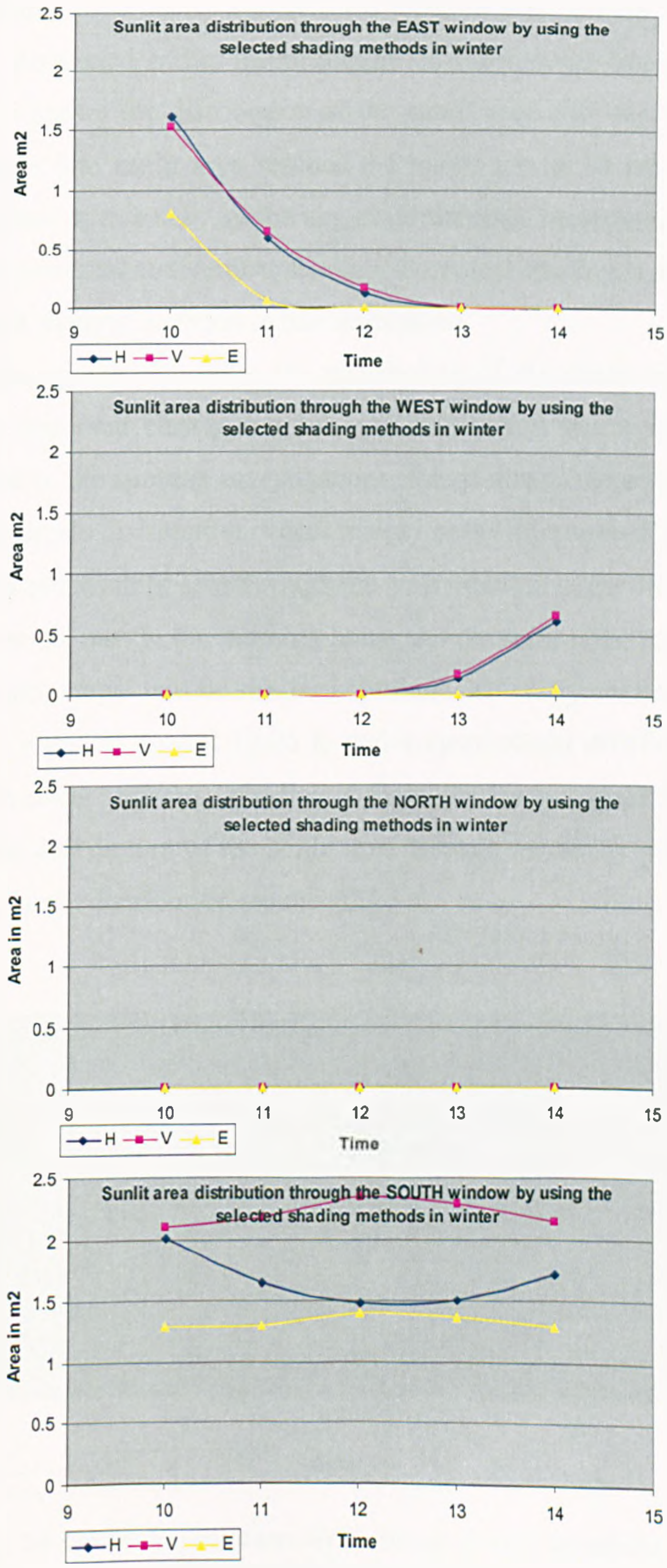


Figure 7.5. The impact of orientation on the internal sunlit area distribution in winter.

This investigation assesses the effect of orientation on the distribution of the sunlit area in winter. As with the summer investigation, four main orientations were selected for this test. The depth of the shading devices selected for this group was .6m, which is an average and commonly used depth. The selected location was latitude 20° N for the same two main reasons mentioned earlier in the section on the summer investigation. The first graph in Figure 7.5 shows the distribution of the sunlit area with the window orientated east. In this example, the sunlit area reaches the maximum at 10 am while the highest efficiency is presented in this case by the egg-crate shading. Moreover, similar efficiency is achieved by the horizontal and vertical shading. Complete shading is achieved after noon by using the selected shading methods in this orientation.

The following graph represents the distribution of the sunlit area using the west window. It can be observed clearly that sunlight distribution is not symmetrical around noon. As mentioned in the summer investigations, this is due to the solar geometry in this location. The sunlit area's distribution occurs mainly in the afternoon hours. Moreover, the internal distribution of the sunlit area through the west window in the afternoon is less than the distribution from the east in the morning hours. As the solar noon angle in Jeddah is at 12:25 h, the solar noon angle will be similar at latitude 20° N. Symmetrical distribution of the sunlit area was found at around 12:25 h. and a symmetrical distribution of the sunlit area around 12:25 h using horizontal shading is shown by the last graph in Figure 7.5. This graph represents the distribution of the sunlit area through the south window. Figure 7.6 shows symmetrical sunlit distribution around 12:25 h.

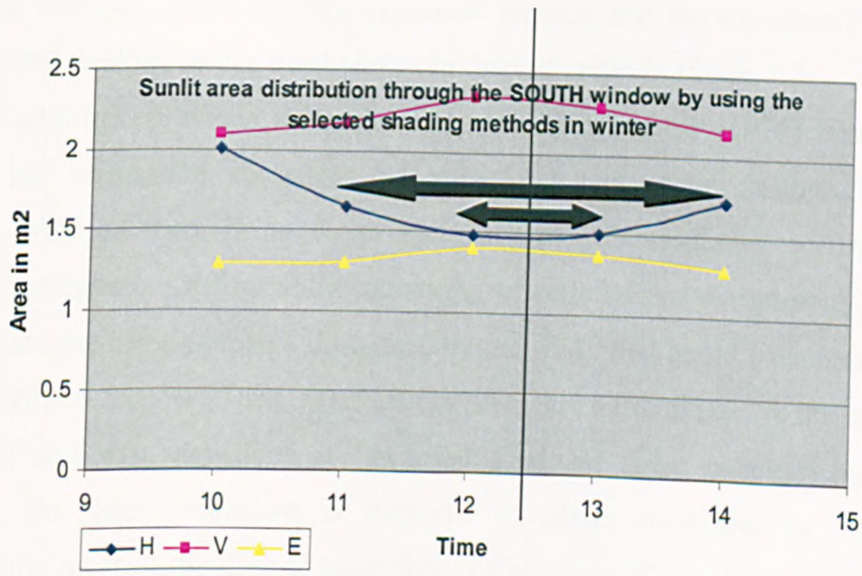


Figure 7.6 Symmetrical sunlit area distribution at 12: 25 h through the south window using horizontal shading.

The third graph in Figure 7.5 shows that there is no solar penetration through the north windows in winter. North windows will be completely shaded during the winter at this location.

The fourth and last graph illustrates the distribution of the sunlit area that penetrates the south window. From the graph it can be observed that the maximum solar radiation that penetrates the room's internal floor comes mainly from the south. The distribution of the sunlit area is continuous through the selected investigation period from 10 am to 2 pm with all the types of shading device. Nevertheless, the maximum sunlit area is achieved by using vertical shading and the minimum sunlit area is achieved by using egg-crate shading. The distribution of sunlight could be useful in winter, however, for heating purposes.

The trend of the curves of the vertical devices is opposite to that of the horizontal devices. The maximum sunlit area is achieved at noon by using vertical devices on the south window. This maximum then decreases each hour before and after to reach the minimum at 10 am and 2 pm. On the other hand, horizontal devices allow a minimum area of sunlight to penetrate at noon; this then starts to increase each hour before and after to reach the maximum at 10 am and 2 pm. Moreover, the curve of the egg-crate devices shows that this shading method allows the minimum penetration of solar radiation from among the three selected shading methods.

This study reveals that noon does not represent the highest sun position in the sky at this latitude (20° N). Maximum solar radiation is achieved through the south windows and minimum solar penetration is achieved through the north windows while the minimum sunlit area will penetrate by using egg-crate shading and the maximum is achieved by using vertical shading, as can be observed in the last graph in Figure 7.5.

In addition, previous research conducted by Harkness (1978) investigating solar radiation and orientation, illustrates that solar heat gain on the northern façades is at a minimum whereas there is no direct incidence of solar radiation on buildings in the northern hemisphere. Diffuse solar radiation, reflection from surrounding buildings, and landscape are the three elements illustrated by the study that could be sources of solar heat gain on northern façades. Thus, solar energy from the north façade is the least favourable while west and east elevations are exposed to direct solar radiation half of the day. Moreover, the south elevation is exposed to direct radiation for the entire day. Subsequently, most of the desired solar energy transfer will be achieved through the south façade in the northern hemisphere. The outcome of Harkness' study is similar when compared to the results achieved here. This is illustrated in the graphs shown in Figure 7.5.

7.2.2.3. The effect of the depth of the devices on the sunlit area distribution

In this study the location is latitude 40 N° and the orientation is south (180°).

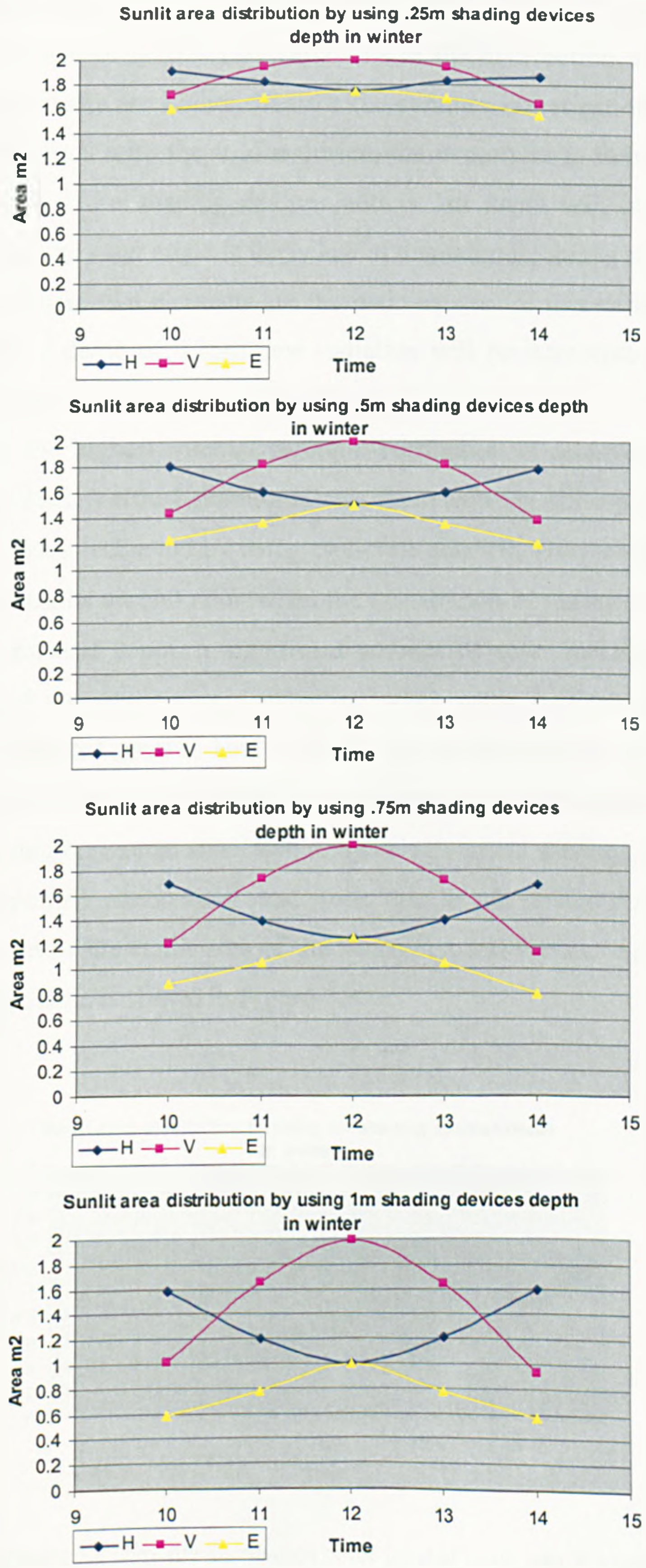


Figure 7.7 The impact of the depth of shading devices on the internal sunlit area distribution in winter.

The four graphs shown in Figure 7.7 illustrate the distribution of the sunlit area by using various shading device dimensions in winter. As with the previous summer investigations, the selected device depths were 0.25m, 0.5m, 0.75m and 1m. It can be observed from the related graphs that variations in the distribution of the sunlit area in these winter experiments are higher than for the summer investigations. However, while the variation is minimal with the 0.25m device, the maximum is found with the devices with a 1m depth because shading devices with a 1m depth will intercept more solar radiation. In winter, the solar angle is fairly low at this latitude; this is about 26.53° at noon on 21 December. These two elements are the main causes for this variation. However, by using devices with a depth of 0.25m, less radiation will be intercepted and therefore the variation in sunlit area distribution will be less.

Generally, the highest internal sunlight distribution is achieved by using devices with a depth of 0.25m. Vertical shading allows the maximum solar penetration while the minimum sunlit area is achieved by using egg-crate shading. Horizontal shading presents the most efficient results around noon when the distribution of the sunlit area is fairly low. However, at 10 am and 2 pm, a significant amount of solar radiation penetrates. The opposite is true of the sunlit area distribution when using vertical shading, as can be observed from the related graphs. This is mainly due to the shading configuration and the solar altitude angle. Much of the internal solar radiation will be prevented from penetrating around noon by using horizontal shading but, by using vertical shading, solar radiation will be allowed to penetrate precisely around noon due to the device's configuration. This opposite distribution of the sunlit area of the horizontal and vertical curves, using devices with a 1m shading depth, is shown in Figure 7.8.

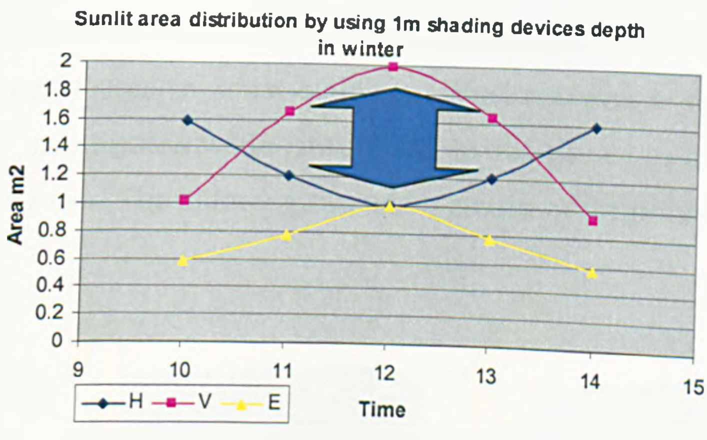


Figure 7.8 Opposite distribution of the internal sunlit area in winter between horizontal and vertical shading.

The trend of the distribution of the sunlit area when using egg-crate shading is similar to that achieved by vertical shading. However, the sunlit area is much smaller in the first case. The sunlit area distribution, achieved at noon using horizontal and egg-crate shading, is quite similar due to the similarity in the devices' configurations. The sunlit area starts to decrease each hour before and after 12 noon because of the effect of the vertical devices. This explains the similarity in the sunlit area's distributions for the egg-crate and the vertical shading.

Generally, sunlit area distribution is higher and more affected by the depth of devices in winter than in summer. Variations in sunlit distribution are significant in winter due to low sun angles and increased depths of shading device. Due to the unclear nature of the investigation into the sunlit area distribution in summer, a further evaluation was conducted to reassess this distribution. Results show that there is no significant variation between the selected depths of the devices. These results, however, might be different if the dimensions or the window sizes of the devices were changed.

7.3. The Effect of Tilted Windows on Internal Sunlit Area Distribution

7.3.1. Introduction

Initial experiments were conducted to investigate the tilt angle of windows on the internal sunlit area distribution. Experiments were undertaken in summer and winter using the SunCast model. Selected window angles were 90° (a normal window) and a 60° angled window, as shown in Figure 7.9. It was decided that these initial experiments would be followed by more detailed experiments if a significant difference was found to exist between the two selected window angles. Results are presented in the form of tables and graphs. A 60° degree angled window was selected after a brief investigation on the most commonly used angles for windows in Saudi Arabia since it was found that 60° degree walls are commonly used in some buildings. Windows with a south orientation were selected for the investigation while latitude 40° N was chosen as this came between hot and cold climate zones. The following two tables consist of the results achieved in summer and winter.

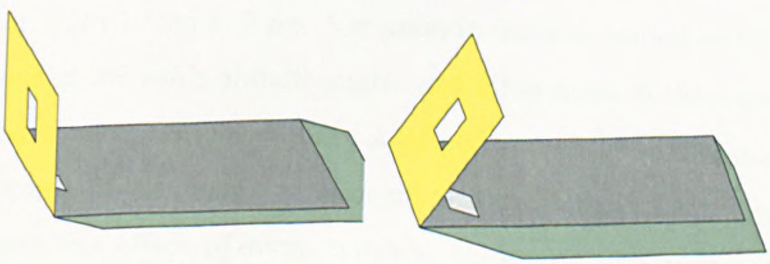


Figure 7.9. 90° and 60° tilted windows

Summer calculation (21 June)

Time	90° Wall	60° Wall
9	0.15	0.64
10	0.24	0.72
11	0.28	0.76
12	0.3	0.77
13	0.28	0.76
14	0.24	0.72
15	0.15	0.64

Table 7.2 Summer simulation in June for 90° and 60° tilted windows.

Winter calculation (21 December)

Time	90° Wall	60° Wall
9	0.5	0.3
10	2.3	2.49
11	2.06	2.28
12	2	2.23
13	2.07	2.29
14	2.27	2.47
15	0.25	0.1

Table 7.3. Winter simulation in December for 90° and 60° tilted windows

7.3.2. Discussion of the results

It can be observed from the graphs in Figure 7.10 that the sunlit area is smaller in summer than in winter. Moreover, the tilted window received more sun radiation as a result of the window's angle being tilted to the south. Obtaining increased solar radiation through tilted windows could be a useful factor for winter heating. The graphs also reveal that variation in the sunlit area in summer is less than in winter so the difference in results achieved by using a normal 90° window and a 60° window is more significant in summer than in winter. From both related graphs, the difference in the curves for the 90° window compared with the 60° window is clear in the summer readings. In winter, however, the results are quite similar at 9 am and 3 pm, as can be seen in the winter graph. Significant differences can also be observed in the sunlit area between 9 am and 10am while the same results were achieved between 2 pm and 3 pm in winter. However, variation is less in the sunlit area distribution from 10 am to 2 pm. Variation in the distribution of the sunlit area is a result of variations in the sun's altitude angles and differences in the window angles. Generally, a 60° tilted window will allow more solar penetration in both seasons, summer and winter. The outcome of this initial experiment illustrates that further assessment is required to investigate the effect of more window angles on sunlit area distribution.

Window angles of 90°, 80°, 70°, 60°, 50°and 40° were selected for the following assessment.

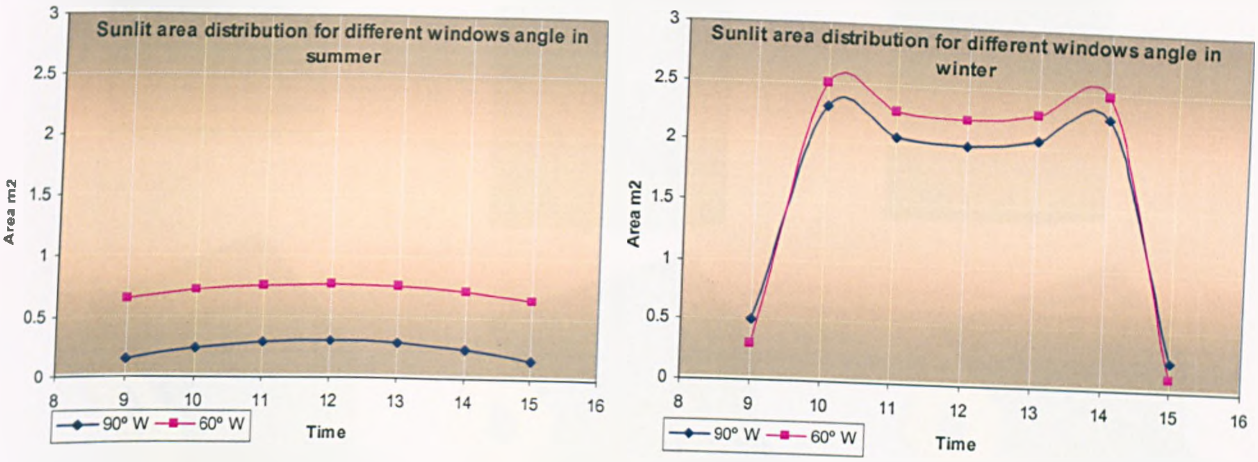


Figure 7.10 The effect of different window angles in summer.

7.4. Evaluation of the Sunlit Area Distribution using Different Window Angles (90°, 80°, 70°, 60°, 50° and 40°)

7.4.1. Introduction

The following study is an extension of the previous investigation and the evaluation sheds light on the distribution of the sunlit area using the selected tilted window angles. The location for the study was latitude 30°N and this change was made to investigate the sunlit area distribution in various locations. Moreover, this latitude is close to some parts of Saudi Arabia which makes the evaluation useful to architects and environmental designers in this region. The main concern of the study was to investigate the effect of the tilted window angle in increasing or decreasing the sunlit area penetrating the selected angled windows in summer and winter. Additional thermal evaluations were conducted by using the Apache thermal calculation and simulation model in the IES model suite. Thermal experiments were conducted to evaluate the required cooling loads in July, one of the hottest months in Saudi Arabia. More thermal analysis is recorded in the following chapter. The assessment results for the six selected window angles can be observed in Figure 7.12 while the following figure (7.11) illustrates the configurations of the angled windows achieved by using the SunCast model.

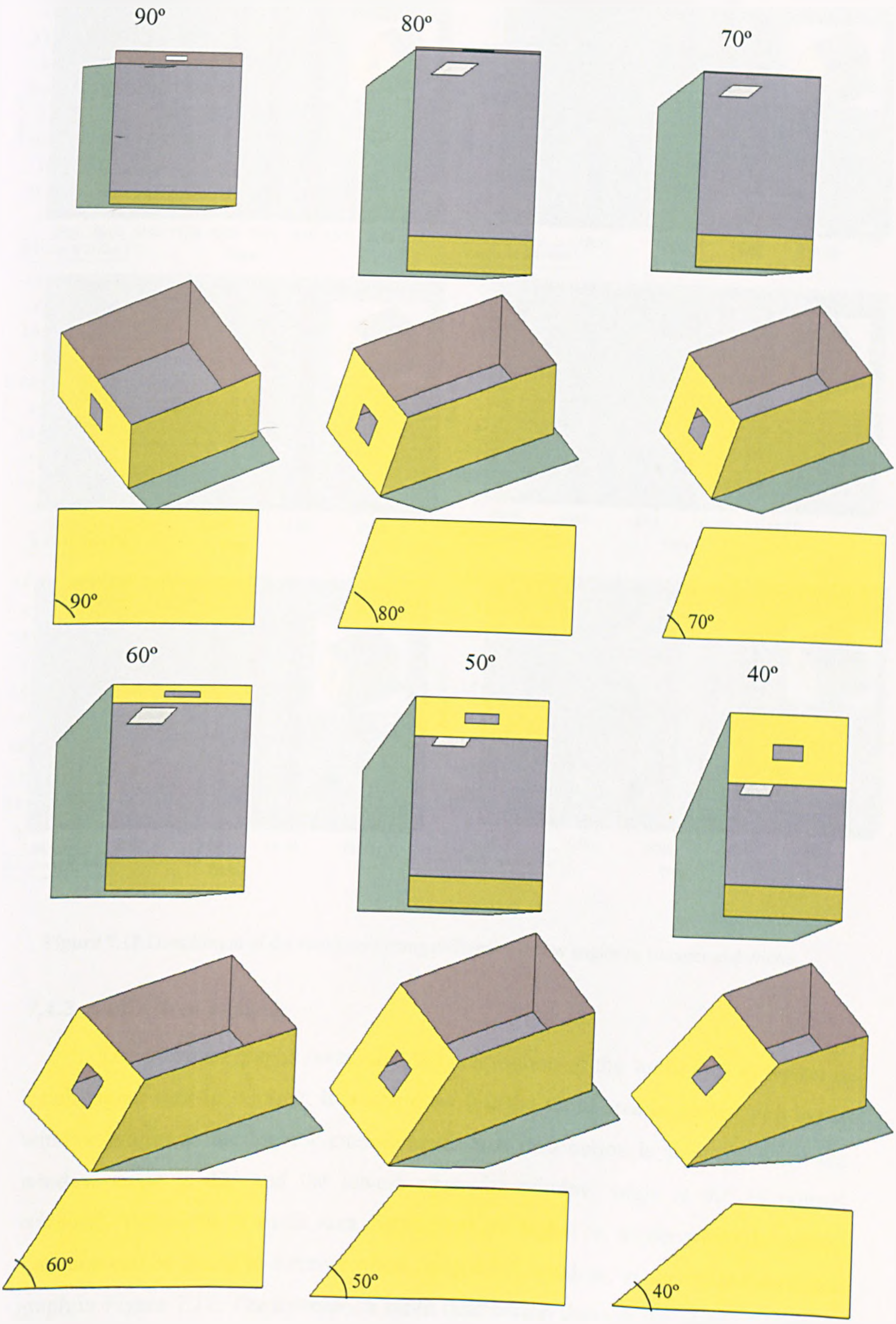


Figure 7.11 Sunlit area penetration through different windows angles: 90°, 80°, 70°, 60°, 50° and 40°.

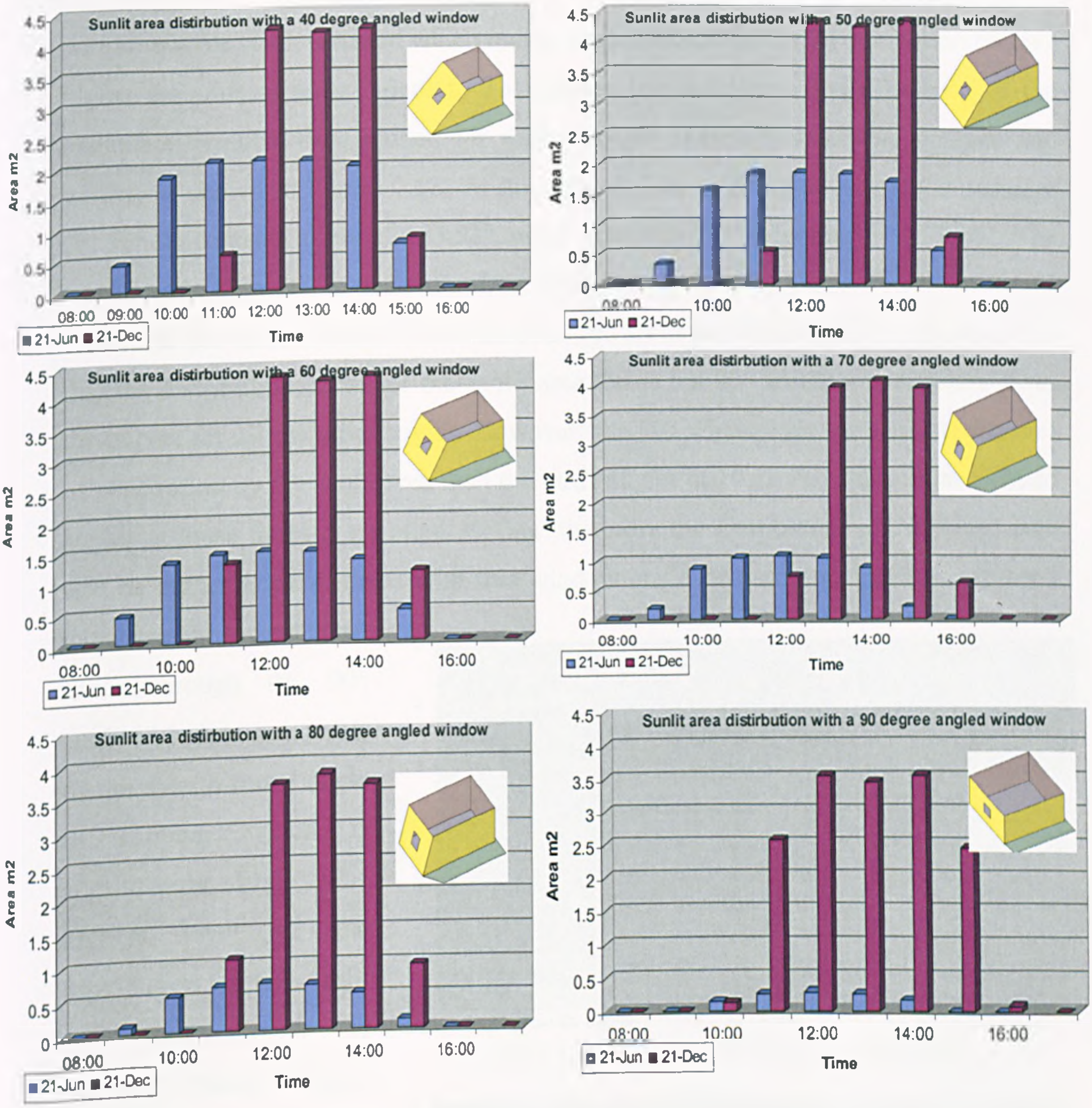


Figure 7.12 Distribution of the sunlit area using different window angles in summer and winter.

7.4.2. Sunlit area analysis

The previous graphs reveal that the distribution of the sunlit area in winter is much higher than in summer. It is also clear that the sunlit area increases with lower window angles as the highest internal sunlit area distribution is achieved when the window angle is 40° and the lowest when the window angle is 90° (a normal window). Variations in sunlit area distribution are higher in winter while the lowest variation can be found in summer when using a 90° window, as shown in the related graph in Figure 7.12. The increase in sunlit distribution through the tilted windows is an effect of both the solar altitude angle and the window angle. Furthermore, these windows were south oriented which makes angled windows in this orientation receive higher amounts of solar radiation. To increase the usefulness and efficiency of the evaluation, results were plotted for each window angle separately in summer and winter, as shown in Figure 7.13. At this latitude, the solar altitude angle in summer (21 June) occurring at noon is 83.52°, while in winter (21 December) it is 36.66°. The results were obtained from the SunCast model using data for Cairo, Egypt, as this is located at the same latitude. It can be observed from the winter graph in Figure 7.13 that the distribution curve for the sunlit area through a 90° window is different from the curves for all the other angles. However, the 90° window shows a higher amount of penetration by the sunlit area than the other angles at 10am and 2pm. Solar altitude angles at these times are around 30° and therefore the distribution of the sunlit area will be higher at these times with this window angle. In summer, sunlit distribution will be at its lowest at all times through the 90° angled window as a result of the solar altitude angle in summer which is significantly high. The highest level of the distribution of the sunlit area in summer is achieved through using a 40° angled window, as shown in the related graph. Tables 7.4 and 7.5 have been added to show the percentages of sunlit area distribution and the area distribution and the average amount of sunlight distribution in summer and winter.

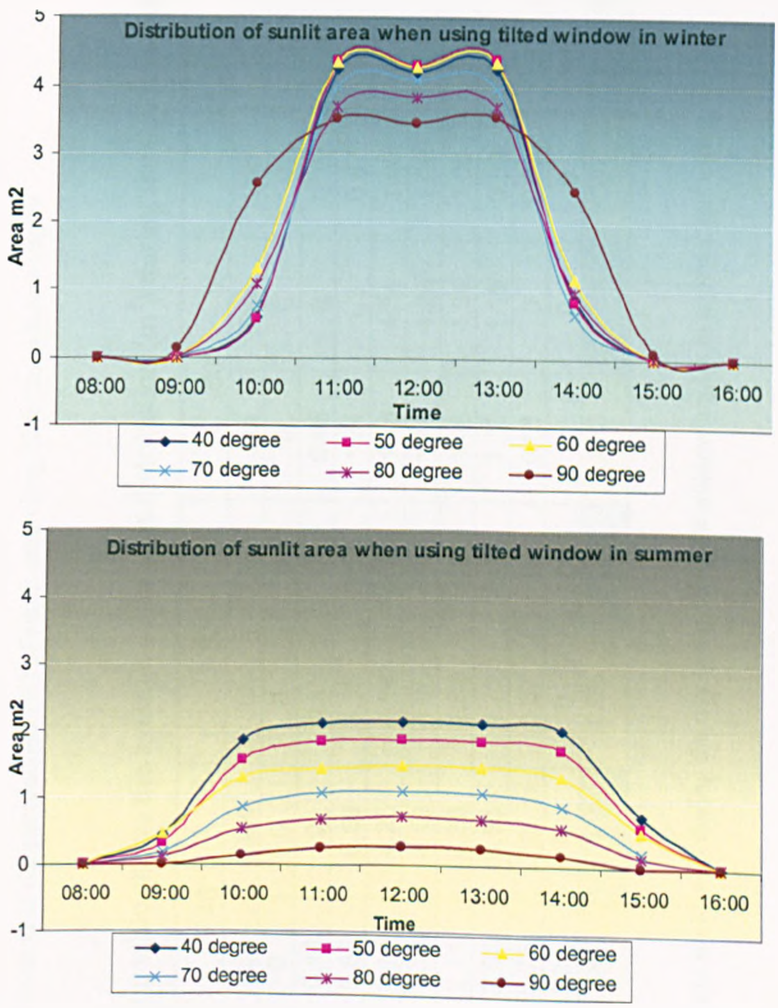


Figure 7.13 Distribution of sunlit area through different window angles as a function of time.

	40°		50°		60°		70°		80°		90°	
	Jun	Dec	Jun	Dec	Jun	Dec	Jun	Dec	Jun	Dec	Jun	Dec
08:00	0	0	0	0	0	0	0	0	0	0	0	0
09:00	0.7	0	0.7	0	1.1	0	0.5	0	0.4	0	0	0.5
10:00	3.1	1	3.1	1.1	3.3	3.2	2.5	2.1	1.8	3.6	0.6	10.3
11:00	3.5	7.1	3.7	8.7	3.6	10.8	3	11.4	2.3	12.3	1	14.2
12:00	3.6	7	3.7	8.6	3.7	10.6	3.1	11.7	2.4	12.8	1.2	13.8
13:00	3.5	7.1	3.7	8.7	3.6	10.9	3	11.3	2.3	12.3	1	14.2
14:00	3.4	1.4	3.4	1.6	3.3	2.9	2.5	1.8	1.8	3.2	0.6	9.8
15:00	1.3	0	1.1	0	1.3	0	0.6	0	0.5	0	0	0.3
16:00	0	0	0	0	0	0	0	0	0	0	0	0

Table 7.4 Variation of the percentages (%) of sunlit area using different window angles

The following table shows the average sunlit area distribution (m^2) during the day using different window angles in summer and winter

	40°		50°		60°		70°		80°		90°	
	Jun	Dec	Jun	Dec	Jun	Dec	Jun	Dec	Jun	Dec	Jun	Dec
08:00	0	0	0	0	0	0	0	0	0	0	0	0
09:00	0.44	0	0.33	0	0.46	0	0.19	0	0.12	0	0	0.12
10:00	1.86	0.59	1.56	0.56	1.31	1.3	0.87	0.74	0.54	1.08	0.15	2.56
11:00	2.11	4.25	1.84	4.36	1.45	4.34	1.06	3.98	0.68	3.69	0.26	3.54
12:00	2.13	4.19	1.86	4.29	1.48	4.26	1.09	4.09	0.71	3.83	0.29	3.45
13:00	2.11	4.25	1.84	4.37	1.46	4.34	1.06	3.96	0.68	3.68	0.26	3.55
14:00	2.02	0.86	1.72	0.81	1.33	1.15	0.89	0.64	0.55	0.96	0.16	2.46
15:00	0.75	0	0.57	0	0.51	0	0.22	0	0.14	0	0	0.08
16:00	0	0	0	0	0	0	0	0	0	0	0	0
Average	1.268	1.571	1.08	1.598	.888	1.71	.597	1.49	.38	1.471	.124	1.75

Table 7.5 Average sunlit area during the day using different window angles in summer and winter.

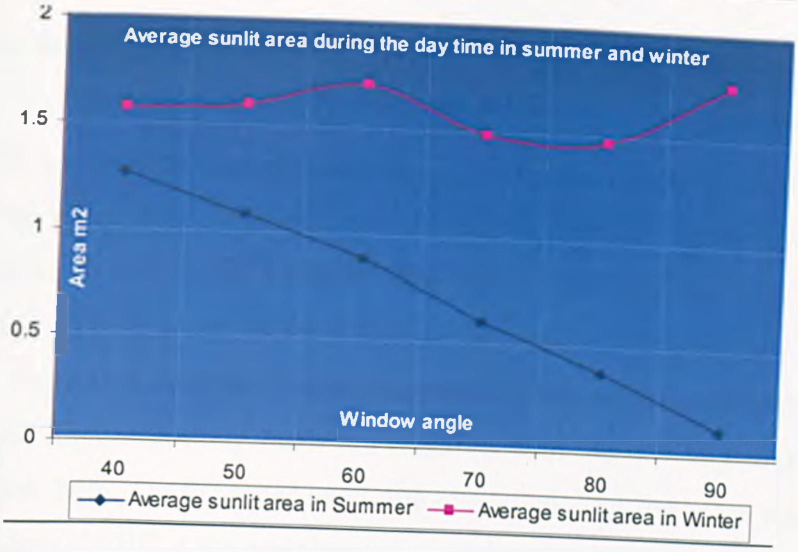


Figure 7.14 Average sunlit area for each window angle per hour during the daytime in summer and winter.

The unstable behaviour of the sunlit area distribution in winter could be due to the following factors which could be responsible for the variations in the average sunlit area during the daytime:

1. Sunlight distribution in winter in much higher than in summer.
2. Changing the windows' sloped angle could result in variations in the amount of penetrated sunlight.
3. The late penetration of sunlight in winter could result in this variation. In Table 7.5, it can be seen that the distribution of sunlight always starts at 10 am and ends at 2 pm. This means there are fewer hours of sunlight distribution in winter than in summer.
4. Due to the low sun angle in winter, the distribution of sunlight could also be distributed on other internal surfaces, like walls. This could result in variations in the amount of sunlight penetrating to the floor. The current investigation considers sunlit distribution on the floor only.

7.4.3. Thermal analysis of the required cooling loads when using different window angles

Thermal analyses were carried out using the Apache model to evaluate the thermal behaviour of the room with tilted windows. Experiments were performed in July, one of the hottest months in summer in Saudi Arabia. The results from the Apache model show that the required cooling loads increase as the tilt angle of the windows also increases. Therefore, the sunlit area distribution and the required cooling loads are strongly related to each other. The highest cooling loads are required with the 40° angled window; this is 685W at the peak hour. On the other hand, the lowest cooling loads are required with the 90° angled window (193W at the peak hour).

Stephenson (2003) noted that solar heat gain could be extensively reduced when tilting the window on the south wall to the opposite direction: 100° degrees, for example. The experiment, which was conducted to assess the required cooling loads with a 115° tilted window, is shown in Figure 7.15. The results show that the required cooling load with this window, under the same conditions of the investigated windows, is 185 W. This emphasizes that solar heat gain is reduced when tilting windows downwards. Stephenson (2003) added that 45 percent of the solar radiation could be reflected if the incident angle is 78°, compared with 23 percent when the window is vertical (90°).

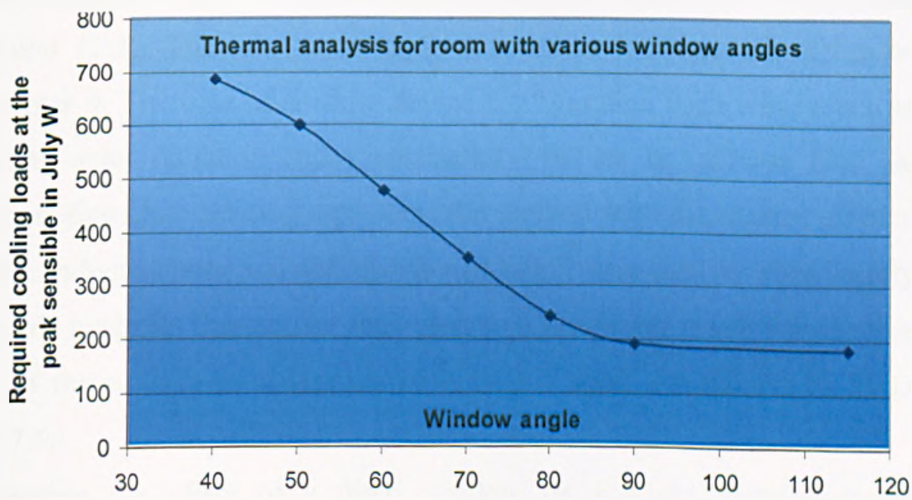


Figure 7.15 Required cooling loads with various window angles, including a 115° angled window.

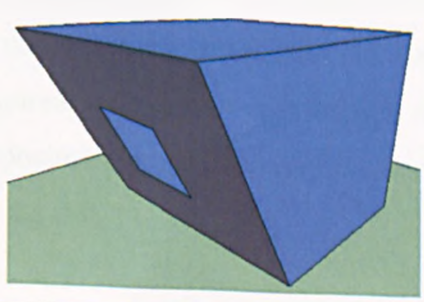


Figure 7.16 115° tilted window.

7.8. Conclusion

After examining and gaining confidence in the tool selected for the study (the SunCast model), experiments were conducted to evaluate factors that affect the distribution of the sunlit area onto the internal surfaces of a designed room.

Each factor from those selected had a significant effect on the sunlight's distribution onto the internal surfaces. Some factors had a stronger impact than others on this distribution, however. Variables like the season (summer or winter) have a strong impact on sunlight penetration so sunlit area distribution is much higher in winter than in summer. Latitude also has a strong impact. Penetrated sunlight at latitude 60°N is much higher than solar penetration at latitude 20°N. On the other hand, variations in the depths of shading devices do not affect the amount of penetrated sunlight, especially in summer. This could be, in this case, due to the dimensions of the windows and shading devices.

Other shading device configurations could also affect solar penetration. Graphical results show that orientation can strongly affect sunlight distribution. South orientations receive high amounts of solar radiation in winter, while in summer less solar radiation is received by this orientation. The distribution of sunlight is generally low in summer due to the sun's angle. North windows, however, will allow a slight amount of solar radiation to penetrate in summer at latitude 20°N.

The investigation also reveals that, at this location (latitude 20°N), the solar noon angle is around 12:25. The solar noon angle at a similar location is investigated in more detail in Chapter 9. The type of shading device configuration used will reduce or increase the penetrating solar radiation and, consequently, reduce or increase heat gain in the internal spaces. Egg-crate shading represents the method with the highest efficiency in the experiments conducted here and the distributed sunlit area can be significantly reduced when using this method. This can be seen clearly in the fourth graph which represents the distribution of the sunlit area at latitude 20°N with a south orientation on 21 December. (See Figure 7.5.)

Examining the effect of a tilted window on sunlight distribution shows that decreasing the vertical tilted window angle will result in increasing the amount of sunlight which penetrates to the internal surfaces. This proves that tilted angled windows are not recommended in hot climate zones due to the increased penetration of solar radiation meaning that extra cooling loads will be required to maintain comfortable temperatures. On the other hand, windows that tilt in the opposite direction are recommended in order to reduce the exposure of the internal surfaces to the sun.

Acknowledging the effect of each factor on sunlit area distribution is useful in evaluating the performance of shading devices. For instance, when a building is located at lower latitudes, the effect of shading devices on sunlit area distribution will be minimal. However, in higher latitudes, where the sun is lower, the effect of shading devices will be maximal. Examining the effect of these factors will also be useful in predicting required cooling loads. Decreasing the penetrated sunlit area could result in smaller cooling loads. The initial thermal analysis conducted in Section 7.4.3 shows that cooling loads will be increased when lower window angles are used. Moreover, the experiments illustrate that, conversely, tilted windows will help in reducing cooling loads, as shown in Figures 7.14 and 7.15. More detailed thermal evaluations, recorded in the following chapter, were conducted using different shading techniques in different climatic regions.

CHAPTER 8

THE THERMAL EFFECT OF DIFFERENT SHADING TECHNIQUES IN VARIOUS CLIMATIC ZONES

8.1. Introduction

Two climatic zones were selected for the evaluation of the thermal performance of shading devices: a hot dry zone (Riyadh, Saudi Arabia; latitude 24.65° N) and a cold climate zone (London, United Kingdom; latitude 51.50° N). Using two climatic zones makes the evaluation more efficient than if it were conducted in one climatic zone only.

In order to evaluate the shading devices, a simulation of the thermal performance of a window without shading needed to be achieved first so, subsequently, a comparison of the varying contributions made by the shading techniques could be made. Six shading techniques were selected for the thermal analysis: horizontal, vertical, egg-crate, horizontal louvers, vertical louvers and light shelves. The shading devices and window dimensions are illustrated in Section 8.3.

The evaluation involves two main aspects. The first involves the simulation of the heat gain and loss that is required to achieve comfortable temperatures in the room using different shading methods. A negative result indicates that a heating load is required while a positive result indicates a cooling load is necessary.

The second aspect is the calculation of the sunlit area distribution that penetrates through the window and onto the room's internal floor when different shading methods are used. Both of the evaluations were performed in summer (21 June) and in winter (21 December). The simulation investigates the relationship between the internal distribution of the sunlit area and the thermal performance of the shading devices in affecting the required cooling or heating loads. Room comfort temperature is also another aspect which is investigated in the study and the efficiency of the selected shading methods is discussed with regard to both hot and cold climates. Shading design, which provides total solar protection of windows, is illustrated by using the ECOTECT model for Riyadh, Saudi Arabia. Optimised shading devices and surrounding shade are the two shading configurations used in this model.

The last part of the chapter evaluates sunlit penetration ratios in Riyadh and Jeddah by controlling sunlit penetration using horizontal shading. The investigation assesses the ratio of the sunlit area in summer compared to winter by allowing 100% and 50% solar penetration in winter. Various sunlit distribution ratios are also investigated in this study. Shading device dimensions are evaluated for each sunlit penetration ratio and the following diagram describes the simulation procedure for evaluating the designed room's thermal behaviour by using the selected shading methods. Both climatic zones (hot and cold) are included.

The start of the chapter illustrates the general thermal performance of a room using different models. The designed room is 6m x 6m square and has a height of 3m. The thermal evaluation includes a room with and without a window to investigate the thermal effect of the window first. This is followed by a thermal evaluation of the shading methods which will include the six shading techniques mentioned previously.

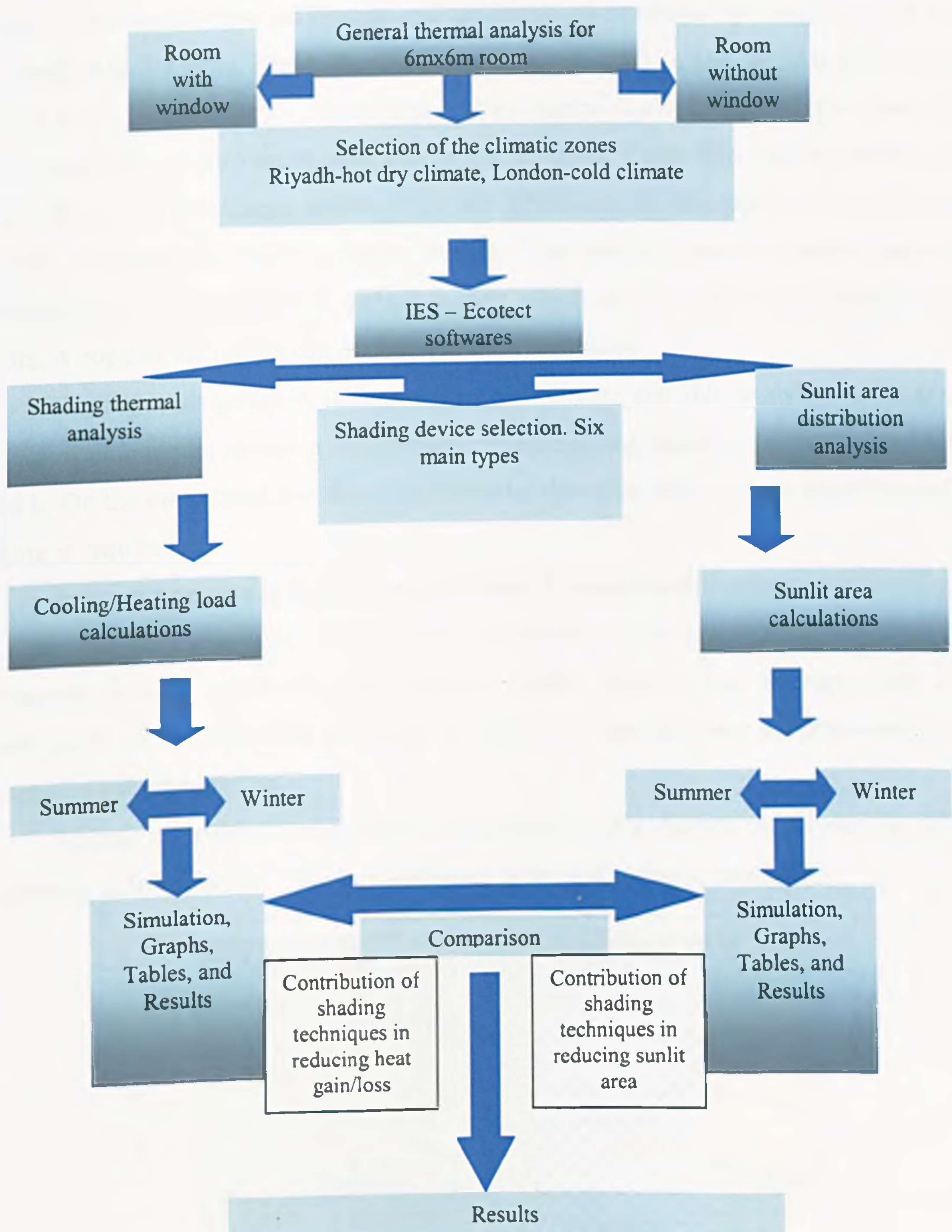


Figure 8.1 Simulation procedure diagram.

8.2. Initial Thermal Analysis

8.2.1. Heat gain/loss simulation comparison using different tools for a 6x6x3m room in the hot dry climate of Riyadh (location 24.65° N)

Initial experiments to examine the thermal behaviour of a room were conducted by using three tools: the ECOTECT, IES Apache, and HEVACOMP models. The graph in Figure 8.2 shows the required heating and cooling loads arrived at by using the three tools in Riyadh, Saudi Arabia. Due to the high temperatures in this region, as shown previously, cooling loads in summer are much higher than heating loads in winter. The evaluation shows similarity in the results achieved by the ECOTECT and IES Apache models. The results from the Hevacomp model illustrate differences in the peak cooling loads in summer compared to the two other models. The results from this model show no consideration for solar radiation loads, however, which could explain the difference in the results. A copy of the results can be found in the appendices.

Cooling loads generally increased between 12 noon and 16h, as shown in the graph. The Hevacomp model shows in summer where high cooling loads are required between 9 h to 16 h. On the other hand, the IES Apache model shows in winter only a slight amount of heating is required.

Average heat loss and gain were calculated for each model and are shown in Figure 8.3. The highest heat gain averages were achieved when using the ECOTECT and Hevacomp models while the IES Apache results showed less average heat gain. Descriptions of the materials are given in Table 8.1 and all three models were set to possess the same properties.

Adding a window to the room changes the room's thermal behaviour due to the penetrating solar radiation. This is investigated in the following section: 8.2.2.

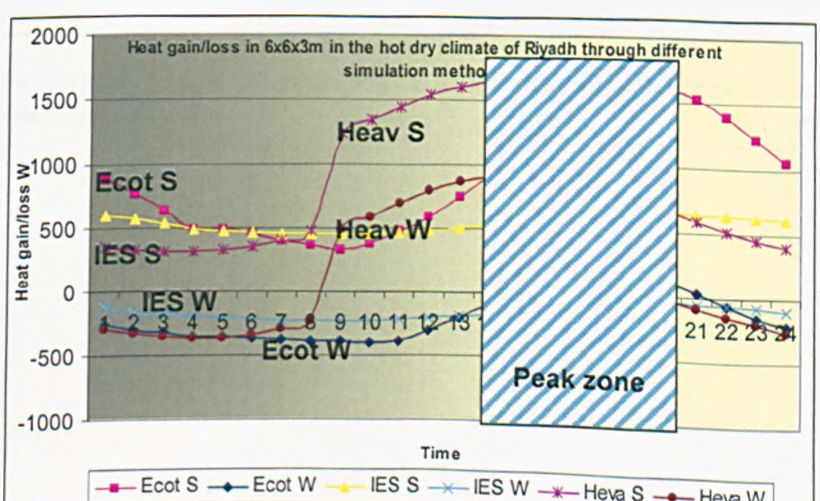


Figure 8.2 Graph of heat gain/loss simulation using different models for a space without a window.

Simulation methods	Average heat gain/loss
Ecot S	901.3 W
Ecot W	-170.9 W
IES S	551 W
IES W	-152 W
Heva S	893 W
Heva W	186.7 W

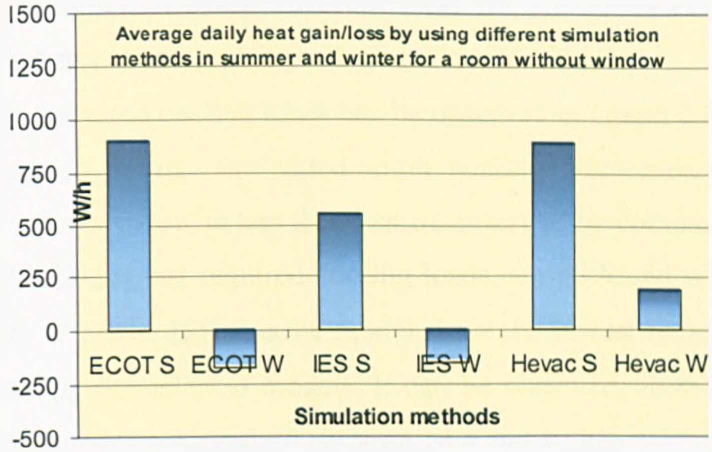


Figure 8.3 Calculation of the average heat gain/loss for a space without a window.

Description of materials in the models (wall)

	Ecotect / IES / HEVACOMP
Thickness	.274m
U-Value	.34 W/m²K
Admittance	4.408 W/m²K
Solar absorption	.7
Transparency	0
Thermal decrement	.30
Time lag	9 h

Table 8.1 Comparison study of different model outputs for materials. Material properties are the same in the three selected models

8.2.2 Heat gain/loss simulation comparison using different tools for a 6x6x3m room, with a 1.6x1.6m window in the hot dry climate of Riyadh (location 24.65° N)

A significant increase in the required cooling loads can be observed in Graph 8.4 as a result of the extra solar penetration through the added south window. However, the variation in the results achieved with a window is less than can be observed by comparing the graphs in Figures 8.2 and 8.4. The highest required cooling loads can be found when using the ECOTECT model (3000 W). The IES Apache model show the lowest required cooling loads in summer from among the selected models. It can be observed, from the related graph, that the highest cooling loads are required between 14 h and 17 h.

The peak zone in the required cooling loads when using a window was similar in the three selected methods. The peak zone can be seen to range from 14 h to 20 h in Figure 8.2. while in Figure 8.4 it ranges from 14h to 17h. IES results shows that, during winter, heating loads will decrease when using a window; this is an effect of natural solar heating.

The study of the average heat gain and loss, illustrated in Figure 8.5, shows that the maximum average cooling load is achieved by the analysis conducted by the ECOTECT model (around 1226 W/h) while the lowest cooling load required in summer is achieved by the analysis conducted by the IES Apache model; this is 764 W/h. Due to the low temperatures in Riyadh during winter, heating will be required, as shown in the graph. Heating loads are mostly required during the early morning hours from 1 h to 8 h and late at night, after 20 h until midnight. (Tabled results are illustrated in Appendix B.)

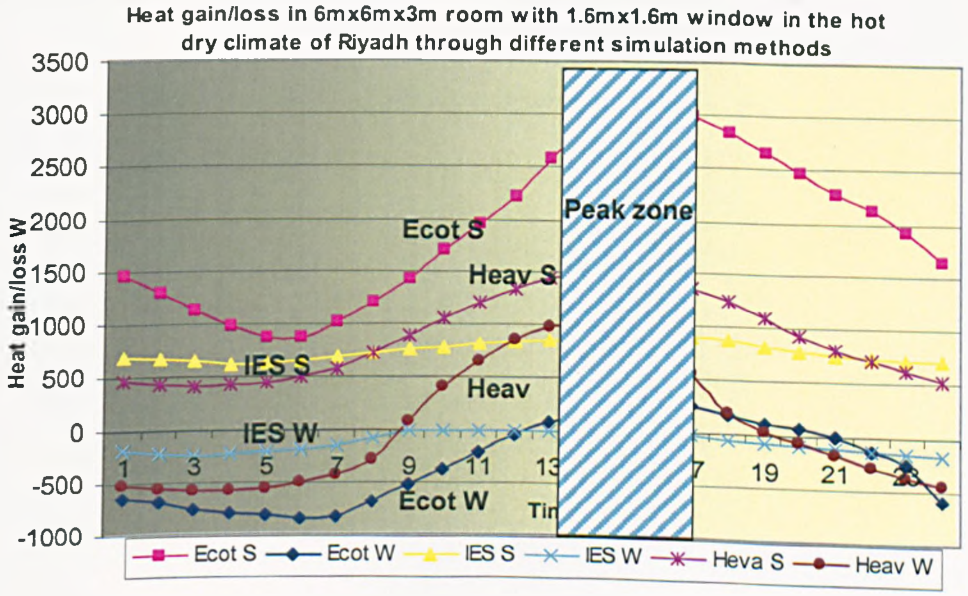


Figure 8.4 Graph showing the heat gain/loss simulation using different models for a space with a window.

Simulation methods	Average heat gain/loss
Ecot S	1226 W
Ecot W	-285 W
IES S	764 W
IES W	-101 W
Heva S	900 W
Heva W	48 W

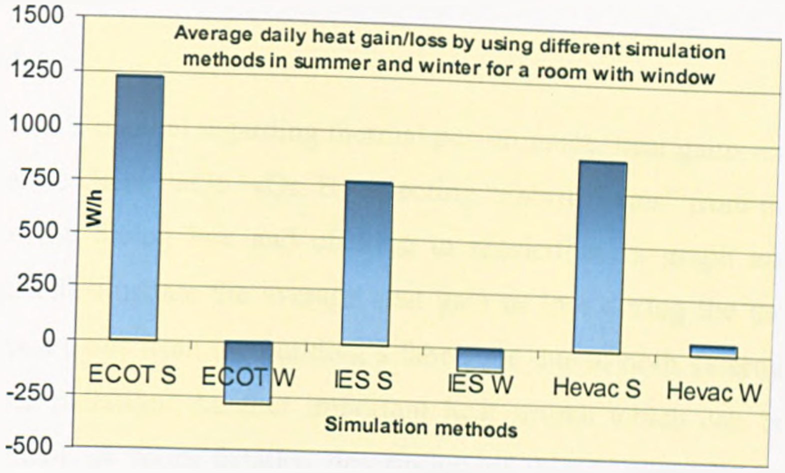


Figure 8.5 Calculation of the average heat gain/loss for a space with a window.

	Ecotect	IES	HEVAC OMP
Thickness	.006m	.006m	.006m
U-Value	5.4 W/m²K	5.8	5.6
Solar absorption	-	.185	-
Transparency	.95	-	.81

Table 8.2 Window glazing description.

8.2.3. Output descriptions of models

8.2.3.1. The ECOTECT Model

As explained in the model's manual regarding thermal performance, heat gains and losses can be calculated by: Fabric Gains –sQc +sQs. By selecting "Fabric Gains" from the thermal calculation section of the dialog box and clicking to recalculate, a graph and results can be obtained which will illustrate the average heat gain or loss during the day each month. This shows that heat gains from the building's fabric are due to both external temperatures and incident solar radiation. Another important heat source which can be calculated is the inter-zonal gains. A more detailed description of this is given in the appendices.

8.2.3.2. IES

One section of the IES software is the Apache thermal model which has the ability to calculate the CIBSE heat loss and heat gain. The results, which appear in table format, give the hourly room conditions and the heat gains for each hour of the design day in the current month. The table displayed on the screen does not contain information on the solar, ventilation and conduction/storage breakdown; (this information can be reviewed by choosing "full details"). Data are given in "average over previous hour format" and therefore, if the results indicate that at 15:00 the temperature is 26.0°C, it means that the average temperature over the period 14:00-15:00 is 26.0°C. All heat is given in Watts of heat gain (cooling is therefore shown as negative). The last two columns show the heat gains (sensible cooling), which shows the heat gain from the cooling system required to meet the set point conditions set in the room's data. It must be noted that a negative gain is cooling and that latent heat gain shows gain from the cooling system required to meet the set point conditions set in the room's data. A more detailed description is given in the appendices.

8.2.3.3. Heavacomp

One or more rooms must be selected to obtain results from this program. If multiple rooms are selected, results for each room can be produced and the total heat gain for the group of rooms will be the hour-by-hour coincident gain. Room temperatures may be specified as "Air temperature" or "Resultant temperature" (Resultant = 1/2 Air temperature and 1/2 Mean Radiant temperature). The selected criteria were used as the basis for heat gain calculations. Different sets of results will be obtained if Air or Resultant temperatures are used as the criteria. The use of Resultant temperature as the basis will generally give higher heat gains as, in summer, mean radiant temperatures will be above room air temperatures. A more detailed description is given in the appendices.

Heat gains: The calculation of heat gain is performed hourly and all gains are considered to have two components: steady and fluctuating, as described in the guide. Steady or average components are computed for fabric (Qf), convective (Qb), solar (Qs), latent (Qlat), lights (Ql) and casual (Qc) heat gains.

Ecotect

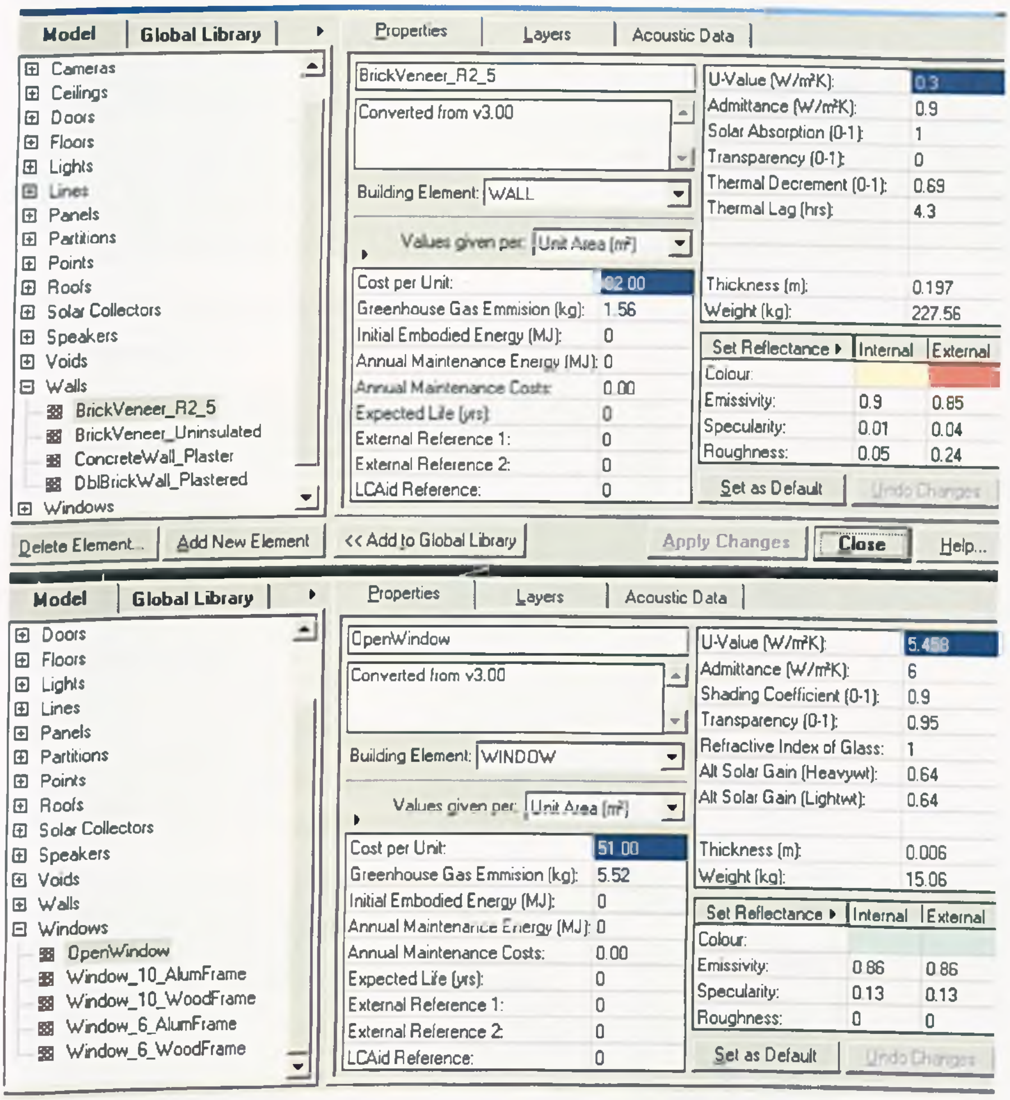


Figure 8.6 Ecotect materials selection.

IES

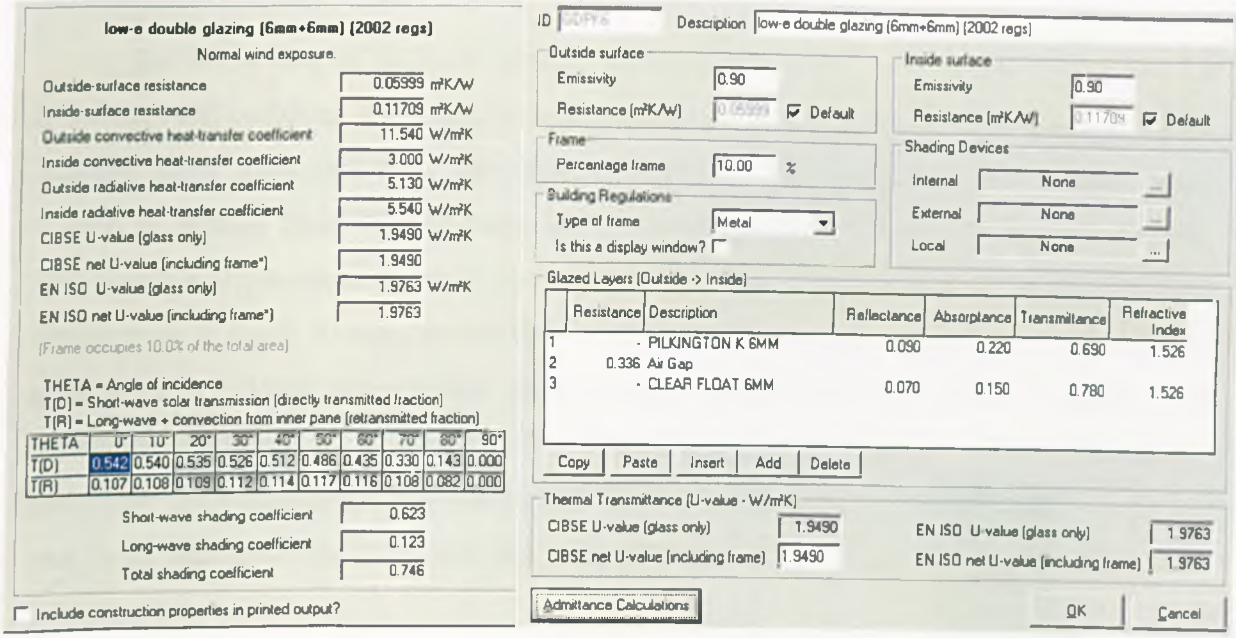


Figure 8.7 IES materials selection.

Hevacomp

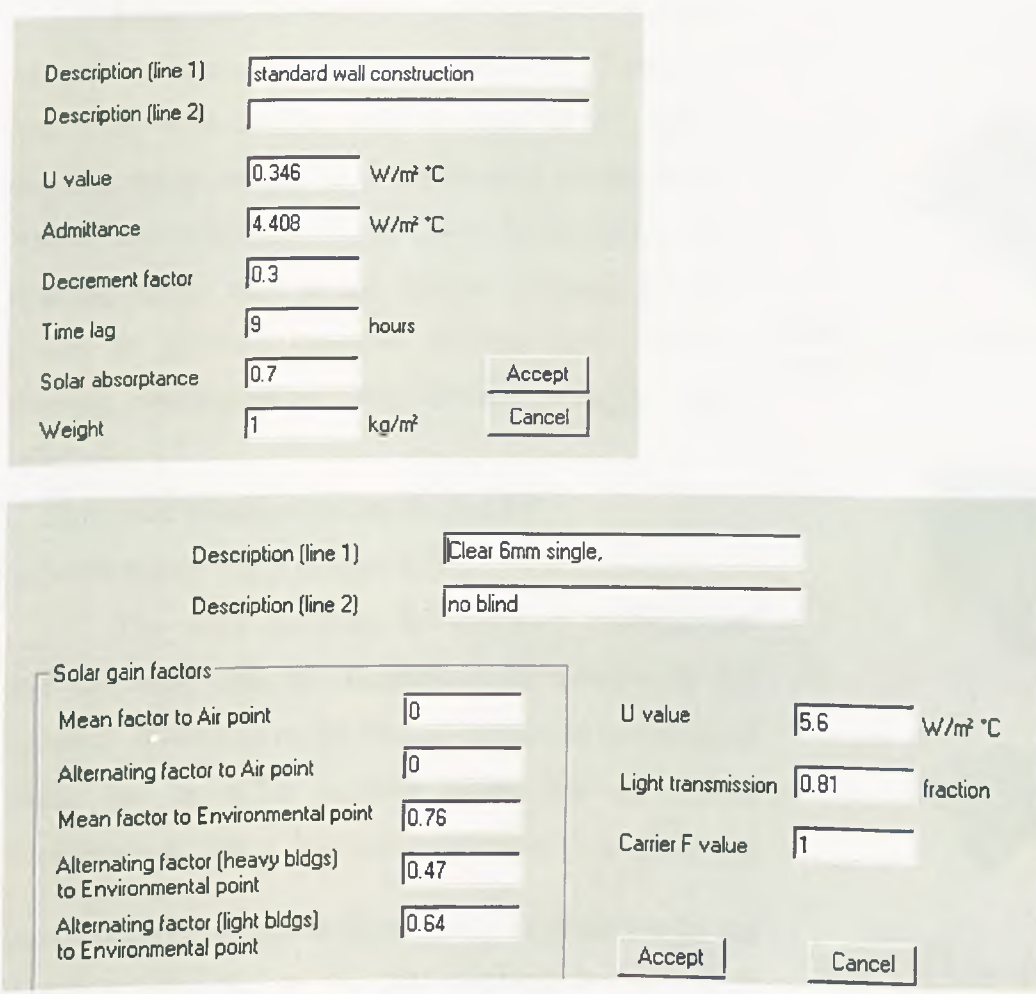


Figure 8.8 Hevacomp materials selection.

8.3. Dimensions of Shading Devices

By using the ECOTECT model, efficient shading device dimensions can be illustrated and optimum shading can be achieved to produce total protection for the whole window from solar radiation. The location selected for this study was Riyadh, Saudi Arabia, at latitude 24.65°N. The room dimensions were 5x5x3m with a 1.6x1.6m window. This window dimensions are selected based on a study on the average window size for a living room in Saudi Arabia, the window was south oriented. The properties of the window glass were as follows: low-e double glazing (6mm+6mm) with .336 air gap; emissivity .90; resistance .059 m^2K/W; U-value 1.94. The simulation period for the experiments was selected to be on 21 June and on 21 December (peak summer and peak winter).

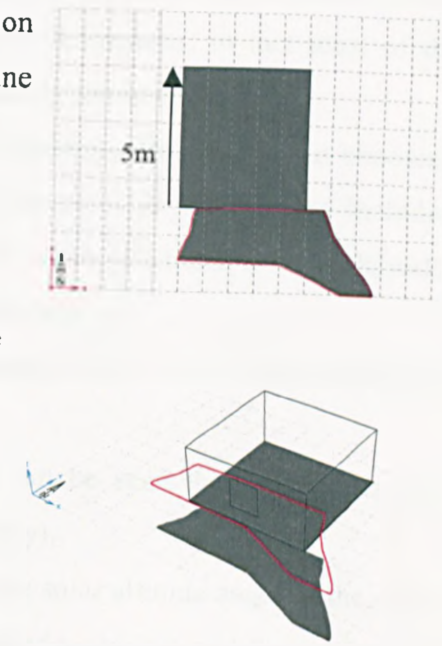


Figure 8.9. View on 21 June at 12:00 (Ecotect V5).

8.3.1. Selection of shading device dimensions

Using the Ecotect program, the shading device dimensions and configurations, as shown in Figures 8.9 and 8.10, were used in order to achieve the optimal shading design and to keep the window shaded for the whole year in Riyadh (24.65° N) in Saudi Arabia. The shading design tool in the Ecotect software has the ability to generate optimum shading from different shading configurations. Two shading strategies were selected:

1. Optimised shading devices (Figure 8.9)
2. Surrounding shade (Figure 8.10).

The study presents the optimum configuration and the most efficient dimensions for devices in this location. As shown in the related figures, an overhang of about 2m in width in both cases, has the ability completely to block the sun's radiation throughout the year. However, some sunlight needs to penetrate in the winter months due to the low temperatures in Riyadh

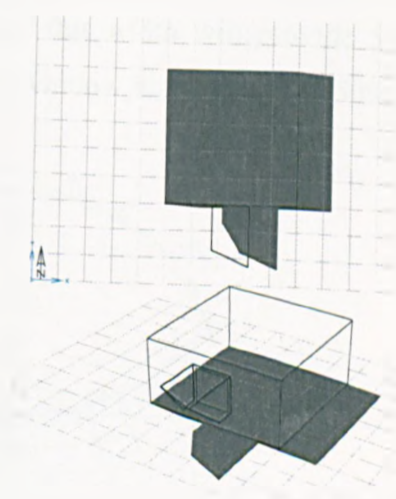


Figure 8.10. View on 21 June at 14:00 (Ecotect V5).

during the winter, as illustrated previously in Chapter 2. Consequently, shorter shading device dimensions should be selected so a depth of .9 m was selected for investigation. This selection was based on experiments conducted using the SunCast model.

Using the IES SunCast software, the selected dimension was examined and found to allow sufficient daylight to penetrate for the climatic conditions of Riyadh. Exceeding this range could result in a complete blocking of the sun's radiation which is not recommended, especially in winter. Nevertheless, if shading depths are less than this range, this could lead to overheating and to extensive solar radiation penetration. Other factors can support this choice of dimension, such as the traditional architecture of Saudi Arabia which contains shading devices with the same range of dimensions; in fact most of the buildings contain shading devices designed within almost the same range.

Simple experiments were performed to help in making a decision about choosing the shading device dimensions for the climatic conditions of Riyadh. These included considering vertical and horizontal shadow angles, a solar chart of latitude 24.6 for Riyadh, and window heights. The following procedures were undertaken:

1- Deciding what time the sun's radiation will start to reach the window and considering the desired level of temperature (for example, 26°C).

2- From the daily temperature analysis of Riyadh, it can be seen that, from 8am, the temperature is already above 30°C in peak summer (21 July).

3- From the solar chart it can also be seen that, at 8 am, the solar altitude angle of the sun is 37°. This angle could be drawn alongside the desired window height and then a decision can be made regarding the overhang width that shades the window for the whole day bay using HSA and VSA. If 100% shading is desired, half of this width will provide 50% shading when the sun's radiation is at a maximum on the window and more than 50% at other times.

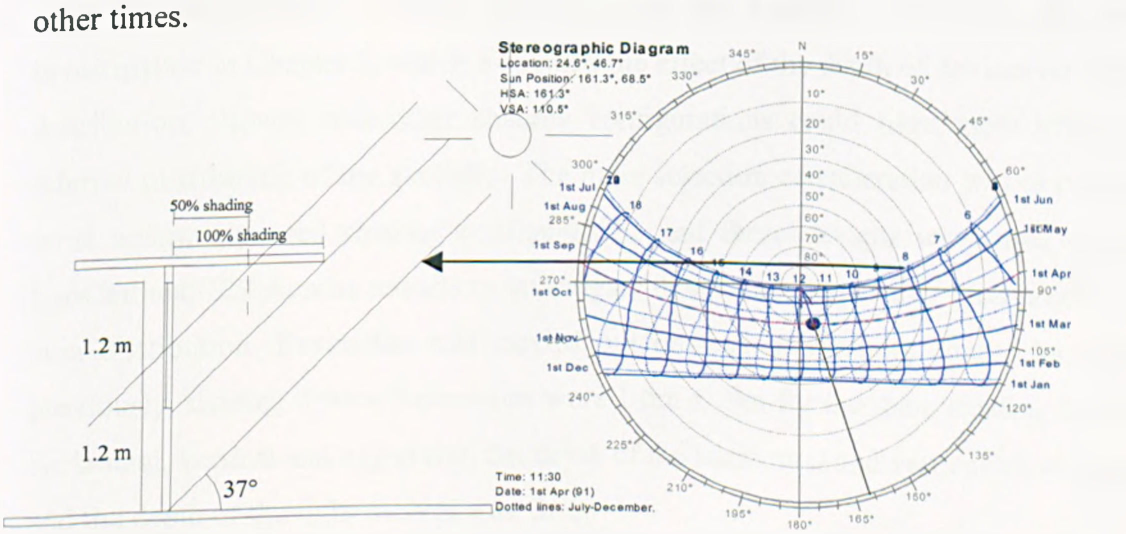


Figure 8.11 Calculation of the overhang length from the sun path diagram (Ecotect ArchiCAD).

In order to obtain complete shading from 8 am to 5 pm, horizontal overhang devices have to be 4 m in width, according to the vertical shadow angle in this location. Such shading width is not practical. To allow some penetration (50%) of the sun's rays, 2m or less is needed for the test, considering the heating in winter. Consequently, shading devices with a .9m of width of overhang were selected for the experiments.

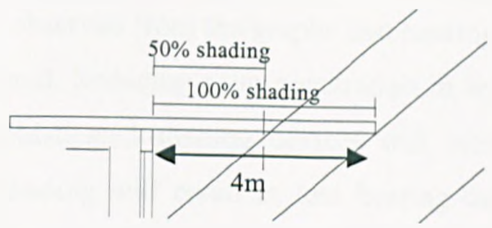


Figure 8.12 Overhang dimension for Riyadh, Saudi Arabia.

8.4. Shading Device Configurations

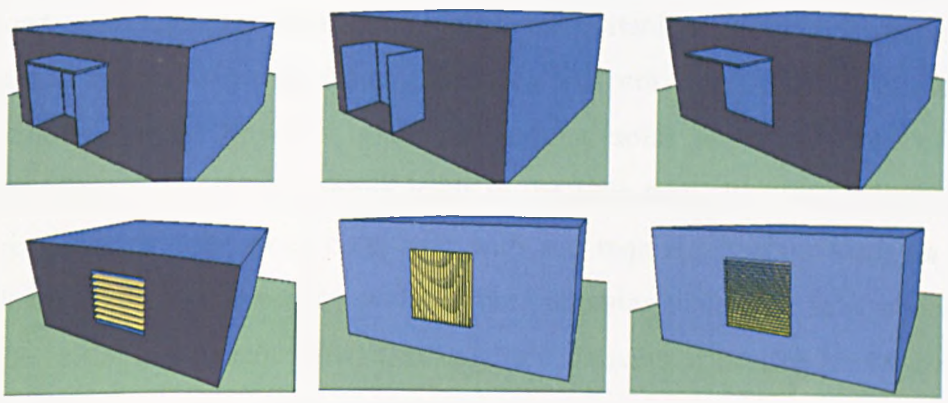


Figure 8.13 Shading device configurations (IES).

Figure 8.13 shows the six designed shading device configurations mentioned previously. Horizontal, vertical and egg-crate were the three basic types that were selected with horizontal and vertical louvers, and light shelves as the other shading types added in order to investigate as many shading types as possible. Moreover, the previous investigation in Chapter 7, which evaluated the effect of the depth of devices on sunlit area distribution, showed that other shading configurations could have more effect on the internal distribution of the sunlight. The main selection consideration was to examine the most commonly used shading configurations and these designs were used in the IES SunCast and IES Apache models to investigate their effect on thermal behaviour and sunlit area distribution. Evaluation was carried out on various climatic zones. As mentioned previously, shading device dimensions were 1.6m x .9m for the main shading devices (the horizontal, vertical and egg-crate), the depth of the horizontal and vertical louvers was .1m, and the depth of the light shelves was. 3m.

8.5. Thermal Analysis of Shading

8.5.1. General analysis

Figures 8.14 and 8.15 demonstrate the required cooling and heating loads in summer and winter for two different climatic zones. June and December represent the two months selected for the evaluation. It can be observed from the graphs that heating loads in Riyadh increase in winter when shading is used. Reducing solar penetration in winter will increase the heating demand and more sophisticated shading devices will increase the heating that is required. However, simple shading will result in less heating demand in Riyadh. This can be observed when comparing the required heating loads shown in the graphs for horizontal shading and for light shelves (Graphs A and F).

Due to the extensive heat in Riyadh, Saudi Arabia, which reaches above 45°C, high cooling loads are required in summer to achieve comfortable temperatures. As can be seen in the related graphs, selected shading methods will not have a strong impact on the required cooling loads. However, glare and internal solar penetration will be reduced which will affect the required cooling loads in the long term. Required heating loads in winter are generally low when compared with the required heating loads in London. Heating loads could be completely avoided when allowing maximum solar penetration in winter. The initial experiment shows that very low amounts of heating are required in the case of the window without shading in Riyadh.

The experiments involving a cold climate, conducted by using London, show higher variations in the required cooling and heating loads. Moreover, the effect of shading devices is more significant in this region. The London graphs reveal that cooling loads in summer are highly affected by the use of horizontal and egg-crate shading, and by the use of horizontal louvers and light shelves. Required cooling loads will be reduced when using these shading methods. However, the effect of vertical shading on summer cooling loads is negligible. The high efficiency of horizontal shading in summer in a cold climate is mostly attributable to protecting internal spaces from solar radiation.

Reducing solar exposure in internal building spaces will reduce room temperatures; consequently, cooling loads will be reduced. The solar altitude angle in London is around 60° in summer and so efficient horizontal shading will exclude solar radiation. Vertical shading configurations will allow solar penetration in summer; this increases cooling load demands. In winter, large amounts of heating are required so shading devices will not have a significant effect on these loads, as shown in the related graphs. The average cooling and heating loads are calculated and illustrated in Section 8.5.3.

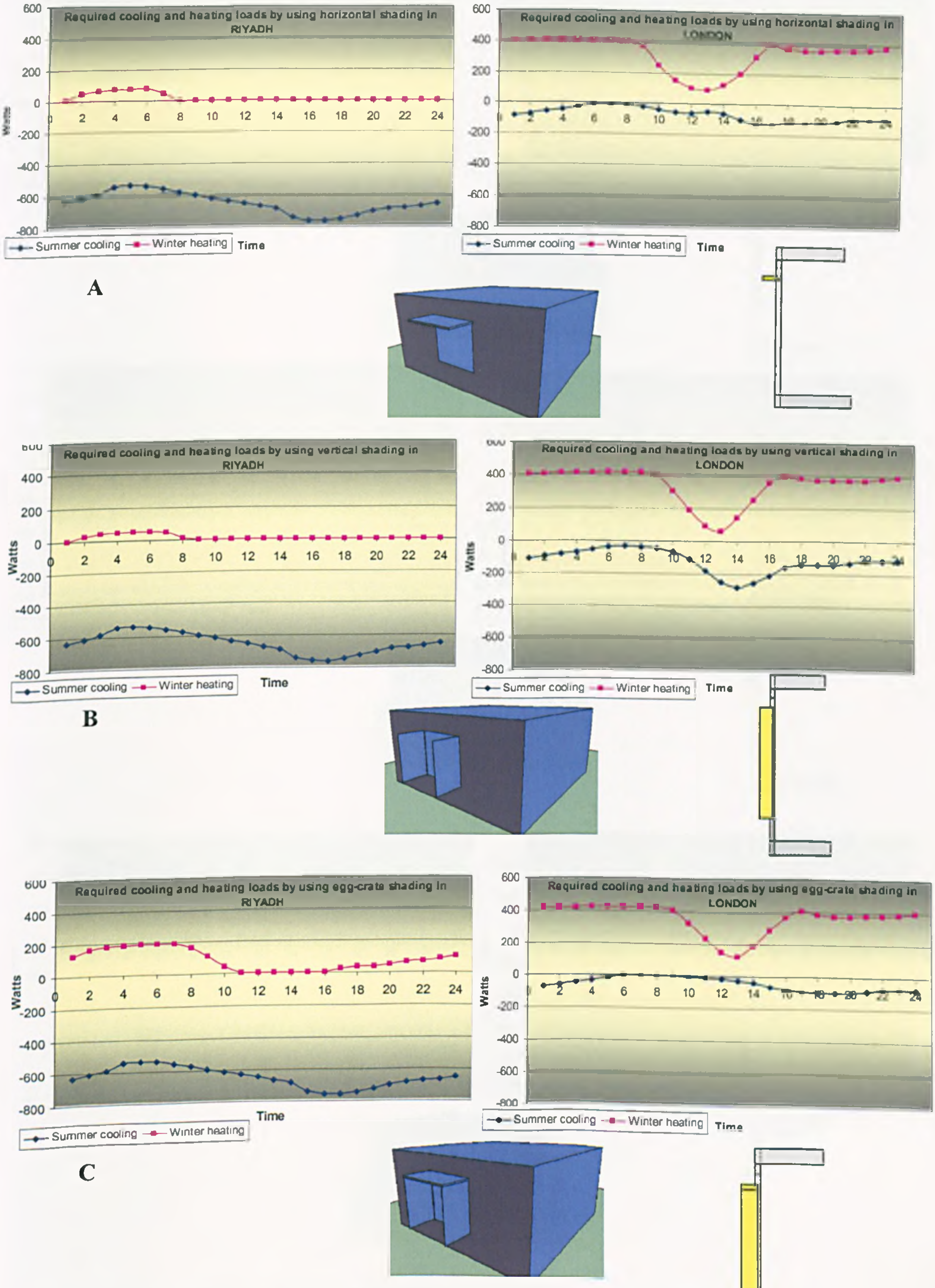
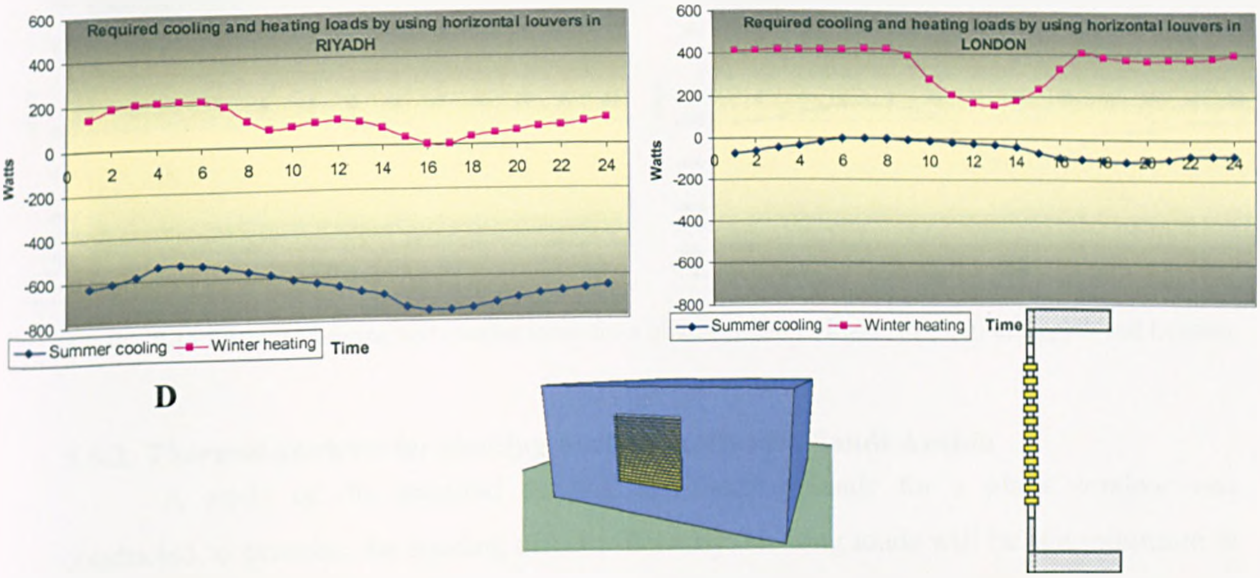


Figure 8.14 The effect of thading of horizontal, vertical and egg-crate shading on the required cooling and heating loads in Riyadh and London.



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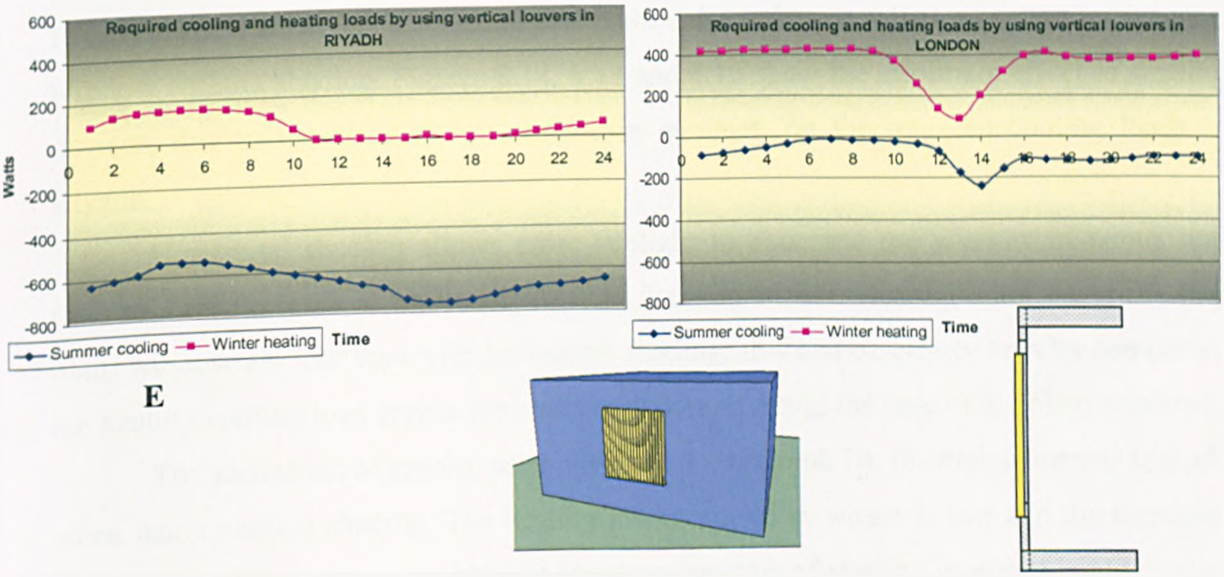

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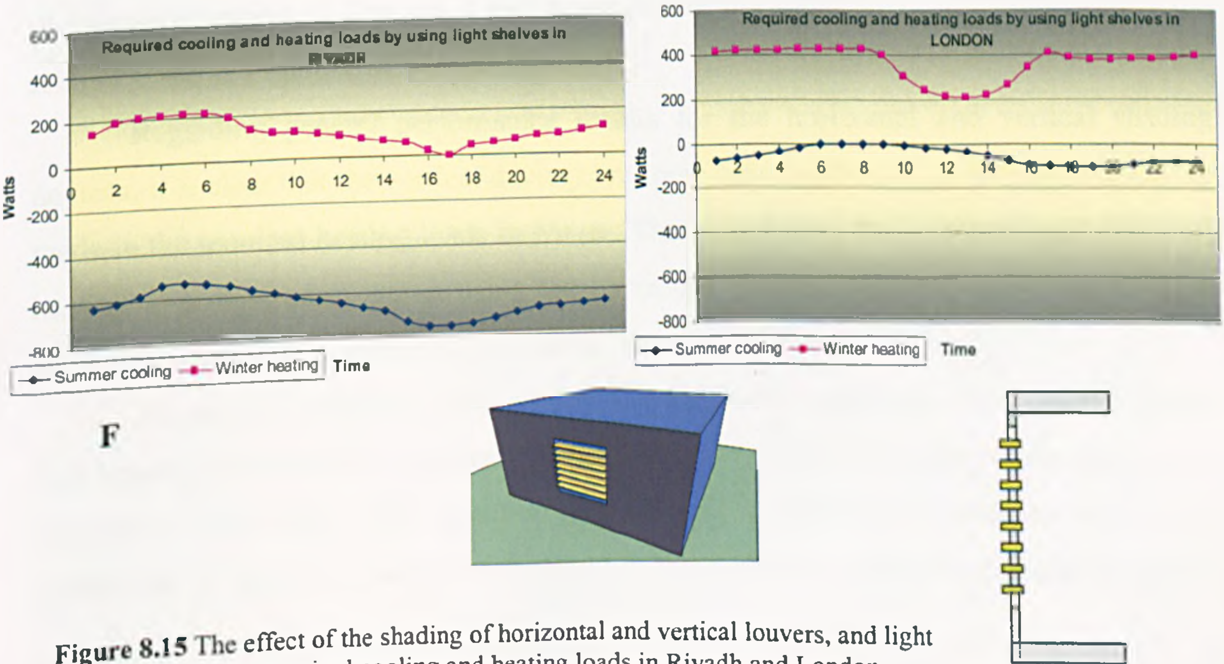


F

Figure 8.15 The effect of the shading of horizontal and vertical louvers, and light shelves on the required cooling and heating loads in Riyadh and London.

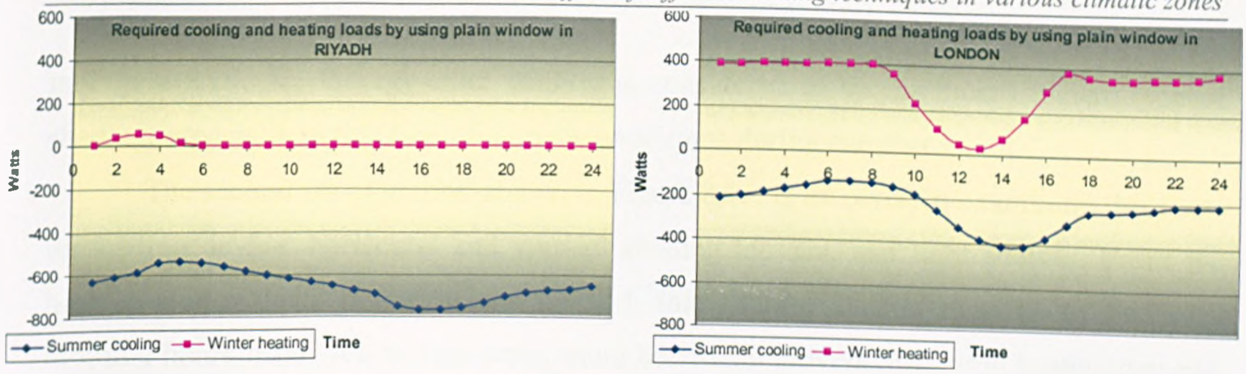


Figure 8.16 Required heating and cooling loads for a plain window (without shading) in Riyadh and London.

8.5.2. Thermal analysis for shading devices in Riyadh, Saudi Arabia

A study of the required cooling and heating loads for a plain window was conducted to examine the shading effect efficiently. Heating loads will be at a minimum in Riyadh during winter as a result of the extra solar radiation which penetrates through a window without shading. Figures 8.14, 8.15 and 8.16 show the minimum effect of shading devices, due to the severely hot climate in summer, on the required cooling loads in Riyadh.

Horizontal shading allows more sunlight to penetrate the window in winter and this, as a result, leads to increasing heating loads in winter. Heating loads using the first plain window are less than with horizontal shading; this can be clearly seen by comparing the heating/cooling load graphs for both cases (Graph A and the case of the plain window).

The second set of graphs, seen in Figure 8.14 (Graph B), illustrates thermal analysis when using vertical shading. The heating load required in winter is low and the increased penetration of the sunlit area obtained by using this type of shading in winter could explain the decrease in heating demand. Less penetration of the sunlit area can be observed in the related graph in Figure 8.14. (Graph B).

Regarding general performance results for the horizontal and vertical shading devices, it is clear that the vertical devices are more efficient due to the savings that can be made in the required heating loads in winter. The results show that, on average, 15.9 W of heating was required in winter using the horizontal shading, while 11.8 W was required when using the vertical shading. This can be observed in Figure 8.14.

An analysis of heating and cooling demand when using egg-crate shading shows that heating is required in winter for the whole day, yet the cooling load required in summer is very high. This shading method will contribute to reducing sunlit area penetration in winter, as can be seen clearly in the sunlit area penetration graph (Graph D) in Figure 8.19. So, the egg-crate shading is considered to be the most efficient type of shading, especially in this type of climatic conditions during summer.

The second set of graphs, shown in Figure 8.15, is involved in examining three sets of shading device: horizontal and vertical shading louvers, and light shelves. From the heating/cooling load graphs, it can be seen that heating load is required in the early morning hours from 2am to 7am when using horizontal louvers. Increased heating demand in Riyadh is due to the low penetration of the sunlit area, together with the shading caused by this type of louver during winter. This can be clearly seen in both thermal analysis and sunlit area graphs illustrated in Graph E in Figure 8.15 and Graph E in Figure 8.20.

Using vertical shading louvers in this region will respond to the high demand of cooling load required in summer as this shading method will allow the penetration of solar radiation caused by the high angle of the summer sun. Nevertheless, there is reasonable penetration of sunlight in winter, as shown in the sunlit area graph for this case (Graph F in Figure 8.20), as the sunlit area can reach around $2m^2$ on the floor space at noon.

The general results for the study can be summarised as follows:

1. There is a high demand for cooling in summer in the hot dry climate of Riyadh.
2. Shading devices can be inefficient when increasing shade for the internal spaces; this could result in extra heating loads being required in winter.
3. In this study, two types of shading system did not result in high heating load requirements in winter. These were the horizontal and vertical shading devices.
4. A maximum amount of sunlit area could always be achieved using the vertical shading. This can be clearly seen in the sunlit area graphs of both the vertical shading devices and the louvers, as will be explained in Section 8.5.4.
5. A window without shading is the only one where a very low heating load is required in winter.

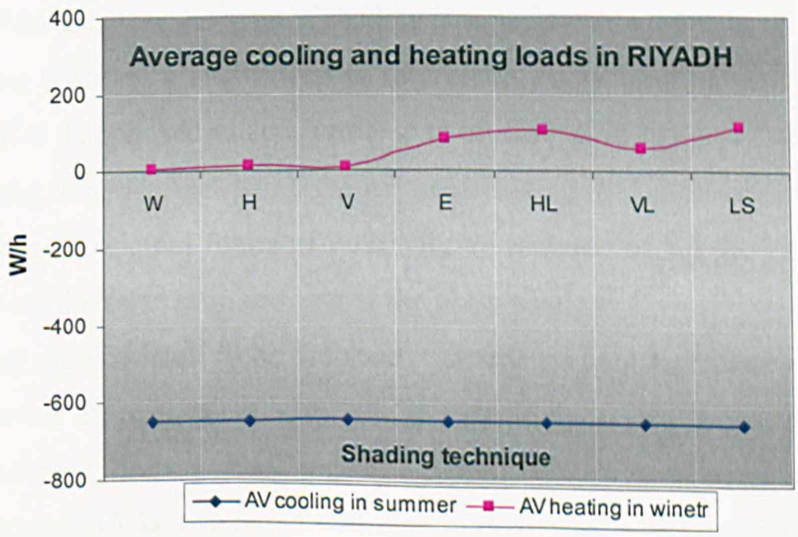


Figure 8.17 Average cooling/heating loads using different shading methods in Riyadh.

8.5.3. Thermal analysis of shading devices in London, United Kingdom

In order to achieve an efficient evaluation of the different shading techniques and to carry out an effective thermal analysis and simulation of the sunlit area, another climatic zone was selected. The region chosen is contrasting: London has a cold, wet climate and Riyadh has a hot, dry one.

An evaluation of a plain window was conducted to assess the contribution of the selected shading methods in affecting both cooling and heating loads and the internal distribution of sunlight. Due to the climatic conditions in this zone, an average 307 W/h heating load is required in winter and an average -239 W/h cooling load is required in summer.

There is a considerable amount of cooling and heating load in this climate generally, unlike in the hot dry zones where the demand is mostly for cooling. This is can be clearly seen by comparing the heating/cooling graphs in the related graphs in Figures 8.14 and 8.15, and in Figure 8.16 for both zones. The sunlit area graphs also show a high penetration of sunlight in cold regions, especially in winter. This can reach up to 4.8 m^2 at noon in the first case (the plain window).

In a cold climate, using horizontal shading will result in a remarkable drop in the required cooling load due to the effect of the horizontal shading on the high summer sun. This is shown by comparing the heating/cooling load graphs in Figure 8.14 (the horizontal case) and in Figure 8.16 (the plain window case). The decrease in the sunlit area in summer, as shown in the sunlit area graph (Graph H in Figure 8.19), could be one of the main reasons for the corresponding drop in the required cooling loads as the cooling load decreased from an average of -239 W/h in the case of the plain window to -69.1 W/h in the case of the window with horizontal shading. This shows a 70% drop in the required cooling loads. These results illustrate that this type of shading is significantly efficient.

Using vertical shading achieves a slight drop in the required cooling load which reaches an average of -123 W/h as opposed to an original load of -239 W/h; this is a drop of 50% in the required cooling. On the other hand, the required heating load increased to an average of 336.6 W/h from an original figure of 307 W/h, an increase of 8.7 %. The sunlit area distribution is almost the same as in the case of the plain window.

The egg-crate shading showed itself to be the most efficient shading technique as summer cooling loads achieved an average of -50 W/h, a reduction of 79% from the original (-239 W/h). The average heating load was 354.7 W/h, which constitutes an increase in the required heating of 15 %, compared with the original case, which was 307

W/h. This remarkable decrease in the required cooling load stems from the decrease in the sunlit area penetration in summer, as shown in the internal sunlit area penetration graphs. These graphs show that there is no penetration of the sunlight using this type of shading.

Figure 8.15 shows the heating and cooling when using horizontal and vertical louvers, and light shelves. In this region, these shading methods will affect efficiently the cooling loads required in summer when cooling loads generally drop, as can be observed in the related graphs. Horizontal louvers and light shelves represent the shading devices which result in the lowest demand for cooling. Vertical louvers will slightly increase cooling load demands at around 14h but the sunlit area distribution is generally high when these shading methods are used in winter.

The required heating loads vary from one shading method to another. Using horizontal louvers in the designed room resulted in an average heating load of 345 W/h, showing a 12 % increase in heating in winter. 336.6 W/h was required in the case of vertical louvers, which makes a 9 % increase in the heating load.

The average cooling load required by using light shelves was -54.7 W/h. This shows a drop of 77.5% when compared with 239 W/h, the figure arrived at if there was no shading. Such a high ratio of energy saving reflects the efficiency of this shading method during the summer period. In winter, the average required heating load during the selected day was 362 W/h. when the average heating load was originally 307 W/h, an increase of 17%. Shading devices should be avoided during winter in this region.

The general results for the study could be illustrated in the following:

1. A considerable amount of heating is required in this type of climate, unlike the hot dry climate which requires mostly cooling, as shown in the related graphs.
2. Sunlit area graphs show that the distribution of sunlight in cold zones is higher than in hot zones, as will be demonstrated in the following section.
3. The performance of the egg-crate shading device shows a high efficiency rate (up to 79% less) in reducing cooling demands in summer.
4. Shading devices could affect the required heating load in winter by increasing it as a result of the reduced penetration of the internal sunlit area.
5. Vertical shading generally will allow greater penetration of the internal sunlit area in both seasons as a result of this shading configuration.
6. The sunlit penetration study shows that the internal distribution of the sunlit area is symmetrical in London which represents the cold climate zone.

7. The efficiency of shading devices is considerable during summer in cold climate zones.

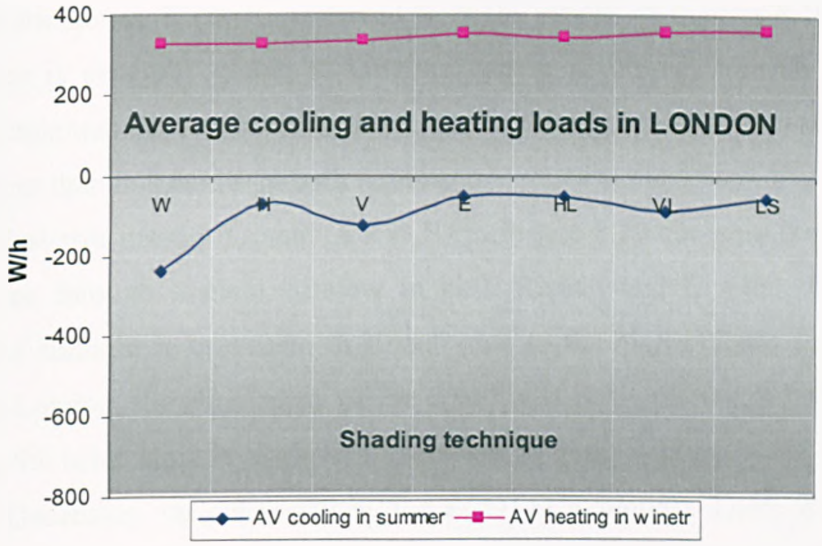


Figure 8.18 Average heating/cooling loads using different shading methods in London

W= without shading, H= horizontal shading, V=vertical shading, E=egg-crate shading, H L=horizontal louvers V L=vertical louvers, L S=light shelves

8.5.4. Sunlit area distribution analysis

After reviewing the thermal effect of the selected shading methods, the distribution of the sunlit area was investigated. The sunlit area distribution results were obtained first by using a plain window to investigate the effects of various shading methods in both selected climatic zones. It can be observed from the graphs in Figures 8.19 and 8.20 that the sunlit area is generally higher in London than in Riyadh as a result of the latitude differences explained earlier; because of the sun's altitude, the distribution of sunlight in winter is higher than in summer in both regions.

The first two graphs (Graphs A and H) in Figure 8.19 compare the distribution of the sunlit area through a plain window in both Riyadh and London. In summer, the penetration of sunlight is prevented in Riyadh due to the high altitude angle of the sun. However, in London, the penetration of the sunlit area is significant in both summer and winter since the solar altitude angle in London on 21 June at noon is 62° and is 15.1° at noon on 21 December, (as calculated by the ECOTECT model). There is a considerable reduction in the distribution of the sunlit area on the room's floor when using horizontal shading in Riyadh during winter, as shown in the second set of graphs (Graphs B and I) in Figure 8.19. However, in London, horizontal shading does not affect solar penetration in winter. The related graphs reveal that sunlit area distribution in winter through a plain window and a window with horizontal shading is similar (Graphs H and I). Nevertheless, in summer, horizontal shading reduces the distribution of sunlight, especially at noon.

Maximum solar penetration occurs at noon when using vertical shading in London during summer. This is shown in Graph J in Figure 8.19. However, during winter, sunlit area distribution will be significantly higher when using the same shading method; this is useful for natural heating. Using vertical shading in Riyadh also results in high internal solar exposure during winter, as shown in Graph C in the same figure.

The third set of graphs (Graphs D and K) in Figure 8.19 represents the sunlit area distribution when using egg-crate shading. Solar penetration is totally prevented in summer in both regions due to high sun altitude. Moreover, the sunlit area distribution in winter is sufficient for natural heating. Therefore, egg-crate shading represents the most efficient shading method in reducing solar penetration in summer and allows sunlit distribution in winter. The high efficiency of egg-crate shading is a result of the double effect of the horizontal and vertical shading devices.

The shading effect of horizontal louvers on the distributed sunlit area can be observed in the first graphs in Figure 8.20 (Graphs E and L) where it can be observed that the sunlit area is significantly reduced during the summer in both regions. In winter, the sunlit area is greatly reduced in Riyadh due to the shading configuration and the solar altitude angle which, in Riyadh, is 41.9°. The low solar altitude angle in London allows a sufficient amount of solar penetration, as can be observed in the graph concerning the performance of the horizontal louvers. The maximum sunlit area is achieved at 11h, 12h and 13h during winter in London (Graph L) while the minimum solar penetration is achieved in Riyadh when using the same shading method (Graph E). The combination of the shading configuration of the horizontal louvers and the low solar altitude angle in Riyadh during winter allows maximum solar penetration at 9h and 15h (Graph E). The ECOTECT model shows that the solar altitude angle in Riyadh at 9h on 21 December is 26.5° and 23.6° at 15h. Viewing the internal sunlit area distribution by using the SunCast model shows more sunlight penetration at 9h and 15h compared with other hours during the day.

Graphs F and M dealing with the vertical louvers reveal that the maximum sunlit area distribution is obtained at noon during the winter in Riyadh because the configuration of these louvers allows solar radiation to penetrate when the sun is at its highest position (the solar noon angle), unlike horizontal shading, which prevents solar penetration at this time. The same result was achieved for London during the winter where the higher distribution of the sunlit area is obtained due to a lower altitude of the sun. In summer, less penetration is achieved in both regions. This would be an efficient solution to combat internal reduction during the overheating periods.

The distribution of sunlight by using light shelves in Riyadh is fairly low during both seasons, as can be observed in Graph G. However, in London, high internal solar penetration is achieved during winter by using this shading method. (See Graph N.) High solar penetration around noon affects significantly the required heating loads. In London, the sun's altitude angle in winter will allow maximum internal sunlit distribution at 11h and 13h. This can be observed in Graph N in Figure 8.20.

It can be seen in all the graphs that the distribution of the internal sunlit area in London is symmetrical around noon with all the shading methods as the solar noon angle in London occurs at around noon. In Riyadh, however, the distribution of the internal sunlit area is not symmetrical in most cases, as can be seen in the related graphs.

The relationship between the results achieved for the sunlit area distribution and for the thermal shading effects can be observed when comparing the related graphs with each other.

Protecting the internal spaces from the penetration of solar radiation in summer by using horizontal shading in London reduces the required cooling loads, as seen in the related graph in Figure 8.14. It can also be observed that, in Riyadh, preventing the penetration of solar radiation in winter by using shading devices will increase the demand for heating. Such an effect can be seen clearly when using egg-crate shading, horizontal louvers and light shelf shading in Riyadh during winter.

The same shading methods will react efficiently during the summer in London where cooling loads will be clearly reduced. Horizontal shading generally will exclude solar radiation generated from a high sun angle, which occurs during summer and a vertical shading configuration will allow sunlit penetration when the sun is at its highest. This shading technique is an efficient solution in winter as a natural heating element. Shading device configurations will strongly affect the internal sunlit distribution and consequently the required cooling and heating loads will, in turn, be affected. Movable shading could also be effective solution. Horizontal shading will act efficiently during summer and the same shading could move to a vertical position to act efficiently during the winter period. (The tabled results are illustrated in Appendix B for both the hot and cold climatic zones. These tables illustrate the thermal and sunlit distribution data.)

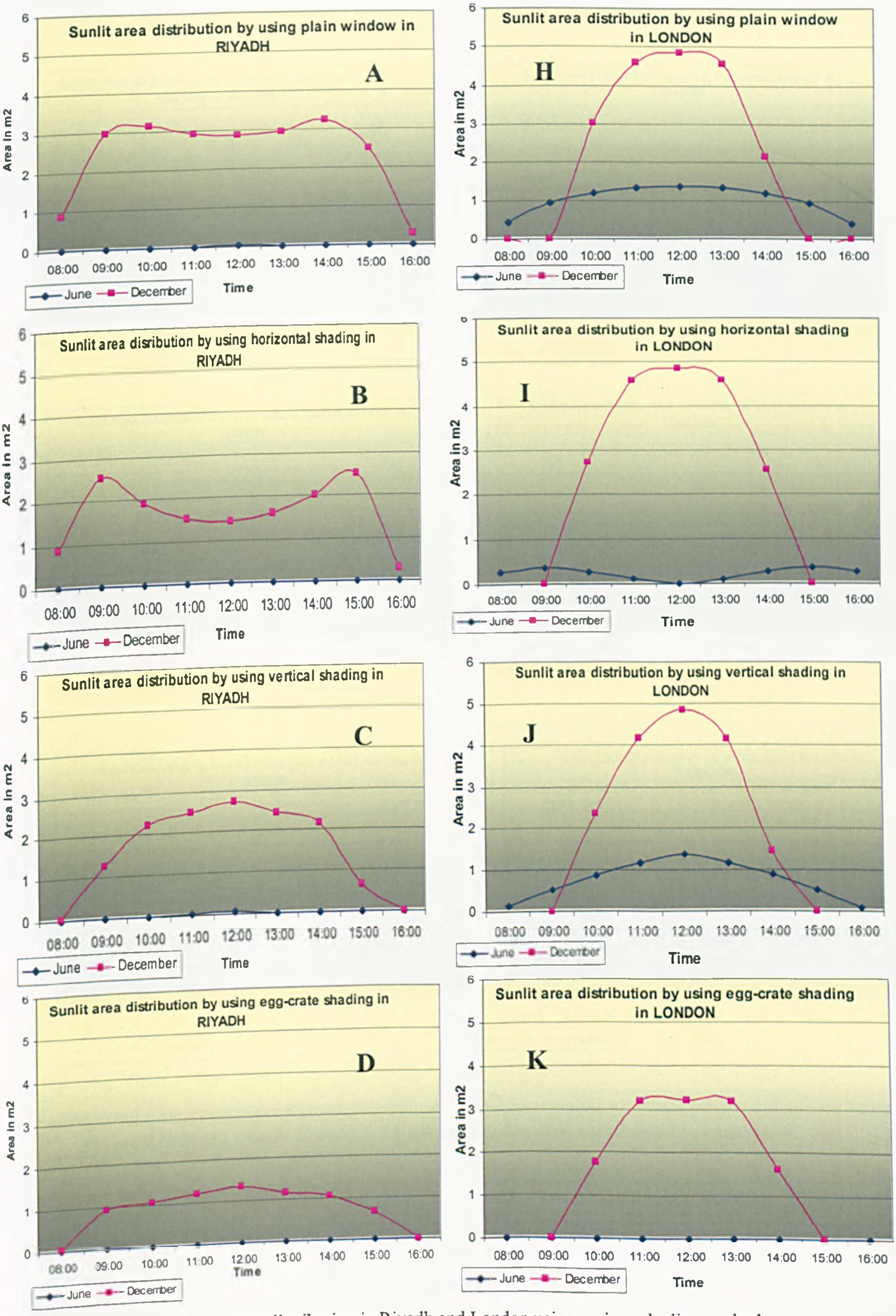


Figure 8.19 Sunlit area distribution in Riyadh and London using various shading methods.

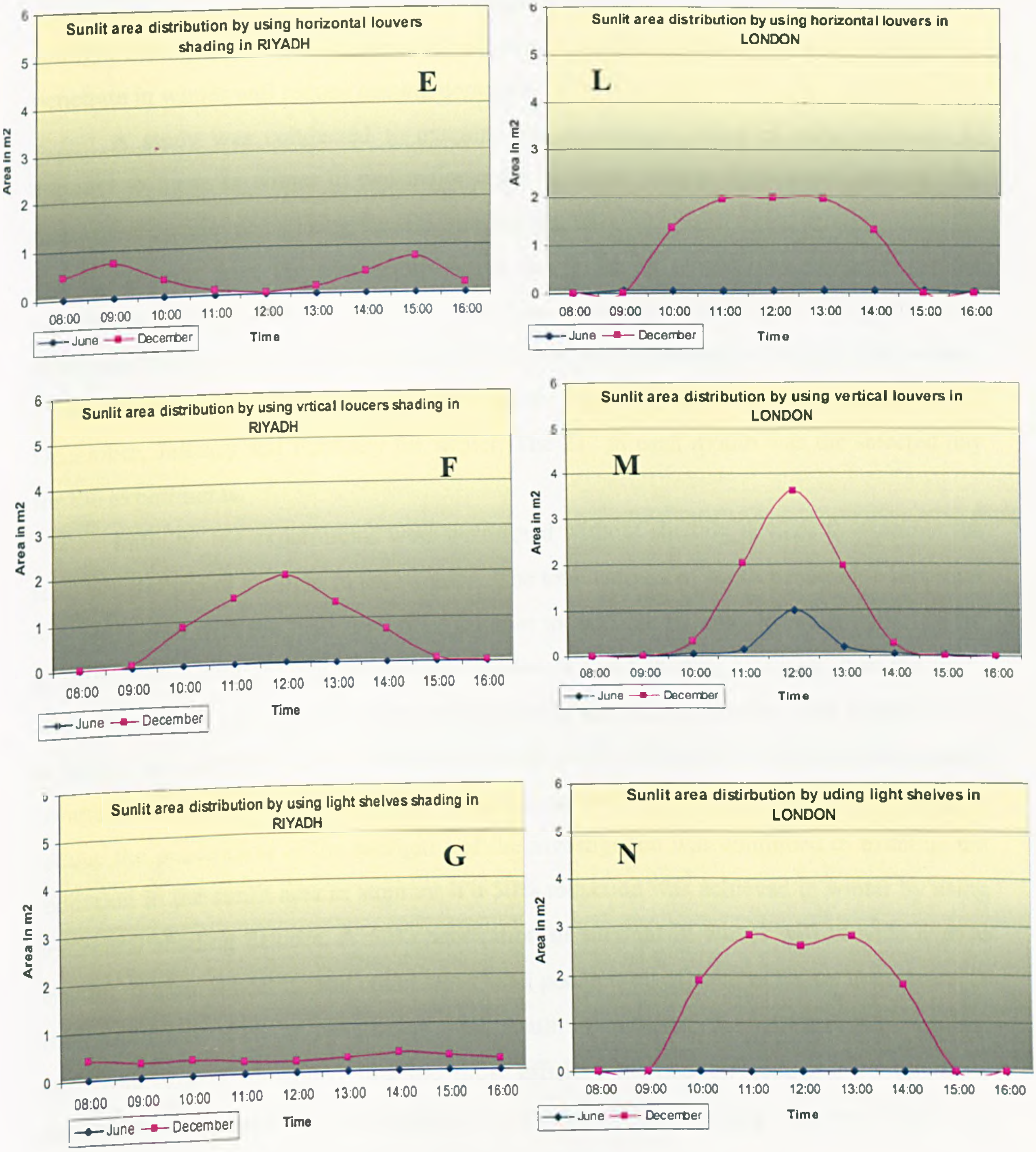


Figure 8.20 Sunlit area distribution in Riyadh and London using various shading methods.

8.6. Indoor Sunlight Distribution Ratios

Due to the different solar altitude angle in summer and winter, the distribution of sunlight during the year varies. In turn, allowing a sufficient amount of solar radiation to penetrate in winter will reduce heating demands.

A study was conducted to examine the penetration ratios of solar radiation in summer to those in winter in two major cities in Saudi Arabia: Riyadh and Jeddah. The results were achieved by using the IES SunCast model.

A room with the dimensions 6m x 6m x 3m in height was designed for the experiment while a window (1.6m x 1.6m) was designed on the south facing wall. The total penetration of sunlight onto the room's floor was calculated in summer and winter. Three months were considered for each season: June, July and August for summer and December, January and February for winter. The 21st in each month was the selected day for the experiments.

Initially, the experiments were performed without shading devices to examine the total penetration of sunlight in each season. The total amount of sunlit penetration in winter was compared with the total amount in summer to examine the ratio between both. If x m^2 is 100% of the sunlight that penetrates a window without shading in winter, then the study seeks to discover how much of the sunlight will penetrate under the same conditions in summer. The answer to this question will be the ratio of the sunlit penetration in summer compared to that in winter. Horizontal shading was used in the second stage of the study to reduce the penetration of the sunlight and the investigation was continued to examine the reduction in the sunlit area in summer if a 50% reduction was achieved in winter by using horizontal shading devices. A 50% penetration of sunlight in winter will provide a good amount of natural heating and could allow total penetration of solar radiation in summer. A total provision of solar penetration will result in reducing the demands for cooling. Athienitis (2002) illustrated that the most efficient method for reducing cooling load demand is to dissipate the sun's radiation before it reaches a building's interior. This could be achieved through the provision of shading.

8.6.1. Solar penetration ratios: the Riyadh model

From the SunCast model, it was found that the total sunlight distribution on the room's floor during the selected summer period was 4.31m^2 while, in the winter period, the total penetration of sunlight was 56.63m^2. This results in a ratio of 7.61% of the summer solar penetration to the penetrated radiation in winter.

So, if the total penetration is 100% in winter, this will equal 7.61 % in summer whereas, if the penetration is 50% in winter, this will result in 3.8 % penetration in summer.

8.6.2. Solar penetration ratios: the Jeddah model

The SunCast results for Jeddah show that the total sunlit area penetration on the room's floor in summer was 4.98m^2. In winter, the total penetration of the sunlight through the same window was 99.33m^2. This results in a ratio of 5% of the summer solar penetration compared to the penetrated radiation in winter. The total winter penetration, which is 100%, will equal 5% in summer. In turn, if only 50% penetration is required in winter, this will lead to 2.5% solar penetration in summer. Calculations of the results in the following table are based on tables 8.5 to 8.8.

City	Solar penetration area (Summer)	Solar penetration area (Winter)	Solar penetration ratio (Summer to Winter)	Solar penetration ratio (Winter)
Riyadh	4.31 m^2	56.63 m^2	7.6%	100%
Jeddah	2.55 m^2	52.62 m^2	4.8 %	100%

By using horizontal shading to allow 50% of the solar radiation to penetrate in winter

City	Solar penetration area (Summer)	Solar penetration area (Winter)	Solar penetration ratio (Summer to Winter)	Solar penetration ratio (Winter)
Riyadh	0.5 m^2	29.89 m^2	1.6 %	50%
Jeddah	0.35 m^2	26.23 m^2	1.3 %	50%

Table 8.3 Amounts and ratios of the penetrated sunlit area through the south window in Riyadh and Jeddah.

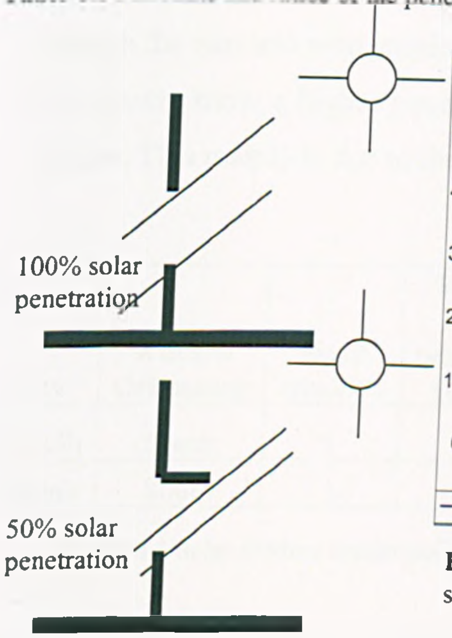


Figure 8.22 Total penetration of sunlight (100%) and reduction of sunlight penetration to 50% by using horizontal shading.

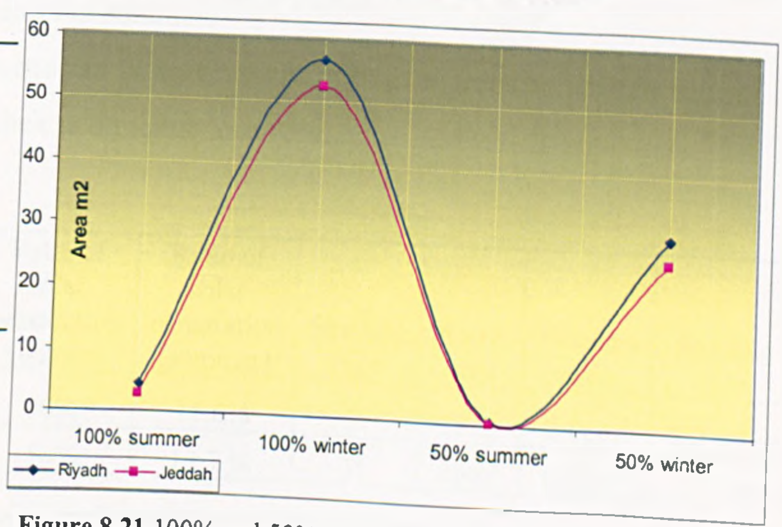


Figure 8.21 100% and 50% sunlit area distribution through the south window in Riyadh and Jeddah.

8.6.3. Results and shading design guidelines

The following design guidelines for shading from the present study could be summarised as follows:

- According to the SunCast model results for Riyadh, the total penetration of sunlight in the three selected days in the winter months is $56.63m^2$. To allow for 50% of this amount of solar radiation, 2.2m x 1m horizontal shading should be used. Such a shading dimension will allow 11.6% of the total solar radiation to be admitted in the three selected months of summer. The total penetration in the summer months without shading is $4.31m^2$. Moreover, with selected shading, the total penetration is $0.5m^2$. So, 0.5/4.31x100= 11.6 which is the ratio of solar penetration in summer.
- By using results from the SunCast model for Jeddah, the total penetration of sunlight in the three selected days of winter is $52.62m^2$. To allow for 50% of this amount of solar radiation, 2m x 1m horizontal shading should be used. Such a shading dimension will allow 13.7 % of the total solar radiation to be admitted in the three selected days of summer. The total penetration in summer without shading is $2.55m^2$. Moreover, with selected shading, the total penetration is $0.35m^2$. So, 0.35/2.55x100= 13.7 which is the ratio of solar penetration in summer. These results are illustrated in Tables 8.4 and 8.7.
- Reducing the sunlight penetration in winter by 50% could result in total solar radiation control in summer. The results achieved in Tables 8.6 and 8.8 show that less than 2 % of the sunlit area will penetrate the room in summer in both regions.
- The penetration of solar radiation in winter is mainly through the south windows and through the east and west windows in summer.
- The results show a higher penetration of sunlit areas in both seasons in Riyadh than in Jeddah. This mainly is due to their geographic locations.

City	Window Orientation	No of windows	Ratio of solar penetration (winter)	Ratio of solar penetration (summer)	Shading type	Room area	Window area	Shading size
Riyadh	South	1	50%	11.6%	H	$36m^2$	$2.56m^2$	2.2 x 1m
Jeddah	South	1	50%	13.7 %	H	$36m^2$	$2.56m^2$	2 x 1m

Table 8.4 Solar shading design guidelines for architects in Saudi Arabia.

Riyadh model results in m^2

Window without shading

	Direct sunlight on the model floor					
	Dec	Jan	Feb	Jun	Jul	Aug
06:00						
07:00	0	0	0	0	0	0
08:00	0.86	0.56	0.66	0	0	0.08
09:00	2.98	2.46	1.86	0	0	0.38
10:00	3.14	2.83	1.99	0	0.06	0.51
11:00	2.91	2.61	1.89	0.03	0.16	0.57
12:00	2.85	2.54	1.85	0.05	0.19	0.59
13:00	2.95	2.59	1.87	0.01	0.16	0.56
14:00	3.24	2.78	1.95	0	0.06	0.5
15:00	2.48	2.66	2	0	0	0.36
16:00	0.29	0.86	0.97	0	0	0.04
17:00						
Total	21.7	19.89	15.04	0.09	0.63	3.59
Dec	21.7			0.09		
Jan	19.89			0.63		
Feb	15.04			3.59		
Total sunlit area penetration	56.63			4.31		

Table 8.5 Solar radiation penetration results for Riyadh (SunCast results).

Window with 2.2m x 1m horizontal shading to allow 50% penetration

	Direct sunlight on the model floor					
	Dec	Jan	Feb	Jun	Jul	Aug
06:00						
07:00	0	0	0	0	0	0
08:00	0.86	0.56	0.66	0	0	0
09:00	2.31	2.03	1.12	0	0	0.07
10:00	1.62	1.36	0.63	0	0	0.11
11:00	1.31	1.02	0.33	0	0.01	0.06
12:00	1.25	0.94	0.25	0	0	0
13:00	1.36	0.99	0.28	0	0	0
14:00	1.76	1.29	0.54	0	0	0.01
15:00	2.4	1.92	0.98	0	0.01	0.07
16:00	0.29	0.86	0.97	0	0	0.12
17:00	0	0	0	0	0	0.04
Total	13.16	10.97	5.75	0	0.02	0.48
Dec	13.16			0		
Jan	10.97			0.02		
Feb	5.76			0.48		
Total sunlit area penetration	29.89			0.5		

Table 8.6 Solar radiation penetration results for Riyadh, when allowing 50% penetration of sunlight (SunCast results).

Jeddah model results in m^2

Window without shading

	Direct sunlight on the model floor					
	Dec	Jan	Feb	Jun	Jul	Aug
06:00				0	0	
07:00			0	0	0	0
08:00	0.1	0.01	0.13	0	0	0
09:00	2.07	1.62	1.26	0	0	0.12
10:00	2.99	2.65	1.84	0	0	0.31
11:00	2.68	2.41	1.71	0	0	0.4
12:00	2.56	2.29	1.65	0	0.04	0.43
13:00	2.58	2.28	1.65	0	0.04	0.43
14:00	2.74	2.38	1.69	0	0	0.39
15:00	2.99	2.64	1.81	0	0	0.3
16:00	1.58	1.87	1.55	0	0	0.09
17:00	0	0.14	0.39	0	0	0
Total	20.29	18.29	13.68	0	0.08	2.47
Dec	20.29			0		
Jan	18.29			.08		
Feb	13.68			2.47		
Total sunlit area penetration	52.26			2.55		

Table 8.7 Solar radiation penetration results for Jeddah (SunCast results).

Window with 2mx1m horizontal shading to allow 50% penetration in the winter months

	Direct sunlight on the model floor					
	Dec	Jan	Feb	Jun	Jul	Aug
06:00			0	0	0	0
07:00	0.1	0.01	0.13	0	0	0
08:00	2.07	1.62	1.26	0	0	0.06
09:00	1.64	1.43	0.74	0	0	0.08
10:00	1.16	0.94	0.34	0	0	0.04
11:00	0.96	0.69	0.07	0	0	0
12:00	0.98	0.68	0.05	0	0	0
13:00	1.26	0.89	0.25	0	0	0.04
14:00	1.82	1.33	0.63	0	0	0.08
15:00	1.58	1.87	1.2	0	0	0.05
16:00	0	0.14	0.39	0	0	0
17:00		0	0	0	0	0
Total	11.57	9.6	5.06	0	0	0.35
Dec	11.57		Jun	0		
Jan	9.6		July	0		
Feb	5.06		Aug	0.35		
Total sunlit area penetration	26.23			0.35		

Table 8.8 Solar radiation penetration results for Jeddah (SunCast results when using horizontal shading to allow 50% of solar radiation).

8.6.4. Summer sunlight distribution in Riyadh

This part of the study investigated different sunlit area penetration ratios on the model floor and was conducted during the summer period. Penetration ratios, specifically 0%, 25%, 50%, 75% and 100%, were the main investigated ratios of sunlit area distribution on the internal model surface (the floor). Each penetration ratio required a specific horizontal shading size so, using the SunCast model, experiments were conducted to determine the exact shading size that would match the desired sunlit area penetration ratio into the internal space.

The penetration ratios were then compared against the base case: 100% sunlight penetration. The window in this example was designed without shading and, as evaluated earlier, it was aimed to obtain full penetration of sunlight in this case. Previous investigations showed that the total amount of sunlight penetration was 4.31m^2 for the selected model in the selected summer period. These results can be seen Table 8.5. As mentioned previously, results for both summer and winter were collected for a selected day (21st) on three selected months for each season. The window area in this investigation covered 15% of the wall facing south. Different window to wall ratios are investigated later in a following chapter.

Riyadh summer model results in m^2
0% penetration: total blocking of the solar radiation in summer

	Direct sunlight on the model floor					
	Dec	Jan	Feb	Jun	Jul	Aug
07:00	0	0	0	0	0	0
08:00	0.86	0.56	0.66	0	0	0
09:00	2.08	1.72	0.72	0	0	0
10:00	1.54	1.23	0.39	0	0	0
11:00	1.31	1.01	0.29	0	0	0
12:00	1.25	0.94	0.25	0	0	0
13:00	1.35	0.99	0.27	0	0	0
14:00	1.64	1.18	0.35	0	0	0
15:00	2.12	1.64	0.6	0	0	0
16:00	0.29	0.86	0.97	0	0	0
17:00	0	0	0	0	0	0
Total	12.44	10.13	4.5	0	0	0
Dec	12.44		Jun	0		
Jan	10.13		Jul	0		
Feb	4.5		Aug	0		
Total sunlit area penetration	27.07			0	Shading dimension	3.6mx1m

Table 8.9 Solar radiation penetration results for Riyadh (SunCast results, total blocking of the sunlight penetration).

25% penetration of the solar radiation in summer

	Direct sunlight					
	Dec	Jan	Feb	Jun	Jul	Aug
08:00	0.86	0.56	0.66	0	0	0.08
09:00	2.83	2.39	1.67	0	0	0.16
10:00	2.67	2.36	1.53	0	0.01	0.13
11:00	2.43	2.13	1.41	0	0.01	0.11
12:00	2.37	2.06	1.37	0	0	0.11
13:00	2.47	2.11	1.39	0	0.01	0.12
14:00	2.77	2.31	1.49	0	0.01	0.13
15:00	2.48	2.49	1.68	0	0	0.16
16:00	0.29	0.86	0.97	0	0	0.04
Total	19.17	17.27	12.17	0	0.04	1.04
Dec	19.17		Jun	0		
Jan	17.27		Jul	.04		
Feb	12.17		Aug	1.04		
Total sunlit area penetration	48.61			1.08	Shading dimension	1.8mx.3m

Table 8.10 Solar radiation penetration results for Riyadh. (SunCast results, allowing 25% penetration of the solar radiation).

50% penetration of the solar radiation in summer

	Direct Sunlight on the model floor					
	Dec	Jan	Feb	Jun	Jul	Aug
08:00	0.86	0.56	0.66	0	0	0.08
09:00	2.91	2.43	1.77	0	0	0.2
10:00	2.9	2.59	1.75	0	0.01	0.29
11:00	2.67	2.37	1.65	0	0.01	0.33
12:00	2.61	2.3	1.61	0	0	0.35
13:00	2.71	2.35	1.63	0	0.01	0.33
14:00	3	2.54	1.71	0	0.01	0.28
15:00	2.48	2.58	1.84	0	0	0.18
16:00	0.29	0.86	0.97	0	0	0.04
Total	20.43	18.58	13.59	0	0.04	2.08
Dec	20.43		Jun	0		
Jan	18.58		Jul	.04		
Feb	13.59		Aug	2.08		
Total sunlit area penetration	52.6			2.12	Shading dimension	1.8mx.15m

Table 8.11 Solar radiation penetration results for Riyadh (SunCast results, allowing 50% penetration of the solar radiation).

75% penetration of the solar radiation in summer

	Direct sunlight on the model floor					
	Dec	Jan	Feb	Jun	Jul	Aug
08:00	0.86	0.56	0.66	0	0	0.08
09:00	2.97	2.46	1.84	0	0	0.29
10:00	3.04	2.72	1.88	0	0.03	0.41
11:00	2.81	2.51	1.78	0.01	0.06	0.47
12:00	2.75	2.44	1.75	0.02	0.09	0.49
13:00	2.85	2.49	1.77	0.01	0.06	0.46
14:00	3.14	2.68	1.85	0	0.03	0.39
15:00	2.48	2.65	1.93	0	0	0.27
16:00	0.29	0.86	0.97	0	0	0.04
Total	21.19	19.37	14.43	0.04	0.27	2.9
Dec	21.19		Jun	.04		
Jan	19.37		Jul	.27		
Feb	14.43		Aug	2.9		
Total sunlit area penetration	54.99			3.21	Shading dimension	1mx.1m

Table 8.12 Solar radiation penetration results for Riyadh (SunCast results, allowing 75% penetration of the solar radiation).

All summer penetration results were compared against the original "without shading" case. The results showed that the total penetration of the sunlit area in summer is 4.31m^2. As an example, in the case of 25% penetration, the total sunlit area was 1.08 m^2 so the percentage is calculated as 1.08/4.31= .2505 x100 = 25%.

8.6.5. Summary of results

Percentage of solar penetration	Total sunlit area for the three days in the selected months	Horizontal shading dimension	Horizontal shading area	Horizontal shading configuration
0 %	0.1 m^2	3.6 x 1m	3.6m^2	
25 %	1.08 m^2	1.8 x 0.3m	0.54m^2	
50 %	2.12 m^2	1.8 x 0.15m	0.27m^2	
75 %	3.21 m^2	1 x 0.1m	0.1m^2	
100 %	4.31 m^2	No shading	No shading	

Table 8.13 Different ratios of sunlit area penetration through the selected window. The required shading devices areas are demonstrated for each penetration ratio in summer.

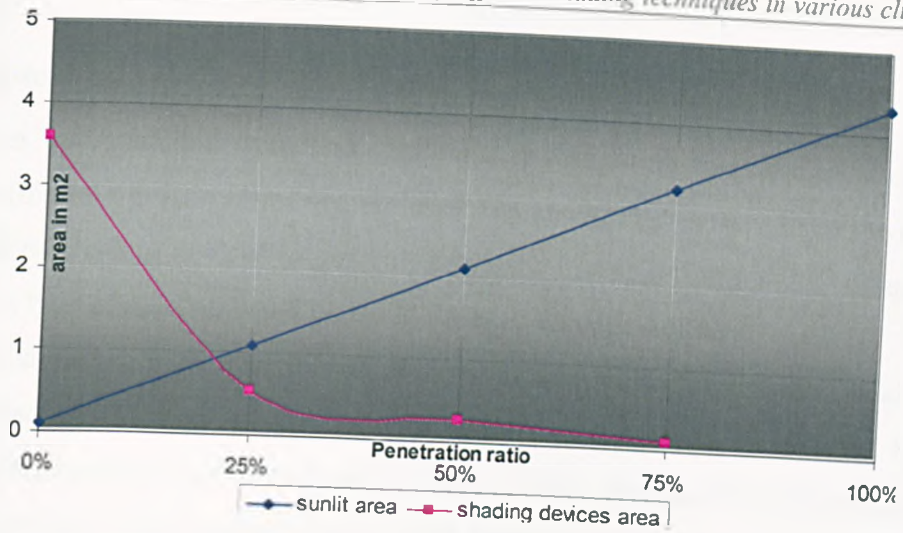


Figure 8.23 Different ratios of sunlit area penetration through the selected window. The required shading device areas are demonstrated for each penetration ratio in summer.

Table 8.13 and Figure 8.23 summarize the results regarding the sunlit area penetration ratios achieved by using various horizontal shading dimensions in Riyadh, Saudi Arabia. The efficiency of the horizontal shading against the high solar altitude angle in lower latitudes is the main reason for selecting this shading method in this study. The study has given an idea about the most effective dimensions for horizontal shading devices for each sunlit penetration ratio. This allows an architect to produce a wide range of options in designing the shading according to the desired solar penetration ratio. Movable shading devices could be designed to allow maximum solar penetration in winter and a minimum in summer while sufficient sunlit area penetration in winter could be achieved when allowing 25% to 50% penetration in summer. Using these ratios in the case of the selected room in Riyadh will allow only 2 m^2 of sunlit penetration in summer. The results are shown in Table 8.13.

The study also reveals that sunlit penetration ratios of 50% and 75% in summer will result in slight variations in sunlit penetration during winter. Tables 8.11 and 8.12 show that a 50% rate of summer penetration will allow a sunlit area of $52.6m^2$ in winter, while 75% will allow $54.99m^2$, a difference of only 4.3%. Moreover, Table 8.5 shows that $56.63m^2$ is the penetrated sunlit area using a plain window, with the high solar altitude angle in Riyadh during both summer and winter being the main reason for this slight variation. An initial investigation revealed that a greater sunlit area could be achieved by using other orientations as the sunlit area distribution during summer through east and west windows in Riyadh is higher than that for south windows. The same penetration ratio study could be conducted using different shading methods. For instance, horizontal louvers could be adjusted to allow the required penetration ratio.

8.7. Conclusion

It can be concluded from this study that investigating the efficiency of shading devices in different climatic zones is quite useful as knowledge is thus gained to assess the performance of shading devices in general. From the investigation results, an appropriate selection of a type of shading could be made for each climatic zone.

As illustrated in the thermal analysis graphs and tables for Riyadh, Saudi Arabia, horizontal shading will slightly reduce the demand for cooling loads in summer. However, due to the intensive heat gain in summer in Saudi Arabia, the reduction of cooling loads is low. On the other hand, thermal analysis for shading in London, UK, shows that the reduction of cooling loads in summer is significant when using the horizontal shading. Figure 8.16 shows that, in Riyadh, high demands for cooling loads are made in summer. Moreover, heating demand increases in winter when using egg-crate shading. Egg-crate shading prevents the winter solar radiation needed for natural heating from penetrating into the internal spaces while the thermal simulation for London, UK, shows that horizontal and egg-crate shading will reduce the demand for cooling loads in summer. Shading in this region is not recommended in winter, however, as heating demand will be increased when using egg-crate shading, horizontal louvers and vertical louvers. Movable shading is highly recommended in this case.

Generally, extensive heat and high temperatures in Riyadh will strongly affect the performance of shading devices in summer so the selected shading methods do not have a strong effect on the required cooling loads in that season. Other shading techniques could possibly have a more significant effect. Movable shading with efficient glazing could have a stronger effect on heat gain. However, shading will directly reduce the undesired heat gain caused by glare and extra sunlit area penetration.

During winter, heating loads will be increased in Riyadh as a result of the sunlit penetration being blocked by shading. Figure 8.15 reveals that maximum heating loads are achieved when using horizontal shading. Using egg-crate, horizontal louvers and light shelf shading will cause an extra heating load in winter, whereas vertical shading in Riyadh will have less effect on heating loads in that season. This is mainly due to the configuration of the vertical shading which allows sunlit penetration during the hours around noon. Sunlight is prevented from penetrating during the hours around noon, however, when horizontal shading is used.

In London, shading devices will have a significant effect on sunlit area penetration in summer. The graphs for London in Figures 8.14 and 8.15 show that using egg-crate, horizontal louvers and light shelves will significantly reduce cooling demand in summer as an average cooling load in summer for a plain window is -239 W/h, while using egg-crate shading will reduce the cooling load average to -50 W/h., a saving of 79%. The three shading techniques mentioned above are efficient in London during summer. However, the fairly low temperatures in this region in winter will reduce the shading effect. The related graphs show less variation in heating loads in winter while heating demand is always high so solar penetration in cold regions is essential during winter. An analysis of the average cooling and heating loads, shown in Figure 8.18, shows an average heating load of 307 W/h. in the case of a plain window while using vertical louvers, for instance, will increase the heating load to 360 W/h, a 17% increase.

The last part of the chapter is mainly concerned with examining the ratios of sunlit penetration in summer and winter. Riyadh and Jeddah were the two cities selected for the experiments and results show that 7.6% of the total sunlit area penetrates the room in summer compared to the penetration in winter in Riyadh. In Jeddah, 4.8% of the total sunlight penetrates in summer compared to winter. By using the designed horizontal shading, 50% of the sunlight will penetrate the internal surfaces in winter so this will allow 1.6% of the total sunlight to penetrate in summer in Riyadh. On the other hand, 1.4% will penetrate in Jeddah. Because of Riyadh's location, this region is exposed to more solar radiation compared to other cities.

The last part of this study examines different dimensions of horizontal shading device which, in turn, allow different solar radiation penetration ratios. Selected ratios were 0%, 25%, 50% and 100%. This study investigates different horizontal shading areas which allow specific ratios of solar radiation to penetrate to the internal surfaces. Such an evaluation should be useful for architects to gain knowledge about the sizes of shading at an early design stage. Moreover, the desired sunlit area penetration ratio could be achieved using the designed horizontal shading. The study revealed that sufficient sunlit distribution during winter could be obtained by allowing 25% and 50% sunlit penetration in summer. These ratios will allow only around $2m^2$ of internal sunlit area into the designed room.

Horizontal shading is an efficient shading method for use in Saudi Arabia. The shading capability of this method in reducing solar radiation caused by the high sun angle during summer is very efficient, especially around noon, as shown in the sunlit study in Section 8.6.4. This is unlike vertical shading, which allows internal solar penetration from a high sun altitude. Obviously, egg-crate shading is an efficient solution to this problem but extra care must be taken to avoid the blocking of solar penetration during winter.

CHAPTER 9

FIELD EXPERIMENTS AND PARAMETRICAL STUDIES

9.1. Introduction

This chapter contains two main parts. The first part covers the study of sunlit area distribution by using a physical model for Saudi Arabia; this is considered to be the main field study experiment. This section involving the physical model experiments is divided into two parts: the first part is the examination of solar penetration in winter, while the second part covers similar experiments in summer. Two main tools are used in this part which are the physical model for Jeddah and a computer (SunCast) model.

The second main part of the chapter contains parametrical studies. These studies are divided into three sections. The first part is the manual calculation of the sunlit area by using the horizontal and vertical shadow angles. The second is an investigation of the potential for saving regarding the required cooling loads in the selected room. This part is further divided into three aspects: the first is an investigation into the required cooling loads by using different shading techniques; the second is an investigation into the required cooling loads by using different window glazing ratios; and the third is an investigation carried out to assess the most significant factor of shading importance so that it will be possible, therefore, to speculate about the key role played by shading.

The third part of the parametrical studies investigates, firstly, a comparison of shading using different types of glazing, glazing ratios and different shading devices. The comparison is mainly used to show the efficiency of the selected shading devices together with different glass types such as double and triple glazing. Due to the complete obstruction of solar radiation, the investigated shading devices should present higher levels of efficiency when compared with glass shading. Moreover, glass shading is generally not recommended in Saudi Arabia due to the extremely hot climate.

Secondly, the parametrical study section investigates the ideal configurations, orientations and slope angles of the shading devices by considering the functions of the shading devices. The functions considered in this study are solar penetration, daylighting, ventilation, view and privacy. Apart from the solar penetration function, which is the main focus of this study, all other functions have been investigated through other studies, with each study concentrating on a specific function. Various studies have been selected for this investigation, with each research recommending a shading type or configuration, an orientation or a slope angle for the studied devices. This investigation was conducted to present shading design guidelines for architects to use. Furthermore, the study aims to provide a complete and simple reference for shading device functions.

The following paragraphs provide a general idea about each part of this chapter; the structure of the entire chapter is illustrated in Figure 9.1.

Shading devices are well known as a strategy for protection against sun glare in the Middle East so assessing the performance of shading devices is essential in hot climates. Efficient shading devices should provide protection from direct solar radiation and should offer both thermal and visual comfort. Many studies have reviewed methods to assess the performance of shading devices on a building's external envelope. Previous investigations in the field indicate that one of the most efficient methods of assessing the performance of shading devices is by using a physical model.

The physical model experiments, as mentioned previously, were conducted in winter (21 December) and summer (21 June). Both experiments were performed in Jeddah, Saudi Arabia, which is at latitude 21.19 N°. The experiments evaluated the performance of three main types of shading device (horizontal, vertical and egg-crate) in terms of sunlight distribution. Various orientations were also examined in the experiments. In winter, a south orientation was selected due to the maximum exposure of this orientation while east and west orientations were selected in summer due to the high solar altitude angle in Jeddah. The initial evaluations showed that there is no penetration of sunlight through the south window in June.

By using the ECOTECT model, a manual calculation of the sunlit area was performed to gain an enhanced understanding of the shading angles. Moreover, this study could be compared with previous methods used; (that is, the SunCast model can be compared with the physical model).

The second part of the chapter (the parametrical study) investigates the potential for saving cooling loads by using different shading methods and glazing ratios. The same shading techniques used in both the SunCast and the physical model were used in this evaluation while the selected window ratios were 15%, 30%, 60% and 90%. This evaluation contributed in assessing the key role played by shading devices in reducing the required cooling loads. This is, throughout the study, the most significant factor to be evaluated, depending on the importance of the shading devices. An estimation of the costs of different types of shading device in Saudi Arabia is also presented in this part.

The parametrical studies in the final part of the chapter include three main studies. The first study examines sunlit area distribution by using different calculation methods. The second study is an evaluation of the potential for saving in cooling loads. This study includes studies on the most significant factors and shading costs in Saudi Arabia. The third study consists of parametrical studies on different glazing types and ratios, and horizontal louvers as significant factors.

Finally, the chapter presents a conclusion concerning the efficiency of the selected types in terms of their required shading functions and a summary of some previous investigations in the field.

9.1.1. CHAPTER 9: Structure of the Study

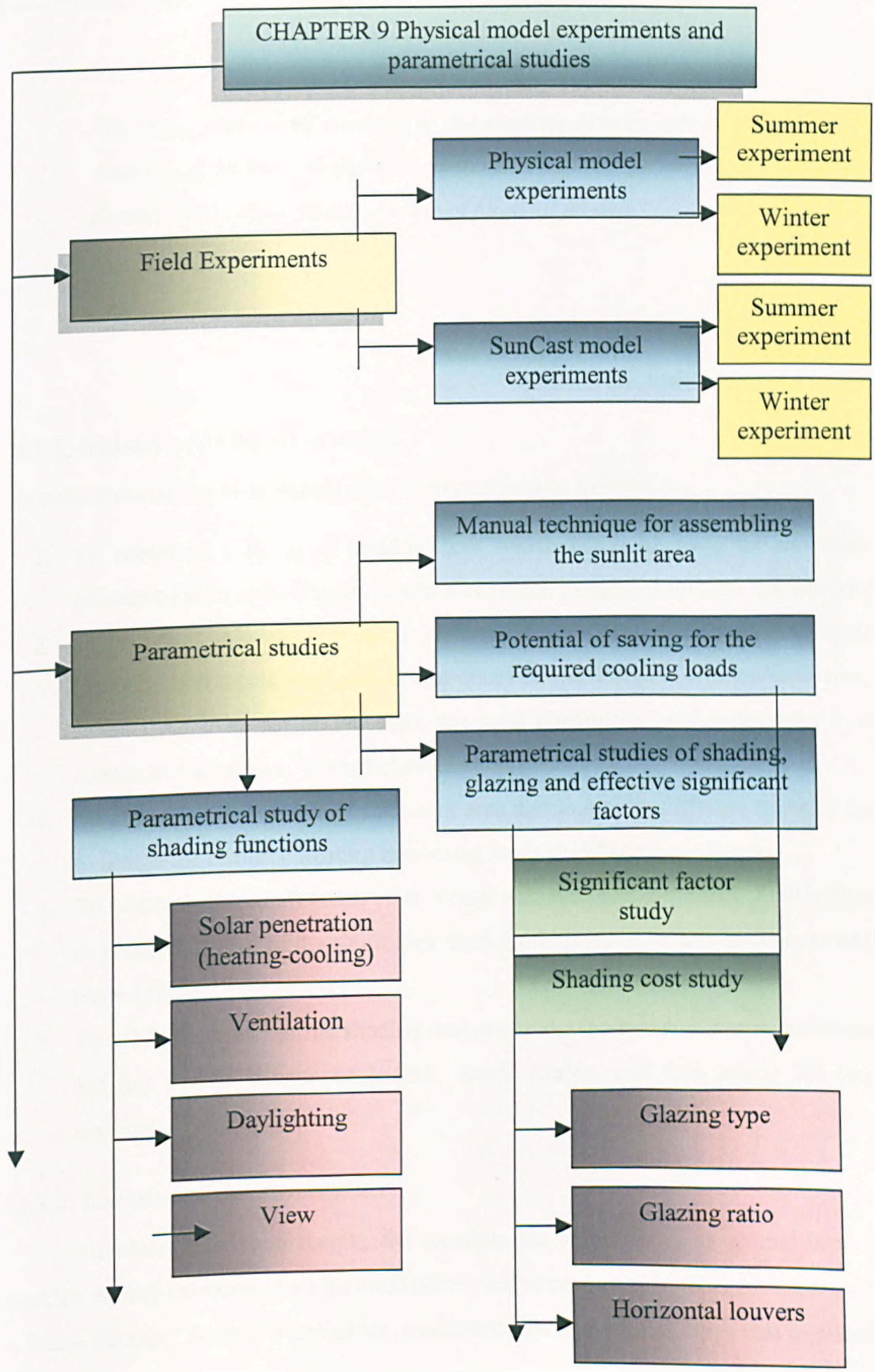


Figure 9.1 Chapter 9: Structure of the Study.

9.2. Physical Model Experiments in Jeddah, Saudi Arabia

9.2.1. Winter Physical Model Experiments in Jeddah, Saudi Arabia

> *"The size, angle, and location of the shading devices can be determined by several different methods. The most powerful, flexible, and informative is the use of physical models."*

Norbert Lechner
From Heating, Cooling, Lighting Design
Methods for Architects

9.2.1.1. Objectives of the experiments

The objectives of the experiments can be summarised as follows:

1. To represent a designed window unit which could be used for assessing the amount of solar radiation as a sunlit area which penetrates through the window.
2. To carry out an evaluation of the performance of different types of shading device (namely, horizontal, vertical and egg-crate) on the designed window-unit area. The selected shading device types are the most commonly used techniques in Saudi Arabia and in most of the hot climate zones.
3. To obtain measurements of the sunlit area distribution at different times of the day to assess the required heating or cooling loads in different conditions.
4. To compare the results with other results achieved using the IES (SunCast) model to predict the size of the sunlit area from more than one source in order to obtain a more efficient evaluation.
5. To study the effect of the shading devices on the internal sunlit area distribution in the hot humid climate of Jeddah, Saudi Arabia, and thus assess the required cooling.

9.2.1.2. Location of the experiments

To achieve efficient results, the location has to be the same as that used in the SunCast model experiment so the evaluation can be comparable. This location is Jeddah in Saudi Arabia. "Jeddah is one of the western region and coastal cities that overlooks the

Red Sea and is located at 21° 19' north and 39° 12' east with an elevation from 3 to 15m above sea level" (Maghrabi, 2000).

9.2.1.3. Instrumentation

1. A pointed stick was used to determine the exact south orientation. The stick was fixed on a board then marks were made every 10 minutes of the shade at the end of the stick. The shortest shade should show the exact orientation of south.

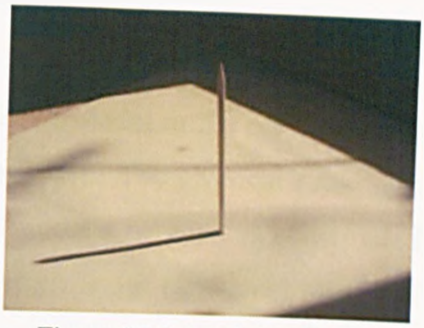


Figure 9.2 Pointed stick for the determination of south.

2. A white board of 3mm thickness was used to construct the model, with the south wall being constructed to the exact scale of a 20 cm wall. So, the wall was doubled to be 2 cm in order to predict the most accurate sunlit area through the exact window thickness. The walls were white in order to reflect the fact that most walls are this colour in Saudi Arabia because of the extremely hot climate.

Figure 9.3 Internal view of the sunlit area distribution.

3. The back wall of the model (the north wall) was constructed as a movable wall so the sunlit area could be measured by using a roll of tracing paper. This movable wall is shown in Figure 9.4
4. The roll of tracing paper for drawing the sunlit area so it could be measured is shown in Figure 9.5.

Figure 9.4 View of the movable north wall to allow measurement of the penetrated sun light

9.2.1.4. Technique of measuring the sunlit area

After choosing the required orientation of the model, which is south, measurements of the internal sunlit area distribution were taken each hour on the 21st of December from 10 am to 2pm, using transparent paper to draw the sunlit area on the internal floor of the model. This area was then measured.

Figure 9.5. Roll of tracing paper for drawing the sunlit area.

9.2.1.4.1. Experimental set-up

Using the same set-up as for the experiments in the previous tests (IES SunCast) and Archi CAD), a 1/10 scale model was built with a 1.6m x 1.6m south-oriented window. The south wall of the model was doubled in size to mirror the actual properties of the wall and to predict more efficiently the results from the scaled model.

9.2.1.4.2. Model Dimensions

The model was built with the same dimensions as the model in the previous tests (the Archi CAD and IES SunCast models): this was 6m x 6m. The physical scale was 1/10 so the model's dimensions were 60cm x 60cm. The model's height was constructed according to the average room height in Saudi Arabia, which is 3m (an actual height of 30cm in the model). The thickness of the south wall was also constructed as an average wall thickness (20cm or 2cm in the model) and was built using two layers of cardboard in order to produce more efficient and accurate results. A single plastic sheet was used to cover the window opening and was fixed on the surface of the internal wall. This represents a single glazed window and matched the actual window design. The window size was 1.6 x 1.6m and the window was placed on the south wall of the model. The dimensions of the whole model were 60cm in width x 60cm in length x 30cm in height. The model was fixed on a baseboard 70cm x 70cm in order to make the model more stable.

9.2.1.4.3. Shading device dimensions

Three louvers shading devices were constructed to be fixed on the model window, as shown in Figure 9.6. Two louvers are shown in this figure while Figure 9.7.shows one louver. The louver in Figure 9.6. was constructed in this shape with a trim of 1square cm in the corners at one side so it could be fixed or inserted in both directions: horizontally to make the horizontal shading and vertically to model a vertical shading device, as shown in Figure 9.8.

The louver in Figure 9.7. was modelled to complete the upper part (the upper horizontal louver) in the egg-crate shading device, along with the vertical devices, as shown in Figure 9.6.

The dimensions of the shading devices in this experiment were .9m both horizontally and vertically. These dimensions were selected due to three main reasons:

1. This is the average size of louvers in Saudi Arabia in both residential and commercial buildings, as illustrated in the previous studies.

2. The previous experiments using Archi CAD and IES were modelled using the same dimensions.
3. These dimensions allow an adequate amount of sunlight to penetrate through the window so this could be useful for heating in winter as well as allowing sufficient natural lighting to enter in summer.

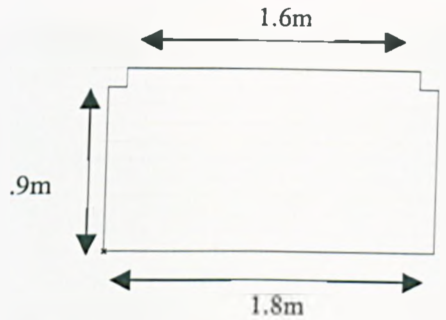


Figure 9.6 Vertical and horizontal shading device configurations.

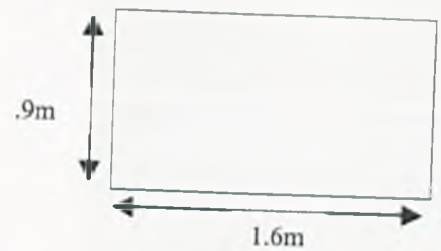


Figure 9.7 Upper louver in the egg-crate shading device configuration.

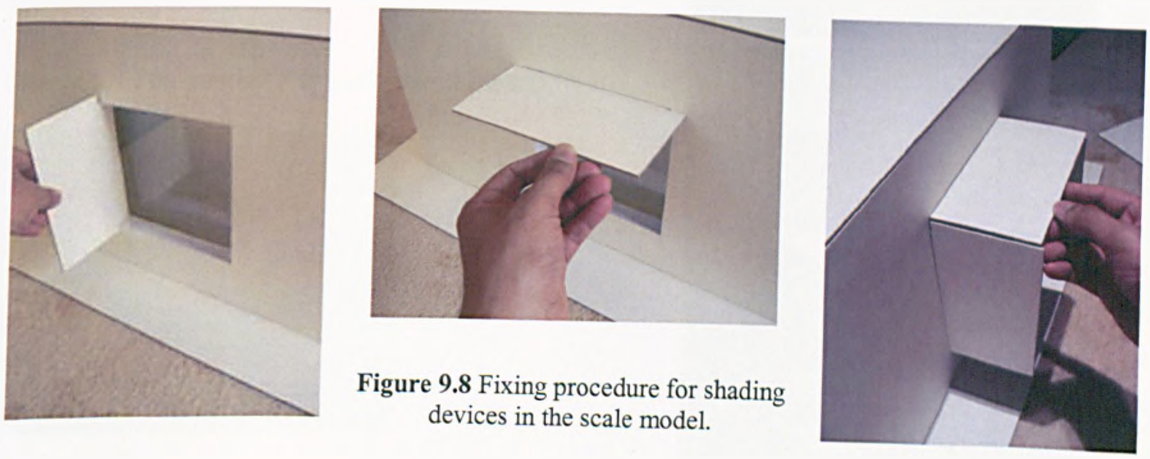


Figure 9.8 Fixing procedure for shading devices in the scale model.

9.2.1.5. Model materials

3mm white cardboard was used for building the model's walls, with the north wall being movable to obtain more accurate results. Sunlit area distribution could then be measured using the roll of paper. The model was fixed on a base made from the same cardboard and received the sun's radiation internally. The single glazed window was modelled by using a fixed single plastic sheet scaled to the actual window size and depth and to the thickness of the glass.

9.2.1.6. Time and technique for testing the sunlit area through the window

A period of time was selected based on the previous studies on comfort temperatures and overheating periods in Saudi Arabia. These times were 10am, 11am, 12am, 1pm and 2pm. At each hour of the selected period the sunlit area was measured by using a roll of tracing paper to draw the penetrated sun light on the model's internal floor. This was done each hour and for each selected shading type; then each case was measured separately.

Figure 9.9 The external views of the scale models.

Measurements from the model of the sunlit areas in square metres taken on the 21 December in Jeddah, Saudi Arabia

Type of shading	Window without shading	Horizontal shading	Vertical shading	Egg-crate shading
Sunlit area at 10am	3.11 m^2	2.24 m^2	2.27 m^2	0.85 m^2
Sunlit area at 11am	2.8 m^2	1.52 m^2	2.32 m^2	0.87 m^2
Sunlit area at 12am	2.5 m^2	1.08 m^2	2.43 m^2	1.04 m^2
Sunlit area at 1pm	2.6 m^2	1.15 m^2	2.1 m^2	0.75 m^2
Sunlit area at 2pm	2.71 m^2	1.27 m^2	2.07 m^2	0.55 m^2

Table 9.1 Sunlit area calculation using the selected types of shading device.

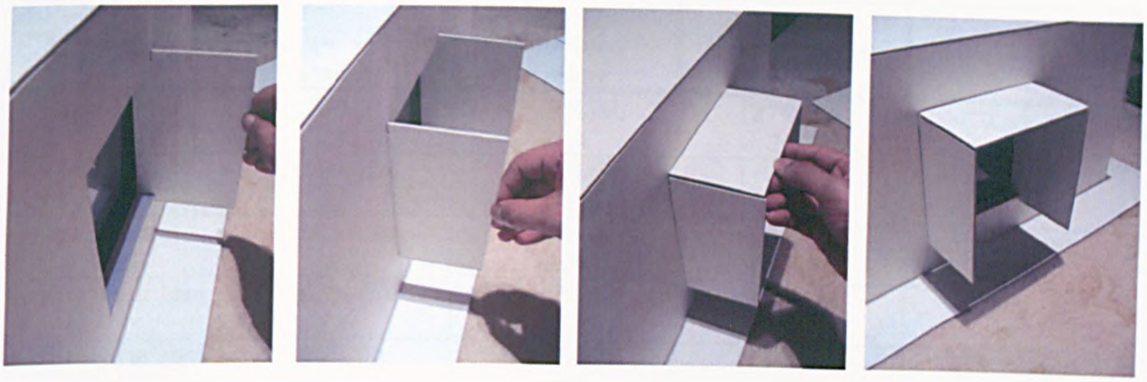


Figure 9.10 Procedure for installing the shading devices on the model window.

9.2.1.7. Discussion and analysis of results

This study aims to investigate sunlit area distribution during winter in Jeddah, Saudi Arabia, as this is obviously higher in winter. Investigations on the solar altitude angles during winter in this location show that the solar noon angle on 21 December is 45.8° at 12:25pm. Such a low sun angle allows solar penetration, even with shading, for natural heating. However, in Jeddah, heating is not required, even during winter, as recent data acquired from a measurement station in Saudi Arabia revealed that the average temperature in Jeddah during December is 24°C and is 21°C in January.

Three main shading methods were selected for this study: horizontal, vertical and egg-crate shading, with results being achieved firstly by using the SunCast model. Moreover, to obtain efficient evaluation results regarding the distribution of the sunlit area, a plain window without shading was used in the first instance. This was followed by investigations to examine the sunlit area distribution using the selected shading methods. Through this study, shaded area percentages could be evaluated for each shading method.

Table 9.2 summarises the results obtained by using the physical model for Jeddah. These results reveal that horizontal and egg-crate shading are the most efficient shading methods to reduce the sunlit area when compared with the vertical shading. The double effect of egg-crate shading reduces the high amounts of penetrated solar radiation and this is required during overheating hours even in winter in Jeddah.

The following results can also be observed in Figure 9.11: the reduction of solar penetration at 10am by using horizontal shading is fairly similar to the results achieved by using vertical shading due to the low solar altitude angle (33.6°) and the azimuth angle (151.23°). These were similar to the results achieved by SunCast. Afterwards, the sunlit area starts to increase when using vertical shading and to decrease when horizontal shading is used. Horizontal shading eliminates the solar radiation caused by the high angle of the sun.

Type of shading	Window without shading	Horizontal shading	Vertical shading	Egg-crate shading
Sunlit area at 10am	**(100%)Ex** 3.11	**(29.9%)Sh** 2.24	**(27%)Sh** 2.27	**(72.6%)Sh** 0.85
Sunlit area at 11am	**(100%)Ex** 2.8	**(45.7%)Sh** 1.52	**(17%)Sh** 2.32	**(69%)Sh** 0.87
Sunlit area at 12am	**(100%)Ex** 2.5	**(56.8%)Sh** 1.08	**(2.8%)Sh** 2.43	**(58.4%)Sh** 1.04
Sunlit area at 1pm	**(100%)Ex** 2.6	**(55.7%)Sh** 1.15	**(19%)Sh** 2.1	**(71%)Sh** .75
Sunlit area at 2pm	**(100%)Ex** 2.71	**(53.1%)Sh** 1.27	**(23%)Sh** 2.07	**(79.7%)Sh** 0.55

Table 9.2 Sunlit area calculations including the shaded area percentages using the selected types of shading device. (Ex is the exposed area, Sh is the shaded area.)

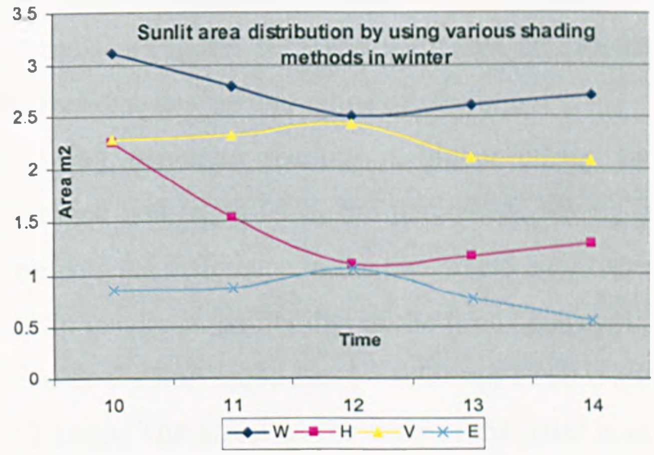


Figure 9.11 Comparison of the results achieved using the selected types of shading device.

The effect of vertical shading at noon is negligible. Figure 9.11 shows that there is no significant difference between the amounts of sunlit area distribution at noon by using vertical shading or a plain window. However, vertical shading reduces the penetrated sunlit area during the morning and afternoon hours. Vertical shading produces a negligible effect and this can also be observed through the performance of the egg-crate shading. At noon, the effect of horizontal and egg-crate shading is fairly similar. Egg-crate shading represents the most efficient shading in reducing solar penetration as sufficient amounts of solar radiation will be allowed to penetrate for natural lighting. Results also reveal, however, that horizontal shading is an efficient method to reduce internal solar penetration.

The efficiency of horizontal shading is at its peak at noon while the efficiency of egg-crate shading is at its lowest level at this time, as can be observed in Figure 9.11. The highest amount of sunlit area distribution is achieved by using vertical shading while the internal penetration of the sunlit area when using horizontal and vertical shading is at its highest level at noon. In Saudi Arabia, horizontal shading is the most efficient shading method as it is highly effective against the high solar altitude angle in this region. Moreover, such a simple shading method could be easily installed and would cost less. (A study on shading cost in Saudi Arabia is conducted later in this chapter.)

A study of the percentage of shaded area using the selected shading methods shows that the maximum shading percentage is achieved by using egg-crate shading. The results for shading ratios in this study were achieved by comparing the result of each shading method during the selected period of time and comparing these with the results for the plain window. Figure 9.12 illustrates that the highest shading percentage (79.7 %) was achieved at 14 h. By using horizontal and egg-crate shading at noon the results for these two types of shading are fairly similar due to the similarity in their configuration.

On the other hand, low shading percentages were obtained when using vertical shading. Due to the high sun angle at noon and the configuration of the vertical shading, the lowest percentage was achieved at this time by using this method. It can be observed, by comparing results achieved in both graphs in Figures 9.11 and 9.12, that an indirect proportion is achieved between the sunlit area distribution and ratios of shading.

The shading ratio achieved by using egg-crate shading is higher during the afternoon than in the morning. As mentioned before, at 14 h, the percentage saving is 79.7%, while it is 72.6 % at 10 h. This reflects the difference in the penetrated sunlit area internally at both hours and this variation in results is mainly due to the time of the solar noon angle, which is around 12:25 h. Similar shading ratios can be achieved at 10 h and 14 h if the solar noon angle occurs at 12 noon. The effect of the time of the solar noon angle is also much clearer on shaded area ratios achieved by using horizontal shading where, at 10 h, the shading ratio is 29.9% and where it is 53.1% at 14 h. Due to the vertical shading configuration, the solar noon angle will not have a significant effect on the shading ratios, as shown in Table 9.2. At 10 h, the shading ratio is 27% and is 23% at 14 h. The solar geometry of Jeddah, Saudi Arabia, is discussed in detail later in this chapter.

A comparative study was conducted and recorded in the following section to assess the results achieved using both the physical model and the SunCast model. The set-up of the experiments was the same in both experiments to achieve comparable results.

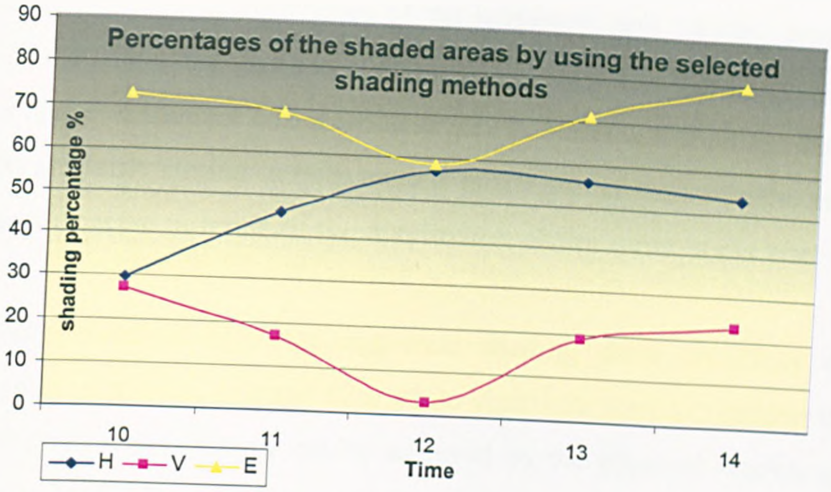


Figure 9.12 Comparison of the shading percentage results achieved using the selected types of shading device.

9.2.1.8. Comparative study of the scaled model results and the SunCast model results (21 December)

For added accuracy, the experiments were conducted using a computer model. The model used was SunCast, which is one part of the IES program. SunCast is a powerful tool used for investigating the impact of the sun on buildings. Visualisations of both shading and solar penetration can be obtained by using this model and also analyses of the solar geometry for any location can be investigated in detail. (More detail regarding the SunCast model is presented in the appendices.) Figure 9.13. illustrates the distribution of the internal sunlit area on the room's floor using a scaled physical model and the IES SunCast model.

Eight curves are presented in this figure and each curve demonstrates the distribution of the sunlit area during the selected period of time. Four curves were produced by using a scaled physical model and four curves were produced by using the SunCast model. The sunlit area was also measured through the window without shading to assess the efficiency of the selected shading methods. In this case, the results achieved by both models were quite similar, especially during the afternoon at 13 h and 14 h. However, during the morning, differences were slightly higher but within an acceptable range.

The results achieved by using horizontal shading show higher levels of difference during the morning hours. However, similar results were achieved at noon while the results for 13 h. reveal that the sunlit area distribution shown in the physical model is higher at 10 h. At 10 h, the performances of the horizontal and vertical shading are the same because of the low winter sun angle although the results achieved by using vertical shading show a higher difference rate than those for the horizontal shading. The only time when the results are fairly similar in both models is at 12 h, as shown in the graph. In the results, variations increase in terms of the distribution of the sunlit areas after and before noon.

The results achieved by using egg-crate shading show similarity during the morning hours (that is, at 10 h, 11h and 12h) while variations start to manifest themselves at 13 h. The sunlit area distribution results achieved by the physical models and by the SunCast model in Jeddah during winter (21 December) are generally similar. However, differences in the results are logical because of the differences in the way the sunlit area is calculated. Furthermore, the time base of the calculation was different in the two selected models. The physical model calculation was based on local time whereas the SunCast model was based on the CIBSE calculation which, in turn, is based on a solar time calculation. The discrepancy rate for the sunlit areas distribution and for the percentages is calculated accurately in the following section. Moreover, the distribution of the sunlit area distribution was recalculated for the summer period (21 June) using both models.

	Physical model results				SunCast model results			
Shading type	Without shading	Horizontal shading	Vertical shading	Egg-crate shading	Without shading	Horizontal shading	Vertical shading	Egg-crate shading
Time								
10	3.11	2.24	2.27	0.85	2.99	1.81	1.93	0.81
11	2.8	1.52	2.32	0.87	2.68	1.35	2.16	0.89
12	2.5	1.08	2.4	1.04	2.56	1.12	2.43	1.01
13	2.6	1.15	2.1	0.75	2.58	1.16	2.35	0.97
14	2.71	1.27	2.07	0.55	2.74	1.45	2.1	0.87

Table 9.3 Comparison of the scale model results and the IES model results for the selected shading devices.

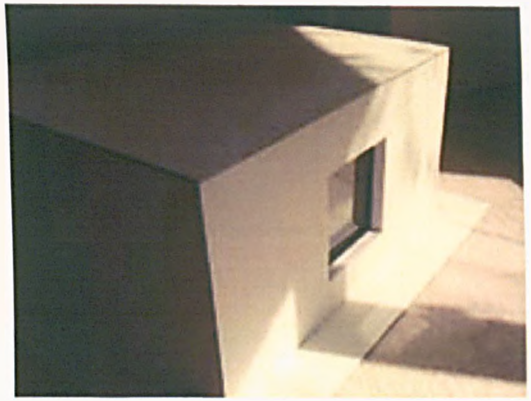
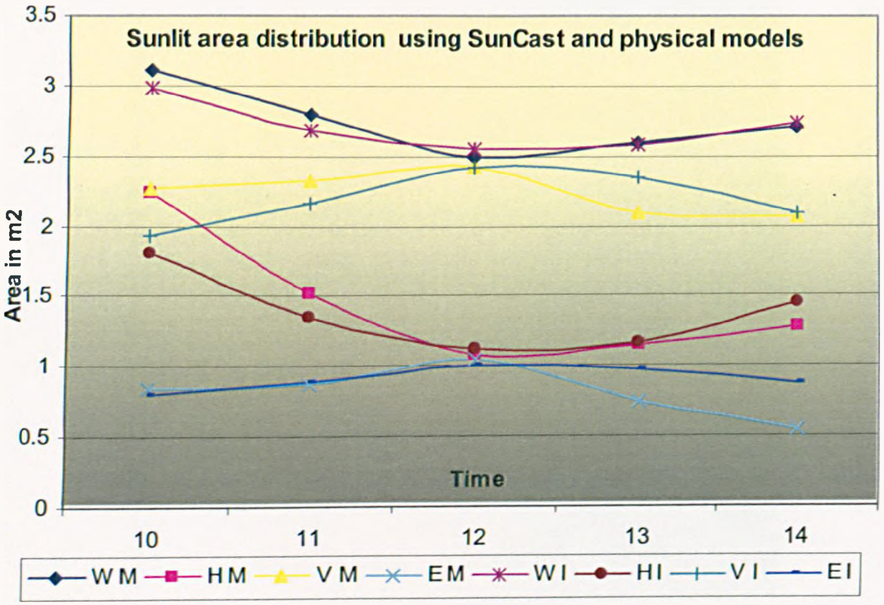


Figure 9.14 Physical model in Jeddah.



W M	W shading Ph model
H M	H shading Ph model
V M	V shading Ph model
E M	E shading Ph model
W I	W shading SunCast
H I	H shading SunCast
V I	V shading SunCast
E I	E shading SunCast

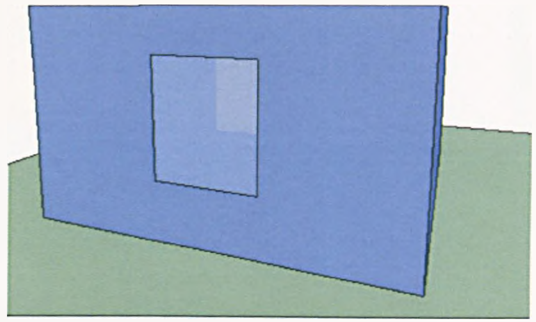


Figure 9.15 SunCast model in Jeddah.

Figure 9.13 Graph showing the comparative study of the scale model and the IES model results for the selected shading devices

9.2.1.8.1. Discrepancy assessment of the two experiments (the physical model and the SunCast model)

Shading type	Time	Physical model results (m^2)	SunCast model results (m^2)	Discrepancy	Discrepancy percentage
Without shading	10	3.11	2.99	0.12	3.85%
	11	2.8	2.68	0.12	4.28%
	12	2.5	2.56	-0.06	2.4%
	13	2.6	2.58	0.02	0.76%
	14	2.71	2.74	-0.03	1.10%
Horizontal shading	10	2.24	1.81	0.43	19.19%
	11	1.52	1.35	0.17	11.18%
	12	1.08	1.12	-0.04	3.70%
	13	1.15	1.16	-0.01	0.86%
	14	1.27	1.45	-0.18	14.17%
Vertical shading	10	2.27	1.93	0.34	14.97%
	11	2.32	2.16	0.16	6.89%
	12	2.43	2.43	-0.03	1.25%
	13	2.1	2.35	-0.25	11.90%
	14	2.07	2.1	-0.03	1.44%
Egg-crate shading	10	.85	.81	0.04	4.70%
	11	.87	.89	-0.02	2.29%
	12	1.04	1.01	0.03	2.88%
	13	.75	.97	-0.22	29.33%
	14	.55	.87	-0.32	58.18%

Table 9.4 Discrepancy assessment of the results of the two experiments.

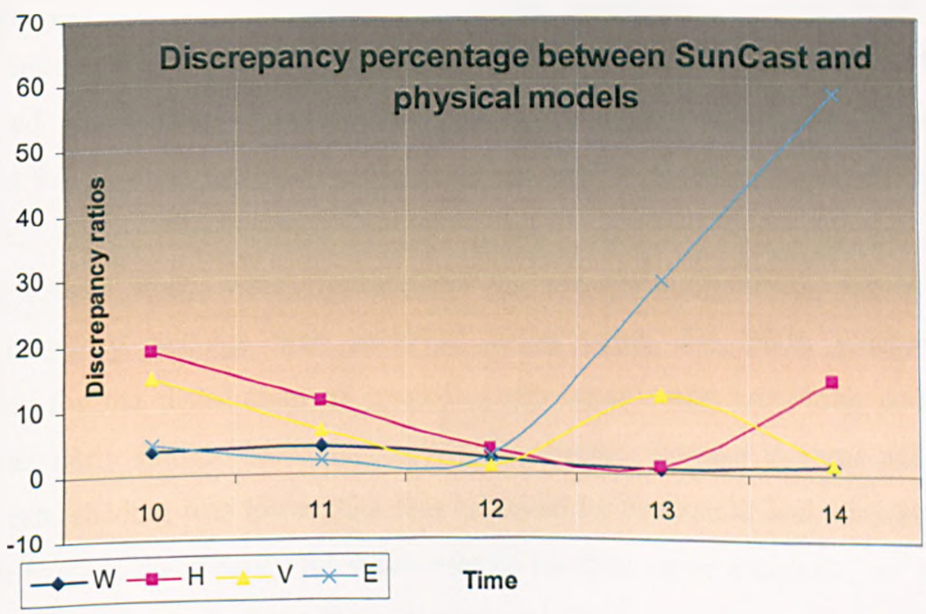


Figure 9.16 Discrepancy percentage between the SunCast and the physical models.

As a part of the validation process to analyse the methods selected here, a discrepancy study was conducted. The results of the sunlit area investigations examined in the physical model were compared with the results achieved using the SunCast model to evaluate the differences in percentage between the two models. Figure 9.16, which shows the discrepancy rate in winter, indicates that the discrepancy rate is largely within 20%. Such a difference can be interpreted as a satisfactory outcome from the results for the selected methods. However, a slightly high discrepancy rate can be noted for the egg-crate shading at 14h (this is a discrepancy rate of around 58%), while the lowest discrepancy rate can be seen in the case of the plain window.

Variations in discrepancy increase with the performance of different shading methods. Vertical shading presents the least variation among the selected shading methods while, on the other hand, egg-crate shading represents the highest discrepancy rate. Measuring such small sunlit areas on the internal surface of the physical model could lead to inaccuracies due to unavoidable manual error which could be one of the reasons for the increased discrepancy rate. Moreover, differences in value are fairly acceptable in cases such as where, for example, the penetrated sunlit area at 14 h is 0.55 m^2 using the physical model and 0.87m^2 at the same time and using the same shading method when working with the SunCast model.

To increase the efficiency of the evaluation, a study of the average discrepancy percentages and areas was conducted; this is shown in Figures 9.17 and 9.18. As shown also in Table 9.6, the lowest discrepancy percentage average was obtained in the case of the plain window; this was 2.4%. The highest discrepancy average rate was 19.4 %; this was achieved when using egg-crate shading. The average discrepancy for horizontal shading was 9.8 % while the discrepancy study for vertical shading showed only a 7.2 % average rate.

The second study, which investigated the average sunlit areas, shows that the lowest discrepancy average was achieved when using the plain window while discrepancies for the distribution of internal sunlit areas using horizontal and vertical shading were fairly similar. Nevertheless, the discrepancy average in areas achieved by using egg-crate shading was lower than that achieved by horizontal and vertical shading. Overall, the average discrepancy for sunlit area in the four cases was 0.131 m^2 while the percentage discrepancy in the same four cases was 6.65 %.

Generally, the discrepancy rates of results achieved by using the physical model and the SunCast model are fairly similar. However, discrepancies occur mainly because of the differences in the calculation methods used in the two models. Calculations in the SunCast model are based on CIBSE calculations which, in turn, are based on solar time, while the calculations used in the physical model are based on local time.

Area discrepancy averages in the four cases

Case 1	Case 2	Case 3	Case 4
Plain window	Horizontal shading	Vertical shading	Egg-crate shading
0.07m^2	0.166 m^2	0.162 m^2	0.126 m^2
Av	.131 m^2		

Table 9.5 Discrepancy averages in the four cases.

Percentage discrepancy averages in the four cases

Case 1	Case 2	Case 3	Case 4
Plain window	Horizontal shading	Vertical shading	Egg-crate shading
2.4 %	9.8 %	7.2 %	19.4 %
Av	6.65 %		

Table 9.6 Percentage discrepancy averages in the four cases.

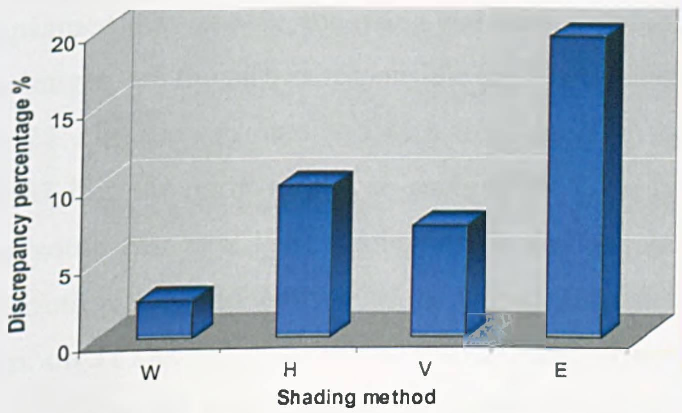


Figure 9.17 Graph showing the overall discrepancy percentage (%) for the selected shading devices.

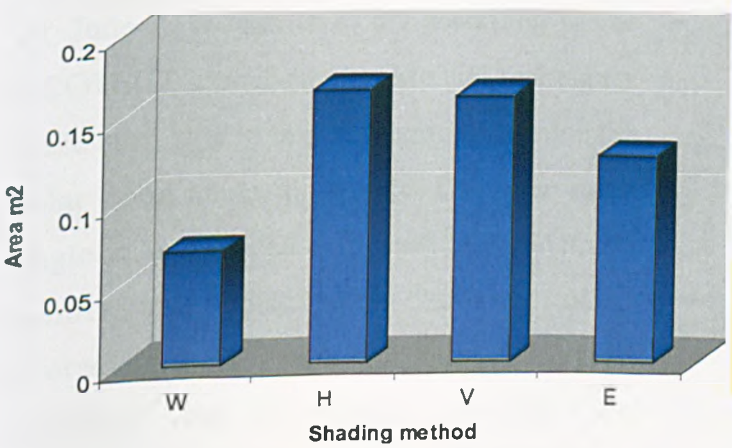


Figure.9.18. Graph showing the overall discrepancy area (m$^{2)}$ for the selected shading devices

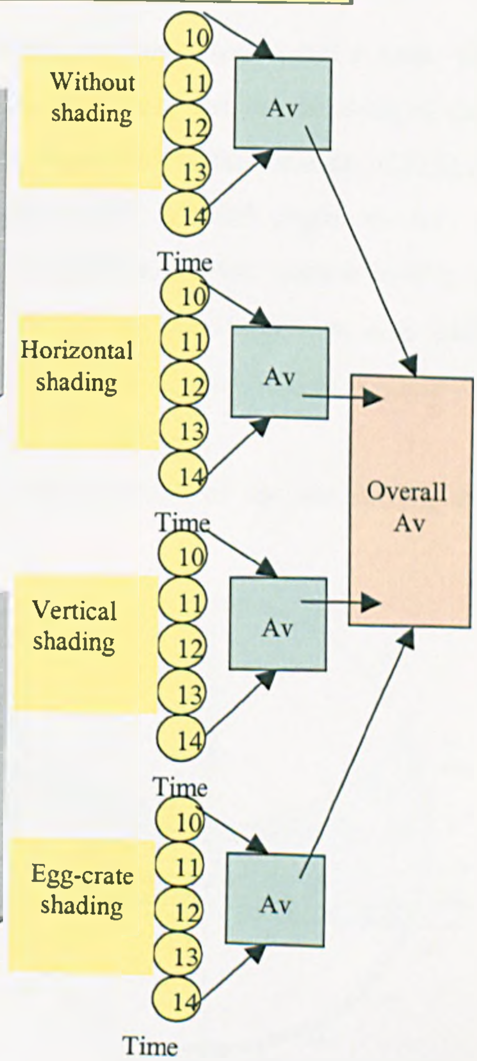


Figure 9.19 Illustrative diagram to show the overall average calculation process.

9.2.1.9. Solar geometry in Jeddah, Saudi Arabia

Studies on sun path diagrams are important elements in investigating sunlit area penetration and investigating the sun path diagram for Jeddah shows that, at noon, the sun is not at its highest position. Initial investigations showed that the solar noon angle in Jeddah occurs at around 12:25 h. The position of the solar noon angle in Jeddah can be observed in Figure 9.22 which shows the internal sunlit distribution at various times on 21 December. An investigation into the sun's position during summer shows that, on 21 June, the sun's position will have shifted slightly to the north. This will prevent sunlit area penetration from occurring at this location during the summer through the south window although the sunlight will penetrate the room through other window orientations as the sun will be directly above the building. The investigation in Chapter 7 related to latitude 20° N, which is fairly close to Jeddah, emphasised this shifting in the sun's position. This was illustrated in the studies on the sunlit area shown in the first graph in Figure 7.1

Roger (2004) illustrated the factors that affect variations in the sun's path. He explained that latitude, the rising and setting positions of the sun, and the duration of day and night, are the factors responsible for this variation. According to the location of Jeddah on 21 Jun, the sun rises at 5:46 h from the north-east at a 65° azimuth angle and sets at 19:03 h in the north-west at an angle of 295°. On 21 December, the sun rises at 6:47 h in the south-east at a 115° azimuth angle and sets at 17:36 h in the south-west at a 245° azimuth angle. The duration of the day on 21 June is 12 h and 16 min. and is 9 h and 49 min. on 21 December, a difference of three hours and seven minutes.

The sun path diagram for Jeddah shows the high position of the sun during the summer period as the solar altitude angle on 21 June in Jeddah is 87.5°, according to the ECOTECT model results. Manual techniques were used later in this chapter to determine the solar noon angle in Jeddah. The solar noon angle in Jeddah also will cause unsymmetrical sunlit area distribution around noon. Moreover, such a high sun angle will cause intensive heat in summer although the intensity of solar radiation is fairly high in Saudi Arabia in any case. According to the

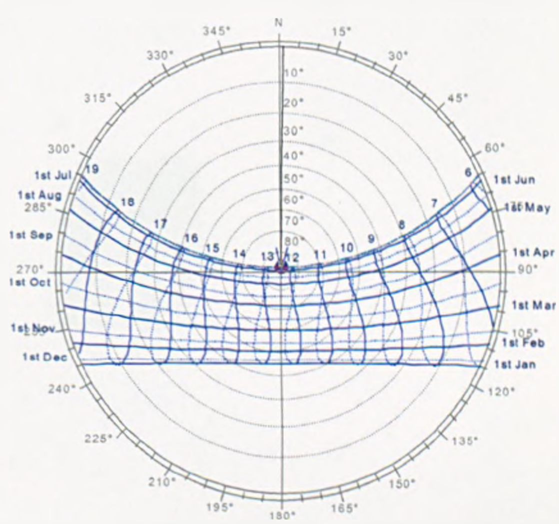


Figure 9.20 Sunpath diagram for Jeddah, Saudi Arabia, showing the sun's position at noon (ECOTECT).

CIBSE guide, Vol. A (1988), solar irradiance on horizontal surfaces at latitude 20° N is 915 W/m^2 at noon on 21 June while, at latitude 25° N, solar irradiance is 910 W/m^2.

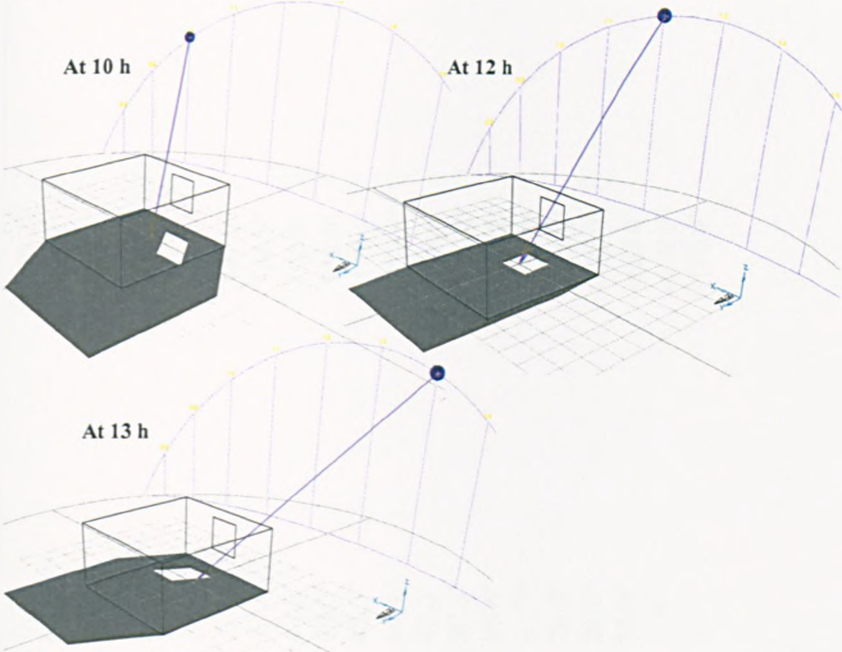


Figure 9.21 Solar geometry of the sun in Jeddah on 21 December with perspectives of the model showing the solar altitude angles of the sun at 10h, 12h and 14h through the window without shading. Note the changing sunlit area penetration at these times (Ecotect, Square one).

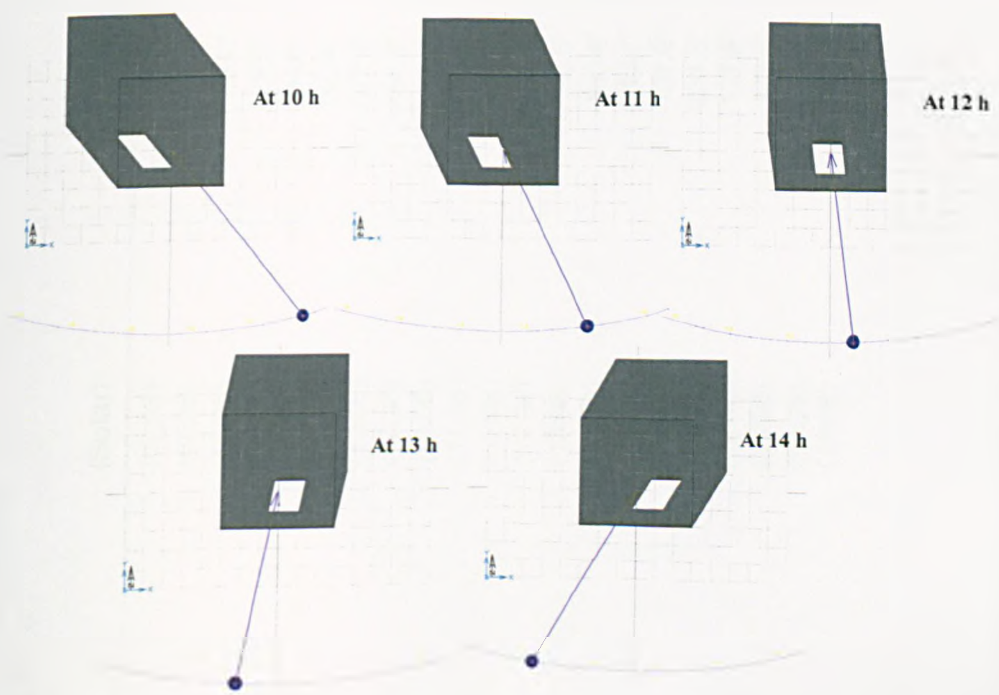


Figure 9.22 Solar geometry of the sun in Jeddah on 21 December with plans of the model showing the solar altitude angles of the sun at 10h, 11h 12h, 13h and 14h through the window without shading. Note the changing sunlit area penetration at these times (Ecotect, Square one).

Latitude: 21.2°
Longitude: 39.1°
Timezone: 45.0° [+3.0hrs]
Orientation: 0.0°

Date: 21st December
Julian Date: 355
Sunrise: 07:00
Sunset: 17:42

Local Correction: -21.4 mins
Equation of Time: 2.1 mins
Declination: -23.5°

Local	(Solar)	Aziumuth	Altitude	HSA	VSA
07:30	(07:08)	118.2°	6.2°	118.2°	167.0°
08:00	(07:38)	121.4°	12.3°	121.4°	157.4°
08:30	(08:08)	125.2°	18.1°	125.2°	150.4°
09:00	(08:38)	129.5°	23.7°	129.5°	145.4°
09:30	(09:08)	134.6°	28.9°	134.6°	141.8°
10:00	(09:38)	140.4°	33.6°	140.4°	139.2°
10:30	(10:08)	147.2°	37.7°	147.2°	137.3°
11:00	(10:38)	154.9°	41.1°	154.9°	136.0°
11:30	(11:08)	163.6°	43.6°	163.6°	135.2°
12:00	(11:38)	173.0°	45.0°	173.0°	134.8°
12:30	(12:08)	-177.2°	45.3°	-177.2°	134.7°
13:00	(12:38)	-167.6°	44.4°	-167.6°	135.0°
13:30	(13:08)	-158.5°	42.3°	-158.5°	135.6°
14:00	(13:38)	-150.4°	39.3°	-150.4°	136.7°
14:30	(14:08)	-143.2°	35.5°	-143.2°	138.3°
15:00	(14:38)	-137.0°	31.0°	-137.0°	140.6°
15:30	(15:08)	-131.6°	26.0°	-131.6°	143.7°
16:00	(15:38)	-127.0°	20.5°	-127.0°	148.1°
16:30	(16:08)	-123.0°	14.8°	-123.0°	154.1°
17:00	(16:38)	-119.5°	8.8°	-119.5°	162.5°
17:30	(17:08)	-116.5°	2.7°	-116.5°	174.1°

Table 9.7 Tabulated daily solar data for Jeddah, Saudi Arabia.

9.2.2. Summer Physical Model Experiments in Jeddah, Saudi Arabia

9.2.2.1. Introduction

The summer experiments, also focusing on Jeddah, constitute the second assessments of the sunlit area following the winter experiments that were performed in December 2003. A clear understanding of Jeddah's solar charts and shading angles was necessary in order to perform efficient shading experiments. It was also necessary to investigate shading techniques for different window orientations because of the solar altitude in this location (21.2 N° in June), and especially as there is no penetration of sunlight through the south window. This study was carried out through three initial experiments and by using three computer programs: ECOTECT, ArchiCAD and SunCast. Olgyay (1963) noted that, in winter, south-facing façades could receive three times more solar radiation than west and east façades. However, in summer, the solar radiation received by the north and south façades might only be half of that received on the east and west elevations. This can be clearly seen in lower altitudes.

These experiments were performed in June to investigate the performance of the selected shading devices and the main focus of the experiments was to investigate the effect of the shading devices on the distribution of the sunlit area on the internal surfaces. Following the process of the previous winter's experiments, these investigations were conducted in two main phases. The first phase was to carry out initial experiments by using the available computer models, ArchiCAD and SunCast. This phase included two sub-phases: the ArchiCAD initial experiments and the SunCast initial experiments, which were performed to predict the results of the main physical model experiments. This, it was hoped, would result in more accurate and efficient results for the whole experiment.

Each of the selected models was set to test the distribution of sunlight, first through the south window, while a second experiment was conducted to examine the sunlit penetration to the internal surfaces through the east and west windows.

The second phase comprised the physical model experiments. These are the main experimental assessments designed to investigate the distribution of the sunlit area through different configurations of shading device. In addition to the investigation of the east and west windows in summer, other orientations were investigated in the experiments. This phase included six main sub-phases: model orientation selection, model set-up, initial data collection, assessment of the initial data, main data collection, and the final data analysis. These two phases are explained in detail, including the sub-phases, in the following section.

9.2.2.2. Phase One: Initial experiment using the computer models (ArchiCAD and SunCast)

9.2.2.2.1. ArchiCAD model experiments on the south window

These experiments were performed to investigate the distribution of the sunlit area to the internal surfaces of the selected model. The period and location of the experiments were peak summer (21 June) in Jeddah (latitude 21.19 °N, 39.12E). The ArchiCAD simulations showed that there is no penetration of the sunlit area on the model's internal surfaces in this month (June). Due to the high altitude of the sun in the summer in Jeddah, the sunlight is prevented from penetrating inside the model through the south window.

Figure 9.23 Internal view of the room's floor. There is no sunlit area distribution in June in Jeddah.

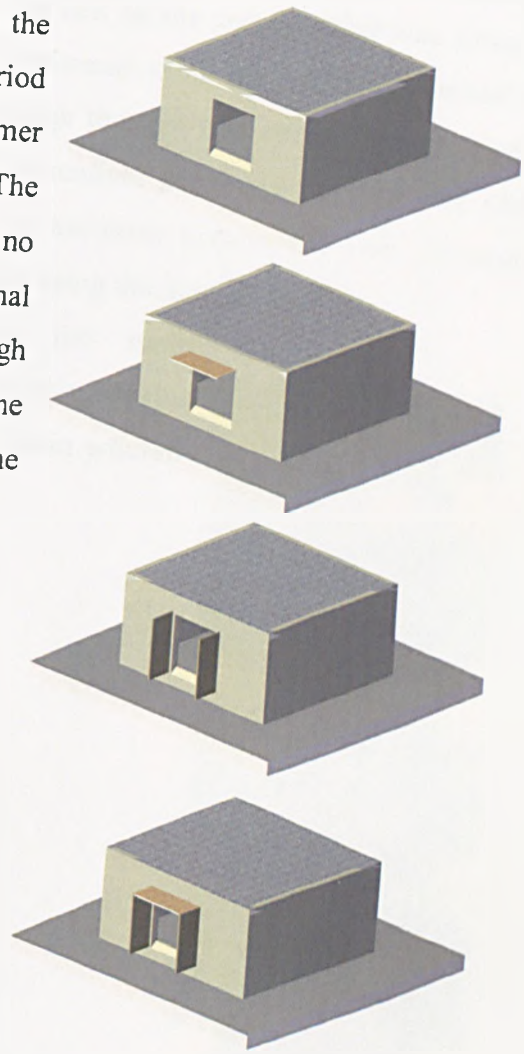


Figure 9.24 Shading device configurations, designed by using the ArchiCAD model.

Time	Without shading	Horizontal shading	Vertical shading	Egg-crate shading
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0

Table. 9.8 ArchiCAD results, which show that there is no sunlit area penetration on 21 June in Jeddah.

9.2.2.2.2 ArchiCAD model experiments on the east and west windows

Due to the sunlit area distribution results achieved regarding the south window, experiments were carried out to examine the distribution of the sunlit area through the east and west windows in the model. Two openings were designed with the same dimensions as the south window. One opening was located on the east façade and the other was situated on the west façade. Then, an initial study was performed using the ArchiCAD model to assess the amount of sunlit area distribution through the east and west openings. These experiments showed that a reasonable amount of sunlight penetrates the east and west windows on 21 June, unlike the south window at the same time of the year. Accurate results regarding the sunlit areas were achieved later using the SunCast model.

Results were achieved by examining the sunlit distribution by using the three main types of shading device (horizontal, vertical and egg-crate shading) and a plain window in order to assess shading performance.

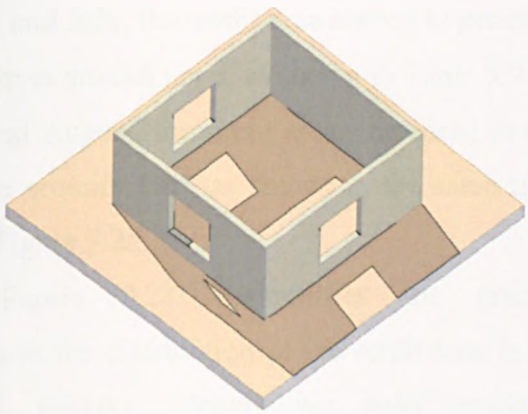


Figure 9.25 Summer experiments (ArchiCAD model perspective) using south, east and west windows.

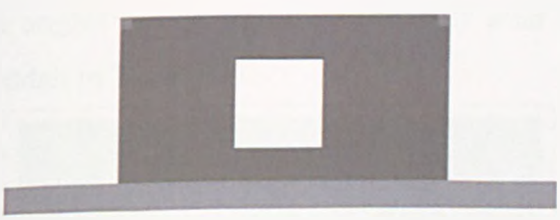


Figure 9.26 Summer experiments: ArchiCAD model elevation.

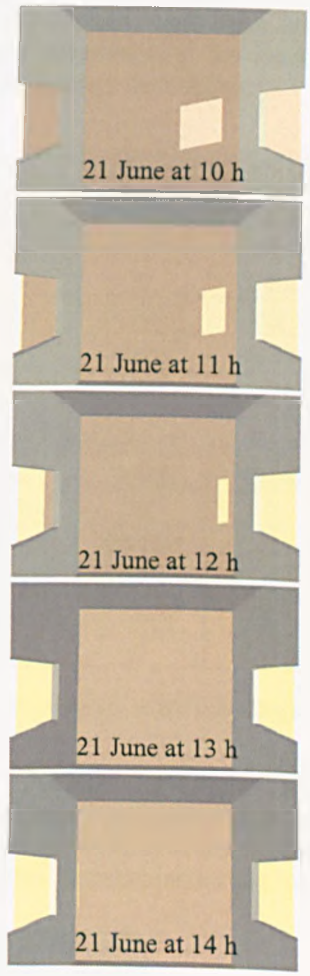


Figure 9.27 Summer experiments (ArchiCAD model internal views). Penetration of the sunlit areas through the east and west window openings.

9.2.2.2.3. SunCast model experiments on the south window

Experiments conducted using SunCast enhanced the results achieved by the ArchiCAD model which showed that there is no penetration of the sunlit area on 21 June in Jeddah through the south window. This, as explained earlier, is due to the high altitude of the sun in June in this location (Jeddah, Saudi Arabia).

Experiments were also conducted to examine the distribution of the sunlit area in other months. The selected months were the two months before and after June, (that is, April, May, July and August). A window without shading was selected for the experiment as, in this case, the distribution of the sunlight would not be prevented by the shading devices. Investigations showed that there is no penetration of the sunlit area through the window to the internal surfaces in June. However, in May and July, the sunlit area started to penetrate the room at around noon, as shown in Table 9.9. In April and August, the sunlit areas increased in size to reach around .5m², as shown in the same table and in Figure 9.28.

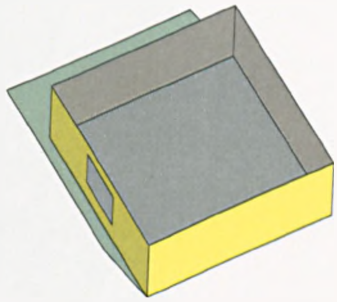


Figure 9.29 Jeddah model view on 21 June at 10am, when there is no sunlight penetration to the internal surfaces through the window.

	Direct Sunlight (on the floor)		
Time	June	July	Aug
10:00	0	0	$0.31m^2$
11:00	0	0	$0.4m^2$
12:00	0	$0.04m^2$	$0.43m^2$
13:00	0	$0.04m^2$	$0.43m^2$
14:00	0	0	$0.39m^2$

	Direct Sunlight (on the floor)		
Time	Apr	May	June
10:00	$0.33m^2$	0	0
11:00	$0.41m^2$	$0.01m^2$	0
12:00	$0.44m^2$	$0.06m^2$	0
13:00	$0.44m^2$	$0.05m^2$	0
14:00	$0.4m^2$	0	0

Table 9.9 Amount of sunlit area penetration in June, April, May, July and August through the window of the selected model for Jeddah (SunCast model results).

Figure 9.28. exemplifies the gradual increase in the distribution of the sunlit area in the selected months. Undertaking solar mapping through the model window shows gradual increases in the sunlit area in April, May, July and August. This is due to the solar altitude angle. These angles can be read from the daily solar data for Jeddah in Table 9.11.

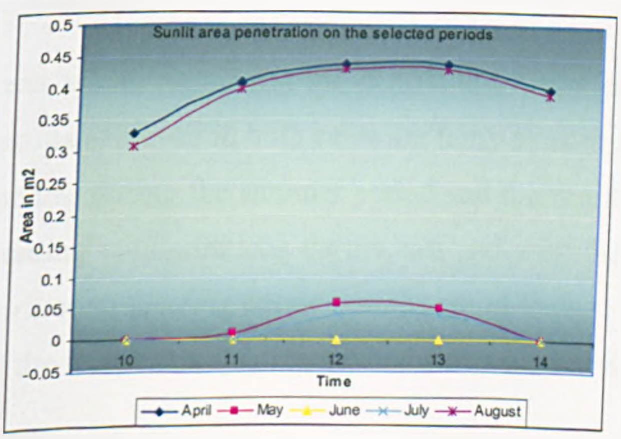


Figure 9.28 Sunlit area penetration in the selected periods.

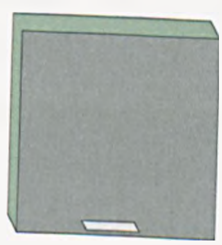


Figure 9.30. Jeddah model view on 21 April at noon, when there is sunlight penetrates to the internal surface.

9.2.2.2.4. SunCast model experiments on the east and west windows

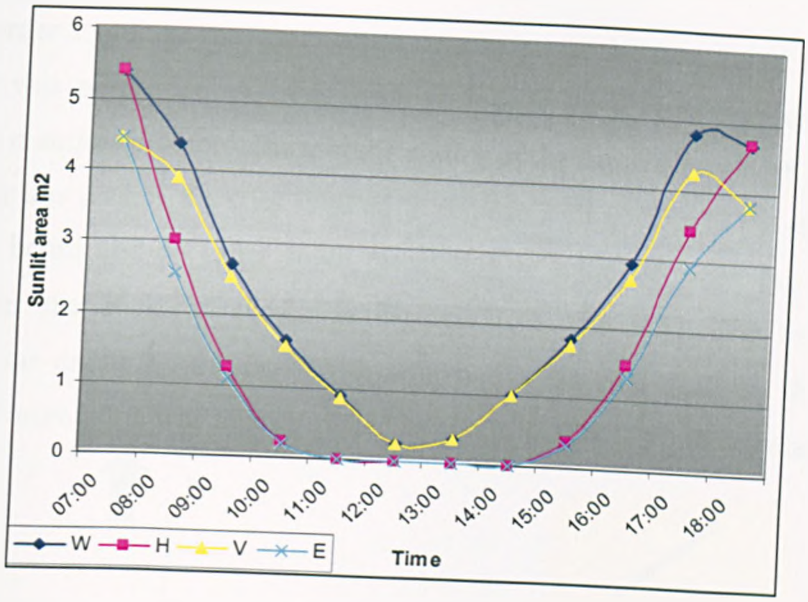


Figure 9.31 SunCast model summer results.

Figure 9.31. shows the distribution of the sunlit area in summer (21 June) using 1.6m x 1.6m windows on the east and west façades. The sunlit area distribution when using egg-crate and horizontal shading is quite similar as a result of the high solar altitude angle. High similarity rates were also achieved around noon for both shading methods. Furthermore, a similar distribution of the sunlit area was achieved with both the plain window and the vertical shading. The similar distribution in these two cases is mainly a result of the high solar angle and the shading's configuration. Horizontal shading is highly effective against high solar angles which can also be influenced by sunlight distribution by using vertical shading. The differences in the distribution of the sunlit area by using vertical and horizontal shading is clearly shown in the graph; higher levels of sunlight distribution are obtained when using vertical shading.

Moreover, the negligible effect of vertical shading on the sunlit area can be clearly seen when comparing the distribution using plain windows and vertical shading as the results achieved in both cases are fairly similar. Horizontal shading is highly recommended for use during the summer period and the results of this study emphasise using horizontal shading configurations on the east and west façades during the summer in Jeddah. Other horizontal shading configurations could include horizontal louvers and an actual example of the use of this shading method exists on the Muawad building in Jeddah.

9.2.2.2.5. Phase Two: the main physical model experiments

9.2.2.2.5.1. Set-up of experiments

In order to locate the exact south orientation in Jeddah, Saudi Arabia, an initial experiment was performed. A tilted stick was fixed on a circular board to monitor its shadow. As mentioned before, the altitude angles of the sun are very high in Jeddah during summer. For this reason, the stick is tilted to achieve a clear view of the stick's shadow on the circular board and an exact south orientation is achieved when the stick's shade is exactly under the stick, as shown in Figures 9.32. and 9.33. The line of the south orientation was drawn on the floor with reference to the line made by the stick's shade. The model's orientation was then corrected to match the exact south orientation.

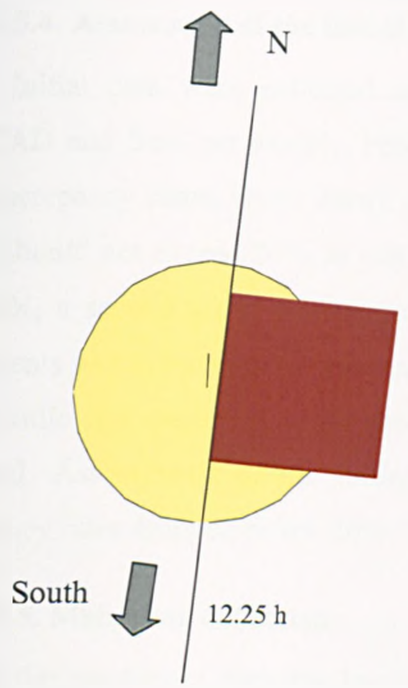


Figure 9.32 Model's orientation according to the stick's shade to locate the exact south.

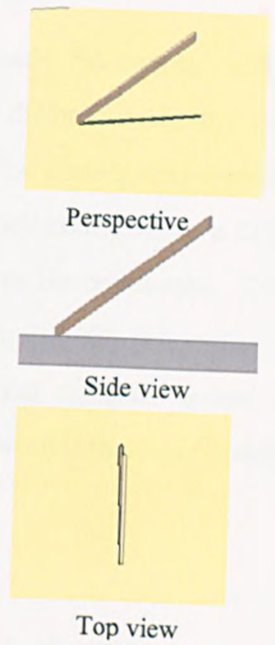


Figure 9.33 Stick shade to pinpoint the exact orientation of south.

9.2.2.2.5.2. Set-up of the model

The original model was constructed with one window opening facing south. From the previous initial investigations, which showed that sunlit area distribution to the internal surfaces occurs through the east and west window openings, the physical model needed to be redesigned. The model was reconstructed with two extra window openings facing east and west. These two openings were to enable the sunlight to penetrate to the internal surface of the Jeddah model during the summer period. The dimensions of the model and the windows were the same as in the original winter experiments and the east and west walls were reconstructed with double layers to achieve more accurate results.

9.2.2.2.5.3. Initial data collection

According to the planned schedule for the experiments, initial experiments were conducted. These experiments were carried out to evaluate the first results that were obtained and to compare them with the results collected using the computer model. These experiments were conducted 3 to 4 days before the date selected for the experiments, which was 21 June. Performing these experiments was to avoid any possible errors in the main experiments conducted later on the selected peak summer day.

9.2.2.2.5.4. Assessment of the initial data

Initial data were collected and compared with the results achieved using the ArchiCAD and SunCast models. Percentages of the differences in the findings, together with discrepancy charts, were drawn and analysed. The discrepancy between both sets of results should not exceed 20% so that if the discrepancy charts show a difference of more than 20%, a second set of assessments would have to be conducted. The second set of experiments would have to be conducted without changing the orientation of the physical model while the measured sunlit areas on the internal surfaces would have to be re-examined. Assessments of the initial experiments would then be continued until the discrepancy rates dropped below 20%.

9.2.2.2.5.5. Main data collection

After reaching a desirable level of discrepancy in the initial experiments, the main experiments were conducted on the selected date (21 June). The results should then have an acceptable level of accuracy. The data, concerning the distribution of the sunlit area on the model's internal surfaces, were collected by using the same techniques and in the same order as in the previous winter experiments. The process of the experiments started with the calculation of the sunlit area distribution through the window without shading; it then continued by using the selected shading techniques.

9.2.2.2.5.6. Final data assessment and analysis

After collecting the final data on the selected date, a comparison was made with the results achieved by the computer model (SunCast) to achieve the final data readings. The results were then analysed and evaluated using graphs and tables. The sunlit area was evaluated in these experiments mainly through the east and west window openings and the effect of the solar geometry of Jeddah on the distribution of the sunlit area was assessed. Furthermore, the effects of the selected shading techniques on the sunlit area distribution were evaluated. Shading methods which affect sunlit area distribution in summer may not have the same effect in winter.

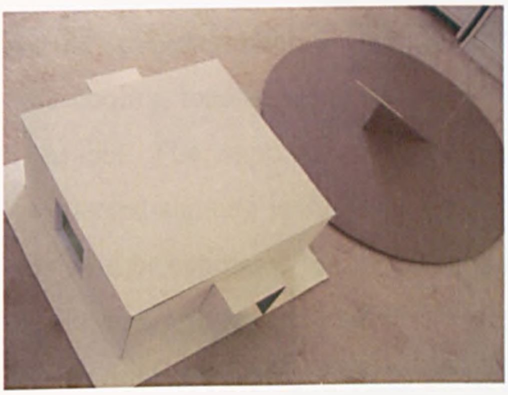


Figure 9.34 The vertical adjustment of the altitude angle tool, reconstruction of the model's walls, the new constructed model and the solar noon angle model tools.

9.2.2.3. Physical model experiments for Jeddah conducted on 21 June. (Results achieved in the summer experiments.)

9.2.2.3.1. Results analysis

The results were presented in two different forms. The first form examines the internal sunlit area distribution against time for the whole of the selected day (21 June). The second form examines the sunlit area distribution on an hourly basis, with each graph representing one hour. The two forms were presented to obtain a more accurate examination of the results and to analyse the results from various directions. The first form of evaluation compared the results from the two methods of achieving sunlit area distribution measurements (the SunCast model and the physical model). This shows the maximum and minimum sunlight distribution during the day.

The second form, which is a comparison of the hourly results, shows the amount of sunlit area for each hour in a separate graph. An assessment in this form helps in analysing and comparing the results from the two measurement methods used for each hour individually.

As can be observed in the graphs, the curves of the sunlit area distribution show the same trend using both selected methods; in other words, the percentages of the sunlit area distribution on the internal surfaces are the same in both the computer and the physical model. However, the amount of the sunlit area is different as the distribution of the solar radiation is higher in the morning and in the afternoon hours. On the other hand, the amount of solar radiation penetrating around 12 noon is lower. These variations of sunlit distribution mainly depend on the solar altitude angle which will be discussed later in this section.

Using the data from the SunCast model, the required cooling load was calculated at the peak sensible hour. The cooling load in watts per hour was then compared with the electricity cost in Saudi Arabia. The required cooling loads were calculated without shading and then with the selected shading techniques for the same room. Consequently, savings in the cooling load could be estimated for all these shading techniques. In general, the measurements of the sunlit area distribution in the physical model were lower than the measurements achieved by the SunCast model. This could be due to unavoidable manual error. The discrepancy between the two methods, as mentioned earlier, could also be due to time constraints in the calculation method.

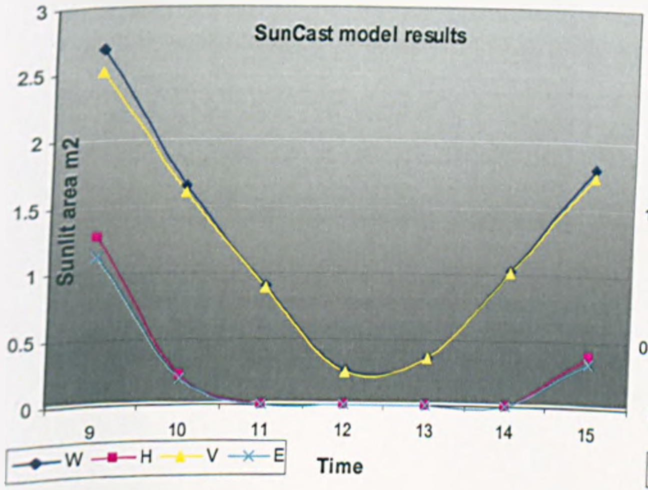


Figure 9.35 Sunlit distribution using different shading techniques in summer (SunCast model results).

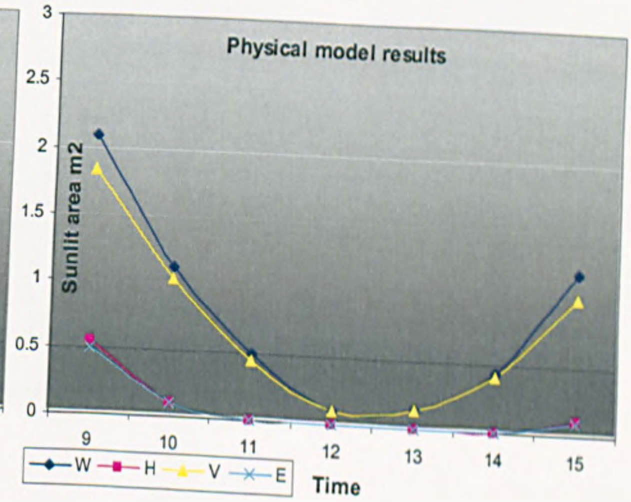


Figure 9.36 Sunlit distribution using different shading techniques in summer (Physical model results).

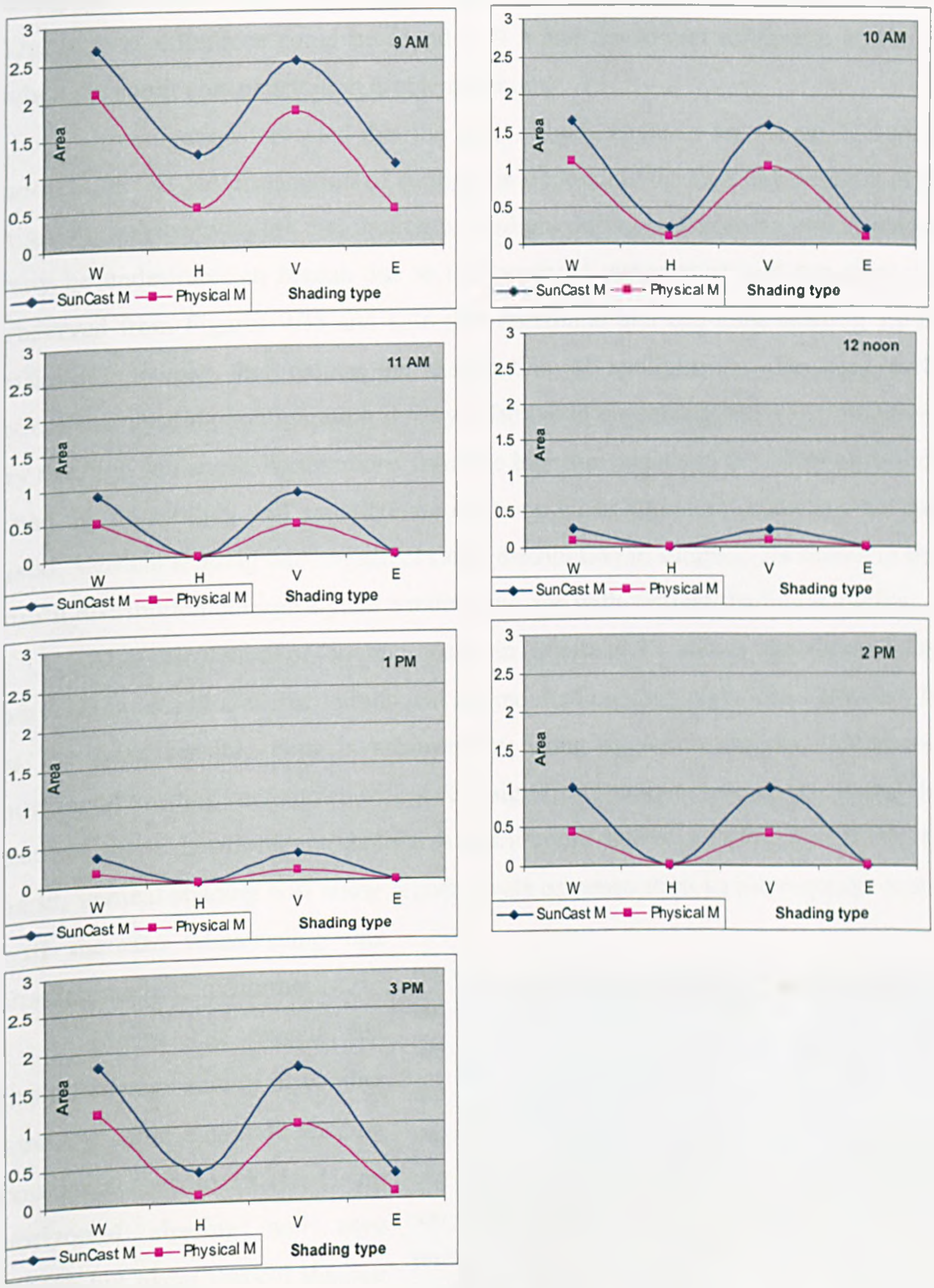


Figure 9.37 Hourly sunlit area distribution results.

The hourly results showed that the calculation of the sunlit distribution achieved by using the SunCast model was slightly higher than that achieved using the physical model. The highest difference could be found at 9 h and the lowest difference at 12h and 13h when the sunlit area penetration is at a minimum.

Investigations revealed that the solar altitude angle in Jeddah on 21 June at solar noon is 88° so the distribution of sunlight is impossible through any window at this very high angle. However, the distribution of sunlight during the morning and afternoon hours may be undesirable in Jeddah due to the increased temperature and sun glare. It can be observed from Figures 9.35 and 9.36 that horizontal and egg-crate shading are the most efficient methods that reduce the distribution of sunlight. As discussed earlier, the horizontal shading configuration is very effective in eliminating the solar radiation caused by the high sun angle. Furthermore, from the high sun angle and the effect of the horizontal shading, no sunlight will penetrate around noon when horizontal and egg-crate shading is used. Vertical shading will not affect sunlit distribution in summer. As shown in the graph, sunlit distribution through a plain window and one with vertical shading is similar.

The calculation of cooling loads in Figure 9.38 shows the direct relationship between the sunlit area distribution and the required cooling loads. The lowest cooling load at the peak sensible hour is achieved by using egg-crate shading. Moreover, using horizontal shading in summer will save a significant amount of cooling. Using these two shading methods will reduce sunlit area distribution, as shown in Figure 9.35. On the other hand, vertical shading will allow higher levels of penetration so the required cooling load will increase when using this shading method in summer.

Figure 9.38 reveals that the percentage saving in cooling load by using egg-crate shading could reach up to 15.2%. Using horizontal shading will save 10.6% but using vertical shading will only save 3.5% of the required cooling load when compared with the window without shading case. This calculation shows that egg-crate and horizontal shading are efficient methods in reducing internal heat gain.

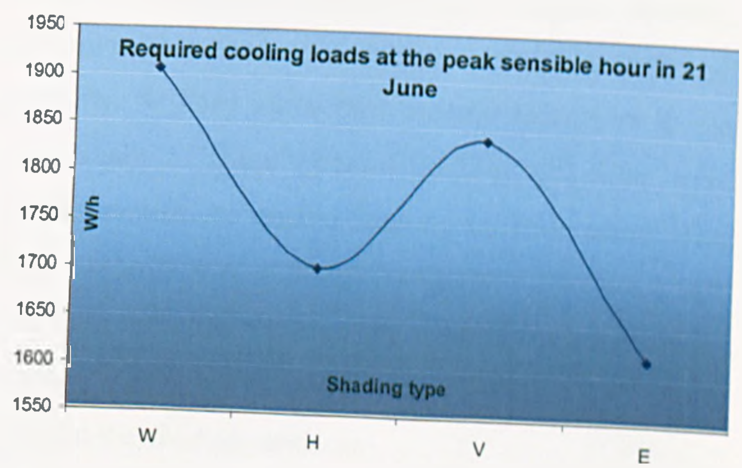


Figure 9.38 Required cooling loads at the peak sensible hour using the selected shading methods in summer.

9.2.2.4. Shading efficiency

Shading problems are a major problem faced by architectural design in hot climate zones. Givoni (1976) noted that various methods are available to examine the efficiency of fixed shading devices. One of these methods is the constructed model which can be used under artificial or natural light. He also added that sufficient shading could be achieved by using egg-crate shading while extra efficiency can be obtained when using vertical shading tilted at 45° to the south. Horizontal shading is characterised by higher efficiency rates against vertical shading (Givoni, 1976).

A lower rate of efficiency is achieved in the summer months by using vertical shading. This can be seen in the previous results which show that there is no significant difference between the sunlit area distribution with vertical shading and the plain window. Comparing these two curves, (the plain window curve and the vertical shading curve) shows the low efficiency of the vertical shading in summer in this region. Vertical shading could be much more effective with the east and west elevations when it consists of multi- or tilted louvers to prevent the penetration of solar radiation, as noted by Szokolay. (2004). Results also indicate that horizontal shading is suitable for east and west window orientations.

Fixed horizontal and egg-crate shading are efficient shading techniques due to the following: 1. They are easy and simple to construct and they do not require highly skilled labourers to fit them. 2. The cost of this type of shading is not generally expensive, especially in Saudi Arabia. 3. This shading shows efficient performance; it can prevent solar radiation from reaching the window's surface. Tinted or reflective glass shading, which allows the sunlight to reach window's surface, causes higher solar heat gain and therefore elevates the indoor temperatures. 4. They allow considerable reductions in the required cooling loads, as shown previously. 5. These types of shading will allow solar radiation to penetrate during the winter months for natural heating. 6. They could offer aesthetic architectural elements when considered at an early design stage.

Tilted shading devices can be more efficient for east and west façades. However, the tilted angle needs to consider the sun's path in the desired location. Alzafarani (2003) suggested that the shading angle on the west façade should be parallel to the sun's path to achieve as efficient a performance as the horizontal shading on the south façade.

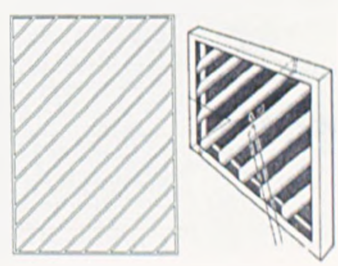
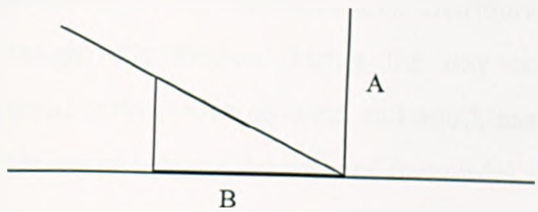


Figure 9.39 Tilted shading devices.

9.2.2.5. Manual calculation of the highest solar altitude angle in Jeddah

A circular wooden board of a 1.2 m radius was used to calculate the solar noon angle in Jeddah. Two elements were fixed on the board to cast a shadow on its surface. The first element was the stick, which was used in the previous winter's experiments, while the second element was a triangle with an extended stick, which was used to cast a longer shadow on the board in summer. This extended element was used because of the high altitude angle of the sun in Jeddah as, consequently, the length of the shadow was too short and could not be seen. The length and angle of this element cast sufficient shade on the board, making the stick's shade visible. The solar altitude angle was calculated for 11am, 12 noon, 12:30, 1pm and 2pm.



A= 30 cm,

where A is the vertical stick length and B is the shadow length.

B	Time	Value	Manual Alt Angle calculation	ECOTECT Alt Angle calculation
B1	10	16	62.0°	56.5°
B2	11	9	75.0°	70.2°
B3	12	2	86.0°	84.0°
B4	12:25	1.4	88.0°	87.5°
B5	13	7.5	77.0°	81.6°
B6	14	13.5	67.0°	68.0°

Table 9.10 Manual and ECOTECT altitude angle results.

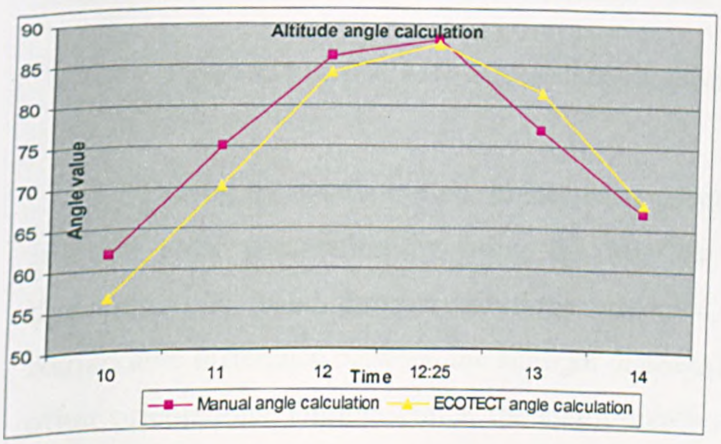


Figure.9.40. Graph of the solar altitude angles

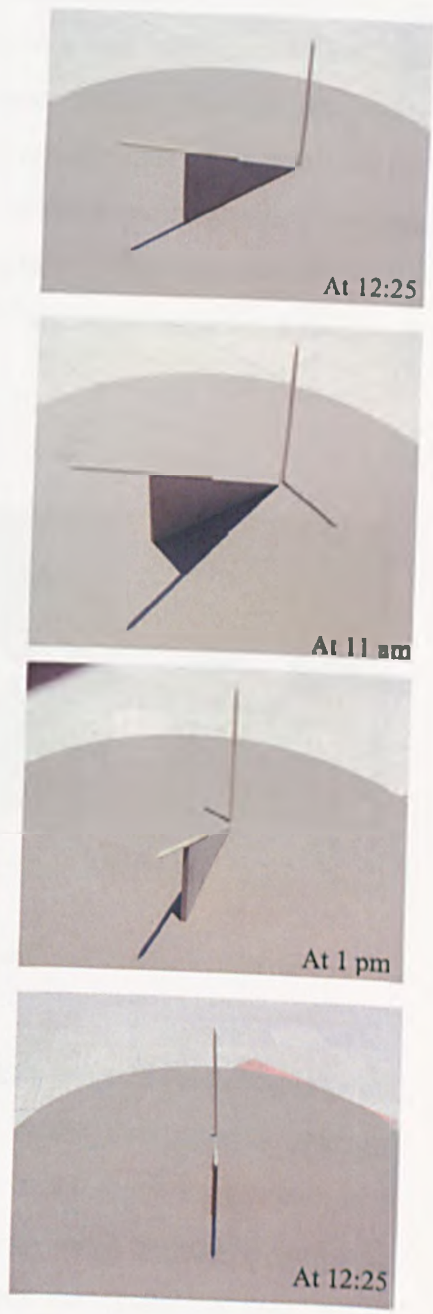


Figure.9.41. The model used to calculate the solar altitude angle manually in Jeddah

9.2.2.6. Sunlit area distribution for different model orientations

Previous experiments investigated the distribution of the sunlit area through the west and east windows while the orientation of the model was due south. Extra experiments were conducted to evaluate the distribution of sunlight through different window orientations. The model was rotated 45° to the south-east and south-west. The distribution of the sunlit area in summer came mainly through the east and west windows, as shown earlier. Due to the model's orientation, the sunlit area will penetrate the south window in summer. In both orientations, in the south-east and south-west, a considerable amount of sunlit area will penetrate. In summer, as shown in Figure 9.42, the sunlit area distribution decreases at noon. Moreover, during the early morning hours (7-8h) and during the late afternoon (around17h), the sunlit area distribution reaches its highest level. The highest total sunlight distribution during the day comes mainly through the south orientation compared with the south-west and south-east orientations. As a result of the solar altitude angle in Jeddah, and because of the model's orientation, the sunlit area in the south-east model will mainly penetrate during the morning hours. However, the sunlit area in the south-west model will mostly penetrate during the afternoon hours in summer, as shown in Figure 9.42.

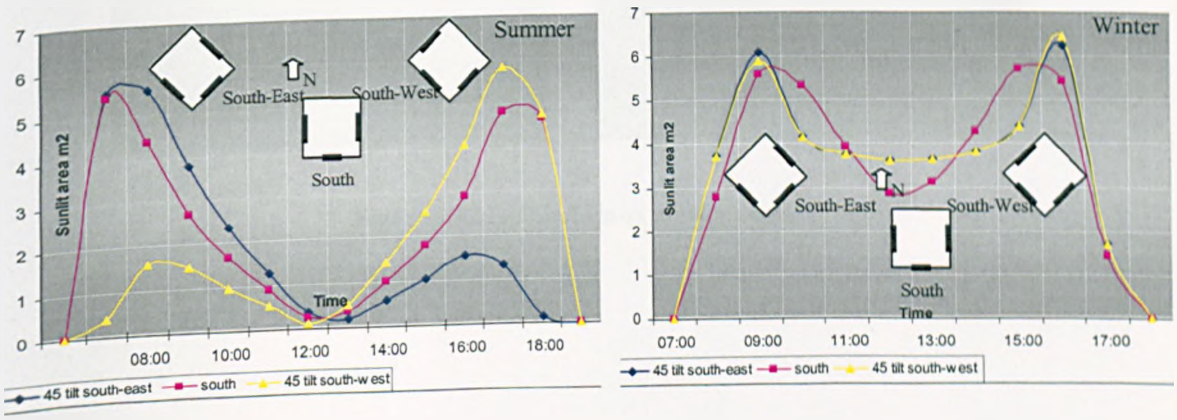


Figure 9.42 Summer and winter sunlit area distributions with different model orientations.

During the winter period, higher solar penetration rates are achieved. Viewing the internal solar penetration by using the SunCast model shows that internal sunlight distribution is equal through the three windows, unlike in summer when there is a remarkable difference between the sunlight distribution with the south orientation and with other orientations. During winter, the sunlit distribution, when the model has a 45° tilt to the south-west and south-east, is fairly similar. However, in summer, the sunlit distribution is totally different when comparing the south-west orientation and the south-east orientation, as shown in Figure 9.42, as in both summer and winter the internal sunlit distribution is at its lowest rate around noon and at its highest at 9 h and 16-17 h. Moreover, the model with the south orientation receives higher solar penetration at noon during winter.

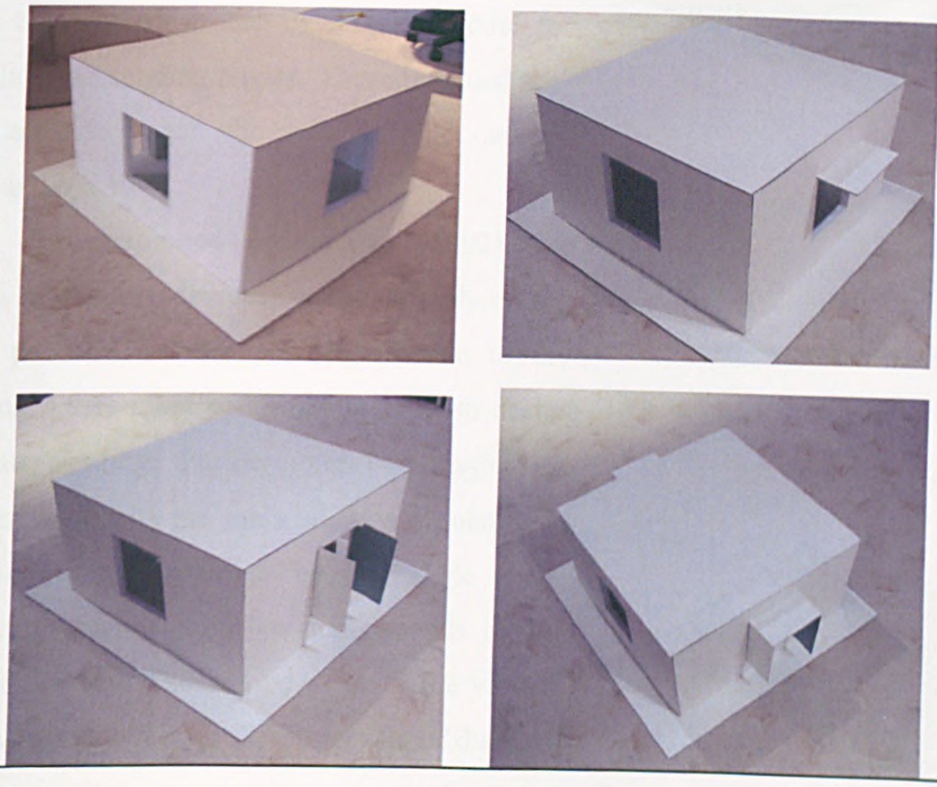


Figure 9.43 External views of the model.

9.3. Parametrical Studies of Shading Devices

9.3.1. The Manual Technique for Assembling the Sunlit Area

By using the ECOTECT model, the VSA and HSA could be calculated for any location. The results of the SunCast and physical models for Jeddah could be verified by constructing the sunlit area on the internal space using the HSA and VSA. The Jeddah models were constructed in the ECOTECT model to calculate the shading angles. These included the solar altitude angle, the solar azimuth angle, HSA and VSA.

As mentioned by Joudah (1992), the design of shading devices depends mainly on the sun's position so this position relative to the building's face must be known in order to design efficient shading. Furthermore, two angles are required to specify the sun's position in relation to the window or building. The first angle is the horizontal shadow angle, which depends on the time of the day. The second angle is the vertical shadow angle, which is the projection of the solar altitude angle onto a plane perpendicular to the building's face. If the sun is directly facing the selected surface of the building, the solar altitude angle in this case will equal the vertical shadow angle. Moreover, the solar azimuth angle will equal the surface azimuth angle.

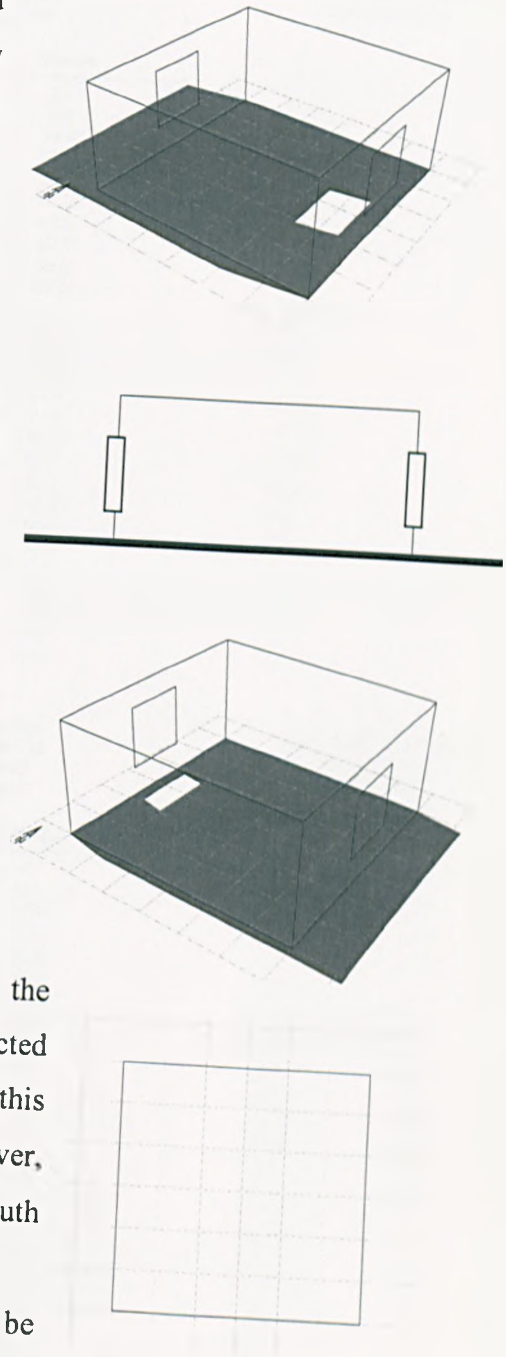


Figure 9.44 The selected room and window configuration for the sunlit area. (ECOTECT)

The performance of shading devices can be assessed using several existing methods. Predicting the solar penetration through a building's opening by using the angles mentioned above is one of these methods. Equations can be used to plot the patches of sunlight on the plan or section drawing. Joudah (1992) noted that a model could be constructed to test this under artificial or natural light.

Tabulated Daily Solar Data

Latitude: 21.2°
Longitude: 39.1°
Timezone: 45.0° [+3.0hrs]
Orientation: 90.0°

East

Date: 21st June
Julian Date: 172
Sunrise: 05:46
Sunset 19:03

Local Correction: -25.1 mins
Equation of Time: -1.6 mins
Declination: 23.4°

Local	(Solar)	Azimuth	Altitude	HSA	VSA
06:00	(05:34)	65.9°	2.9°	-24.1°	3.2°
06:30	(06:04)	68.4°	9.3°	-21.6°	10.0°
07:00	(06:34)	70.5°	15.9°	-19.5°	16.8°
07:30	(07:04)	72.5°	22.5°	-17.5°	23.5°
08:00	(07:34)	74.2°	29.2°	-15.8°	30.2°
08:30	(08:04)	75.8°	36.0°	-14.2°	36.8°
09:00	(08:34)	77.1°	42.8°	-12.9°	43.5°
09:30	(09:04)	78.3°	49.6°	-11.7°	50.2°
10:00	(09:34)	79.2°	56.5°	-10.8°	56.9°
10:30	(10:04)	79.7°	63.3°	-10.3°	63.7°
11:00	(10:34)	79.5°	70.2°	-10.5°	70.5°
11:30	(11:04)	77.4°	77.1°	-12.6°	77.4°
12:00	(11:34)	67.7°	83.8°	-22.3°	84.2°
12:30	(12:04)	-26.6°	87.5°	-116.6°	91.1°
13:00	(12:34)	-72.8°	81.6°	-162.8°	98.0°
13:30	(13:04)	-78.5°	74.8°	-168.5°	104.9°
14:00	(13:34)	-79.7°	68.0°	-169.7°	111.7°
14:30	(14:04)	-79.6°	61.1°	-169.6°	118.5°
15:00	(14:34)	-78.9°	54.2°	-168.9°	125.3°
15:30	(15:04)	-78.0°	47.4°	-168.0°	132.0°
16:00	(15:34)	-76.7°	40.5°	-166.7°	138.7°
16:30	(16:04)	-75.3°	33.7°	-165.3°	145.4°
17:00	(16:34)	-73.7°	27.0°	-163.7°	152.0°
17:30	(17:04)	-71.9°	20.3°	-161.9°	158.7°
18:00	(17:34)	-69.9°	13.7°	-159.9°	165.4°
18:30	(18:04)	-67.6°	7.2°	-157.6°	172.2°
19:00	(18:34)	-65.1°	0.8°	-155.1°	179.1°

Latitude: 21.2°
Longitude: 39.1°
Timezone: 45.0° [+3.0hrs]
Orientation: -90.0°

West

Date: 21st June
Julian Date: 172
Sunrise: 05:46
Sunset 19:03

Local Correction: -25.1 mins
Equation of Time: -1.6 mins
Declination: 23.4°

Local	(Solar)	Azimuth	Altitude	HSA	VSA
06:00	(05:34)	65.9°	2.9°	155.9°	176.8°
06:30	(06:04)	68.4°	9.3°	158.4°	170.0°
07:00	(06:34)	70.5°	15.9°	160.5°	163.2°
07:30	(07:04)	72.5°	22.5°	162.5°	156.5°
08:00	(07:34)	74.2°	29.2°	164.2°	149.8°
08:30	(08:04)	75.8°	36.0°	165.8°	143.2°
09:00	(08:34)	77.1°	42.8°	167.1°	136.5°
09:30	(09:04)	78.3°	49.6°	168.3°	129.8°
10:00	(09:34)	79.2°	56.5°	169.2°	123.1°
10:30	(10:04)	79.7°	63.3°	169.7°	116.3°
11:00	(10:34)	79.5°	70.2°	169.5°	109.5°
11:30	(11:04)	77.4°	77.1°	167.4°	102.6°
12:00	(11:34)	67.7°	83.8°	157.7°	95.8°
12:30	(12:04)	-26.6°	87.5°	63.4°	88.9°
13:00	(12:34)	-72.8°	81.6°	17.2°	82.0°
13:30	(13:04)	-78.5°	74.8°	11.5°	75.1°
14:00	(13:34)	-79.7°	68.0°	10.3°	68.3°
14:30	(14:04)	-79.6°	61.1°	10.4°	61.5°
15:00	(14:34)	-78.9°	54.2°	11.1°	54.7°
15:30	(15:04)	-78.0°	47.4°	12.0°	48.0°
16:00	(15:34)	-76.7°	40.5°	13.3°	41.3°
16:30	(16:04)	-75.3°	33.7°	14.7°	34.6°
17:00	(16:34)	-73.7°	27.0°	16.3°	28.0°
17:30	(17:04)	-71.9°	20.3°	18.1°	21.3°
18:00	(17:34)	-69.9°	13.7°	20.1°	14.6°
18:30	(18:04)	-67.6°	7.2°	22.4°	7.8°
19:00	(18:34)	-65.1°	0.8°	24.9°	0.9°

Table 9.11 Calculation of the horizontal and vertical shading angles using the ECOTECT model.

9.3.1.1. Manual Technique for Assembling the Sunlit Area

The amount of sunlit area on the internal surfaces can be calculated on a certain day and for a certain time of the day by using the HSA and the VSA. The first step in constructing the sunlit area on the internal surface is by establishing the sun's location. As explained previously by equations, the horizontal shadow angle is the difference between the azimuth and the window's orientation. The vertical shadow angle is the angle on the vertical section between the line perpendicular to the window (wall) and the projection of the sun's rays. Through these two angles, the distribution of the sunlit area on the internal floor or work plane can be drawn, as shown in Figure 9.45.

Two examples were tested using this technique in Jeddah though shading devices were not considered in this evaluation. In this evaluation, a room with the same physical dimensions was used with windows on the west and east sides of the model as in the previous example. The evaluation date was 21 June and the evaluation set-up was exactly the same as that of the physical model experiment in order to enable a comparison of the results to be made. The time selected for the first evaluation was 10 h with 14 h selected for the second.

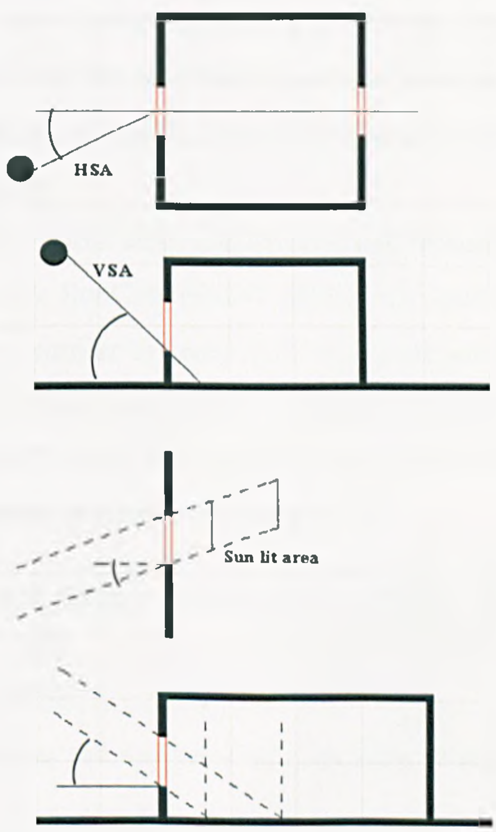


Figure 9.45 Manual technique for assembling the sunlit area by using the HSA and VSA angles.

9.3.1.1.1. Example 1

According to the daily solar data in the previous table, taken from the ECOTECT model for the Jeddah location, the azimuth angle on the east side of the selected room at 10 h was 79.2 °, the altitude angle was 56.5 °, the HSA was -10.8 °, and the VSA angle was 56.9 °. By following the techniques in Figure 9.45, the sunlit area at 10 h in Jeddah was 1.5 m^2 while the result from the SunCast model for the same location and time was $1.66m^2$. The result achieved from the physical model experiments using the same evaluation set-up was $1.12m^2$. The next example used the same evaluation but a different time. The selected time for the second evaluation was 14 h.

and, for added accuracy, the evaluation was conducted using the ECOTECT model to calculate the internal sunlit distribution.

9.3.1.1.2. Example 2

According to the daily solar data in Table.9.11, taken from the ECOTECT model for the Jeddah location, the azimuth angle at 14 h on the west side of the selected room was -79.7 ° while the altitude angle was 68.0 °, the HSA was 10.3 ° and the VSA angle was 68.3°. According to the manual technique using the HSA and the VSA, the sunlit area at this time was .8m^2.

The result achieved using the SunCast model was 1.02m^2 while the result achieved from the physical model experiments, with the same evaluation set-up, was .435m^2. The following graph illustrates the results from the selected evaluation times and from the three selected evaluation methods, (the SunCast model, the physical model and the manual technique using the HSA and VSA angles).

Table 9.12. and Figure 9.46. illustrate the results achieved by the three selected methods. As shown in the graph, the results from the SunCast model, ECOTECT model and from the manual technique (HSA and VSA) are similar to each other when compared to the physical model results. However, the results from the physical model are slightly dissimilar from the SunCast and manual method results while the results of the ECOTECT model show a high level of similarity when compared to the other three methods.

Time	SunCast model	Ecotect model	Physical model	Manual tech by HSA & VSA
10 h	1.66	1.5	1.12	1.5
14 h	1.02	0.8	0.435	0.8

Table 9.12 Amount of sunlit area penetration through the east and west windows using three different methods.

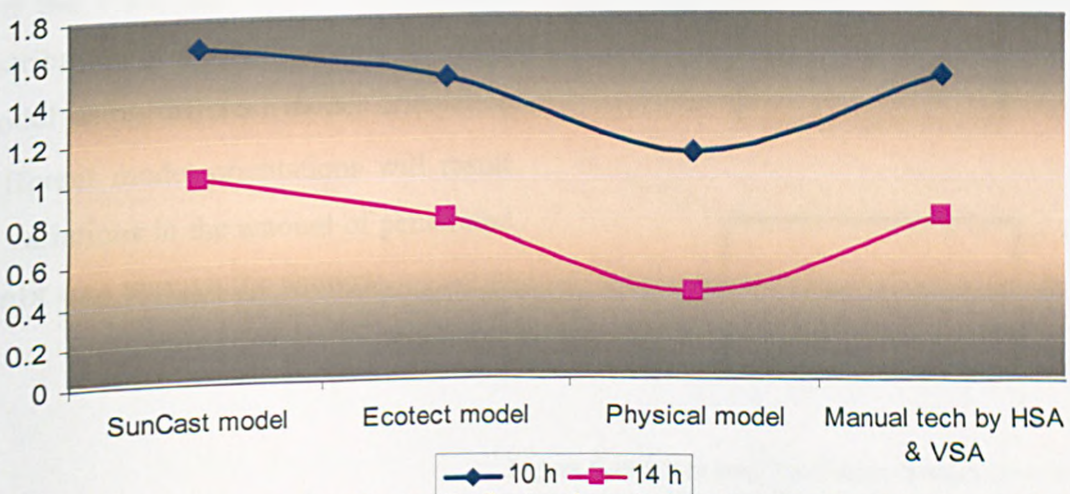


Figure.9.46. Amount of sunlit area distribution through the east and west windows using four different methods. Due to Jeddah's location, which is close to the Tropic of Cancer, curves are not symmetrical around 12 noon. Solar noon in Jeddah is at 12:25, as shown in Table 9.10.

9.3.1.1 Advantages of the Manual Technique Evaluation (using HSA and VSA)

The following points demonstrate the main advantages of the manual technique for constructing a model to assess the amount of sunlit areas for the Jeddah model:

1. It provides a good understanding of the shading angles, including the solar altitude angle, the solar azimuth angle, the horizontal shading angle (HSA), and the vertical shading angle (VSA). The manual technique also shows the relationship between these angles. For example, the VSA will equal the solar altitude only at noon when the solar rays are perpendicular on the window. The same concept will apply to the HSA.

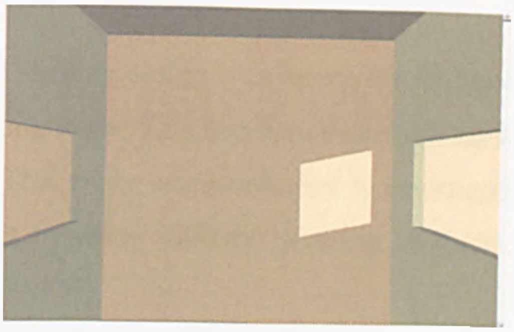


Figure 9.47 Sunlit area penetration through the east window, view at 10 h in Jeddah model (ArchiCAD simulation).

2. Manual simulation can be compared with other methods which are used for calculating the amount of sunlit area. This can validate the three methods used, namely the SunCast method, the physical model method, and the ECOTECT model simulation method.

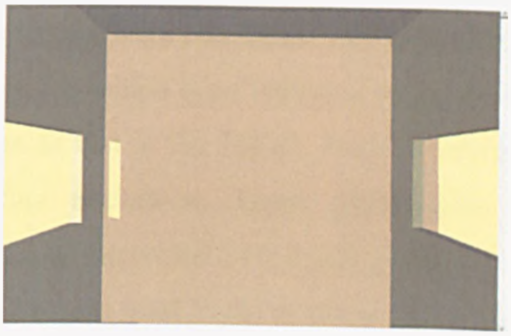


Figure 9.48 Sunlit area distribution through the west window. View at 14 h in the Jeddah model (ArchiCAD simulation).

3. Understanding the manual simulation technique, by using the HSA and the VSA, can help in examining the distribution of the sunlit area in the Jeddah model using different model orientations. Different model orientations will result in variations in the amount of penetrated sunlit area through the window.

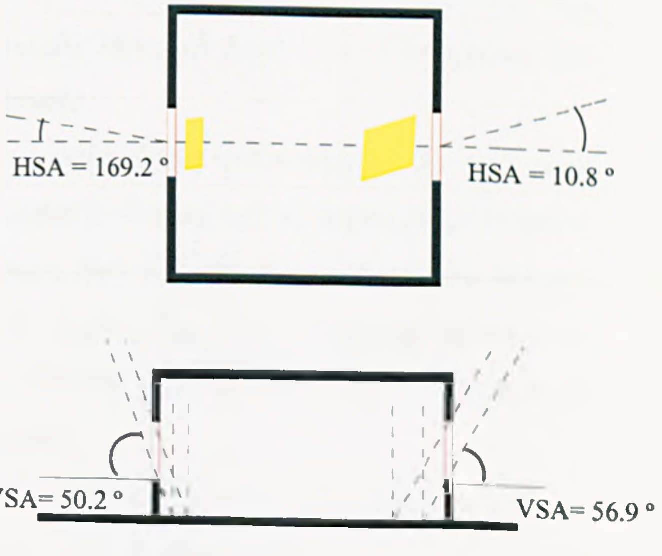


Figure 9.49 Sunlit area distribution through the west and east windows. View at 10h and 14h in the Jeddah model. Manual technique (HSA and VSA simulation).

9.3.2 Potential of Saving the Required Cooling Loads by using Different Glazing Ratios and Shading Devices

9.3.2.1. Introduction

The key to a successful energy efficient shading design is to assess the ability of the shading in making savings in the required cooling loads. This becomes essential, especially in hot climate regions such as Saudi Arabia. This study was conducted to investigate the potential for saving in terms of cooling loads by using different shading methods with different window glazing ratios.

The studies were carried out with the assistance of the IES Apache (Thermal) model. Furthermore, a collection of data regarding electricity, shading construction and glazing construction in Saudi Arabia were obtained. Tables and graphs were categorised and provided to exemplify the costs and these studies were conducted also to evaluate the need for shading by considering a significant factor, which is an indicator of the necessity for installing shading. By using the same room as that in the Jeddah model experiments, further experiments were performed for this evaluation. These experiments were performed by using four different window glazing ratios and two shading methods. The ratios selected for the experiment were 15%, (the ratio used in the previous Jeddah model experiments), 30%, 60% and 90%. The shading techniques used in the experiment were the horizontal and egg-crate shading devices but, due to the negligible effect of vertical shading, this type of shading was not considered in the evaluation. The objectives of the experiment and the results of the investigation for the four cases (15%, 30%, 60% and 90%) are presented below. By using the results obtained from this investigation, the significant factor, mentioned above, was illustrated.

These experiments were followed by a comparative evaluation for the two main shading methods. A double-glazed window without shading and a single-glazed window with horizontal shading were selected to evaluate their efficiency in reducing the demand for cooling loads. The cost of cooling loads, double-glazing and shading devices are discussed in this study and the main aim of this evaluation was show the enhanced efficiency of shading devices against glazed shading.

Glass shading is well known and used in Saudi Arabia. However, this type of shading is inefficient in such a climatic region which experiences high solar radiation exposure throughout the whole year. The heat caused by intensive solar radiation must be obstructed before it reaches the window or opening surface and this can be achieved by using well-designed shading devices. This research effort is offered to be of value to architects for use, not only in Saudi Arabia, but also in regions with the same climatic characteristics.

9.3.2.2. Electricity Cost and Cooling Load Calculations in Saudi Arabia

KW/h		Residential Commercial, and Governmental	Industrial	Agricultural
0	1000	5	12	5
1001	2000	5	12	5
2001	3000	10	12	10
3001	4000	10	12	10
4001	5000	12	12	10
5001	6000	12	12	12
6001	7000	15	12	12
7001	8000	20	12	12
8001	9000	22	12	12
9001	10000	24	12	12
more than	10000	26	12	12

Table 9.13 Electricity costs in Saudi Arabia according to the building type and the consumed amount of electricity. (Costs are shown in halalah per watt. 1 Saudi riyal = 100 halalah and £1= 7 Saudi riyals.)

Electricity costs in Saudi Arabia vary depending on two main factors: 1.The amount of electricity consumed. 2. The type of building. This is shown in Table 9.13. which illustrates the cost of electricity for every building type and the amount consumed. By using the available data from the Saudi Electric Company (SEC) regarding the cost of electricity in Saudi Arabia and the required cooling loads, possible savings in electricity can be calculated. This phase of the research shows the actual amount of saving in electricity that could be made by using different types of shading. The amount of electricity was calculated for August, one of the hottest months in summer in Riyadh, Saudi Arabia. The required cooling loads were already calculated by using the SunCast model for the selected room and the same room was examined in this assessment. Cooling loads were calculated, first for a room with a plain window, and then this was compared with the other shading techniques. Two shading techniques, horizontal and egg-crate shading, were selected for this investigation.

The scope of this work focused on residential, commercial and government buildings. These three types of building are categorised in the same cost group, as shown in Table.9.13. The costs of electricity are shown in KW/h and the higher the electricity consumption, the higher the cost. These tariffs encourage the use of energy efficient methods like shading as such methods could save considerable amounts of cooling load and, consequently, electricity in buildings.

As results from the Apache (the thermal building simulation model) show, the month of August is the peak sensible month in Riyadh and, as mentioned earlier, three cases were involved in the evaluation: a plain window, and windows with horizontal and egg-crate shading devices. Vertical shading will not have a significant effect on the thermal behaviour in this case, especially in summer.

The evaluation included examining the performance of shading with different window glazing ratios. The original investigation, used in the SunCast and physical models, assessed the solar penetration through a glazed window with a 15 % window to wall ratio. 30%, 60% and 90% window to wall ratios were added in this evaluation. The output results of the Apache (thermal simulation) showed the room's floor area, the peak sensible month (August, in this case), the peak sensible time, the peak sensible cooling loads, and the peak sensible cooling loads per m^2.

9.3.2.3. Evaluation Objectives

The evaluation objectives can be summarised in the following points:

1. To assess the thermal performance of shading devices in the hot summer of Riyadh, Saudi Arabia. The selected month for the assessment was August, which is the peak sensible month in Riyadh.

2. To assess the required cooling loads for an average room in Saudi Arabia with and without the effect of different shading methods. This will show the percentage of saving in cooling loads using a shaded window when compared with a non-shaded one.

3. To assess the potential for financial saving by using different shading methods (horizontal and egg-crate shading) and different glazing ratios. This assessment was carried out using governmental tariffs for electricity.

4. To show the ability of simple shading methods in reducing the required cooling loads and consequently electricity bills in Saudi Arabia. Moreover, the shading methods used are simple in construction, cheap and do not require highly skilled labour to fit.

5. To assess the performance of the shading devices according to a significant factor, namely the need for shading according to the thermal performance of the room. This factor is discussed in detail in the following section.

6. To select an ideal shading method to be used in Saudi Arabia. This method should match the environmental necessities of the region.

9.3.2.4. Significant Factor

The significant factor is used mainly to assess the use of shading devices in buildings so, in this study, the factor evaluates the importance of shading and will vary from 0.1 to 1, showing the importance of using shading in buildings. A significant factor of around 0.1 will indicate that shading is less important while factors around 0.9 and 1 will indicate that the use of shading devices is highly recommended. It can be assumed that the ratio of the glazing area in the room will have a direct effect on the significant factor so a large glazing area could raise the significant factor. On the other hand, if the glazing area in the room is small, the significant factor will also be lower and therefore the importance of shading will become less. Various glazing ratios were used in this evaluation. As mentioned earlier, the selected glazing ratios for this evaluation were 15%, 30%, 60% and 90%. The significant factor was evaluated according to the results of this investigation.

9.3.2.5. Significant Factor Evaluation

As mentioned earlier, the significant factor will vary from .1 to 1 depending on the need for shading. Factors less that 0.5 will indicate less need for shading while factors more than .5 will indicate a greater need. This factor should be linked with the glazing ratio so a glazing ratio of 100% of the wall will be equivalent to a significant factor of 1. Moreover, glazing percentages of 10% will be equivalent to a significant factor of 0.1. This will be one of the main significant factor indications. The following tables and graphs contain results achieved in Riyadh by using various glazing ratios and shading types while the heat gain calculations represent the case of the plain window to achieve an efficient evaluation. Other cases were compared with this one to calculate the savings in the required cooling loads. The results are discussed and analysed in the following sections.

Heat Gain Summary for 15% window area (without shading)				
Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W	Peak sensible cooling/Area (W/m^2)
36	August	13:00	775	21.5

Heat Gain Summary for 30% window area (without shading)				
Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W	Peak sensible cooling/Area (W/m^2)
36	August	13:00	976	27.1

Heat Gain Summary for 15% window area with horizontal shading				
Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W	Peak sensible cooling/Area (W/m^2)
36	August	13:00	757	21
Cooling loads saving percentage				2.32%

Heat Gain Summary for 30% window area with horizontal shading				
Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W	Peak sensible cooling/Area (W/m^2)
36	August	13:00	916	25.4
Cooling loads saving percentage				6.1%

Heat Gain Summary for 15% window area with egg-crate shading				
Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W	Peak sensible cooling/Area (W/m^2)
36	August	13:00	754	20.9
Cooling loads saving percentage				2.7%

Heat Gain Summary for 30% window area with egg-crate shading				
Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W	Peak sensible cooling/Area (W/m^2)
36	August	13:00	909	25.2
Cooling loads saving percentage				6.8%

Table 9.14 Apache (IES Thermal simulation) results which show the required cooling loads and the saving percentage. Results were achieved using the selected shading techniques for 15% and 30% window to wall ratios.

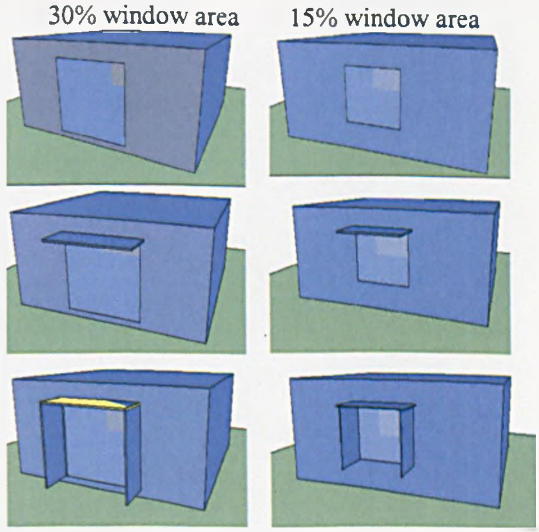


Figure 9.50 The selected room with 15% and 30% window areas.

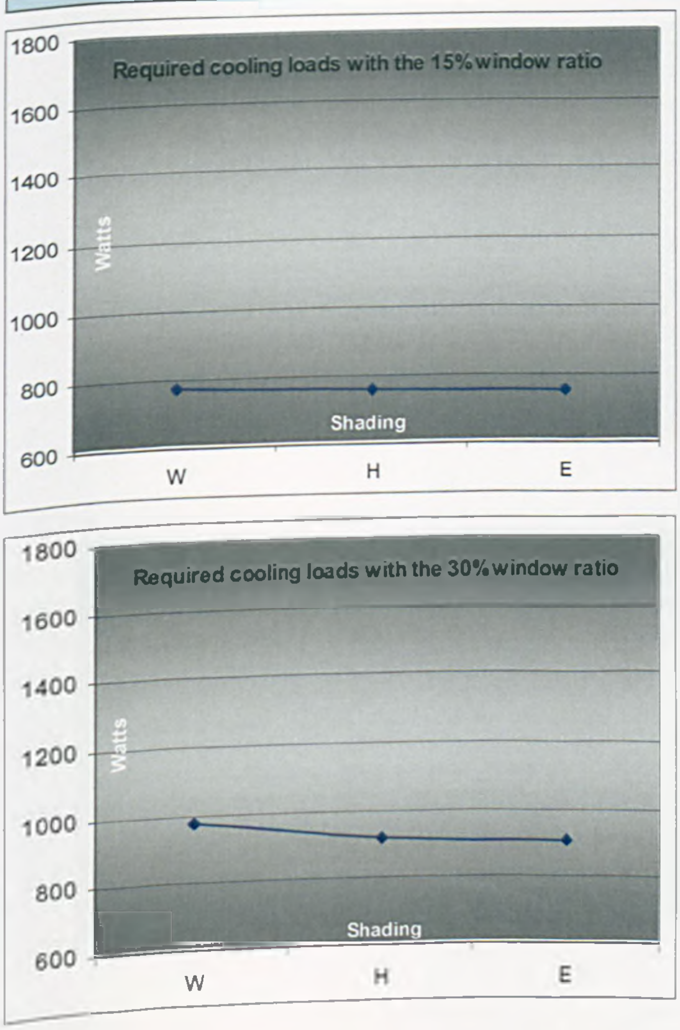


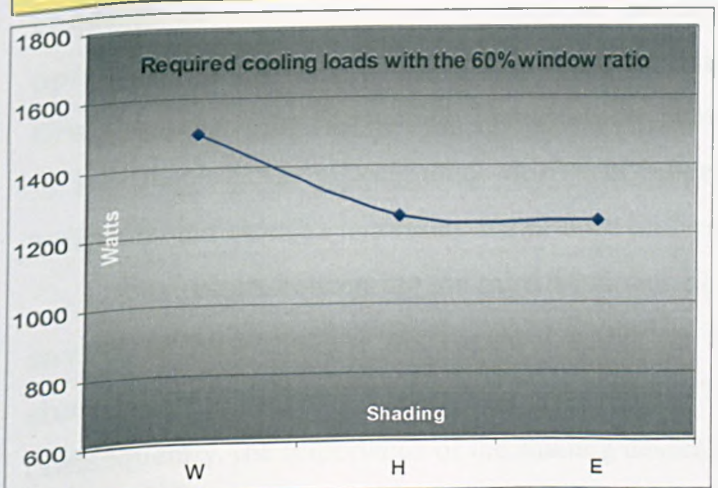
Figure 9.51 Graphs showing the required cooling loads with 15% and 30% window areas.

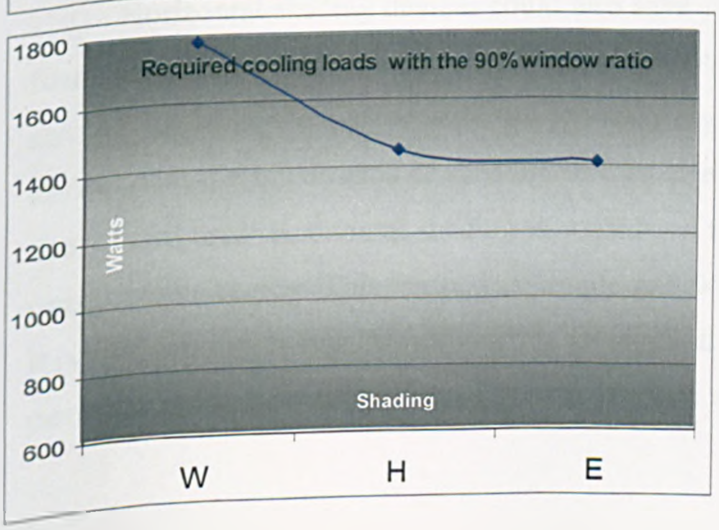
Heat Gain Summary for 60% window area (without shading)					Heat Gain Summary for 90% window area (without shading)				
Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W)	Peak sensible cooling/Area (W/m^2)	Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W)	Peak sensible cooling/Area (W/m^2)
36	August	13:00	1499	41.6	36	August	13:00	1785	49.5

Heat Gain Summary for 60% window area with horizontal shading					Heat Gain Summary for 90% window area with horizontal shading				
Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W)	Peak sensible cooling/Area (W/m^2)	Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W)	Peak sensible cooling/Area (W/m^2)
36	August	13:00	1254	34.8	36	August	13:00	1447	40.1
Cooling loads saving percentage				16.3%	Cooling loads saving percentage				19%

Heat Gain Summary for 60% window area with egg-crate shading					Heat Gain Summary for 90% window area with egg-crate shading				
Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W)	Peak sensible cooling/Area (W/m^2)	Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W)	Peak sensible cooling/Area (W/m^2)
36	August	13:00	1239	34.4	36	August	13:00	1408	39.1
Cooling loads saving percentage				17.3%	Cooling loads saving percentage				21%

Table 9.15 Apache (IES Thermal simulation) results which show the required cooling loads and the saving percentage. Results were achieved using the selected shading techniques for 60% and 90% window to wall ratios.





90% window area   60% window area

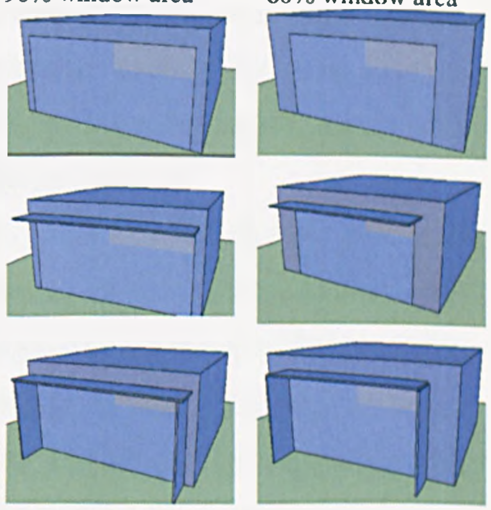


Figure 9.52 The selected room with 60% and 90% window areas.

Figure 9.53 Graphs showing the required cooling loads with 60% and 90% window areas.

9.3.2.6. Discussion of the Results

As discussed previously, the evaluation consists of four cases with four different glazing ratios. In the first case, which considers a window with a 15% glazing to wall ratio (the case in the main evaluation using the physical and the SunCast models), there is little saving in the required cooling. The reduced size of the window will only allow a slight amount of solar radiation to penetrate internally. Consequently, shading devices will not be highly effective. In each of the selected window ratios, three cooling load results were achieved, these three cases representing a plain window, a window with horizontal shading and a third with egg-crate shading. The horizontal and egg-crate shading cases were compared with the plain window to calculate the saving ratio in cooling loads. The cooling load results were obtained using Apache clac simulation.

In the first case, (the 15% percent window to wall ratio), the saving in the cooling loads was only 2.32% with the horizontal shading and 2.7% with the egg-rate shading. In the second case, which represents a 30% window to wall ratio, the saving in cooling load percentage increased to 6.1% with the horizontal shading and 6.8% with the egg-crate shading. These saving ratios influence the use of shading techniques with larger window openings in Riyadh, Saudi Arabia. In these two cases, the significant factor was .15 for the first case and .3 for the second. Moreover, the increase in the significant factor from .15 to .3 is a result of the glazing ratio which was influenced by the saving in the cooling load. This also indicates an increasing importance of the shading device.

The results concerning the third window with a 60% window to wall ratio indicate a saving of 16.3% of the cooling load using the horizontal shading; by using egg-crate shading the saving percentage could be raised to 17.3%. As the significant factor increases, consequently, the importance of the shading device will increase.

Horizontal shading devices could also save 19% of the required cooling loads in the fourth case (the 90% window to wall ratio). The results in Table 9.15 indicate that a 21% saving percentage could be achieved by using egg-crate shading devices. The evaluation shows that the importance of shading devices increases in Saudi Arabia with increases in the glazed area. Horizontal shading is considered to be an efficient shading method to be used in this region. This method is simple and will cost less than egg-crate shading. In Riyadh, during winter when heating is required, horizontal shading will allow solar penetration for natural heating. The solar altitude angle is relatively low in winter which will allow solar penetration then by using this shading method. The general results achieved in this investigation are illustrated in the following points:

1. There is only a slight difference in cooling loads between the horizontal and the egg-crate shading. As mentioned previously, vertical shading was not considered in this evaluation due to its negligible effect on solar penetration during summer in Saudi Arabia. Furthermore, the cooling loads required using vertical shading devices can be calculated by deducting the savings made when using horizontal shading from those made with egg-crate shading.
2. The amount of saving in cooling loads increases with increases in the window glazing ratio. Therefore, the significant factor also increases with increases in the window to wall ratio.
3. Although there is no significant difference between the savings made in cooling loads between horizontal and egg-crate shading, egg-crate shading is slightly more efficient in saving cooling loads; this is shown in the graphs and tables presented here. The double effect of egg-crate shading (horizontal and vertical shading together) increases the shading efficiency.

The results are organised in two groups. The first group contains the results achieved for the 15% and 30% glazing ratios while the second group contains the results obtained for the 60% and 90% glazing ratios. The results for each glazing ratio are presented in a different colour.

These tables present the room area, the peak sensible month (August in this case) and time, the peak sensible cooling loads, and the peak sensible cooling loads per m^2. In the case of the shading devices, the percentages of saving in cooling loads for the two selected shading techniques are also shown. The graphs show the required cooling loads when using the selected four glazing ratios. The cooling loads required for the selected room will vary from 600 W to 1800 W depending on the glazing ratio, as shown in the graphs illustrated in Figures 9.51 and 9.53.

9.3.2.7. Summary of the Results

Two main aims were achieved in this study. The first aim was to calculate the significant factor which was used to identify the level of demand for shading devices. This factor varies from .1 to 1, where .1 is less need for shading and 1 indicates a strong need for shading.

The second aim of this investigation was to calculate the percentage saving in cooling loads gained by using different shading techniques and glazing ratios. There is a slight difference in the performance of the two selected shading techniques (horizontal and egg-crate shading). The second demonstrates a slightly better performance, as shown in Tables 9.14. and 9.15. A discrepancy percentage of an average of 1.5% was achieved between the two shading methods. Saving in cooling loads, which reflect the shading's efficiency, can reach up to 20% with the 90% glazing ratio. The following graph in Figure 9.54 illustrates the increases in the saving percentages of cooling loads using the selected shading techniques and glazing ratios.

A smaller saving percentage was achieved with the 15% and 30% glazing ratios due to the lower penetration of solar radiation into the internal surfaces through these windows sizes. These amounts of solar radiation penetration do not require extensive amounts of cooling in the first place. As a result, it was found from this study that the maximum amount of saving that could be achieved with this shading was around 20% to 25%, assuming that the 25% saving could be achieved if the wall was 100% glazed. Higher saving percentages could be achieved with different shading device configurations and dimensions. In this investigation, the shading dimension was 0.9m for both the horizontal and egg-crate shading but lower solar radiation penetration rates would be achieved with 1.2m shading, for example.

The effect of windows and shading devices on thermal performance will obviously depend mainly on the size of both the window and the shading device compared with the size of the space or room. Moreover, other factors could have a significant impact on the performance of the window and shading devices, such as wall thickness, ventilation rates, and the thermal properties of the materials.

A study was conducted later to carry out a comparative evaluation between the investigated shading devices and the glazing shading systems. This study compared the cost and the efficiency of both shading techniques. Sunlight can be prevented from reaching the window's surface by using the selected shading devices. On the other hand, glass shading enables the solar radiation to reach the window's surface, resulting in increased heat gain. The study was conducted using the Apache model on both shading methods. The cost of shading in Saudi Arabia was also evaluated in the study.

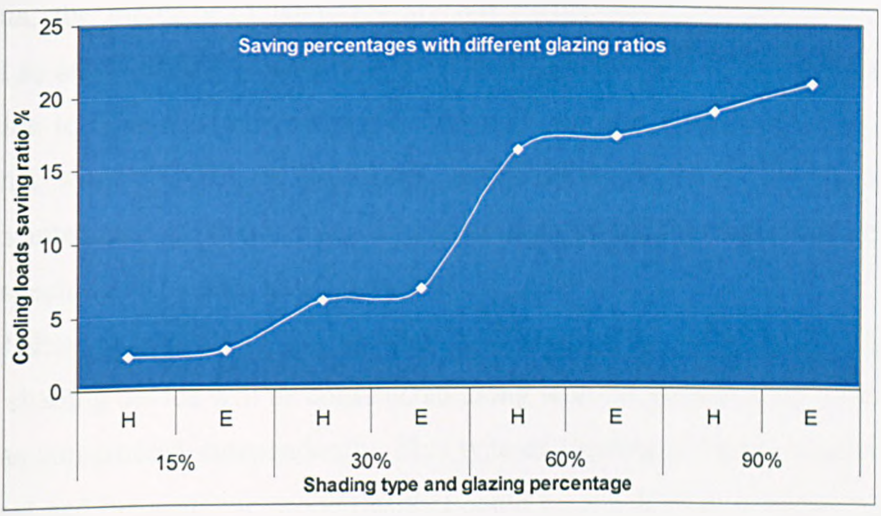


Figure 9.54 Cooling load saving ratios plotted against different glazing ratios and shading device configurations. Ratios are referenced to the window without shading.

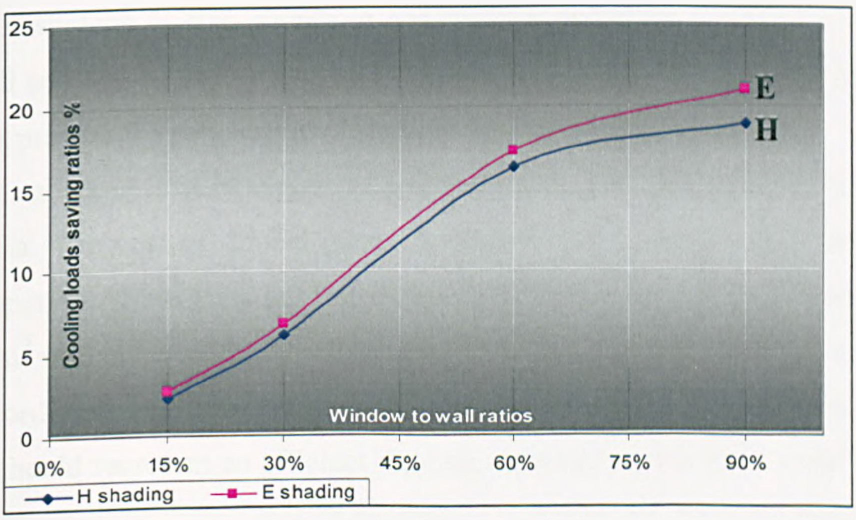


Figure 9.55 Performance of horizontal and egg-crate shading separately in reducing the required cooling loads as percentages. Ratios are referenced to the window without shading.

9.3.2.8. The Cost of Shading Devices in Saudi Arabia

Three contractors were selected to estimate the cost of shading devices in Saudi Arabia as consulting more than one contractor will result in more accurate results. The estimates included different types and materials of shading devices, selected according to the most commonly used shading devices in Saudi Arabia. The selected types were concrete, GRC, steel, wood, block, wall, fabric and concrete fixed on the building. The cost of shading devices varied depending on the type and material and ranged from 70 SR/m^2 = £10/m^{2}to 3300 SR/m^2 = £471/m^2.

A constructed wall presented the cheapest method of shading as this would be a part of the building itself. On the other hand, fabrics were the most expensive because of their aesthetic properties while steel shading represented an average cost. However, in Saudi Arabia, the majority of labourers are not sufficiently qualified to construct steel shading and so steel shading is usually ugly in its design. Wooden shading devices are also expensive due to their aesthetic properties although wooden shading devices are used in the traditional windows such as Rowshans, explained in detail in the literature review. Also, the maintenance of wooden shading devices is expensive due to the high rates of humidity, especially in Jeddah, Saudi Arabia.

Wall shading is relatively cheap when considered at an early design stage. Because this type of shading device will be constructed along with the building, the cost will be less than if it was constructed independently. This type of shading is highly recommended due to its low cost and the aesthetic properties that could be considered in the early stage of the design. Block shading devices are the cheapest. However, they are very simple in design. This type of shading is also simple in construction and does not require highly skilled labour. Wall and block shading are recommended due to their low cost and high efficiency as they both prevent the penetration of sunlight into the internal spaces.

Glass shading is very expensive compared with the usual shading devices used in Saudi Arabia. The cost of double glazed windows varies depending on the quality and thermal properties of the glass but tinted double-glazed shading costs between 300 SR/m^2 to 900 SR/m^2 in Saudi Arabia. The following graph illustrates the average cost of shading devices according to the three selected contractors. Low cost shading devices, like blocks and walls, should represent an efficient shading technique in the long term. Moreover, the maintenance factor for these types of shading is 0, unlike the electrical and glass shading which require maintenance and extra electricity.

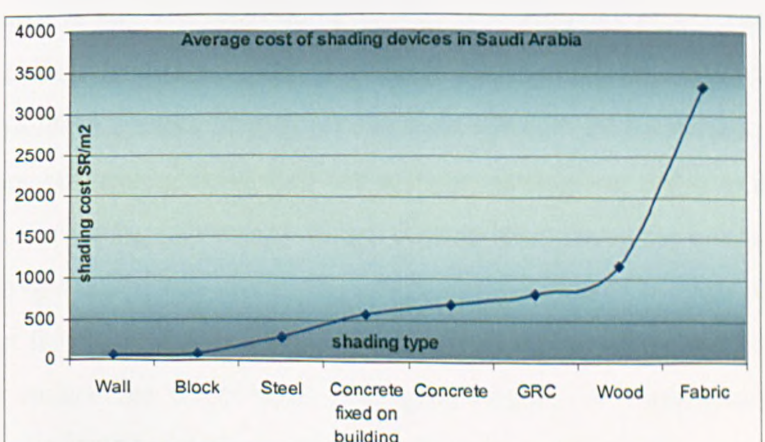


Figure 9.56 Average cost of shading devices in Saudi Arabia.

9.3.3. Parametrical Studies of Shading, Glazing Types and Horizontal Louvers as Effective Significant Factors

9.3.3.1. Comparative Study of Glazing and Shading Devices

When solar radiation strikes window glass it can be transmitted, reflected or absorbed. According to Wulfinghoff (1999), the maximum efficiency of glass shading is reached when the glass blocks 80% of the visible sunlight without obstructing the external view when compared to clear glass. This type of glazing is characterised by high reflectivity and absorption properties. The maximum reduction of the direct radiation heat gain by using highly reflective glazing can reach 50% to 70%. Moreover, the maximum redaction in high absorption glazing can reach about 40% to 60%. These figures show highly efficient glazing because they are compared to the figures for clear, unshaded glass.

Glass shading is a well-known shading technique applied recently in hot climate regions. However, this method of shading is not recommended in regions such as Saudi Arabia because, due to the intensive solar radiation, glass shading could result in increasing the required demand for cooling. Furthermore, the cost of the installation of this type of glass is usually very expensive and requires highly skilled labourers.

In the previous model experiments (using SunCast), the windows were constructed using low-e double-glazing (6mm+6mm) with a .336 air gap. Simple experiments were conducted to demonstrate the different ratios of saving in cooling loads for three types of glazing. The first type was the same double-glazed variety while the second type of glazing was single 6mm glazing. The experiments were performed with and without horizontal shading. The main aim of these experiments was to show the efficiency of simple horizontal shading and experiments were performed with the SunCast model using a 60% area of glazed window in Riyadh, Saudi Arabia.

Olgyay (1963) discussed the effect of shading devices and illustrated that this method of solar radiation control is an *"interception of energy that happens at the right place before it attacks the building. In this way the obstructed heat is reflected and can dissipate into the outside air. Shading devices give by far the most efficient performance."*

A study of the performance of triple glazing with and without shading was added to the study. As shown in Table 9.16, the saving percentage of the cooling load decreased to reach 15.5 %. The most effective form of shading was found when using a single-glazed window. On the other hand, the lowest effect from shading was found when using a triple-glazed window. While shading devices mainly reduce the direct solar heat gain, double- or triple-glazing reduces the conducted heat gain. Reflected glazing could reduce both types of heat gain.

The following table illustrates the horizontal shading efficiency in reducing cooling loads by using single, double and triple glazed windows

Heat Gain Summary for 60% window area (without shading) with triple glazing				
Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W)	Peak sensible cooling/ Area (W/m^2)
36	August	13:00	1321	36.6

Heat Gain Summary for 60% window area (without shading) with double glazing				
Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W)	Peak sensible cooling/Area (W/m^2)
36	August	13:00	1499	41.6

Heat Gain Summary for 60% window area (without shading) with single glazing				
Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W)	Peak sensible cooling/Area (W/m^2)
36	August	13:00	2309	64.1

Heat Gain Summary for 60% window area with horizontal shading and triple glazing				
Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W)	Peak sensible cooling/ Area (W/m^2)
36	August	13:00	1116	31
Cooling loads saving percentage				15.5%

Heat Gain Summary for 60% window area with horizontal shading and double glazing				
Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W)	Peak sensible cooling/Area (W/m^2)
36	August	13:00	1254	34.8
Cooling loads saving percentage				16.3 %

Heat Gain Summary for 60% window area with horizontal shading and single glazing				
Floor area m^2	Peak sensible month	Peak sensible time	Peak Sensible cooling load (W)	Peak sensible cooling/Area (W/m^2)
36	August	13:00	1930	53.6
Cooling loads saving percentage				16.4%

Table 9.16. Saving percentages of cooling loads by using single, double and triple glazing with and without horizontal shading.

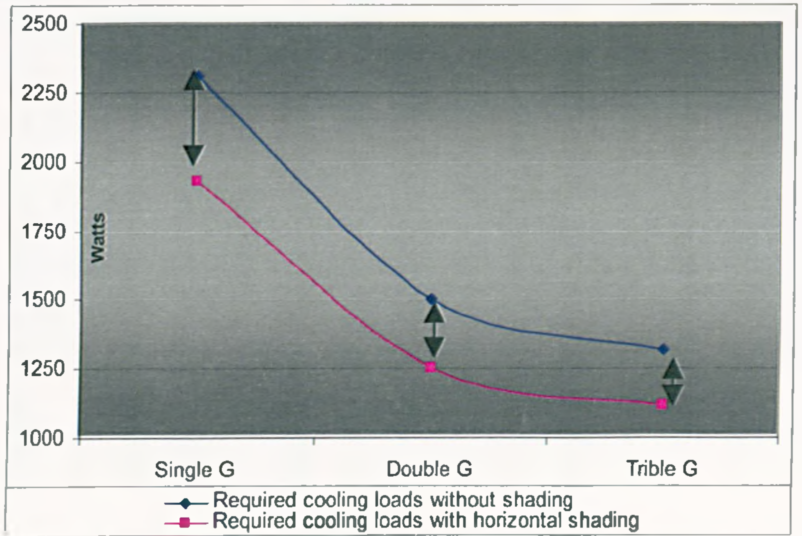


Figure 9.57 Saving percentages of cooling loads by using single, double and triple glazing with and without horizontal shading.

9.3.3.2. The efficiency of glazing and horizontal shading

The study illustrated in Table 9.16. is divided into two main parts, the first part showing the required cooling loads with the three selected glazing types, namely, single, double and triple glazing. The cooling loads were calculated in the first part without shading devices to evaluate the efficiency of different glazing types while the second part of the study examined the effect of horizontal shading (overhangs) on each type of glazing. By comparing the results from the two parts, the saving percentage in terms of cooling load could be predicted when using horizontal shading. As shown in the results table, cooling loads decreased with increases in layers of glazing. The lowest required cooling load achieved by using the triple glazing for the selected room was 1321W at the peak hour. On the other hand, the highest required cooling load was 2309W for the single glazed window; in both cases the window was not shaded. Horizontal shading devices will contribute to reducing the required cooling loads and cooling loads were reduced by 16.4% with single glazing, 16.3% with double glazing, and 15.5% with the triple glazed window.

This experiment shows that the effect of horizontal shading decreases with increases in the glazing layers. The investigation showed that a 16.4% reduction in cooling load could be obtained when using the single glazing. This ratio decreased to 15.5% when using triple glazing; this shows less of an effect from the horizontal shading. Triple glazing will provide extra insulation for the window which decreases the effect of horizontal shading. However, shading will still provide a sufficient reduction (15.5%) in the required cooling loads, even with a triple-glazed window, as shown earlier.

Shading devices will reduce the radiated heat gain while layered glazing will reduce the conducted heat gain. Shading devices will prevent solar radiation from reaching the window's surface. In such a case heat gain will be through conduction while on the glazing plain window, including single, double and triple glazing, there will be direct solar heat gain.

9.3.3.2.1. Conducted heat gains

According to Marsh (2003), conducted heat gain is the transfer of heat from outside the building to the inside through the building's external envelope. This mainly occurs by conduction. The external envelope normally consists of walls, windows, doors, roofs and floors. Immediate heat flow in buildings will depend mainly on the properties of the material, the surface area of the material, and the temperature difference between the outside and the inside. Therefore, conducted heat flow can be calculated through the following equation:

$$QC = UA\,\Delta T$$

where QC is total heat flow in watts, A is the surface area of the building element, U is the material U-value, and ΔT is the temperature differences.

9.3.3.2.2. Solar heat gain

Solar heat gain is the additional heat flow from the sun to the building's interiors. It can occur directly through the windows or indirectly through opaque surfaces. Solar heat gain through transparent elements (or windows) can be calculated by using the following equation:

$$Qs = GA\,sgf$$

where **Qs** is the total direct solar gain in watts (W), **G** is the total solar radiation incident on the window, **A** is the window area, and **sgf** is the solar gain factor (Marsh, 2003).

The solar gain factor or the Solar Heat Gain Coefficient (SHGC) measures how well a product blocks heat caused by sunlight. The SHGC is the fraction of incident solar radiation admitted through a window, both directly transmitted and absorbed, then subsequently released inward. SHGC is expressed as a number between 0 and 1. The lower a window's SHGC, the less solar heat it transmits (U.S Demartment of Energy, 2004).

9.3.3.3. Effect of glazing type, ratio and horizontal louvers on cooling loads

9.3.3.3.1. Introduction

This evaluation was conducted to assess the most effective significant factor in reducing the required cooling load. Three factors were selected for the investigation. The first factor evaluated the window glazing type: single, double and triple; the second significant factor assessed the window glazing ratios (30%, 60% and 90% window to wall ratio); the third and last factor assessed the performance of the number of horizontal louvers. Three numbers were selected to assess this factor: 1, 2 and 3 horizontal devices. This parametrical study is a continuation of the previous parametrical studies designed to assess the factors that affect the thermal behaviour of the window which, in turn, affect the thermal behaviour of the room. Each case in the evaluated significant factors consisted of a base case which was used to compare with other factors in each case. The assessment procedure can be illustrated through the following points, including the three aspects of the evaluation of the significant factors:

1. The first aspect which contributes in evaluating the significant factor is the type of glazing. Single glazing is the base case while double and triple glazing are compared with this case.
2. The second aspect mainly depends on the glazing ratio. Ratios of glazing used to evaluate the significant factor are 30%, 60% and 90% window to wall ratio. The 90% glazing ratio is the base case which is used for comparison with the 30% and 60% glazing ratio.
3. The third aspect is the number of horizontal shading louvers. The horizontal shading depth is .9 m and the width depends on the window size. Three cases (one, two and three horizontal louvers) were studied for this significant factor in which the base case is the one horizontal louver which is then compared against the other two cases.

Significant factor 1	Significant factor 2	Significant factor 3
Glazing type	Glazing ratio	Number of horizontal shading louvers
Single glazing	30%	1
Double glazing	60%	2
Triple glazing	90%	3

Table 9.17 The three selected significant factors for the investigation including the three factors for each case.

9.3.3.3.2. Results and discussion

In the first factor, the window glazing area was 30% of the wall while the window area in the third factor was 60%. Moreover, in the first and second cases there was no shading device fixed on the window. All calculations were performed in August, which is one of the hottest months in Riyadh. August was selected in this evaluation instead of June to provide variety in terms of the examined months, although previous investigations were conducted in June. The results show that the glazing ratio is the most effective factor in reducing or increasing the required cooling loads compared with other two factors.

These results are presented in Tables 9.18, and in Figures 9.58 and 9.59. Figure 9.58 shows the saving ratios for the three selected factors in one curve to show the difference in saving ratios across the selected factors while Figure 9.59 shows the results of the cooling load saving ratios separately for each factor. Investigating the results in different directions will have a positive impact on the overall evaluation. The results reveal that the highest saving ratio in cooling load was achieved through reducing the glazed area in the wall. Savings of up to 45.3% could be made by reducing the glazed area to 30%, as shown in Table 9.18.

Moreover, reducing the glazed area reduces the amount of penetrated sunlight and heat. A satisfactory saving percentage in cooling load could also be obtained by using double and triple glazing where savings could reach up to 33%, as shown in the results table. Double and triple glazing will mainly reduce the conducted heat in a room. As mentioned by Harkness (1978), solar heat gain through a glazed area is achieved by two main methods: the first method is the conducted heat due to the difference between the outside and inside temperatures while the second method is the transmitted heat due to the incidence of direct and diffuse radiation. However, using more than one shading device, as explained in the third significant factor, is not recommended. This is due to the very low saving percentage in cooling loads that can be obtained when using this method. Due to the high solar altitude angle in August in Riyadh, which is about 77° at noon on the 21 August, the number of horizontal shading devices will not be so effective as the effect of the number of shading devices on heat gain caused by conduction is minimal in this case. However, the effect of the number of devices on heat caused by solar heat gain is greater as the sunlit area distribution can be reduced by increasing the shading numbers. On the other hand, temperatures will not be greatly reduced so cooling loads will not be highly affected by this method. High temperatures in this region during summer, (and consequently high heat gains), require efficient strategies for extra saving in cooling loads.

A combination of a reduced glazed area, double-glazed windows and simple horizontal shading devices will offer an efficient shading solution for buildings in Saudi Arabia. This combination will provide protection against both solar and conducted heat gains. Window area is the most effective significant factor and therefore extra care needs to be taken when selecting window size; orientation should also be seriously considered. South, east and west windows should be reduced as far as is reasonable although south windows could be useful for natural heating in winter. The variation ratio is at its highest rate when changing the glazing percentage and significant variation is also achieved when using various glazing types. However, the lowest variation rate is achieved when increasing the number of shading devices. These results can be observed in Figure 9.59 which also reveals that the ratios and types of glazing are fairly similar in efficiency. On the other hand, shading numbers are far less efficient than these two methods. Using more efficient triple glazing could increase the saving ratio in cooling loads to match the saving ratio achieved by using a 30% glazed area.

Significant factor 1	Required cooling loads at 1300 h	Saving percentage %
Single glazing (SG)	1429 W	**Base case**
Double glazing (DG)	1091 W	**23.6%** saving
Triple glazing (TG)	951 W	**33.4%** saving

Significant factor 2	Required cooling loads at 1300 h	Saving percentage %
90% glazing area (90%GA)	1785 W	**Base case**
60% glazing area (60%GA)	1499 W	**16%** saving
30% glazing area (30%GA)	976 W	**45.3%** saving

Significant factor 3	Required cooling loads at 1300 h	Saving percentage %
1 shading device (1sh)	1214 W	**Base case**
2 shading devices (2sh)	1196 W	**1.5%** saving
3 shading devices (3sh)	1184 W	**2.5%** saving

Table 9.18 Saving ratios of each factor in the three selected significant factors.

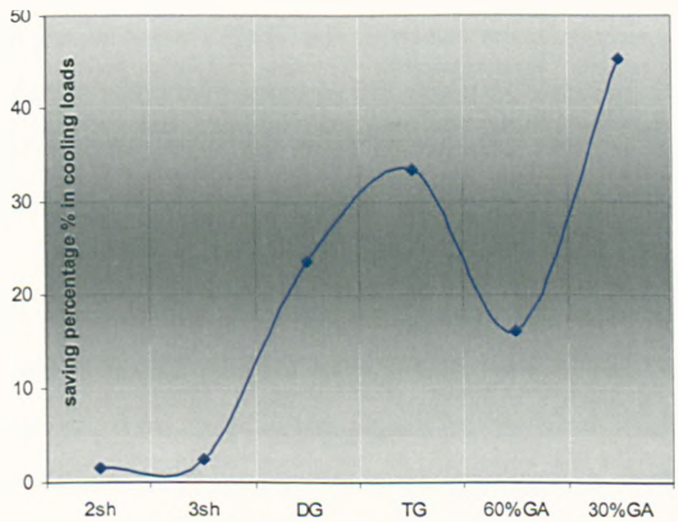


Figure 9.58 Saving ratios through each factor in the three selected significant factors.

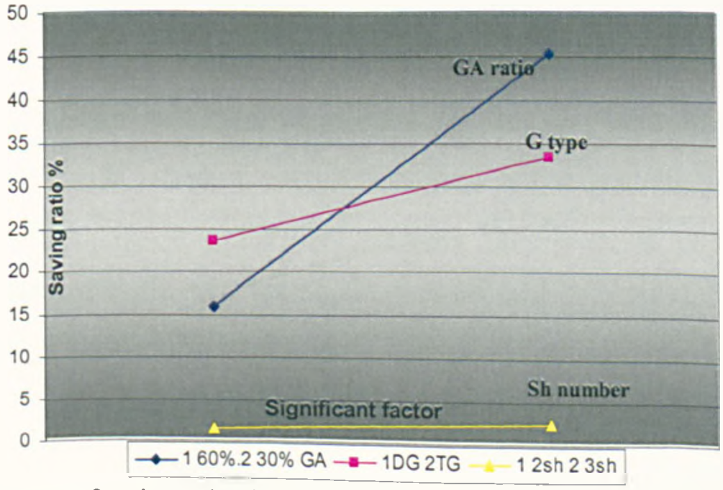


Figure 9.59 Results of saving ratios for each factor in the three selected significant factors (separated).

9.3.3.4. Shading design options in Saudi Arabia according to the cost of shading devices

After reviewing the aspects that affect both the internal distribution of the sunlit area and the savings in cooling loads, shading design options can be reviewed and then these options could be provided for architects to design shading depending on its efficiency and cost. Previous studies show the high efficiency of horizontal and egg-crate shading and the cost of shading has also been provided here according to the Saudi market. Egg-crate shading obviously shows higher efficiency compared with horizontal shading. Horizontal shading could be redesigned, however, to reach a level of efficiency similar to that of the egg-crate. The results in Figure 9.53 show that 1254W/h is required as a cooling load for the 60% window to wall area when using .9m x 4.8m horizontal shading. On the other hand, by using egg-crate shading, the required cooling load is reduced to 1239W/h. This shows a 16.3% reduction in cooling load when using horizontal shading compared with the window without shading. According to the IES thermal calculation, the efficiency of the horizontal shading could be increased if the dimensions of devices were changed. The required cooling load would reach 1234W/h if fixed horizontal shading of 4.8m x 1m were used. This would give the same efficiency as the egg-crate shading. Decisions could then be made by the architect to select the most appropriate shading design to match the building design criteria. By using the available data in Saudi Arabia, cost could also be provided.

Shading costs were calculated for both horizontal and egg-crate shading and three materials were selected to investigate the costs. These were block, GRC and fabric. The materials were selected based on the price per square metre. Block shading was found to be the cheapest and fabric the most expensive while the shading cost of GRC ranged between the two. In such a case, a decision could be made by the architect to select the most suitable material for the building according to the available budget and the environmental necessities.

According to the three selected contractors, the average cost of block shading is 83 SR/m^2, which is £11.7. GRC shading costs 817 SR/m^2, which is about £116.7, and fabric shading costs 3333 SR/m^2 (£476.1 in British pounds). The following table shows the total cost for the two selected types of shading (horizontal and egg-crate) fixed on the 60% window to wall ratio window. The total area of the redesigned horizontal shading device is

4.8m x 1m= 4.8m^2. Moreover, the total area of the egg-crate shading is .9m x 4.4m + 2.5m x .9m x 2 = 8.46m^2.

Horizontal shading device area = 4.8m^2

Egg-crate shading devices area = 8.46m^2

	Area	Block shading cost SR	GRC shading cost SR	Fabric shading cost SR
Horizontal shading	4.8m^2	4.8 x 83= 398 SR	4.8 x 817 = 3921 SR	4.8 x 3333 = 15998 SR
Egg-crate shading	8.46m^2	8.46 x 83= 697 SR	8.46 x 817 = 6911 SR	8.46 x 3333 = 28197 SR
Cost of horizontal shading in British pounds		£56.8	£560	£2258
Cost of egg-crate shading in British pounds		£99.5	£987	£4028

Table 9.19. Horizontal and Egg-crate shading devices cost for the selected window in Saudi Riyals and British pounds.

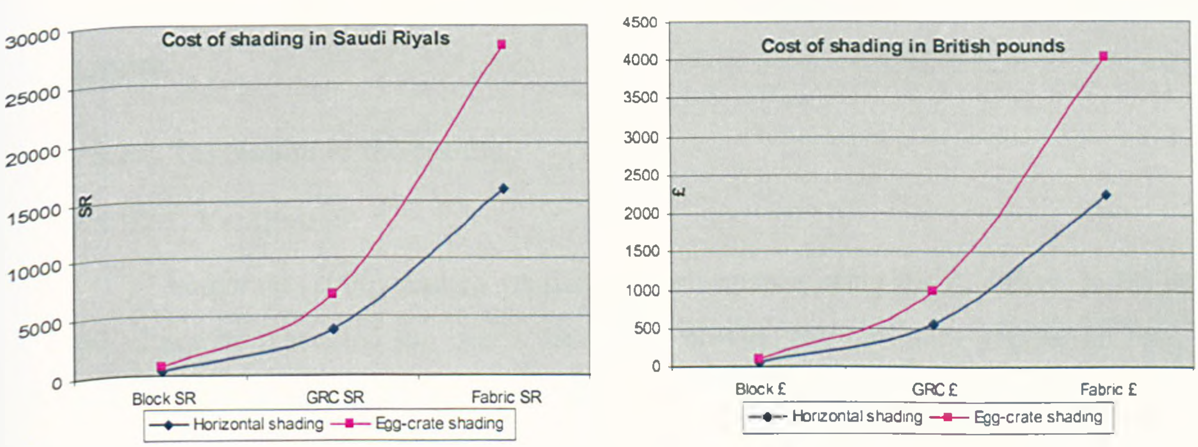


Figure 9.60 Cost of horizontal and egg-crate shading devices for the selected window in Saudi Riyals and British pounds.

The study showed that the cost of the horizontal shading is reasonably acceptable, especially when using blocks where the cost will be around 400 SR. A higher budget would allow more options for shading device materials. Furthermore, horizontal shading is an efficient shading solution for the high summer sun in Saudi Arabia and the cost could be reduced if shading devices were considered at an early design stage as then shading would be part of the building when it was first constructed. Using egg-crate shading would cost more and could block essential solar radiation during the winter months whereas the horizontal shading configuration would also allow solar distribution during winter when natural heating is required. Such low cost shading would save money in the long term as it would reduce solar penetration in summer and, consequently, heat gain and cooling loads. GRC shading could be used as a screen; this is commonly used in governmental buildings in Saudi Arabia and fabric shading could also be used as a tent shading; this is used mainly in residential buildings in Saudi.

9.5.1. Comparative Parametrical Study of Shading Functions

9.5.1.1. Introduction

The study aims to investigate the optimum shading device configuration, orientation and slope angle and was conducted by exemplifying recommendations made by different researches. Various functions and aspects of shading were selected for the study. These aspects were ventilation, day lighting, cooling and heating through sunlit area distribution (current study), view and privacy and the research studies selected were located in different climatic zones. It was recommended that these should focus on hot climate zones as the current research mainly investigates shading in this type of climate. The study also aims to provide design guidelines for architects to use when design shading devices.

9.5.1.2. Discussion of the results

9.5.1.2.1. Ventilation

Maghrabi (2000) studied ventilation performance using the Rowshan. In his design guidelines he discussed the best solutions to provide the optimum ventilation rate. The design guidelines demonstrated that optimum ventilation performance inside the room is achieved when horizontal inclinations of louvers are employed. Rowshan louvers with an inclination of $\theta \geq 60°$ results in poor ventilation performance and this should be avoided in the design of the louvers. As a result of this study, the inclination of the louvers *(θ)* should be less than 60° to achieve the optimum ventilation rate inside the room. The assumed optimum orientation is north-west and the prevailing wind in Jeddah is mainly from this direction.

9.5.1.2.2. View

Tabt (1991) investigated the optimum view through various types of shading device. Designers should consider the location of the shading devices in relation to eye level and devices should be designed to be below or above the eye level height. Moreover, it should be noted that eye level is not a standard measure; it can vary depending on the users, activity and/or building type, such as children in a school classroom or patients in a hospital.

Three concepts were considered in this investigation: viewer satisfaction, clarity and enclosure-spaciousness. Tabet's investigation (1991) showed that overhang shading is the most efficient and positively rated type of the three selected concepts.

The study also showed that vertical shading is the second most efficient after the overhangs as viewers have shown that they prefer an unobstructed and balanced view. The use of overhanging shading, instead of elements that divide the view, is preferred.

9.3.4.2.3. Summer cooling and winter heating through sunlit distribution

The current research on the effect of sunlit distribution on cooling loads show significant effect of internal sunlight distribution and cooling loads. Horizontal shading shows the best efficiency in both seasons heating and cooling. Horizontal shading will work efficiently against the high summer sun in Saudi Arabia. Furthermore, in winter this shading configuration will allow low sunlight to penetrate internal in winter. Obviously, in summer egg-crate shading will present higher efficiency when compared against horizontal shading. However, materials used in the horizontal shading are more likely to be less than in egg-crate shading.

9.3.4.2.4. Daylighting

Ahmed (2000) investigated the possibility of daylighting through various types of shading device. His study tested the performance of five types of shading device, which included vernacular and modern structures, louvers, horizontal overhangs, sloped overhangs, the modern light shelf and a newly designed sloped overhang. The experiments showed that the light shelf with a sloped overhang performed efficiently. This type of shading provides sufficient illumination for the selected room. From the experiments, the optimum slope of the overhang was found to be at an angle of 45° and in the research recommendations, Ahmed (2000) illustrated that shading devices made up of a 0.5m horizontal light shelf and a 0.5m sloped overhang of 45° to the horizontal were recommended for large windows, which should be at least 40% WFR, where W= wall, F =floor and R= ratio.

9.3.4.2.5. Solar penetration in summer and winter

The current research investigated the distribution of the sunlit area to the internal surfaces through various types of shading. Two main tools were used for the assessment of the investigation, which were computer models (SunCast) and a physical scaled model. Three main types of shading were included in the study: horizontal, vertical and egg-crate shading. The experiments were performed in both peak summer (21 June) and peak winter (21 December). For the hot dry climate region of Saudi Arabia, the most efficient shading in summer is the egg-crate shading. Horizontal shading also showed an efficient performance in reducing the sunlit area that penetrated to the internal surfaces.

9.3.4.2.6. Privacy

A practical example of privacy with windows is the Rowshan. This traditional window has a screened cover made of wood which prevents people inside being seen by others on the street. Lack of privacy through windows is the undesirable feeling of being overlooked and observed by people outside the building (Tabet, 1991). Tabet (1991) noted that Appleton (1975) pointed out a preference for and a feeling of comfort in environments that allow to people to "see without being seen".

In order to achieve privacy, apertures in the window shading have to be as small as possible. The inclination angle of horizontal louvers has to be as small as possible to achieve a high level of privacy so, if the horizontal inclination of the louvers is around 90°, as shown in Figure 9.61, privacy will be provided.

9.3.4.2.7. Reduction of solar radiation in hot humid climates

Three selected shading devices (horizontal, vertical and egg-crate) were evaluated under different sky conditions by Hassan (1996). His results show that horizontal shading devices performed efficiently for all window orientations. The vertical shading devices were much less efficient than the other window orientations, with egg-crate shading devices being slightly more efficient than the horizontal shading. The experiments' results showed that egg-crate shading could eliminate up to 57% of solar gain with a west orientation while, for the same orientation, horizontal shading could reduce about 46% and vertical shading reduce about 10%. Horizontal shading was also found to be effective against the high sun for both east and west orientations and vertical shading was found to be generally effective for the south orientation. Egg-crate shading was the most effective type due to its efficiency in all orientations.

The following table consists of the recommended shading angles, orientations and configurations achieved by different researchers and the current research. The study includes all selected shading functions. This table is followed by two graphs which illustrate the recommended angle and orientation for each shading function.

Function	Angle	Orientation	Configuration	Research	Research Location
Ventilation	More than 60°	Assumed north-west	Horizontal louvers	Magrabi 2000	Saudi Arabia
View	0	No specific orientation	Overhang, Horizontal	Tabt 1991	
Daylighting	Overhang angle 45°	No specific orientation	Light shelf and sloped overhang	Al-Shareef 1996 Ahmed 2000	Malaysia
Solar distribution in summer (current research)	0	East-west	Horizontal	S.Waheeb 2005	Saudi Arabia
Solar distribution in winter (current research)	0	South	Horizontal	S.Waheeb 2005	Saudi Arabia
Reduction of solar radiation in hot humid climates	0	East and west	Horizontal	Hassan 1996	Malaysia
Reduction of solar radiation in hot humid climates	0	South	Vertical	Hassan 1996	Malaysia
Reduction of solar radiation in hot humid climates	0	All orientations	Egg-crate	Hassan 1996	Malaysia

Table 9.20 Recommendations for shading made by previous studies.

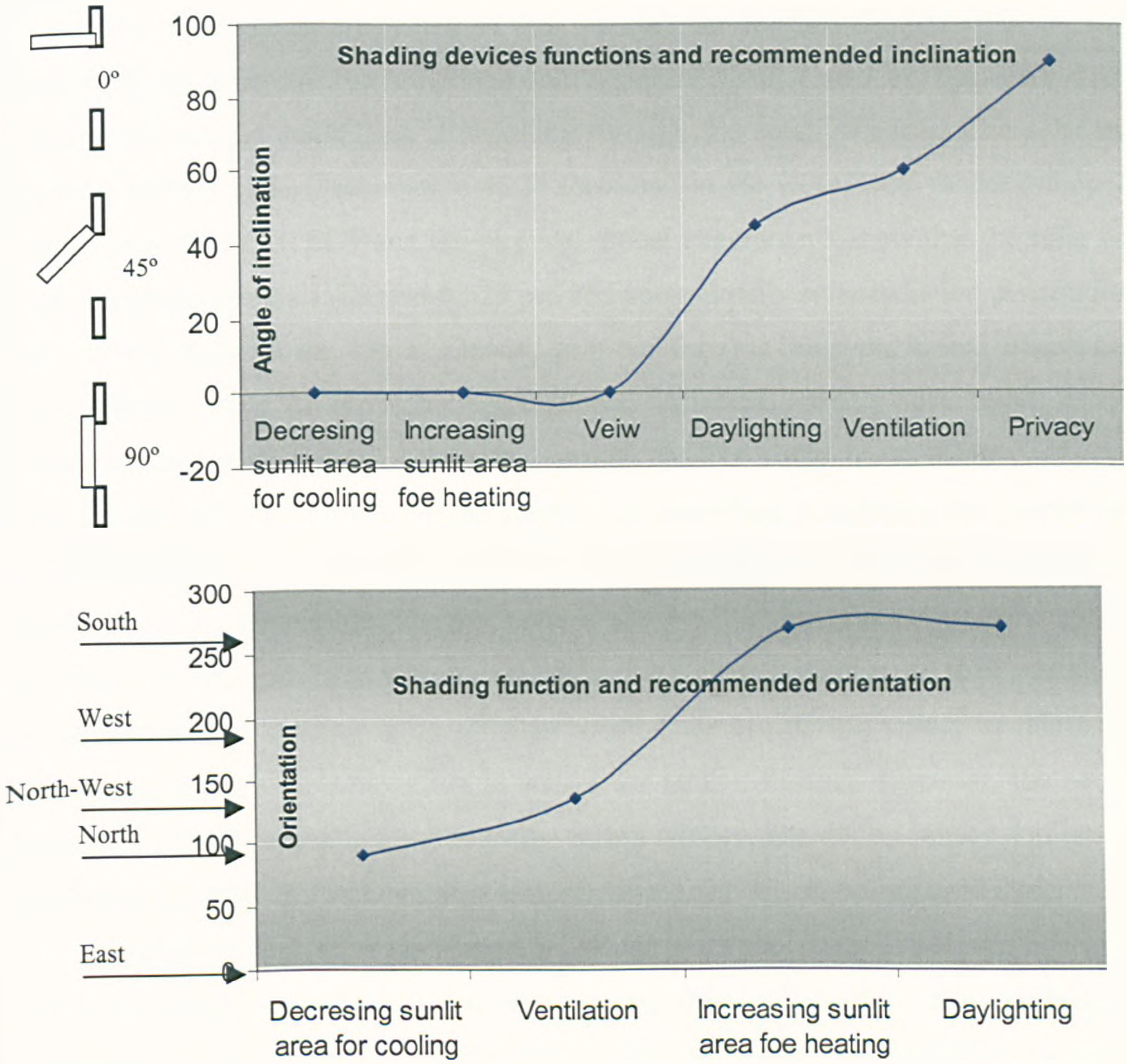


Figure 9.61 Optimum orientation and inclination solutions for shading functions.

Function	Shading Type
Ventilation	Horizontal
View	Overhang
Daylight	Lightshelf and sloped overhang
Solar distribution in summer	Horizontal shading
Solar distribution in winter	Vegetation and fixed adjustable shading
Reduction of radiation in hot humid climate	E-W Horizontal
Reduction of radiation in hot humid climate	South Vertical
Reduction of radiation in hot humid climate	Egg-crate
Privacy	Egg-crate

Table 9.21 Recommended shading types for various functions.

9.6. Conclusion

The experiments conducted in this research for Jeddah, Saudi Arabia, in winter show high efficiency for the horizontal and egg-crate shading devices. Egg-crate shading achieves the lowest sunlit area distribution through the south window. The solar noon angle in Jeddah on 21 December is 45.3° according to the ECOTECT model (v5.2). The results from the ECOTECT and the physical model experiments show that the solar noon angle in Jeddah occurs at around 12:25 pm and consequently solar radiation penetration at the selected hours (10am, 11am, 12noon, 1pm and 2pm) is not symmetrical around noon. The results in Table 9.2 show that egg-crate and horizontal shading have higher levels of efficiency than vertical ones. However, vertical shading could be valuable during early morning and late afternoon as vertical shading can contribute in reducing the internal sunlit area distribution by 27% at 10am and by 23% at 2pm from the south window in winter, as illustrated in the same table. The egg-crate shading will reduce the penetrated sunlit area by 72% at 10am and 79% at 2pm, which is the highest reduction of solar radiation in winter. Horizontal shading is an efficient method for use during winter as this method allows significant solar penetration in winter for natural heating. However, the need for heating in Jeddah is negligible due to the raised temperature during winter and previous investigations show that in December temperatures of 21° C can be achieved there.

Due to the high solar noon angle in Jeddah in summer, mentioned previously, there will be no penetration of solar radiation in summer through the south window. Thus, other orientations were selected to examine the internal distribution of sunlight in the summer experiments. Initial experiments revealed that a sufficient sunlit area penetrates the east and west windows in summer so these windows were selected to be evaluated during the summer. Generally, distribution of the sunlight in summer is less than in winter due to the solar altitude angles in both seasons. Higher efficiency rates also occur when using horizontal and egg-crate shading but, due to the high solar altitude angle, vertical shading has a negligible effect on reducing the penetrated solar radiation.

It can be concluded from both experiments (summer and winter) that horizontal shading is the most suitable shading type. This shading is efficient in reducing the penetration of solar radiation in summer when the solar altitude angle is high. Thus, it is appropriate for use in shading buildings in Saudi Arabia. This shading will also allow the penetration of sunlight in winter for natural heating when the angle of the sun is fairly low. This could be applicable to other regions of Saudi Arabia such as Riyadh, for instance. However, in fact, since egg-crate shading provides less penetration of sunlight into the internal surfaces, smaller cooling loads will be required with this form of shading but it can also reduce some of the essential solar penetration used for natural heating in winter. From an architectural point of view, horizontal is preferable to egg-crate shading due to its form and properties, and although vertical shading devices are not as effective as horizontal and egg-crate shading in summer for the region of Saudi Arabia, they could be useful for other climatic zones.

The parametrical investigations showed that physical and SunCast models were efficient methods to investigate the internal distribution of the sunlit area. However, the results from the ECOTECT model showed acceptable discrepancy rates when compared with other methods. Using a manual technique to investigate the sunlit area is also an efficient method that helps in understanding shading angles. Investigations into savings in cooling load revealed that higher saving rates could be achieved when using shading on large glazed areas while the importance of shading devices increased with large glazed areas. A saving ratio of 21% in cooling load could be obtained when using egg-crate shading. Furthermore, it was found that using horizontal shading could save up to 19% of the required cooling loads. Shading devices protect windows from solar heat gain and double and triple glazing is an efficient method of reducing conducted heat gain.

The study of significant factors showed that the glazing area factor is the most effective factor influencing cooling loads. Using a 30% window area in the selected room in Riyadh could save up to 45% of the required cooling load while using horizontal shading with a reduced glazed area would be an ideal solution for shading in Saudi Arabia. Horizontal shading was shown to be efficient against the high summer sun angle in Saudi Arabia. Moreover, horizontal shading is a simple shading method that could be easily constructed without the need for highly skilled labour.

CHAPTER 10

CONCLUSION AND RECOMMENDATIONS

10.1. Introduction

The first five chapters of this thesis consist of the main literature review, starting by reviewing the climate and architecture of Saudi Arabia in the second chapter and ending by examining solar geometry and offering shading descriptions in Chapter Five; the introduction to the main study is also presented in this chapter. Windows and shading types and their functions are explained in detail in the third chapter while Chapter Four contains the most important part of the literature review, the previous efforts made in this field. This part acts as a general guide for the main investigation. In the sixth chapter the initial experiments, which were conducted for the main study, are presented. This chapter examines the capability of the selected computer models. The main research study is illustrated in the last five chapters with the internal distribution of the sunlit area as the principle aspect in this investigation. Thus, factors affecting the penetration and distribution of sunlight are explained in detail in Chapter Seven. Evaluating these factors helps in determining which are the most highly effective.

The effect of thermal simulation by using shading systems is also one of the major aspects of the study and this is demonstrated in Chapter Eight by using different shading systems in different climatic zones. The third and final main part of the research is included in Chapter Nine which contains accounts of the physical model experiments conducted in Jeddah, Saudi Arabia, to examine the effect of different shading systems in reducing the internal penetrated sunlit area, and consequently reducing required cooling loads. The results achieved using the computer model, SunCast, and the physical model were compared; a discrepancy percentage between the two models was also achieved.

The literature review covers traditional methods of natural lighting and shading and the main shading technique found in the traditional architecture of Saudi Arabia is the Rowshan. Types of conventional windows, the functions of windows in architecture and aspects of daylight design concepts are discussed in the study. Six research topics, including investigating ventilation using shading devices, the thermal performance of selected types of shading device, natural lighting using shading devices, and the view through the devices, were also investigated and are presented here.

The results of most of the investigations show that there is a need for shading devices even with the minimum acceptable window size. It has been proved by Tabt-Aoul (1991) that the best view out from the window is achieved through horizontal apertures, with a width that occupies a minimum of 35% to 40% of the wall width and with an optimum area of 45% to 60%. Another study concentrating on the performance of the internal shading devices, conducted by Joudah (1992), showed that the shaded fenestration of the blinds could make reductions from between 11% and 34% in heat transmission in buildings.

10.2. The Climate and Architecture of Saudi Arabia

Climatic conditions in Saudi Arabia have a strong impact on architectural approaches as various architectural styles that exist in the region depend on climatic conditions. The climate of Saudi Arabia is divided into two main climatic zones: hot dry and hot humid regions. The hot humid zones are mainly located in the west and middle parts of the country, while hot dry zones are located in the south-east and middle parts. Extremely hot summer weather is the main characteristic of Saudi Arabian weather. The dry bulb temperature in Jeddah can reach up to 38°C while relative humidity can reach 90%. Discomfort in the western part of the country is mainly caused by three major factors: high temperatures, high percentages of relative humidity, and direct solar radiation. Specifically in Jeddah, winter temperatures can fall to an average of 23°C. Thus, no heating is required and therefore most investigations need to concentrate on cooling strategies and shading methods to reduce the direct penetration of solar radiation.

Traditional techniques are found in the vernacular architecture to provide natural lighting and natural ventilation. Small openings in the traditional architecture of Riyadh are used to provide natural lighting without allowing extra solar heat to penetrate. Adobe buildings in the same region have been proved to have efficient thermal properties. Therefore, most of the buildings in old Riyadh are built with thick walls made of mud for insulation; thick walls minimise heat gain by conduction. The strategy of including fewer windows is another major characteristic of the houses' façades; this prevents the internal spaces from receiving solar radiation. Courtyard houses can also be found in Riyadh. This is an efficient method for cooling by shading the internal spaces. The courtyard method also provides natural lighting for the internal spaces.

The climatic study in this research concentrates on the west region, which is the region targeted for the study. Most of the experiments in the main study were conducted in Jeddah, which is located in the west region and an intensive study was performed on the climate and architecture of Jeddah. The Rowshan was the main traditional technique investigated in terms of natural lighting, ventilation and shading as the indirect penetration of sunlight, natural ventilation and privacy are the main three functions of the Rowshan. The Rowshan also used to be an element which reflected the social status of the house owner. Exist of the Rowshan technique emphasis the investigation in the solar shading techniques methods. Moreover, according to previous studies, this traditional technique provides an efficient distribution of air flow and natural lighting, thus supplying the desired comfort level for the occupants. Furthermore, energy consumption can be decreased using this method as less solar penetration will result in a reduction in the required cooling loads.

10.3. Summary of Previous Investigations

From among the selected six studies of previous work, three were directly related to the current research area while the other three were related only indirectly. These latter studies mainly investigated other functions of shading devices. However, protecting buildings from direct solar radiation is the main function of shading devices while the other functions were investigated in three selected Ph.D. studies: natural ventilation was the focus of Maghrabi's study (2000), Ahmed's work (2000) centred around natural lighting, and view out was the main concern of Tabt-Aoul's research (1991). Most of these studies were conducted in similar climatic conditions and, moreover, the three studies are directly related to the climate of Saudi Arabia, which was the region selected for this current research. One of the main motivations for investigating the other functions of shading devices was to produce a study that summarized the optimum shading device configurations for different functions.

Hassan's study (1996) is the study most closely related to the scope of work in the current research and similarity can be found in two main areas in both studies: shading device types and climatic conditions. The selected types of shading device in both studies are horizontal, vertical and egg-crate shading. However, most of the experiments conducted by Hassan (1996) depended mainly on the three shading techniques mentioned above while the main research of the current study, on the other hand, depends on those devices but also on other factors that affect sunlit area distribution. Some of the results of the current study are compared with Hassan's study (1996) to validate the effect of the shading devices on the thermal behaviour researched here. The main concern of Hassan's study (1996) was to examine the effect of shading devices on diffused and reflected solar radiation and to consider the internal thermal effect of these devices. The experiments were conducted in the climatic conditions of the UK and of Malaysia. However, the main concern of the current study is to examine the effect of different factors (but mainly shading devices) on the internal penetration of the direct solar radiation. These experiments were conducted mainly in Saudi Arabia although some of the experiments were conducted in the UK. The following table offers the results regarding the contribution of the selected shading methods in reducing direct solar radiation in both studies.

Sun-cast Results	Hassan's Results
Horizontal shading 45%	Horizontal shading 63%
Vertical shading 42%	Vertical shading 42%
Egg-crate shading 95%	Egg-crate shading 91%

Table 10.1 Results achieved by both studies for the three selected shading techniques.

Joudah (1992) aimed to present yearly climatic data for Saudi Arabia and examining the energy performance of internal shading devices (curtain and blinds) was the main concern of his work. The effect of the selected internal devices on the indoor thermal comfort of occupants was assessed by using design tools developed in the same research. The final conclusion of this research indicated that blinds are more efficient than curtains in reducing both solar heat gain and the transmission coefficient of double glazed fenestration (Joudah, 1992). His results showed that, by using blinds, the transmission coefficient of double glazed fenestration could be reduced by 11% and the solar heat gain factor could be reduced by 34%. However, curtains could reduce the transmission coefficient by 8% and the heat gain factor by 29% only.

.Ahmed's investigations (2000) were processed to examine the potential of natural daylighting as a major source of indoor lighting in Malaysia. The investigation also aimed to present solid and practical knowledge about daylighting in hot humid regions in Malaysia. The main aspect of the research was to create low energy and thermally comfortable buildings by integrating daylighting into building design by using different window sizes and shading devices. This goal was mainly achieved by investigating the results of three main studies: evaluating new and old daylighting techniques was the first part of the study; the second study involved a statistical analysis of climatic data; and the third was a field study to determine conditions for thermal comfort.

Maghrabi's study (2000) investigated the ventilation aspects of a traditional architectural element, the Rowshan. The other two functions of the Rowshan, as mentioned earlier, are solar control and privacy. Comparative studies were conducted by using different types of Rowshan to assess their ventilation efficiency. Maghrabi (2000) presented the minimum acceptable inclination angle to provide the most desirable level of ventilation, (which is ± 60°).

The view out from the window is a function that could be affected by shading devices. The effect of window design and shading devices on view was investigated in

Tabt-Aoul's study (1991). Window size was evaluated in this study as a function of view and investigations were performed to examine the effect of shading devices on the view from the windows. Two main window design concepts were evaluated in the study; these were the minimum acceptable window size for view and the optimum window size for view. The research results showed that the minimum acceptable window size for view should be a window to wall ratio of between 12% and 17% while, for the optimum window size for view, the study showed that a window to wall ratio of 21% to 30% is acceptable.

10.4. VARIABLES AFFECTING THE SUNLIT AREA

An evaluation of the performance of different shading techniques was carried out in this study using the "SunCast" computer program, a well known model developed in the UK as part of a large suite of programs. SunCast has already been used for more than a decade by many researchers to investigate the solar performance of building components. The experiments in this research were, first, conducted to gain confidence in the SunCast model by comparing its results against independent full-scale tests. The evaluation then examined criteria and techniques that could be used to evaluate the effects of variables like latitude, orientation and other factors on the internal distribution of the sunlit area.

Each variable had a significant effect on the sunlit area distribution. Location, for instance, has a significant impact on increasing or decreasing this area due to the sun's altitude angle. The solar altitude angle can amplify the penetration of solar radiation in high latitudes and decline the penetration in lower ones. Different types of shading device also affect the distribution of the sunlit area. Previous studies indicate that horizontal devices are most effective with high sun angles and vertical devices are more effective with low sun angles while egg-crate devices are effective in both cases.

A period of time from 10 am to 2 pm was the period selected to examine the distribution of the sunlit area. This was discussed with emphasis being placed on the graphs which illustrate the behaviour of the solar radiation on the horizontal surfaces as a function of time in different latitudes. The selected latitudes were 20°N, 30°N, 40°N, 50°N and 60°N.

Another important variable that had a powerful effect in this study was the summer and winter seasons. The selected days for the evaluation were 21 June, which represents the summer period, and 21 December, which represents the winter period. In both experiments, the results of the physical and computer models indicated that, with all selected types of shading, penetration in winter is higher than penetration in summer.

Furthermore, orientation was found to affect sunlit area distribution. In Jeddah, Saudi Arabia, south windows receive the most solar radiation during the winter period while, in summer, most of the solar radiation is received by the east and west façades. Solar infiltration to the internal spaces varies from one orientation to another as the orientation of some windows will allow more solar radiation to enter than others; this is an effect of the sun's location from these orientations.

To obtain an efficient evaluation of the thermal performance of shading devices, two climatic zones were selected for the investigation: a hot dry zone (Riyadh, Saudi Arabia) at latitude 24.65° N and a cold climate zone (London, United Kingdom) at latitude 51.50° N. This made the evaluation more efficient than if it was carried out in one climatic zone only. In order to evaluate the efficiency of the shading devices, a simulation of the thermal performance of the window without shading must first be achieved so that, subsequently, a comparison of the contribution of shading types can be made. According to the results in the graphs for these two regions, the distribution of the sunlit area during summer in London is higher than the distribution in Riyadh. There was almost no penetration of sunlight from the south window in Riyadh with all the selected shading types in summer. However, by using vertical shading on the south window in London in summer, the sunlight penetration will be higher than if horizontal shading is used. Horizontal shading in London will inhibit most of the solar radiation in summer. Graphs also revealed that high amounts of heating are required in London in winter while, in Riyadh, high amounts of cooling load are required in summer. Horizontal and egg-crate shading in Riyadh will decrease the required cooling loads. This is also applicable to the climate in London.

Investigations on the effect of the sloped windows indicated that, with lower window angles, the penetration of solar radiation will increase. The experiments showed that sunlight distribution through a 40° degree angled window is higher than through a normal 90° angled window. Consequently, a smaller cooling load will be required when using higher window angles.

10.5. THE INVESTIGATION OF THE MAIN STUDY

10.5.1. Results of the Suncast model experiments

SunCast enables the researcher to perform shading and solar insolation analysis; it can also generate images and animations quickly and easily. SunCast can be used at any stage of the design process and creates solar shading and insolation information from a model created by the IES ModelBuilder or from 2D or 3D CAD data.

The model can be used to investigate:

1. The external obstruction and self-shading of a building;
2. Solar mapping through windows and openings;
3. The effects of changing the orientation of a building.

The SunCast model generates shadows and internal solar insolation using any sun position defined by date, time, orientation, and site latitude and longitude. This shadow information can be stored for subsequent analysis by:

1. Viewing shadows from any eye position;
2. Animating the solar analyses by generating a sequence of images and creating an avi movie that could be used for detailed investigation;
3. Making opaque surfaces "transparent" to permit the user to better view the solar insolation on internal surfaces e.g. "removing" roofs or surfaces to identify internal solar insolation paths;
4. Displaying solar surface shading/insolation statistics.

SunCast can be used in a variety of studies, including passive solar design, and is essential at the planning stage to visualise the effect of the building on surrounding buildings. The model has also been used to study problems such as grass growth in sports stadia and 'right of light' issues. In addition, because it is possible to remove surfaces to investigate solar penetration, SunCast can be used to investigate internal design issues from office layouts to the positioning of art in museums.

The main experiments in the research, (located in Jeddah, as mentioned before), were conducted by using this model. The experiments were performed in both seasons, that is, in summer (21 June) and in winter (21 December) so results could be compared with the physical model used in the main research.

Horizontal and egg-crate shading will reduce a significant amount of solar penetration. However, by using vertical shading, more sunlight will penetrate to the internal spaces from the south window. Because of the increased prevention of sunlight penetration in winter when using egg-crate shading, horizontal shading is, overall, a more efficient shading method as it allows a reasonable amount of solar radiation to penetrate to the internal surfaces during winter for natural heating. A very limited percentage of solar radiation is required for natural heating in Jeddah. In summer, due to Jeddah's location and the solar geometry, there will be no penetration of sunlight through the south window.

Consequently, other window orientations were selected for the investigation. The results of the initial experiments showed that most of the sunlight in summer would penetrate the east and west windows in this location. Therefore, a sunlit area evaluation was conducted regarding the east and west windows in summer. Results indicated that horizontal and egg-crate shading are highly efficient in excluding solar penetration in the hours around noon (that is, at 11,12,13 and 14h). By using vertical shading, a significant percentage of sunlight will be transmitted to the internal surfaces at these times while, due to similarities in the efficiency of horizontal and egg-crate shading, horizontal shading is recommended despite the decreased cost when compared with egg-crate shading. Due to the solar geometry in summer, the efficiency of vertical shading is negligible.

A calculation of the sunlit area distribution in summer was performed for both east and west windows while, in winter, calculations were only performed for the south window.

10.5.2. Results of the physical model experiments

The physical model experiments, also focussing on Jeddah, constituted the second stage of the main investigation. A scale model was constructed with 1.6m x1.6m window opening on the south wall; the window covered about 15% of the wall's area. The room was 6m x 6m at a scale of 1/10. Previous research strongly supports investigating shading efficiency by using a physical model.

Results achieved from the experiments were compared with the results achieved from the SunCast model and the outcomes were tested to calculate the discrepancy rates. The maximum discrepancy percentage achieved between the two models was 20%, which is an acceptable rate. Winter experiments were conducted twice for two main reasons. Firstly, the discrepancy rate between the results achieved from the SunCast model and the physical model was high and secondly, the experiments were repeated for added accuracy.

10.6. Possibility of Reducing Cooling Loads through a Reduction in the Sunlit Area

Two main computer models were used to investigate the potential savings in cooling loads by reducing the sunlit area.

ApacheCalc is a thermal analysis model and SunCast is a sunlit area calculation tool and the interaction of these two models was the main tool for this investigation. The physical model experiments on Jeddah during the summer showed a direct relationship between the amount of sunlit area that penetrated the space and the required cooling loads.

Increased penetration directly affects and increases the required cooling loads. These calculations were based on the sunlit area penetration through east and west windows in summer, with each window measuring 1.6m x 1.6m. The calculations of the cooling loads carried out using the ApacheCalc model were based on the peak sensible hour. The total penetrated sunlit area in June was calculated and then compared with the required cooling loads. The results are displayed in the following table and graphs.

Shading type	Sunlit area distribution m^2	Required cooling load at the peak sensible hour W
W (without shading)	260.7	1907
H (horizontal shading)	56.7	1703
V (vertical shading)	250.8	1839
E (egg-crate shading)	49.8	1150

Table 10.2 Sunlit area distribution and the required cooling loads during June using different shading techniques and a plain window without shading.

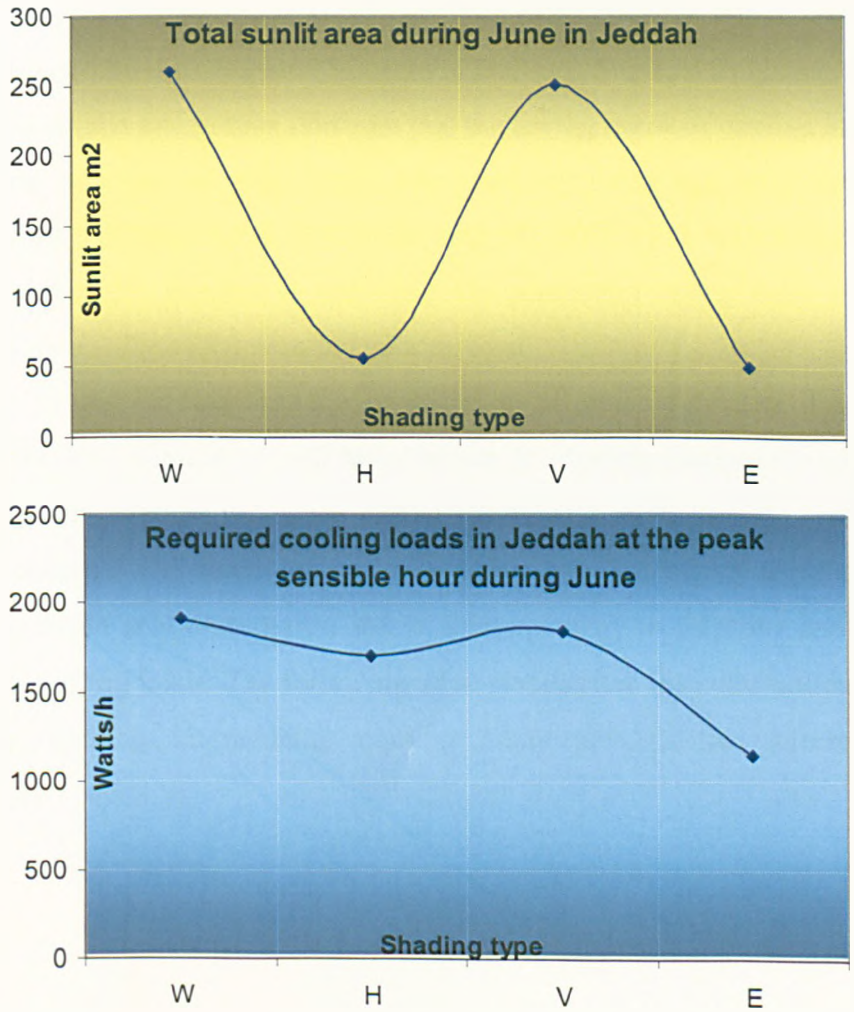


Figure 10.1 The distribution of the sunlit area and cooling loads during the month of June in Jeddah, Saudi Arabia.

10.7. Window to Wall Area Percentage and the Required Cooling Loads in Riyadh, Saudi Arabia

The window area is the most effective variable regarding sunlit area distribution. The study conducted here on window to wall ratios included ratios of 15%, 30%, 60% and 90% while the study's main objective was to calculate the required cooling loads for the space with different window areas. Two shading configurations were included in the study, as well as a window without shading. The shading methods selected for the experiments were horizontal and egg-crate shading; the effect of vertical shading could be predicted from the results achieved from both the other shading methods.

The experiments were conducted using one of the thermal applications, the ApacheCalc thermal model, developed within the IES model suite. However, the results of this model are based on the results of the SunCast model and a link is created between them. For more accurate and efficient thermal results, simulations had to be performed in the SunCast model first. The heat gain and loss calculations in this model are based on the procedures used by the Chartered Institute of Building Services Engineers (CIBSE).

The results and graphs illustrate that the saving ratios of cooling loads are increased in the case of windows with larger areas and, by using egg-crate shading, savings in cooling loads will reach up to 21% in the case of a 90% window to wall ratio. However, in the case of the 15% window to wall ratio, the percentage saving made by using egg-crate shading is only 2.7% of the required cooling load.

So, it can be seen that the contribution of shading devices is significant in this study. In the 90% window to wall ratio, horizontal shading reduces the required cooling by 19% while the average reduction ratio is 20% with both the egg-crate and horizontal shading methods. The study shows that window area is a highly significant variable that affects the sunlit area distribution and is, consequently, an effective factor in reducing or increasing cooling loads. The following table summarises the contribution of egg-crate and horizontal shading in reducing cooling loads through the selected window area percentages.

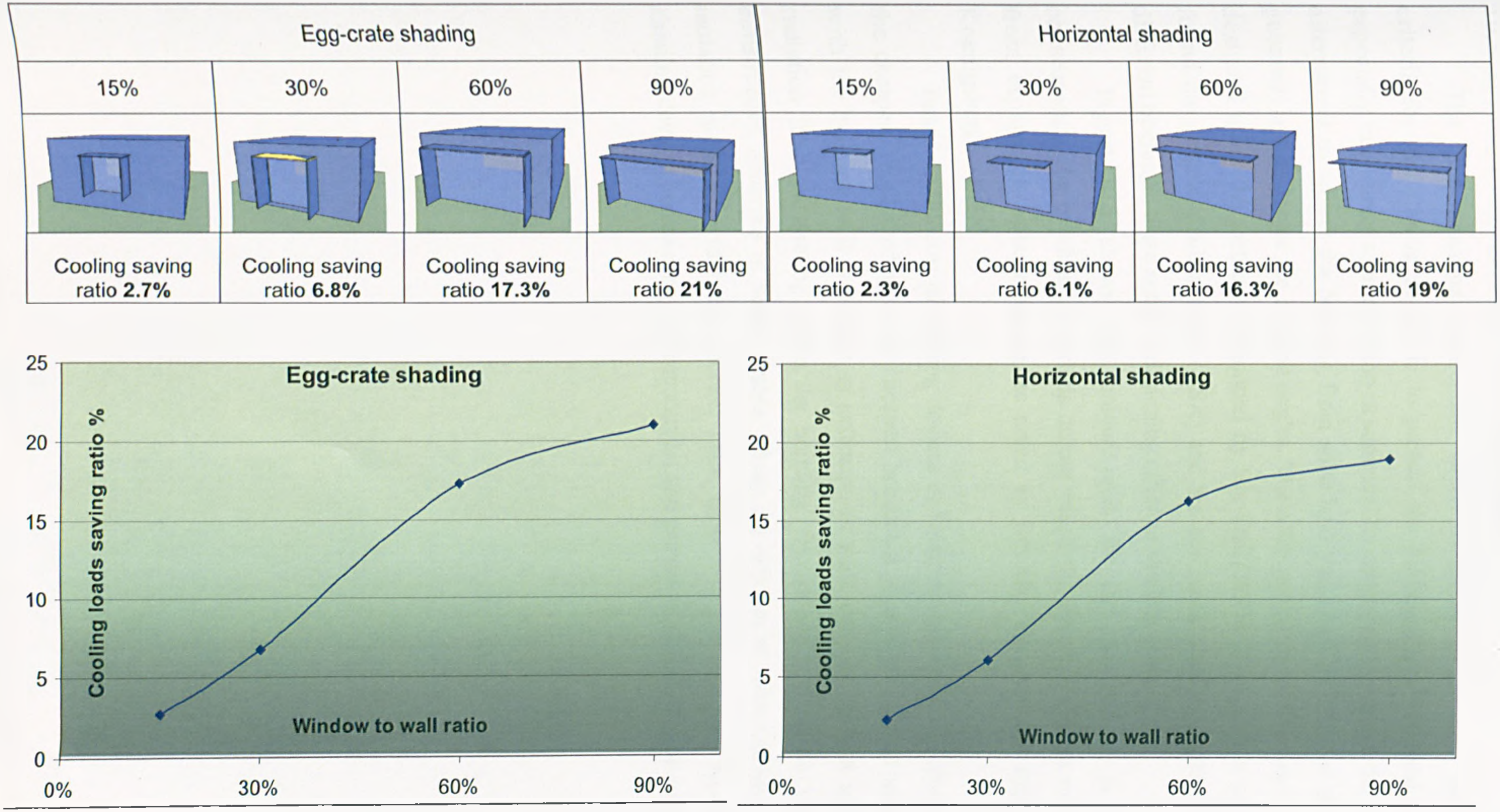


Figure 10.2 Effect of the window area percentage on the saving in cooling loads by using horizontal and egg-crate shading devices.

10.8. Shading Design guidelines for Saudi Arabia

The most important requirement, which should be included in the basic design criteria for hot climate zones, is to protect the building generally and the openings especially from direct solar radiation in summer. To understand what are the best available alternatives to protect the building from solar heat gain, it is essential to study the solar geometry and to locate the shading angles. The solar geometry for the sun in Riyadh was designed using the methods mentioned by Bin Oaf (1994). Through his study, Bin Oaf found the vertical shadow angle (VSA) and the horizontal shadow angle (HSA) for the different openings; these assist in designing efficient shading devices.

Figure 10.3 shows the contour lines for the temperature in Riyadh and consequently, the overheating periods during which the internal surfaces need protection from exposure to solar radiation, as noted by Bin Oaf (1994), after Said (1991) and Koenigsberger (1973).

Based on the cost of shading devices in Saudi Arabia, wall and block shading are the cheapest. Wall shading is the cheapest because it is can be designed and constructed with the building as it is mainly an extension of wall; this can prevent undesired solar radiation from penetrating inside the building. Blocks are one of the most common construction materials in Saudi Arabia. These are efficient in reducing heat gain due to isolation materials within the blocks. Thus, these two materials are recommended as shading devices because they are economical and possess effective thermal properties.

10.8.1. Advantages of fixed horizontal shading devices (overhangs)

Horizontal shading has been shown to be highly efficacious and effective in reducing solar heat gain. The following points demonstrate the main advantages of horizontal shading:

1. It is effective in most window orientations, especially those with a south orientation.
2. The view out function of the window is not disturbed by horizontal shading.
3. External horizontal shading will intercept direct solar radiation before it passes through the glazing.
4. Ventilation can be enhanced because there is no shading directly next to the window. Air movements are not disturbed by this type of shading.
5. Horizontal shading is suitable for high sun in lower altitudes. This is an efficient solution for shading buildings in Saudi Arabia.
6. Horizontal shading is a simple form of shading device and is therefore easy to design. Stack et al. (2005) noted that a simple device which is correctly designed can be as efficient as a hi-tech shading system.
7. The shape of the devices affects the cost. Low cost is one of the main advantages of horizontal shading as this could be part of the building's structure if considered from an early design stage.
8. Horizontal shading can be constructed from different materials, depending on the building's type, location and budget allowance.
9. Current research shows that horizontal shading devices are effective in reducing the distribution of the sunlit area to the internal spaces. Low penetration of this sunlit area is achieved in both summer and winter, and penetration of the sunlit area in winter in Saudi Arabia is not highly desirable, especially in a city like Jeddah where heating is not required.
10. Daylighting studies indicate that horizontal shading is efficient in allowing desirable levels of daylight to penetrate the building.
11. Most of the previous investigations have recommended horizontal shading. Ventilation studies show that ventilation rates increase when using horizontal shading while view-out studies also illustrate that a clear view out can be obtained by using horizontal shading.

10.9. Recommendations for Further Research

Recommendations for further investigations are outlined in the following points:

- The design criteria for shading devices should be carefully considered in hot climate zones but other design considerations should be examined and studied, such as the colour and texture of shading devices, which could affect internal thermal comfort.
- Further research could be conducted to investigate the effect of external elements, such as trees and other surrounding buildings, on the distribution of the sunlit area inside the space.
- No consideration has been given to the effect of the design of a group of buildings on the internal distribution of sunlight although site layout has a great effect on sunlit penetration and thermal comfort.
- Further research could be conducted to investigate adjustments of different shading devices. Different shading angles could be investigated in both horizontal and vertical directions.
- This research was concerned with using a south shading orientation in winter, and east and west orientations in summer. Further investigation could be conducted to examine the distribution of the sunlit area with respect to other window and shading device orientations. South-west and south-east orientations could have a significant effect on the sunlit area distribution.
- It is very important to produce and develop the computer models concerned with environmental design. Such tools are lacking in Saudi Arabia and in other Arabic countries for architects to use to predict the efficiency of a building's design at an early stage. Moreover, these tools, such as SunCast and ECOTECT, could also provide a deeper understanding of environmental design problems and solar geometry.

  These tools are most needed in hot climate zones and could be highly useful in promoting energy efficient design in the Arab countries. In addition to increasing knowledge of shading design and solar geometry, these tools could also provide insight into other aspects of energy efficient design like ventilation and thermal performance (heat loss and gain).

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APPENDICES

APPENDIX A

SanCast (solar analysis), Apache (thermal analysis), and ECOTECT model descriptions

1. SunCast model (solar analysis)

1.1. Introduction

SunCast is a well-known model developed in the UK as part of a large suite of programs. This influential solar analysis model could be used at an early design stage to perform solar geometry studies on buildings. The model can be used to maximise or minimise the solar exposure of buildings through building orientation. The numerical results achieved by the SunCast model could be used evaluate the thermal performance of the APACHE model. The APACHE model is part of the IES virtual environment suite and is the main thermal model. Assessments of the required cooling or heating loads could be achieved by using the two models, the SunCast and APACHE models. This could be very useful in reducing the demand of cooling in hot regions like Saudi Arabia.

1.2. Model's ability

This model can be used to perform graphical and numerical solar studies. It can also be used to visualise shading on the external and internal surfaces, as well as solar penetration. SunCast calculates the sun's location and locates solar radiation through the building's interior. This allows the model to calculate the sunlit areas through a window or an opening onto the internal surfaces. To achieve these results three main elements have to be identified: 1. The location of the site (latitude and altitude), 2. The date and time, and 3. The viewing position (altitude and azimuth). Images of the building affected by the sun, including the shaded and unshaded surfaces, can be created using this model. Surfaces on the images can be set to be invisible so the internal penetration of the sunlight through a window or an opening can be easily seen on any desired surface. For example, if the roof of the model is set to be invisible, the penetration of sunlight through any window in this room could be tracked at different times and months, as shown in the present study. The model's numerical analysis can be used to calculate the amount of sunlight distributed on the external and internal surfaces. Results can be achieved in two forms, which are in square metres or in ratios. SunCast creates a file which contains the solar shading information for each surface. This can be used by the APACHE model to assess the solar gain calculation in thermal analysis. Solar shading devices can be created in the IT model and then can be easily assessed by the SunCast model. The productivity of the model is straightforward, which could save time in the evaluation process.

1.3. Model results

The SunCast model can generate images for the designed buildings showing the effect of the sun on the building surfaces. A series of images can be generated to show the effect of the sun during a selected period of time. These images are created as a movie format so the study of the sun's movement will be more accurate. Results can be directly transferred to an Excel programme so graphs can be created for extra investigations.

One of the most beneficial aspects of the model is the ability to calculate the sunlit area on any internal surface for any chosen location at any time. Three main areas or categories can be calculated: the first category is the sunlit area which penetrates directly through openings without glazing; the second area is the transmitted sunlight, which is calculated through glazed windows; and the last area category is the shaded area on the selected surface.

Figure 11.1 Sunlit and shaded areas on a group of building. Image generated by SunCast. model

Shading Results

m² %

Room	Surface	Opening	Area	Orient	Slope
ROOM	0001 Floor	-	36.000	0.00	180.00

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
01:00												
02:00												
03:00												
04:00												
05:00												
06:00					00.00	00.00	00.00					
07:00		00.00	00.00	03.53	05.22	05.46	04.90	03.88	02.81	01.06	00.00	00.00
08:00	02.80	04.60	05.96	05.30	04.46	04.34	04.68	05.17	05.55	06.05	04.73	02.91
09:00	04.00	04.58	03.81	03.07	02.70	02.67	02.83	03.03	03.14	03.28	03.54	03.47
10:00	02.59	02.58	02.22	01.84	01.65	01.65	01.75	01.84	01.85	01.87	02.06	02.28
11:00	01.40	01.39	01.21	00.98	00.87	00.89	00.96	01.00	00.95	00.91	00.99	01.19
12:00	00.47	00.51	00.41	00.27	00.21	00.24	00.30	00.30	00.21	00.11	00.12	00.28
13:00	00.39	00.29	00.33	00.41	00.43	00.38	00.32	00.36	00.51	00.68	00.73	00.59
14:00	01.32	01.14	01.12	01.15	01.12	01.04	00.99	01.06	01.30	01.58	01.72	01.57
15:00	02.51	02.22	02.11	02.06	01.97	01.84	01.78	01.92	02.31	02.81	03.10	02.78
16:00	04.03	03.91	03.60	03.42	03.20	02.95	02.88	03.16	03.91	05.01	04.94	03.86
17:00	03.42	05.68	06.23	06.09	05.46	04.89	04.77	05.45	05.87	03.82	01.11	01.12
18:00		00.00	00.00	01.44	03.34	04.56	04.74	03.27	00.00			
19:00						00.00	00.00					
20:00												

Figure 11.2 Results in square metres showing the transmitted sunlit area.

Shading Results

m² %

Room	Surface	Opening	Area	Orient	Slope
ROOM	0001 Floor	-	36.000	0.00	180.00

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
01:00												
02:00												
03:00												
04:00												
05:00												
06:00					00.00	00.00	00.00					
07:00		00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
08:00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
09:00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
10:00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
11:00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
12:00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
13:00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
14:00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
15:00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
16:00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
17:00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
18:00		00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00			
19:00						00.00	00.00					

Figure 11.3 Results in square metres showing the direct sunlit area.

m² %

Room	Surface	Opening	Area	Orient	Slope
ROOM	0001 Floor	-	36.000	0.00	180.00

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
01:00												
02:00												
03:00												
04:00												
05:00												
06:00					36.00	36.00	36.00					
07:00		36.00	36.00	32.47	30.78	30.54	31.10	32.12	33.19	34.94	36.00	36.00
08:00	33.20	31.40	30.04	30.70	31.54	31.66	31.32	30.83	30.45	29.95	31.27	33.09
09:00	32.00	31.42	32.19	32.93	33.30	33.33	33.17	32.97	32.86	32.72	32.46	32.53
10:00	33.41	33.42	33.78	34.16	34.35	34.35	34.25	34.16	34.15	34.13	33.94	33.72
11:00	34.60	34.61	34.79	35.02	35.13	35.11	35.04	35.00	35.05	35.09	35.01	34.81
12:00	35.53	35.49	35.59	35.73	35.79	35.76	35.70	35.70	35.79	35.89	35.88	35.72
13:00	35.61	35.71	35.67	35.59	35.57	35.62	35.68	35.64	35.49	35.32	35.27	35.41
14:00	34.68	34.86	34.88	34.85	34.88	34.96	35.01	34.94	34.70	34.42	34.28	34.43
15:00	33.49	33.78	33.89	33.94	34.03	34.16	34.22	34.08	33.69	33.19	32.90	33.22
16:00	31.97	32.09	32.40	32.58	32.80	33.05	33.12	32.84	32.09	30.99	31.06	32.14
17:00	32.58	30.32	29.77	29.91	30.54	31.11	31.23	30.55	30.13	32.18	34.89	34.88
18:00		36.00	36.00	34.56	32.66	31.44	31.26	32.73	36.00			
19:00						36.00	36.00					
20:00												
21:00												

Figure 11.4 Results in square metres showing the shaded sunlit area.

2. APcalc model (Thermal analysis)

2.1. Introduction

Thermal simulation for buildings is essential, especially for buildings in hot climate regions. Thermal simulation is used to evaluate the required cooling loads for buildings. APcalc (APACHE) is the main thermal simulation model in the IES virtual environment suite. Daily and annual thermal performance of a selected room or a building can be performed. Real weather data are used by this model to produce accurate thermal results. Heat loss and gain in this modelare achieved by using the procedures of the Chartered Institute of Building Services Engineers (CIBSE), which is an internationally recognised body. Changes in the design construction and other thermal parameters like glazing type can be performed by using APACHE view.

2.2. Model ability

The APcale model is mainly used to calculate heat loss and gain, consequently calculating the required cooling loads. Methods for heat loss and gain in this model are calculated by conduction, infiltration and mechanical ventilation. Thermal calculations are performed for the 24 hours of each design day. Solar and causal gains are considered in the model. The solar gain factor is used to calculate solar gain through glazed windows. External shading devices in the design are considered in the thermal analysis through linking the shading files created by SunCast model. APlocate is part of the Apache thermal model. In this model, direct solar irradiance data are generated by using factors set in this model. These factors are: latitude and longitude, standard meridian (time zone) and local time correction, and height above sea level.

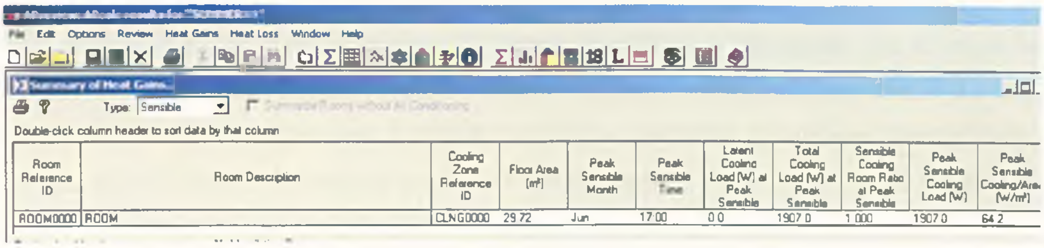
2.3. Model results

Heat gain analysis and results in the model are viewed by using the APreview. According to the description of Al Qeeq (2004), this model can offer the following: "a summary of all rooms, a detailed table of results, graph results, peak total building loads, and air conditioning zones." Moreover, the model can calculate the peak sensible cooling loads at the peak hour, as shown in Figure 11.5. It is also possible to obtain detailed results for each hour.

According to the model manual, three types of thermal analysis can be conducted in the Apache view using programs as follows:

- Building regulations Part L (2002) compliance checks
- CIBSE Heat Loss & Heat Gain (ApacheCalc)
- ApacheSim (ApacheSim)

Heat loss and heat gain using CIBSE methods are the two most useful tools of this application. Heat loss is used for calculating heating loads and heat gain for calculating cooling loads. Solar radiation is calculated in the model is based on actual weather data. The variables related to solar radiation in the weather files are direct solar radiation measured perpendicular to the beam W/m^2, diffused solar radiation measured on the horizontal planeW/m^2, and solar altitude and azimuth (°) which is calculated from the chosen site location.



Room Reference ID	Room Description	Cooling Zone Reference ID	Floor Area (m²)	Peak Sensible Month	Peak Sensible Time	Latent Cooling Load (W) at Peak Sensible	Total Cooling Load (W) at Peak Sensible	Sensible Cooling Room Ratio at Peak Sensible	Peak Sensible Cooling Load (W)	Peak Sensible Cooling/Area (W/m²)
ROOM0000	ROOM	CLNG0000	29.72	Jun	17:00	0.0	1907.0	1.000	1907.0	64.2

Figure 11.5. Required cooling loads achieved by using the ApacheCalac model.

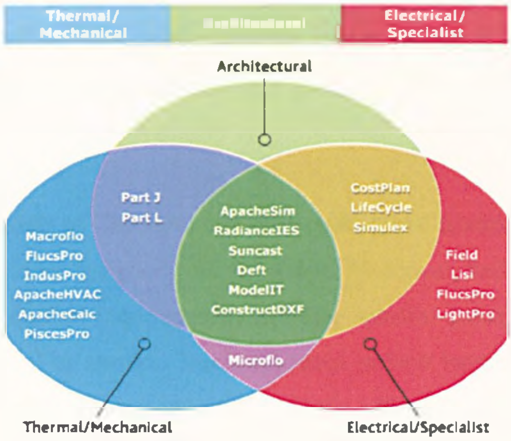


Figure 11.6 Illustrated graph showing all programs included in the IES virtual environment model and their fields of application.

3. ECOTECT model description

3.1. Introduction

The ECOTECT model is an analysis tool that has been developed to illustrate many different aspects of building energy performance. To help designers and architects to produce more efficient designs, ECOTECT requires simple information initially such as building shape and location. A 3D analysis is produced by this model which includes sunlight penetration, shading design options, and solar analysis. Changing building properties, such as adding a window, will immediately show the thermal effect in 3D. Analysis is also supported by graphs and tables that illustrate building performance. Part of the ECOTECT features are illustrated as follows:

3.2. Shadows and shading

ECOTECT has the ability to show shadow internally and externally; this is very useful in shading design. In the shading design tool, two main options are available. The first option is the optimum shading design and the second option is the surrounding shading design.

Sun-path diagrams can be created by using this model for any location to help in the shading design process. The sun's position in the sky can also be displayed. Moreover, the annual sun-path over the selected model can also be displayed by this software.

3.3. Solar analysis

Solar analysis is one of the major aspects in building design, especially in hot regions. High exposure of solar radiation is the main cause of thermal discomfort in hot regions. On the other hand, solar radiation is one of the most efficient sources of natural heating. Solar analysis is one of the ECOTECT's main features. The amount of incident solar radiation can be calculated for surfaces. Hourly, daily, monthly and annual solar incident rates can be calculated. Solar exposure for any surface of the building in any location can also be calculated using the location's climate data and geometrical analysis.

3.4. Lighting design

ECOTECT can calculate daylight factors. The internal lighting level can be estimated. Artificial lighting system methods can also be designed using this model.

3.5. Thermal performance

ECOTECT uses methods of CIBSE to calculate cooling and heating loads for buildings. This can be performed for any zone or building designed with any shape. Moreover, building materials and properties can be selected according to the desired requirements. Building internal gains, operation hours and occupancy can be set in the model input. The comfort level and mean radiant temperature can be predicted by using ECOTECT. The required monthly heating and cooling loads can be calculated by using actual climate data. In this calculation direct/indirect solar radiation are considered, as well as overshadowing and internal gains.

APPENDIX B

1. Tables showing the thermal behaviour of the selected room using various calculation methods

	ECOT		IES		HEVACOMP	
HOUR	JUN	DEC	JUN	DEC	JUN	DEC
1	874	-259	593	-121	359	-298
2	763	-299	570	-167	329	-332
3	638	-317	540	-188	314	-355
4	492	-357	487	-201	314	-366
5	489	-357	474	-212	329	-367
6	446	-363	463	-221	359	-340
7	405	-384	455	-228	403	-294
8	365	-395	452	-231	477	-236
9	332	-393	452	-230	1230	485
10	384	-402	457	-226	1337	587
11	472	-394	465	-219	1441	693
12	580	-305	477	-209	1532	787
13	738	-202	498	-197	1602	861
14	914	-100	522	-182	1646	906
15	1090	-4	589	-161	1655	918
16	1262	89	622	-120	1634	896
17	1434	178	643	-78	1582	843
18	1559	214	653	-58	1507	766
19	1616	196	655	-50	766	31
20	1601	128	648	-52	666	-23
21	1522	37	637	-62	581	-82
22	1386	-64	634	-65	515	-143
23	1225	-142	626	-76	454	-201
24	1045	-207	613	-96	402	-254
AV	901.3	-170.9	551	-152	893	186.7

Table 11.1 Heat gain/loss simulation through different models for a space without a window.

	ECOT		IES		HEVACOMP	
HOUR	JUN	DEC	JUN	DEC	JUN	DEC
1	943	-308	633	0	474	-520
2	826	-349	614	0	436	-561
3	695	-370	589	0	419	-582
4	542	-411	544	0	425	-581
5	533	-412	538	0	453	-561
6	496	-420	542	0	498	-511
7	467	-440	562	0	588	-437
8	442	-439	581	0	727	-281
9	430	-423	600	0	888	90
10	506	-418	619	0	1053	407
11	619	-396	637	0	1204	661
12	752	-293	654	0	1339	857
13	935	-177	674	0	1446	976
14	1130	-69	691	0	1484	1011
15	1315	26	746	0	1479	954

16	1486	109	764	0	1436	811
17	1648	185	765	0	1346	565
18	1755	207	753	0	1232	202
19	1789	178	729	0	1085	23
20	1748	101	702	0	927	-71
21	1647	2	684	0	808	-173
22	1494	-105	677	0	707	-276
23	1316	-186	666	0	613	-373
24	1114	-258	651	0	532	-458
AV	1026	-194	650	0	900	45

Table 11.2 Heat gain/loss simulation through different models for a space with a window.

2. Thermal analysis in various climatic zones results for Riyadh and London

2.1. Riyadh thermal simulation

Window without shading devices

	Summer simulation 21 June			Winter simulation 21 December		
Time	Temperature	Sunlit area m^2	Required cooling/heating load - cooling + heating	Temperature	Sunlit area m^2	Required cooling/heating load - cooling + heating
1	23.81	0	-633	20.82	0	0
2	23.79	0	-614	20.63	0	0
3	23.76	0	-589	20.56	0	0
4	23.7	0	-544	20.53	0	0
5	23.69	0	-538	20.51	0	0
6	23.7	0	-542	20.51	0	0
7	23.72	0	-562	20.64	0	0
8	23.75	0	-581	21.15	0	0
9	23.77	0	-600	21.79	.94	0
10	23.8	0	-619	22.25	1.77	0
11	23.82	.01	-637	22.56	1.64	0
12	23.84	.03	-654	22.75	1.61	0
13	23.86	.01	-674	22.82	1.66	0
14	23.88	0	-691	22.75	1.79	0
15	23.95	0	-746	22.56	.61	0
16	23.97	0	-764	22.31	0	0
17	23.97	0	-765	21.84	0	0
18	23.96	0	-753	21.3	0	0
19	23.93	0	-729	21.21	0	0
20	23.9	0	-702	21.16	0	0
21	23.87	0	-684	21.1	0	0
22	23.86	0	-677	21.07	0	0
23	23.85	0	-666	21	0	0
24	23.83	0	-651	20.92	0	0

Window with horizontal shading devices

	Summer simulation 21 June			Winter simulation 21 December		
Time	Temperature	Sunlit area m^2	Required cooling/heating load - cooling + heating	Temperature	Sunlit area m^2	Required cooling/heating load - cooling + heating
1	23.81		-633	19.01		0
2	23.79		-614	18.95		40
3	23.76		-589	18.93		55
4	23.7		-543	18.92		62
5	23.69		-538	18.92		67
6	23.7		-542	18.92		68
7	23.72		-562	18.95		39
8	23.75	0	-581	19.28	.86	0

9	23.77	0	-600	19.73	2.52	0
10	23.8	0	-619	19.94	1.87	0
11	23.82	0	-637	20.02	1.51	0
12	23.84	0	-653	20.05	1.41	0
13	23.86	0	-673	20.09	1.58	0
14	23.88	0	-691	20.17	2.01	0
15	23.95	0	-746	20.21	2.48	0
16	23.97	0	-764	20.21	.29	0
17	23.97	0	-765	19.94	0	0
18	23.96	0	-753	19.48		0
19	23.93		-729	19.4		0
20	23.9		-702	19.35		0
21	23.87		-684	19.29		0
22	23.86		-676	19.25		0
23	23.85		-666	19.19		0
24	23.83		-651	19.11		0

Window with vertical shading devices

	Summer simulation 21 June			Winter simulation 21 December		
Time	Temperature	Sunlit area m^2	Required cooling/heating load - cooling + heating	Temperature	Sunlit area m^2	Required cooling/heating load - cooling + heating
1	23.81		-633	19.09		0
2	23.79		-614	18.98		20
3	23.76		-589	18.96		36
4	23.7		-543	18.95		42
5	23.69		-538	18.94		47
6	23.7		-542	18.94		48
7	23.72		-562	18.95		42
8	23.75	0	-581	19	.03	3
9	23.77	0	-600	19.42	1.27	0
10	23.8	0	-619	19.95	2.22	0
11	23.82	.02	-637	20.45	2.49	0
12	23.84	.05	-654	20.86	2.73	0
13	23.86	.01	-673	21	2.41	0
14	23.88	0	-691	20.69	2.16	0
15	23.95	0	-746	20.3	.65	0
16	23.97	0	-764	19.95	0	0
17	23.97		-765	19.65		0
18	23.96		-753	19.5		0
19	23.93		-729	19.48		0
20	23.9		-702	19.44		0
21	23.87		-684	19.38		0
22	23.86		-676	19.34		0
23	23.85		-666	19.28		0
24	23.83		-651	19.19		0

Window with egg-crate shading devices

	Summer simulation 21 June			Winter simulation 21 December		
Time	Temperature	Sunlit area m^2	Required cooling/heating load - cooling + heating	Temperature	Sunlit area m^2	Required cooling/heating load - cooling + heating
1	23.81		-632	18.79		164
2	23.79		-613	18.74		204
3	23.76		-589	18.72		220
4	23.7		-543	18.71		226
5	23.69		-537	18.71		231
6	23.7		-541	18.71		232
7	23.72		-562	18.71		227
8	23.75	0	-581	18.74	.02	205
9	23.77	0	-600	18.79	.27	167
10	23.8	0	-618	18.81	.11	147
11	23.82	0	-636	18.82	0	144
12	23.84	0	-653	18.82	0	141
13	23.86	0	-673	18.83	0	130
14	23.88	0	-690	18.85	.16	115

15	23.95	0	-746	18.88	.19	90
16	23.97	0	-764	18.92	0	64
17	23.97		-765	18.92		61
18	23.96		-752	18.9		74
19	23.93		-728	18.9		77
20	23.89		-702	18.88		87
21	23.87		-683	18.87		102
22	23.86		-676	18.86		110
23	23.85		-665	18.84		124
24	23.83		-651	18.82		143

Window with horizontal shading louvers

	Summer simulation 21 June			Winter simulation 21 December		
Time	Temperature	Sunlit area m^2	Required cooling/heating load - cooling + heating	Temperature	Sunlit area m^2	Required cooling/heating load - cooling + heating
1	23.81		-633	19		0
2	23.79		-614	18.95		45
3	23.76		-589	18.92		63
4	23.7		-544	18.91		72
5	23.69		-538	18.91		78
6	23.7		-542	18.9		80
7	23.72		-562	18.93		55
8	23.75	0	-581	19.02	.17	0
9	23.77	0	-600	19.07	.11	0
10	23.8	0	-619	19.05	.15	0
11	23.82	0	-637	19.14	.12	0
12	23.84	0	-653	19.21	.11	0
13	23.86	0	-673	19.27	.13	0
14	23.88	0	-691	19.34	.16	0
15	23.95	0	-746	19.39	.08	0
16	23.97	0	-764	19.56	.09	0
17	23.97		-765	19.73		0
18	23.96		-753	19.55		0
19	23.93		-729	19.47		0
20	23.9		-702	19.42		0
21	23.87		-684	19.34		0
22	23.86		-677	19.29		0
23	23.85		-666	19.22		0
24	23.83		-651	19.12		0

Window with vertical shading louvers

	Summer simulation 21 June			Winter simulation 21 December		
Time	Temperature	Sunlit area m^2	Required cooling/heating load - cooling + heating	Temperature	Sunlit area m^2	Required cooling/heating load - cooling + heating
1	23.81		-633	18.85		114
2	23.79		-614	18.8		155
3	23.76		-589	18.78		171
4	23.7		-544	18.78		178
5	23.69		-538	18.77		182
6	23.7		-542	18.77		184
7	23.72		-562	18.78		178
8	23.75	0	-581	18.8	.03	159
9	23.77	0	-600	18.83	.08	133
10	23.8	0	-619	18.86	.12	109
11	23.82	0	-637	18.96	1.18	33
12	23.84	.03	-654	19.78	1.99	0
13	23.86	0	-673	20.11	.91	0
14	23.88	0	-691	19.23	.11	0
15	23.95	0	-746	18.94	.07	48
16	23.97	0	-764	18.96	.02	30
17	23.97		-765	18.97		16
18	23.96		-753	18.97		22
19	23.93		-729	18.96		25

20	23.9		-702	18.95		36
21	23.87		-684	18.93		51
22	23.86		-677	18.92		58
23	23.85		-666	18.91		72
24	23.83		-651	18.88		91

Window with light shelves

	Summer simulation 21 June			Winter simulation 21 December		
Time	Temperature	Sunlit area m²	Required cooling/heating load - cooling + heating	Temperature	Sunlit area m²	Required cooling/heating load - cooling + heating
1	23.81		-633	18.83		135
2	23.79		-614	18.78		177
3	23.76		-589	18.76		193
4	23.7		-544	18.75		200
5	23.69		-538	18.74		204
6	23.7		-542	18.74		206
7	23.72		-562	18.77		180
8	23.75	0	-581	18.86	0.47	115
9	23.77	0	-600	18.89	0.38	89
10	23.8	0	-619	18.89	0.31	83
11	23.82	0	-637	18.91	0.23	70
12	23.84	0	-653	18.92	0.2	60
13	23.86	0	-673	18.94	0.24	49
14	23.88	0	-691	18.95	0.34	36
15	23.95	0	-746	18.97	0.39	23
16	23.97	0	-764	19.06	0.25	0
17	23.97		-765	19.13		0
18	23.96		-753	18.96		29
19	23.93		-729	18.94		47
20	23.9		-702	18.92		57
21	23.87		-684	18.9		73
22	23.86		-677	18.89		80
23	23.85		-666	18.88		94
24	23.83		-651	18.85		113

2.2. London thermal simulation

Window without shading devices

	Summer simulation 21 June			Winter simulation 21 December		
Time	Room ComfortTemp	Sunlit area m²	Required cooling/heating load - cooling + heating	Room ComfortTemp	Sunlit area m²	Required cooling/heating load - cooling + heating
1	23.15		-120	18.5		391
2	23.13		-107	18.5		393
3	23.12		-94	18.5		395
4	23.10		-82	18.5		397
5	23.08		-66	18.49		398
6	23.06		-49	18.49		400
7	23.06		-48	18.49		400
8	23.07	.42	-53	18.49	0	400
9	23.08	.92	-64	18.54	0	362
10	23.12	1.18	-97	18.71	3.04	227
11	23.20	1.32	-160	18.86	4.59	112
12	23.30	1.36	-232	18.94	4.84	43
13	23.36	1.32	-282	18.96	4.57	28

14	23.39	1.19	-306	18.91	2.15	71
15	23.39	.93	-305	18.79	0	167
16	23.34	.39	-266	18.62	0	295
17	23.25		-200	18.51		383
18	23.20		-162	18.54		362
19	23.20		-158	18.55		351
20	23.19		-154	18.55		350
21	23.18		-144	18.55		355
22	23.16		-127	18.55		355
23	23.16		-128	18.54		361
24	23.16		-127	18.52		373

Window with horizontal shading devices

	Summer simulation 21 June			Winter simulation 21 December		
Time	Room ComfortTemp	Sunlit area m²	Required cooling/heating load - cooling + heating	Room ComfortTemp	Sunlit area m²	Required cooling/heating load - cooling + heating
1	23.10		-83	18.49		400
2	23.09		-72	18.49		402
3	23.07		-59	18.49		403
4	23.06		-47	18.48		405
5	23.04		-31	18.48		407
6	23.02		-14	18.48		408
7	23.02		-13	18.48		409
8	23.02	.27	-18	18.48	0	409
9	23.03	.37	-26	18.52	0	373
10	23.06	.27	-43	18.68	2.72	249
11	23.08	.11	-61	18.80	.11	152
12	23.09	0	-66	18.87	0	99
13	23.07	.1	-58	18.89	.1	88
14	23.08	.26	-66	18.85	.26	120
15	23.14	.36	-108	18.75	.36	195
16	23.17	.28	-138	18.61	.28	308
17	23.17		-135	18.50		392
18	23.15		-124	18.53		371
19	23.15		-122	18.54		360
20	23.15		-119	18.54		358
21	23.13		-108	18.54		364
22	23.11		-92	18.54		364
23	23.11		-92	18.53		369
24	23.11		-91	18.51		381

Window with vertical shading devices

	Summer simulation 21 June			Winter simulation 21 December		
Time	Room ComfortTemp	Sunlit area m²	Required cooling/heating load - cooling + heating	Room ComfortTemp	Sunlit area m²	Required cooling/heating load - cooling + heating
1	23.14		-109	18.49		401
2	23.12		-97	18.49		402
3	23.11		-85	18.49		404
4	23.09		-73	18.48		406
5	23.07		-57	18.48		408
6	23.05		-40	18.48		409
7	23.05		-39	18.48		409
8	23.06	.13	-43	18.48	0	410
9	23.07	.5	-51	18.51	0	382
10	23.09	.85	-71	18.65	2.34	277
11	23.15	1.15	-118	18.79	4.17	162
12	23.24	1.36	-188	18.91	4.83	73
13	23.33	1.16	-256	18.94	4.13	47
14	23.37	.87	-289	18.85	1.45	115
15	23.34	.51	-266	18.72	0	221
16	23.28	.09	-217	18.58	0	332
17	23.21		-166	18.50		392

18	23.19		-148	18.53		372
19	23.19		-148	18.54		361
20	23.18		-144	18.54		359
21	23.17		-134	18.53		364
22	23.15		-118	18.53		365
23	23.15		-118	18.53		371
24	23.15		-116	18.51		383

Window with egg-crate shading devices

	Summer simulation 21 June			Winter simulation 21 December		
Time	Room ComfortTemp	Sunlit area m^2	Required cooling/heating load - cooling + heating	Room ComfortTemp	Sunlit area m^2	Required cooling/heating load - cooling + heating
1	23.09		-75	18.47		418
2	23.08		-64	18.47		420
3	23.06		-51	18.46		422
4	23.05		-39	18.46		424
5	23.03		-23	18.46		425
6	23.01		-6	18.46		426
7	23.01		-5	18.46		427
8	23.01	0	-10	18.46	0	427
9	23.02	0	-15	18.48	0	406
10	23.03	0	-20	18.58	1.78	328
11	23.03	0	-25	18.69	3.18	244
12	23.04	0	-31	18.77	3.2	182
13	23.05	0	-39	18.79	3.18	166
14	23.07	0	-53	18.73	1.62	210
15	23.10	0	-78	18.64	0	285
16	23.12	0	-97	18.54	0	365
17	23.13		-105	18.48		410
18	23.14		-111	18.50		390
19	23.14		-113	18.52		379
20	23.14		-109	18.52		378
21	23.12		-98	18.51		383
22	23.10		-83	18.51		384
23	23.10		-83	18.50		389
24	23.10		-81	18.49		401

Window with horizontal shading louvers

	Summer simulation 21 June			Winter simulation 21 December		
Time	Room ComfortTemp	Sunlit area m^2	Required cooling/heating load - cooling + heating	Room ComfortTemp	Sunlit area m^2	Required cooling/heating load - cooling + heating
1	23.15	0	-120	18.47	0	415
2	23.13	0	-107	18.47	0	417
3	23.12	0	-94	18.47	0	419
4	23.1	0	-82	18.46	0	421
5	23.08	0	-66	18.46	0	423
6	23.06	0	-49	18.46	0	424
7	23.06	0	-48	18.46	0	424
8	23.07	.01	-53	18.46	0	425
9	23.08	.05	-64	18.5	0	393
10	23.12	.05	-97	18.63	1.35	291
11	23.2	.05	-160	18.71	1.95	230
12	23.3	.05	-232	18.74	1.97	202
13	23.36	.05	-282	18.75	1.96	196
14	23.39	.05	-306	18.73	1.29	211
15	23.39	.05	-305	18.68	0	254
16	23.34	.02	-266	18.57	0	335
17	23.25	0	-200	18.48	0	407
18	23.2	0	-162	18.51	0	386
19	23.2	0	-158	18.52	0	375
20	23.19	0	-154	18.52	0	374
21	23.18	0	-144	18.52	0	379
22	23.16	0	-127	18.52	0	380

23	23.16	0	-128	18.51	0	385
24	23.16	0	-127	18.49	0	397

Window with vertical shading louvers

	Summer simulation 21 June			Winter simulation 21 December		
Time	Room ComfortTemp	Sunlit area m²	Required cooling/heating load - cooling + heating	Room ComfortTemp	Sunlit area m²	Required cooling/heating load - cooling + heating
1	23.15	0	-120	18.46	0	428
2	23.13	0	-107	18.45	0	430
3	23.12	0	-94	18.45	0	431
4	23.1	0	-82	18.45	0	433
5	23.08	0	-66	18.45	0	435
6	23.06	0	-49	18.45	0	436
7	23.06	0	-48	18.44	0	437
8	23.07	.01	-53	18.44	0	437
9	23.08	.03	-64	18.45	0	432
10	23.12	.05	-97	18.48	.32	409
11	23.2	.16	-160	18.57	2.02	338
12	23.3	1	-232	18.77	3.6	180
13	23.36	.2	-282	18.87	1.96	100
14	23.39	.05	-306	18.67	.27	262
15	23.39	.03	-305	18.51	0	386
16	23.34	.01	-266	18.47	0	413
17	23.25	0	-200	18.47	0	420
18	23.2	0	-162	18.49	0	399
19	23.2	0	-158	18.5	0	387
20	23.19	0	-154	18.51	0	386
21	23.18	0	-144	18.5	0	391
22	23.16	0	-127	18.5	0	392
23	23.16	0	-128	18.49	0	397
24	23.16	0	-127	18.48	0	409

Window with light shelves

	Summer simulation 21 June			Winter simulation 21 December		
Time	Room ComfortTemp	Sunlit area m²	Required cooling/heating load - cooling + heating	Room ComfortTemp	Sunlit area m²	Required cooling/heating load - cooling + heating
1	23.15		-120	18.48		410
2	23.13		-107	18.48		412
3	23.12		-94	18.47		414
4	23.10		-82	18.47		416
5	23.08		-66	18.47		417
6	23.06		-49	18.47		419
7	23.06		-48	18.47		419
8	23.07	0	-53	18.47	0.47	420
9	23.08	0	-64	18.51	0.38	386
10	23.12	0	-97	18.65	0.31	276
11	23.20	0	-160	18.74	0.23	204
12	23.30	0	-232	18.78	0.2	170
13	23.36	0	-282	18.79	0.24	162
14	23.39	0	-306	18.77	0.34	183
15	23.39	0	-305	18.7	0.39	235
16	23.34	0	-266	18.59	0.25	326
17	23.25		-200	18.49		402
18	23.20		-162	18.51		381
19	23.20		-158	18.53		370
20	23.19		-154	18.53		369
21	23.18		-144	18.52		374
22	23.16		-127	18.52		374
23	23.16		-128	18.51		380
24	23.16		-127	18.5		392

APPENDIX C

Hevacomp model results

UNIVERSITY OF NOTTINGHAM
Institute of Building Technology, Architecture Department
University Park, Nottingham, NG7 2RD

Project SUNLIT AREA
Engineer SAHL
File C:\Hevacomp Projects\SOLAR SHADING\General\General\Hevacomp DDB\

Design basis
Location Riyadh **Design day 15 June**
Resultant room design temperatures used, no room heat losses are added to project totals
Supply air temp 12.0 degC, Central plant fresh air 12.00 l/s/person
No fixed temperature air is included
Outside 43.4 dry bulb/24.2 wet bulb, Room temperatures not allowed to rise

Rooms included : All rooms selected

Results for room R 1 No. off 1

Sun time	Outside temp	Solar load (W)	Fabric load (W)	Convective load (W)	Latent load (W)	Casual load (W)	Total load (W)	
1.00	25.7	0	436	48	-107	32	409	
2.00	24.7	0	430	31	-109	32	383	
3.00	24.4	0	425	25	-110	32	372	
4.00	24.7	0	420	31	-109	32	373	
5.00	25.7	0	415	48	-107	32	388	
6.00	27.2	0	407	75	-102	32	413	
7.00	29.1	0	400	111	-93	32	449	
8.00	31.4	0	421	152	-82	32	523	
9.00	33.9	0	464	196	-67	682	1,275	
10.00	36.4	0	509	240	-49	682	1,382	
11.00	38.6	0	552	282	-29	682	1,486	
12.00	40.6	0	588	317	-10	682	1,576	
13.00	42.1	0	613	344	6	682	1,645	
14.00	43.1	0	629	361	17	682	1,689	
15.00	43.4	0	629	367	20	682	1,698	peak
16.00	43.1	0	617	361	17	682	1,677	
17.00	42.1	0	594	344	6	682	1,626	
18.00	40.6	0	570	317	-10	682	1,558	
19.00	38.7	0	538	282	-29	32	822	
20.00	36.4	0	499	241	-49	32	722	
21.00	33.9	0	475	196	-67	32	636	
22.00	31.4	0	466	152	-82	32	568	
23.00	29.2	0	454	111	-94	32	503	
24.00	27.2	0	442	75	-102	32	448	

Peak room load 1,698 W at 15.00 hrs (47.2 W/m2 and 15.7 W/m3)
Solar load average 0.0 W/m2 (7.30 to 17.30 hrs)
Supply air flow rate 0.1271 m3/s Room design temperature 23.0 degC

Design Database
CIBSE gains Version 19.01

UNIVERSITY OF NOTTINGHAM

Institute of Building Technology, Architecture Department
University Park, Nottingham, NG7 2RD

Project SUNLIT AREA
Engineer SAHL
File C:\Hevacomp Projects\SOLAR SHADING\General\General\Hevacomp DDB\

Design basis
Location Riyadh **Design day 15 December**
Resultant room design temperatures used, no room heat losses are added to project totals
Supply air temp 12.0 degC, Central plant fresh air 12.00 l/s/person
No fixed temperature air is included
Outside 29.9 dry bulb/18.0 wet bulb, Room temperatures not allowed to rise

Rooms included : All rooms selected

Results for room R 1 No. off 1

Sun time	Outside temp	Solar load (W)	Fabric load (W)	Convective load (W)	Latent load (W)	Casual load (W)	Total load (W)
1.00	10.3	0	-26	-228	-198	32	-420
2.00	9.3	0	-34	-247	-199	32	-448
3.00	8.9	0	-43	-254	-199	32	-464
4.00	9.3	0	-54	-247	-199	32	-468
5.00	10.3	0	-69	-228	-198	32	-463
6.00	12.0	0	-73	-198	-196	32	-435
7.00	14.1	0	-71	-159	-191	32	-390
8.00	16.7	0	-66	-114	-184	32	-332
9.00	19.4	0	-56	-65	-172	682	389
10.00	22.1	0	-17	-16	-157	682	491
11.00	24.6	0	25	30	-139	682	597
12.00	26.8	0	61	69	-121	682	690
13.00	28.5	0	89	99	-106	682	764
14.00	29.5	0	104	118	-95	682	809
15.00	29.9	0	106	124	-91	682	821 peak
16.00	29.5	0	94	118	-95	682	799
17.00	28.5	0	72	99	-106	682	746
18.00	26.8	0	40	69	-122	682	669
19.00	24.7	0	12	30	-139	32	-66
20.00	22.1	0	15	-16	-157	32	-126
21.00	19.4	0	13	-65	-172	32	-192
22.00	16.7	0	6	-114	-184	32	-260
23.00	14.2	0	-5	-159	-191	32	-324
24.00	12.0	0	-18	-198	-196	32	-380

Peak room load 821 W at 15.00 hrs (22.8 W/m2 and 7.6 W/m3)
Solar load average 0.0 W/m2 (7.30 to 17.30 hrs)
Supply air flow rate 0.0691 m3/s Room design temperature 23.0 degC

Design Database
CIBSE gains Version 19.01