**Daylighting and Sun-shading in Buildings in Tropical Regions:**

An Example of Virika Hospital, Kasese, Uganda.

# DISSERTATION

approved by the

Faculty of Building (Civil Engineering and Architecture)

of the University of Dortmund

for the Degree of

**Doctor of Science in Engineering**

**(Dr.-Ing.)**

by

**Ssengooba-Kasule (Dipl.-Ing. Architect)**

**from Uganda**

Dortmund, Germany, 2003

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**Universität Dortmund**

# Tageslicht und Sonnenschutz an Gebäuden in tropischen Regionen:

Am Beispiel des Virika Hospitals in Kasese, Uganda.

von der Fakultät Bauwesen (Bauingenieurwesen und Architektur)

der Universität Dortmund genehmigte

**DISSERTATION**

zur Erlangung des Grades eines

**Doktors der Ingenieurwissenschaften**

**(Dr.-Ing.)**

von

**Ssengooba-Kasule (Dipl.-Ing. Architekt)**

**aus Uganda**

Dortmund, Deutschland

2003

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**Universität Dortmund**

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|---|---|
| **Date of Submission:** | 13.01.2003 |
| **Date of Oral Examination:** | 15.05.2003 |

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*To my lovely daughters*
*Nanungi and Balungi*
*and in memory of my lovely mother, Kate Norah Nakabuugo*


## Acknowledgements

I wish to express my great debt of gratitude to all individuals and institutions that have in diverse ways contributed to the successful completion of this work. The list is really long. Therefore, those whose names are not mentioned here should not in any way feel that their precious contribution is underestimated.
I am particularly indebted to my supervisor Prof. Dr. –Ing. Helmut F. O. Müller, whose assistance, advice and healthy criticism were instrumental in the successful conclusion of this work. The period, during which I worked in his department as a research fellow and the opportunity he gave me to work on different research projects, not only opened the way to my future career but also provided the financial support that enabled me to work on this thesis. Please accept my sincere appreciation.

I would also like to express my gratitude to my co-supervisor Prof. Dr.-Ing. Bernd Baier, whose constructive criticism guided me to a successful completion of this work.

My former colleague Dr.-Ing. Till Pasquay introduced me to some of the tools used in this work; I will always treasure the period we worked together. I cannot escape mentioning my appreciation for the cooperation and team spirit I shared with all my colleagues and student-assistants at the department of Environmental Architecture. I will reflect on that wonderful period for the rest of my life.

I am personally indebted to some individuals particularly for the moral and in some cases material support, without which, the realisation of this work would have been very difficult if not impossible. Special thanks go to my friends Detlef Hansen and Martina Godbersen for their assistance in different forms and above all their readiness to listen to me whenever I needed someone to talk to. Please accept my appreciation for all your efforts.

Special thanks go to MISEREOR AACHEN - a Catholic Organisation, which was responsible for the reconstruction of Virika hospital after the disastrous earthquake that reduced the old hospital buildings to rubbles, for providing me with the necessary information as well as the detailed drawings of the newly constructed buildings which I used throughout this work.

Prof. H. Sprungala, Mr. Joachim Loseck, Ms Mechtihild Wienecke, and Mrs Betty Flynn who proof-read this work, and all those other individuals whose names have not been listed here, thank you for being reliable friends.

Prof. Dr. L. S. Luboobi and family, Mr. James Lwegaba and family, all my sisters, brothers and other relatives: Thank you for the different roles you have played in my life. They have contributed to shaping the person I am today.

I would like to thank my father Mr. G. Kasule, my uncle Mr. G. Kasujja as well as all my aunts for the compassionate, caring and parental heart you passed on to us which has made us respectable persons in the eyes of others.

Last but not least, to Samalie Naluyange for taking care of our daughter Balungi for the whole period I was away.

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# 1 Introduction

The desire for sustainable development while protecting the environment, is not only a concern of the developed world but rather an international issue. Development is coupled with the availability of energy. This therefore, is a race to find alternative energy sources which are affordable and less destructive to the environment. The first step to a lasting and affordable solution to chronic energy shortages is identifying the areas where most energy is consumed. Buildings, Industry and Transportation are among the largest consumers of energy irrespective of climatic region. People all over the world increasingly spend most of their time in buildings. Making buildings habitable demands energy for either heating or cooling to create a comfortable thermal environment while on the other hand, huge quantities of energy are needed to illuminate buildings. The aim of this work is to examine approaches to building construction which would achieve the due aims of minimum energy consumption and cost effectiveness.

Buildings can be designed to minimise the energy needed for heating, cooling and illuminating. Extra energy may be needed in cases where design measures do not adequately create a comfortable environment within the building. Proper building design is the cheapest source of energy which is at the disposal of every architect and designer. Concepts for an energy conscious design differ from region to region and require the designer's acquaintance with the climatic conditions of the region in question. This is however not an easy task and knowledge of the climatic conditions alone may not be enough to design a low energy consuming building. Generally, buildings in tropical regions have a net solar heat gain during most of the working time in a day (Chapter 3). There is therefore a need to cool the buildings during hot periods. In some tropical regions, however, the temperatures inside the building can be too low for comfort during some hours of the day so that some kind of heating may be necessary. This can be remedied by carefully allowing solar radiation to penetrate the building to warm the air inside. Daylight can be used for lighting the buildings.

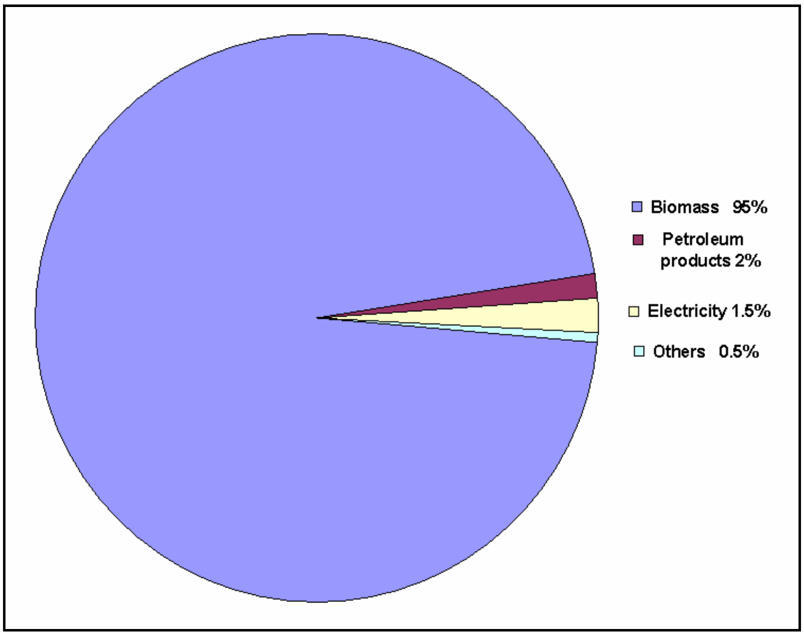
Modern tools can help designers make predictions of the thermal performance and the extent to which daylight will be sufficient to illuminate a building. If applied at an early stage, designers can easily modify their concepts and even convince building owners of the usefulness of their design strategies. Analysing parts or the whole building using three dimensional models, enables designers to quickly and critically evaluate the performance of buildings regarding the use of daylight with relatively high precision.

## 1.1 The energetic problems in tropical regions, in particular Uganda

There are no known fossil (oil and gas) energy resources in many topical regions. For those regions which have deposits of these fossil energy resources, there is almost no national capacity for exploiting and distributing these resources. The lack of technical independency forces these regions to contract foreign firms for the exploitation and marketing of their energy resources which leaves the majority of the population without a share of this wealth. Energy problems are even more serious for regions which do not have fossil energy reserves. Countries in these regions have to import the needed energy. The majority of the people in tropical regions still live in abject poverty in rural areas with virtually no infrastructure. They are usually cut off from the main national energy supplies. These areas depend mainly on biofuel (wood, animal waste) for most of their domestic energy needs.

An example of such a country is Uganda. Uganda imports all its petroleum products mainly for use in transportation and lighting of buildings. This consumes almost 12% of the Gross National Product. Although the country has a very high potential to develop alternative energy sources like hydro-electricity, wind, solar, thermal energy etc., lack of proper planning has led the country to be one of the lowest energy consumers in the world.

The major energy sources in Uganda are biomass, electricity and petroleum (Figure 1.1). Since over 80% of the population is in rural areas and depends on agriculture for their livelihood, biomass covers over 90% of their energy demands.




*Source: Energy Information Administration (EIA)*

**Figure 1.1:** The main energy sources in Uganda

The continuing uncontrolled use of biomass has had enormous negative consequences not only on the people themselves but also on the environment.

A rapidly growing population that depends on biomass for their daily energy needs has resulted in widespread deforestation, land degradation, extinction of many plant species and, in the worst cases, climate change. Air and water pollution as a result is taking its toll on the lives of people themselves. There is increasingly a marked movement of people from rural areas to towns in search of a better life.

Uganda is undoubtedly among the countries with the highest potential of electricity production in Africa. The country's electricity production is basically hydro. The current capacity is around 1.6 billion kWh. This capacity could be many times higher if all the possible channels of generating hydro electricity were exploited. Less than 3% of the population (mostly urban) has access to electricity. They consume 1.3 billion kWh, the rest is exported to nearby countries like Kenya and Tanzania. These controversies in the distribution of energy are remnants of the colonial system which forces Uganda to sell what it has even though it does not have enough.

The changing lifestyles of people in towns as well as the slowly improving living standards of people in rural areas, can no longer be sustained by the meagre energy production in many tropical countries. There is a need to look for different alternatives to supplement the available energy in order to support and maintain the improvement in living standards of the people in both rural and urban areas. The use, for instance, of daylight for illuminating buildings supplemented by the development and use of locally available energy sources like hydro, solar or wind energy, can help minimise energy consumption in buildings and reduce the total dependency on imported energy. Buildings which can positively benefit from the use of daylight are mostly public buildings like hospitals, schools, office buildings as well as those used in industry.

## 1.2 Objectives of this work

The use of daylight for illumination in buildings in tropical regions is intended among other expectations to have the following advantages:

- reduce the amount of energy used for illuminating the building
- reduce the operating costs in a building
- reduce heat gain inside buildings as a result of using artificial lights
- improve the quality of room illumination

There are, however, several negative effects as a result of allowing daylight into buildings which should never be underestimated. Among these negative effects are the following:

- increase in solar heat gain inside the building
- glare threats inside the building
- limitation of flexibility in planning buildings (e.g. the depth of the rooms)
- increased costs for the construction of daylighting systems intended to allow more and qualitative daylight into the building for a longer period

These factors will be analysed in detail in the subsequent chapters.
By identifying these negative effects, the task is to work out a balanced solution in order to optimally utilise daylight in buildings. Daylight is a very complex issue. We restricted this work within the perimeters of the behaviour of daylight and the benefits of using it in buildings. It was necessary to establish two important aspects regarding the use of daylight. These are the extent to when and how daylight will be sufficient for illumination in the building and the identification of the problems which are a result of the use of daylight in the building as well as working out solutions to these problems.
The main objective of this work is to try to establish architectural and technical possibilities of the extent and how we can meaningfully use daylight to realise the above mentioned advantages while minimising the influences of the above mentioned negative effects in buildings in tropical regions. The economic advantages of the different measures will also be assessed.
The administration building at Virika hospital, Kasese, Uganda introduced in chapter 3, is used as an example for a detailed study.
Lack of daylight data for many regions (especially in tropical regions) was to a certain extent a hindrance for us to be able to carry out exact analysis. The availability of

daylight, which is an integral part of solar radiation, is directly influenced by changes in atmospheric conditions. Throughout this work, we will substitute daylight data by solar radiation as an approximation. The relationship between daylight and solar radiation, referred to as the luminous efficacy of radiation, has a constant value of 115 lumen / watt even though this may vary between 80 and 180 lumen / watt depending on the state of the sky. The availability of daylight can then be roughly determined by considering the horizontal illumination at a specified place at a given time.

## 1.3 Structure and Methodology of this work

The main subject of this work is the use of daylight and solar control in buildings in tropical regions. Tropical regions have the highest potential for daylight use in buildings because of the long daytime hours throughout the year. These regions however, have the highest intensity of solar radiation which complicates the use of daylight in buildings due to the intensive heat that may accumulate inside the buildings. There are variations in climatic conditions across the tropical regions (Chapter 2). The use of daylight and solar heat control inside a building must be based on proper analysis of the climatic characteristics of the particular region considered. Although tropical regions are generally characterised as hot regions, the intensity of heat, temperature variations between day and night, the source of illumination and other climatic factors, widely differs from region to region. Although the methods of controlling heat gain inside the building as a result of incoming solar radiation (sun-shading) may be similar throughout the tropical regions, methods of reducing accumulating heat inside buildings are different (discussed later).

The different building simulations carried out to establish the thermal behaviour of the building by considering the impacts of several parameters (Chapter 3), were very useful as a starting point for this work. The results of such simulations clearly demonstrate the influence of changing climatic conditions on the thermal conditions inside a building.

We chose one of the newly constructed buildings housing the hospital complex at Virika, Kasese, Uganda, for a detailed study of the behaviour of daylight in a building. The administration building (described in chapter three and appendixes 1-10) is a typical structure of the buildings at Virika hospital which we used as a prototype for our detailed study.

The several investigations and analyses carried out throughout this work were as a result of the different building simulations which involved thermal as well as daylight calculations.

This work was carried out under the following conditions:

1. We were not able to carry out climatic measurements of the region of Kasese. We used the weather information from the computer program METEONORM taken from the weather station in Kasese.
2. The construction details of the building were considered as they were provided to us by MISEREOR AACHEN – a catholic missionary organisation which is the main contractor for the re-construction of the 126 bed hospital at Virika, Kasese, Uganda, which was devastated by an earthquake in the early nineties.
3. Since we did not have daylight data for the region of Kasese, daylight calculations were performed using the available solar radiation data which were used as an approximation.

This work is divided into eleven chapters.

***Chapter one*** introduces this dissertation thesis and outlines the objectives, structure and methodology of this work.

***Chapter two*** introduces the different climatic classifications in tropical regions, the geography and climate of Uganda, Kasese in particular, and a brief survey of the building forms in different tropical regions.

***Chapter three*** analyses the thermal behaviour of buildings in hot and humid regions. This was carried out using three dimensional simulations of the administration building by considering several parameters. The building was simulated as it was planned.

***Chapter four*** defines daylight, analyses the behaviour and the different methods of allowing daylight into the building. The computer method quantification of daylight inside the building is also analysed. The advantages and special problems of using daylight in hospitals are also discussed.

***Chapter five*** discusses the general problems of using daylight in buildings in tropical regions.

***Chapter six*** outlines the possible solutions to the problems discussed in Chapter five.

***Chapter seven*** outlines the proposed modifications on the administration building in order to improve on the use of daylight in the building. A worked example of possible modifications on the administration building aiming at improving the use of daylight while minimising solar heat gain inside the building was included. A general survey of the characteristics of several daylighting and sun-shading systems is shown in a form of matrix.

***Chapter eight*** deals with the economic benefits of using daylight in buildings in tropical regions by considering the administration building at Virika hospital as an example.

***Chapter nine*** summarises the results of this dissertation thesis.

**List of books and other references used throughout this work.**

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# 2 Geographical location of Uganda

Uganda lies in the heart of Africa along the equator extending from latitudes 1° South to 4° North and longitudes 30° to 35° East. She shares borders with Sudan in the north, Kenya in the east, Tanzania and Rwanda in the south and the Democratic Republic of Congo in the west (Figure 2.1). Uganda covers an area of 241,038 square kilometres and occupies the largest part of the Lake Victoria basin, a result of the great African geological shift that formed the East African Rift Valley. This shift elevated the country to a mixed topography with an average altitude of 1,200 meters above sea level. In the east of the country are the Elgon mountains along the Uganda-Kenya boarder. On the western border with Congo lies the Rwenzori mountains (mountains of the moon), whose highest peak, Margherita Peak, is 5,110 m above sea level. Along the foothills of mount Rwenzori is Kasese which is over 900m above sea level. Kasese lies 0.1° North of the Equator and at longitude 30° East .

About 18% (44,000 sq km) of the country's total area is covered with water and swamps. Almost half of Lake Victoria, Africa's largest water mass, is within Uganda's political demarcations. The River Nile which begins its journey from lake Victoria to the Mediterranean, meanders across the whole length of the country from the upper south to the north before continuing into the Sudan. A lot of other small rivers and estuaries connected to numerous lakes across the country empty their waters into the Nile, making Uganda one of the most water-rich nations in Africa.


**Figure 2.1:** Geographical map of Uganda

## 2.1 The climate of Uganda, Kasese in particular

Since Uganda is a landlocked country, 800km from the ocean, she does not experience maritime climate. The country experiences an equatorial climate moderated by the relatively high altitude across most of the country. There is however marked climatic variations depending on the altitude of the region. The lower regions of lake Victoria and the river Nile basin experience higher temperatures than the higher regions in the south west and west of the country. There is heavy vegetation in the south which gives way to Savannah grassland further north to almost dry plains in the north-east, an important deciding factor in the climatic distribution in Uganda.


**Figure 2.2:** Map of East Africa

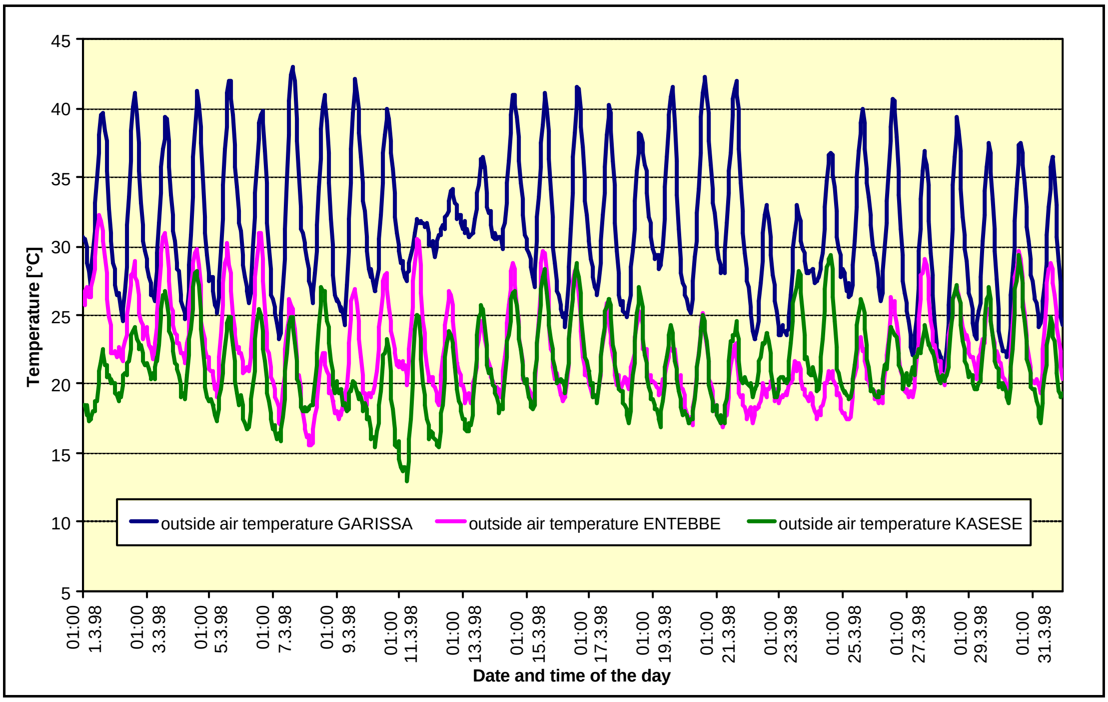
Parts of the country, especially the southern regions around Lake Victoria, the southwest and the west of Uganda, experience two rainy seasons. These regions receive an average of between 1500 - 2000mm of rainfall annually. This trend changes as one goes north and north west, where the annual average is in the range of 500mm of rainfall. The months from June to August are the driest in the year. The climate of Uganda can generally be classified into dry and rainy seasons. There is a noticeable temperature variation between daytime and night-time though the magnitude depends on the region.
The regions around lake Victoria experience a drop of about 10°C in air temperature during the night whereas in the southwest and west of the country (including Kasese), night time temperatures can drop to 15°C below daytime temperatures.

To demonstrate how the altitude and surrounding features can affect the climate (temperature) of a region despite the geographical location, three regions were chosen for comparison. These regions are: Kasese, Entebbe and Garissa, marked on the map of east Africa shown in figure 2.2.

Table 2.1 shows the geographical coordinates of the three regions.

| Region | Height above Sea level [m] | Latitude | Longitude |
|---|---|---|---|
| Kasese | 959 | 0.11°N | 30.06°E |
| Entebbe | 1155 | 0.03°N | 32.37°E |
| Garissa | 138 | 0.28°S | 39.38°E |

**Table 2.1:** Geographical coordinates and altitude for Garissa, Entebbe and Kasese



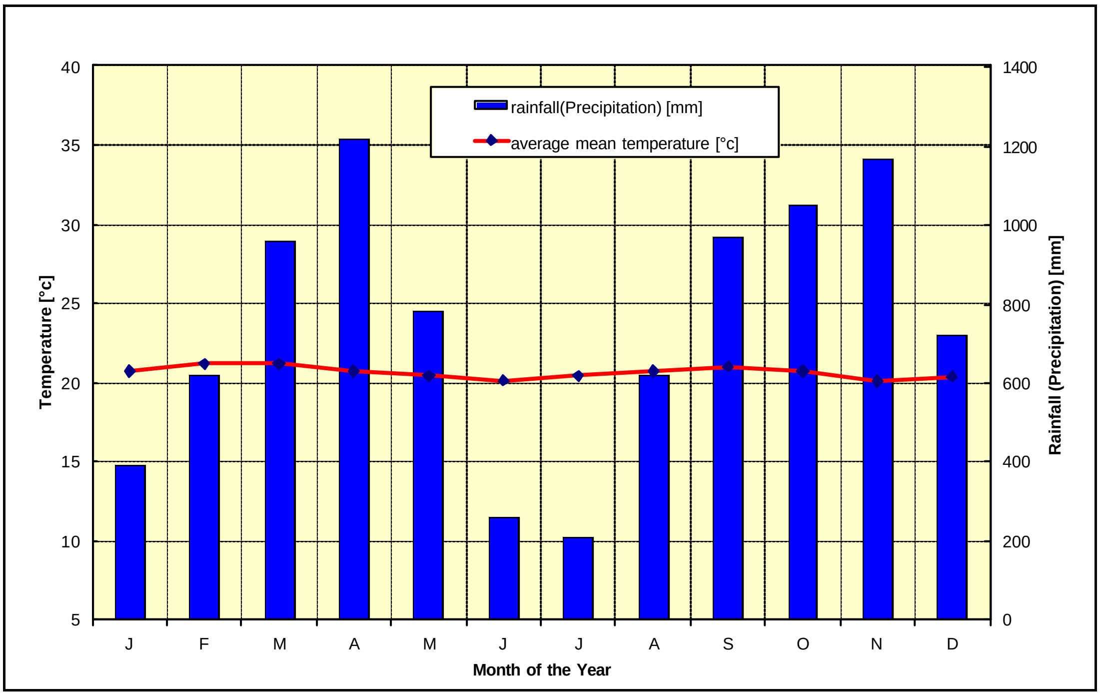

*Source: METEONORM*

**Figure 2.3:** Air temperature for Garissa, Entebbe and Kasese

In figure 2.3, the average air temperature of the three regions was compared.

Although all of these three regions lie along the equator, they experience diverging temperature ranges. This may be as a result of their different altitudes and also their proximity to the sea. Garissa which is 138m above sea level, and just about 300km from the Indian ocean has the highest temperatures averaging between 25°C and 40°C. This may partly be due to its proximity to the sea. Such regions experience maritime climates characterised with very high temperatures. The semi-arid nature of the region (less vegetation), contributes to a rise in air temperature as a result of intensive solar radiation.

Entebbe and Kasese stand at a comparatively higher altitude than Garissa and both these regions are far away from the coast. The climate for Entebbe region, which is on the shores of lake Victoria, is directly influenced by the lake characterised by more rains averaging above 2000mm in a year. The average temperature of both these regions is far less compared to that of Garissa.




Source: METEONORM

**Figure 2.4:** Annual average temperature and precipitation variation for the region of Kasese, at latitude 0.11°N, Uganda

Figure 2.4 illustrates the average monthly variation of air temperature and rainfall for Kasese. The average temperature is just above 20°C. The region experiences two rainy seasons from March to May and from September to November. In April and November which are the peak months of the rainy season, the average rainfall is around 1200mm whereas in June and July the region is virtually dry with around 200mm of rainfall.

## 2.2 Defining tropical climate

Climate has been defined as the interaction of solar radiation with the atmosphere and the gravitational forces, taking into account the distribution of land and water [1]. Much as the relationship between these factors may be the basis of determining the climate of a given location, the human factor is increasingly playing a role in defining climate. This factor, apart from the other criteria widely accepted by many researchers for the classification of climate, can no longer be considered a secondary issue. Increasing populations which has resulted in for instance, the construction of congested human settlements, depletion of rain forests, is causing a marked impact on the climate.

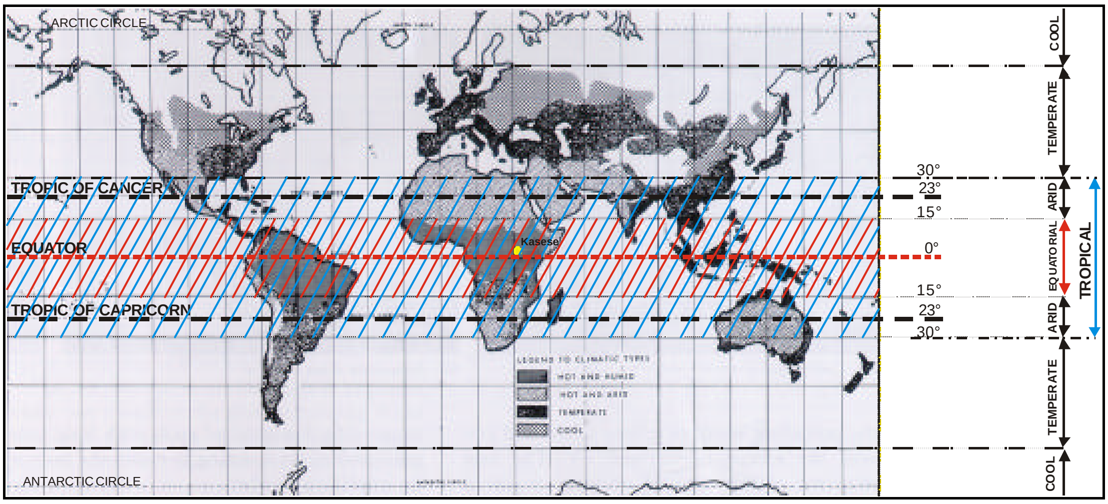



**Figure 2.5:** Map of the world showing the different major climate classifications

There are three major climatic classifications i.e. cool, temperate and tropical climate. These major climatic classifications can be sub-divided into distinguished zones with special climatic features. This is mostly the case for regions commonly referred to as the tropics. These are regions between the geographical co-ordinates of 30° around the tropic of Cancer and Capricorn north and south of the Equator as shown on figure 2.5. Tropical climatic zones merge into temperate climatic zones the further we go north or south. Temperate zones eventually merge into cool zones extending as far as the Arctic and Antarctic regions.

Temperature and humidity, are the two environmental factors that define human comfort on which the traditional classification of climate is based.

Temperate climate is characterised by relatively cool temperatures compared to that in tropical regions. Temperatures on average decrease the further we get away from the Equator. We will concentrate more on the tropical climate as it is the main theme of this work.

It is not logical to refer to a tropical climate as a definite climate. Tropical regions constitute of different climatic zones that together make up the tropical climate. Air movements, height above sea level, proximity to the sea or large water masses are among the factors that determine the climate of a region. Vegetation cover of a region and population density - in reference to their daily activities and their lifestyles, also has an influence on the regional climate (micro-climate).

The major climatic zones in tropical regions are shown in table 2.2.

| Classification of climatic zones in tropical regions | | | | | | |
|---|---|---|---|---|---|---|
| Zone | Estimated geographical boundaries(latitude) | Special characteristics of the zone | | | | |
| | | temperature [°C] | relative humidity [%] | wind speed [m/s] | average annual rainfall [mm] |
| Warm and humid | Between 15° North and South of the Equator | 20 - 32 | 55 - 100 | up to 30 | 500 - 5000 |
| Warm and humid island | Between 15° North and South of the Equator | 18 - 32 | 55 - 100 | above 6 | 1200 - 1800 |
| Tropical upland (*between 900 - 1200m above sea level )* | Between 20° North and South of the Equator | 10 - 30 | 45 - 100 | up to 15 | above 1000 |
| Hot and dry desert | Between 15°- 30° North and South of the Equator | 10 - 50 | 10 - 55 | up to 10 | 50 - 155 |
| Hot - dry maritime desert | Between 15°- 30° North and South of the Equator | 10 - 38 | 50 - 90 | up to 10 | up to 100 |
| Monsoon/ Composite | Along the tropics of Cancer and Capricorn | 3 - 43 | 20 - 55 | varies with the period | 500 - 1300 |

*Source: Koenigsberger, Ingersoll, Mayhew, Szokolay. Manual of Tropical Housing and Building*

**Table 2.2:** Classification of the major climatic zones of tropical regions [1]

These climatic zones are classified according to the uniqueness of the prevailing atmospheric conditions of the regions. The differences in climatic conditions have a direct influence on the architectural development of a region. This is not only visible in the form of buildings, there are wide variations in construction methods too. The region of Kasese is classified under the tropical upland climatic zone.

## 2.3 The influence of climate on building form and methods in tropical regions

The development of different styles and forms of buildings in tropical regions, is an attempt to create shelter in which extreme climatic conditions in an open environment can be controlled or regulated. It is worth mentioning at this point that, even though the conditions in an open space may be comfortable for a certain period, there are changes in weather conditions which are likely to upset the thermal balance. Man has constructed shelters to protect himself from these unavoidable and unpredictable extreme weather conditions. These shelters are a reflection of the different living habits of the people as well as the available building materials in a specific area.

In tropical regions, shelters may be categorised into two types: temporary and permanent.

Temporary shelters are structures put up by nomads who keep on moving from place to place looking for pasture. These shelters are characterised by their functional and architectural simplicity and their ability to be easily constructed or dismantled. They are basically light wooden constructions covered with straw or other light fibres. They do not directly reflect the climatic conditions of a region.
Permanent shelters on the other hand have evolved to take up shape taking into account the climatic conditions of the region.

In hot and arid tropical regions, because of the wide daily temperature variations - between 10° and 50° depending on the season – buildings are constructed with very thick walls (adobe) and roofs with very high thermal capacities to be able to respond to the extreme weather. The most common building materials are earth, bricks or stones [13]. There is a high shortage of timber in these regions, which may also explain the choice of these as the main building materials.
Many buildings have a square form which takes into account the relationship between volume and surface area of the walls, and very small openings to minimise solar heat penetration into the building. A combination of these factors guarantees less heat into the building during hot periods but keeps the buildings relatively warmer during cold periods. Any changes to one of these factors e.g. an increase in the openings to allow more solar radiation into the building, may upset the heat balance inside the building.
Buildings are constructed so close to one another creating an enclosed out-door space (courtyard) where private family activities take place. These out-door spaces are at times relatively cooler than inside the buildings and are used as sanctuaries when the buildings are rendered uninhabitable due to high temperatures. Most buildings have small windows which are placed high up to prevent solar radiation from entering the building and direct exposure to the horizon, the main source of light that may cause disability glare. Small window openings may not adequately allow air circulation through the building, which in turn might create hygiene and health problems.

In equatorial regions of the tropics – between latitude 15° north and south of the Equator - shown on figure 2.6, the climate is categorised into two periods: rainy and dry periods. There is a noticeable daily temperature variation i.e. temperatures during the day are higher than during the night, though not well pronounced as is the case for hot and dry regions. The temperature ranges vary from region to region as shown in table 2.2 and also from season to season.

There is a need to protect the buildings from the high temperatures during the day while keeping them warmer during the night when temperatures drop below comfortable levels.

Traditional buildings in hot and humid climates are basically light constructions and more open than buildings in hot and dry regions, to allow cross air ventilation. They are mostly constructed out of timber or bamboo wrapped with fibres or with walls constructed with earth and the roof covered with straw or other fibres. Buildings within the climatic sub-groups of the hot and humid climatic region like the tropical upland or hot and humid tropical island zones, have special features unique for these climatic zones which also influences their building methods. Traditional buildings in these regions and in hot and humid regions in general, are subjected to constant attacks by insects which easily break down the fibres and also destruction by heavy rains. This to a certain extent explains why some building materials like bamboo, which is not easily attacked by insects, is widely used.

We will not be able to discuss in detail the characteristics of the different traditional buildings in tropical regions within the scope of this work. However, we will try to analyse the trends in modern buildings relating to the shape of the building and construction methods, which reflect the different climatic conditions of these regions.

Apart from climatic considerations, modern building methods are developed to meet the increasingly changing social and economic demands of the people in tropical regions. Traditional building methods have limitations and shortcomings which render them inapplicable in modern societies. They are constructed out of materials which are susceptible to easy destruction for instance by fire, with catastrophic consequences. Economically, there is a need to put up structures that can accommodate many people in a small space. This has led to the need to construct high rise buildings used as office or residential buildings. These buildings can only be constructed using different methods and materials other than those used in traditional buildings. Concepts in traditional buildings, for instance for controlling the heat build up in buildings, are widely being incorporated into many modern buildings though in a modified way.

Modern buildings in hot and dry zones of the tropics are preferably high-rise massive cubical forms or rectangular shapes slightly elongated on the east - west axis. There is a tendency to construct buildings close to one another with walls casting shadows on neighbouring buildings. Vegetation within the spaces provides shading for the building.

Elongated, narrow rectangular shaped buildings along the east-west axis are preferable in hot and humid tropical zones. This guarantees the cross ventilation necessary to cool the building. Unlike in hot and dry zones, buildings in hot and humid regions have to be spaced to allow air movement between them. Air movement as well as vegetation are important elements in cooling buildings in these regions [3], [42]. Buildings may be orientated to trap the cool breeze even though such a measure my contradict other necessary precautions to maintain a thermal balance inside the building.

Buildings that develop along the north-south axis are the most disadvantageous in tropical regions as they expose large surfaces of the buildings to east and west orientations which receive the highest intensities of solar radiation (Chapters 3 and 5).

# 3 Thermal behaviour of buildings in hot and humid tropical regions

The thermal balance in buildings is influenced by solar radiation. Buildings in tropical regions are subjected to long hours of intensive solar radiation which, when permitted into the building, raises the room temperature. The increase in heat gain can upset the thermal comfort in the building. The magnitude of heat gain depends on several factors which will be discussed in detail later in this chapter. The achievement of an acceptable thermal environment within a building may require the use of machines to control the build-up of heat inside the building. In tropical regions, there is always a need to cool the building though at times the temperature inside the building can be so cold that some heating might be necessary.

Cooling may concern both room and the human body. For rooms, cooling of the ambient air and the surfaces will help reduce the room temperature whereas for the body it occurs by convective heat loss from the skin. This depends on the surrounding air temperature and also the velocity of the air. With proper planning and a prior consideration of several climatic factors, we can achieve a certain degree of comfort within a building without resorting to the use of machines. Through building simulations, we will try to establish how different factors may influence the thermal behaviour of buildings in hot regions especially in hot and humid tropical regions.

## 3.1 Factors that influence thermal comfort in buildings

Heat balance of the human body is the pre-requisite of an acceptable thermal comfort level. The environmental factors that determine thermal comfort are basically temperature, air movement, the humidity of the air and solar radiation. Other factors that may influence thermal comfort are the clothing of an individual and the activities carried out. Food, sex and age can to a certain extent influence comfort. The thermal behaviour of buildings can be analysed by considering two separate approaches individually or complementary. These approaches are:

a) analysing the traditional methods used to construct buildings based on long time accumulated experience and
b) scientific analysis methods mostly by evaluating measurements of different parameters in and around the building or by simulation studies of the building.

Traditional construction methods differ from region to region dependent on not only the different cultures but also the climatic conditions of the regions. Some aspects of traditional building methods will be discussed later though we will, within this chapter, concentrate more on the aspects of the scientific analysis methods (building simulation) to determine the thermal behaviour of buildings in hot and humid regions. We will examine, through building simulation, how the different environmental factors interact with each other and how they influence the thermal behaviour of buildings in these regions. Such analysis can guide us to determine whether thermal comfort in a building can be obtained by considering design strategies or with the help of mechanical equipment. For the purpose of this work, we used the administration building at Virika hospital, Kasese, Uganda, described below, as our prototype building.

### 3.1.1 Building simulation, parametric analysis and presentation of different simulation results

Building simulations can provide us with almost accurate predictions regarding the anticipated thermal behaviour of buildings in a given climatic situation. There are several computer programs which differ in their ability to execute climatic data and the choice depends entirely on the aims of the simulations undertaken. We will not however, devote ourselves to the task of listing the different programs, their advantages and shortcomings and why one should chose one program and not the other. The choice remains entirely the decision of the user.

However, for an accurate computer simulation, estimation of the climatic factors like moisture and temperature in a built environment at a given time, the simulation model should be able to accurately interpret the necessary climatic information which influence the thermal changes inside the building. Such climatic information may be among others:

- solar radiation
- precise calculation of the short and long wave radiation inside the room
- accurate simulation of the window (glazed surface)
- accurate calculation of the internal thermal mass
- precise physical simulation of the surfaces of the materials within the room, like wall surfaces
- accurate calculation of the indoor moisture generation
- taking account of the ventilation rate inside the building

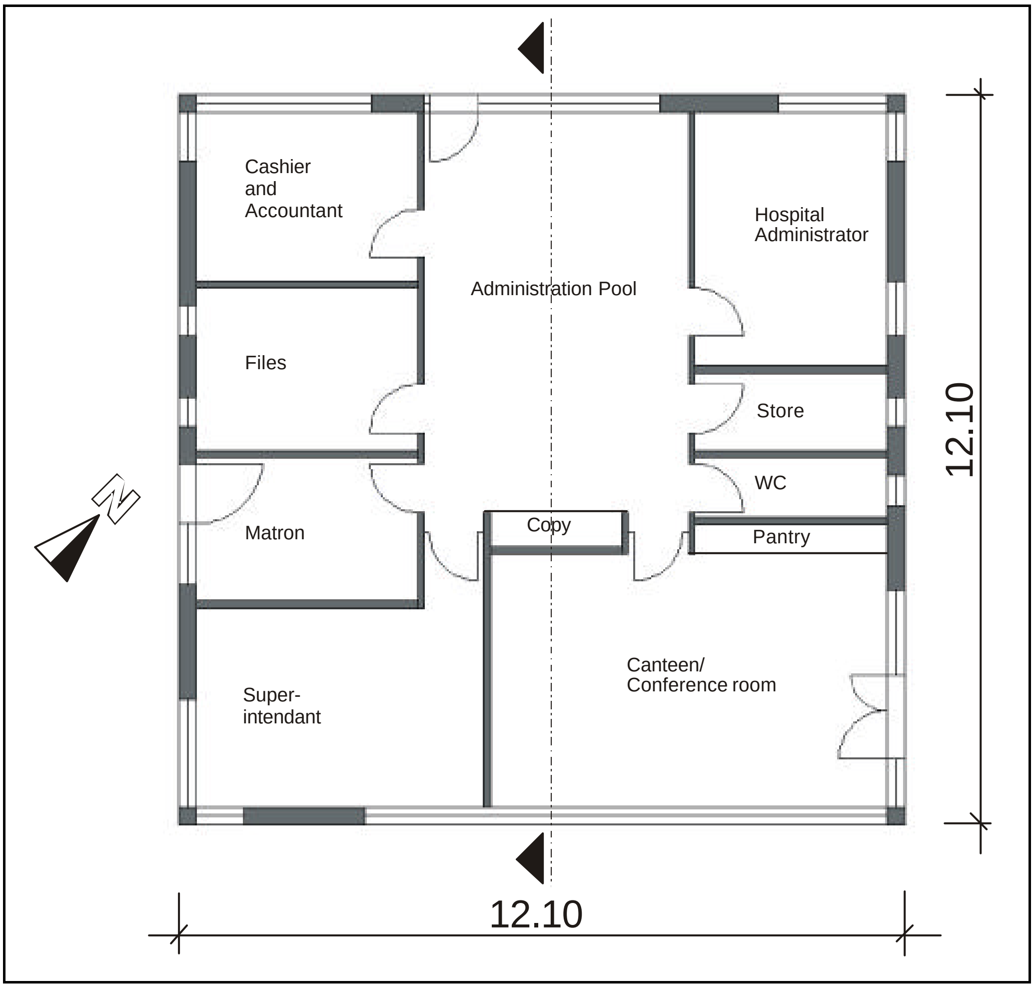
We used the dynamic Transient System Simulation program (TRNSYS) to carry out several thermal simulations. We were able to test variations in thermal conditions inside the building under different climatic conditions. This program is a modular simulation program with which we were able to collectively test the performance of several identified components of the building, to conclusively judge the thermal behaviour of the whole building.

The prototype (administration) building is a one storey office building along the NW-SE axis. It is 12m wide by 12m long with a double pitched roof [*Appendixes 3-7*], typical of the structures of the Virika hospital complex. External walls are 24cm thick and constructed out of red clay bricks plastered on the inner side. Inner partition walls are constructed out of massive bricks with a thickness of 11.5cm. The ceiling is constructed with insulating material which thermally separates the building into two zones to prevent the heat absorbed by the roof from getting into the working area. The roof is of a light construction with a highly reflective aluminium covering and separated from the main body by airspace to allow constant cross air ventilation.

The following parameters were considered as the basis for the simulation:

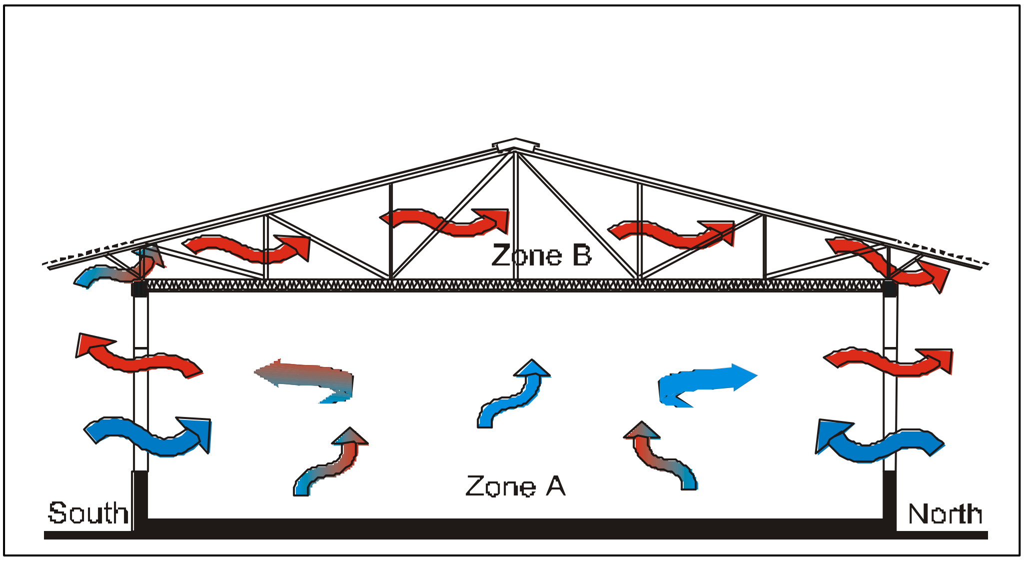
- glazed area on South façade Area = 19m²
  North façade Area = 11m²
  East façade Area = 11m²
  West façade Area = 12m²
- single glazing with transmittance (U-value) of 5.8 W/m² K and solar factor (g-value) of 0.86 and a wooden frame covering 10% of the total window area
- external walls constructed out of red bricks plastered on the inner side with a total thickness of 25cm and a total transmittance (U-value) of 2.052 W/m² K
- the roof is covered with highly reflective light aluminium sheets laid on a wooden roof framework. The roof has a total transmittance (U- value) of 1.492 W/m² K
- interior walls are 11.5cm thick with a transmittance (U-value) of 3.207 W/m² K
- the floor has an area of 147m², constructed to prevent the moisture from penetrating the building from the ground
- a constant hygienic ventilation rate was set at v = 1 air change per hour
- windows were directly exposed to incoming solar radiation

A full description of the building is diagrammatically illustrated below. Figure 3.1 shows the plan of the administration building whereas figures 3.2a shows the section through the building. Figures 3.2b-e shows the elevations of the different orientations of the building.



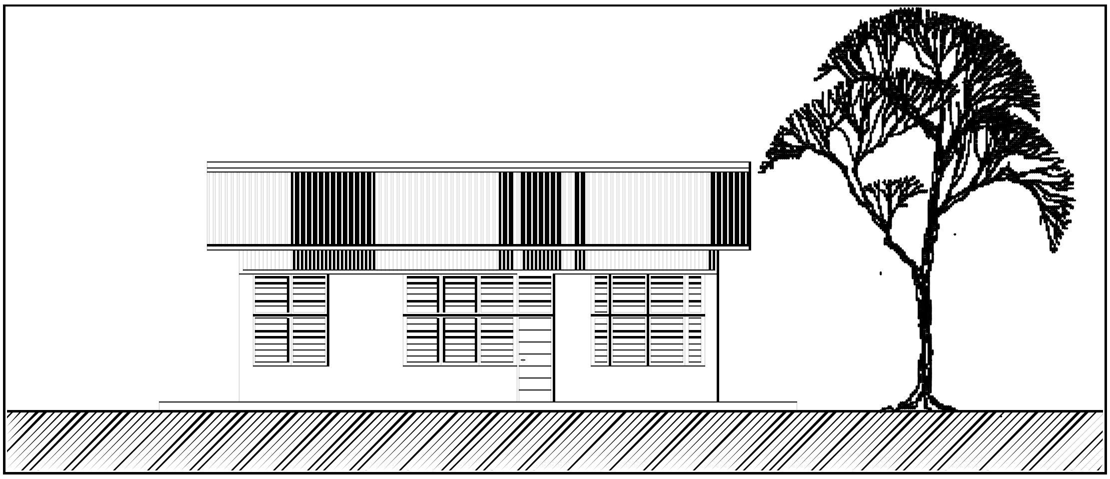

source: Misereor, Aachen

**Figure 3.1:** Floor plan of the administration building



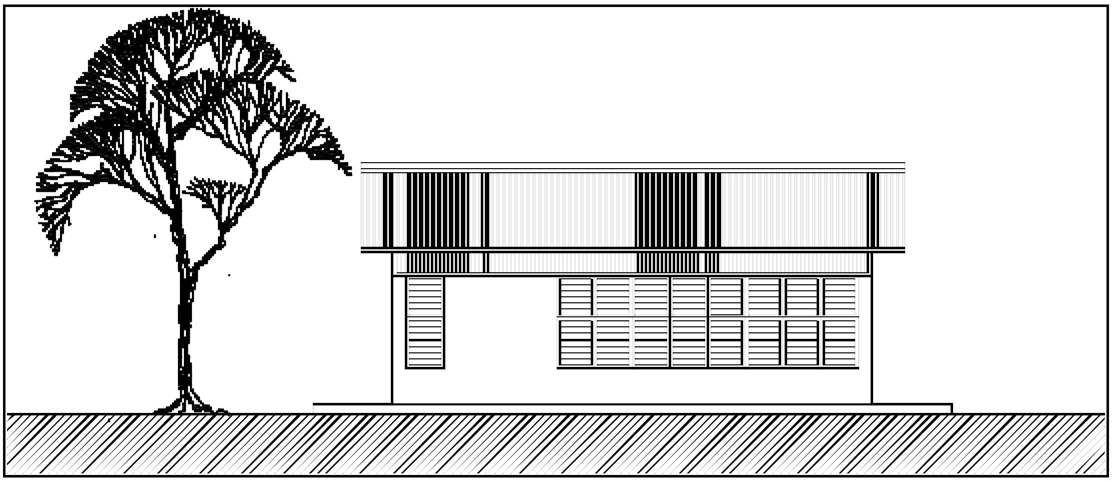

source: Misereor, Aachen

**Figure 3.2a:** North-South vertical section without the interior partition walls showing air circulation inside the building



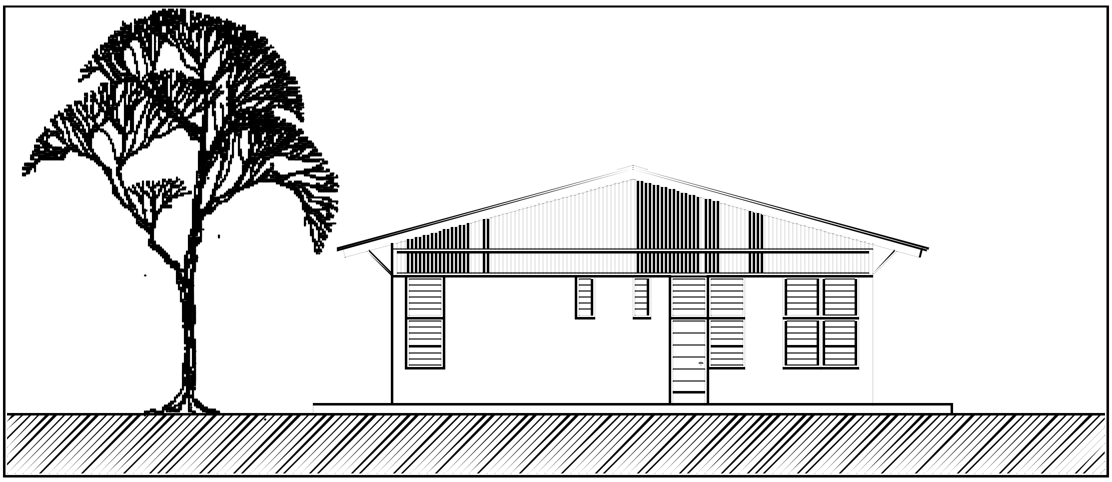
*source: Misereor, Aachen*

**Figure 3.2b:** North-east Elevation



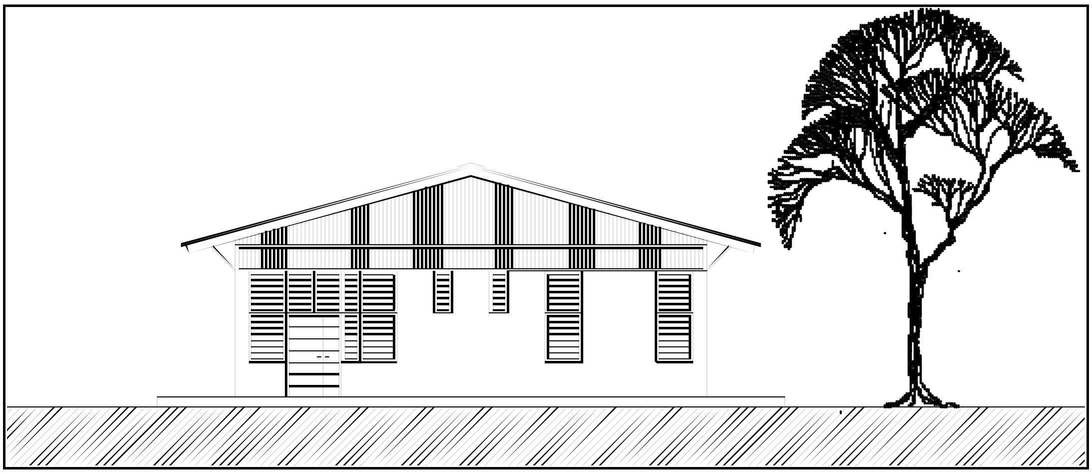
*source: Misereor, Aachen*

**Figure 3.2c:** South-west Elevation



*source: Misereor, Aachen*

**Figure 3.2d:** North-west Elevation



source: Misereor, Aachen

**Figure 3.2e:** South-east Elevation

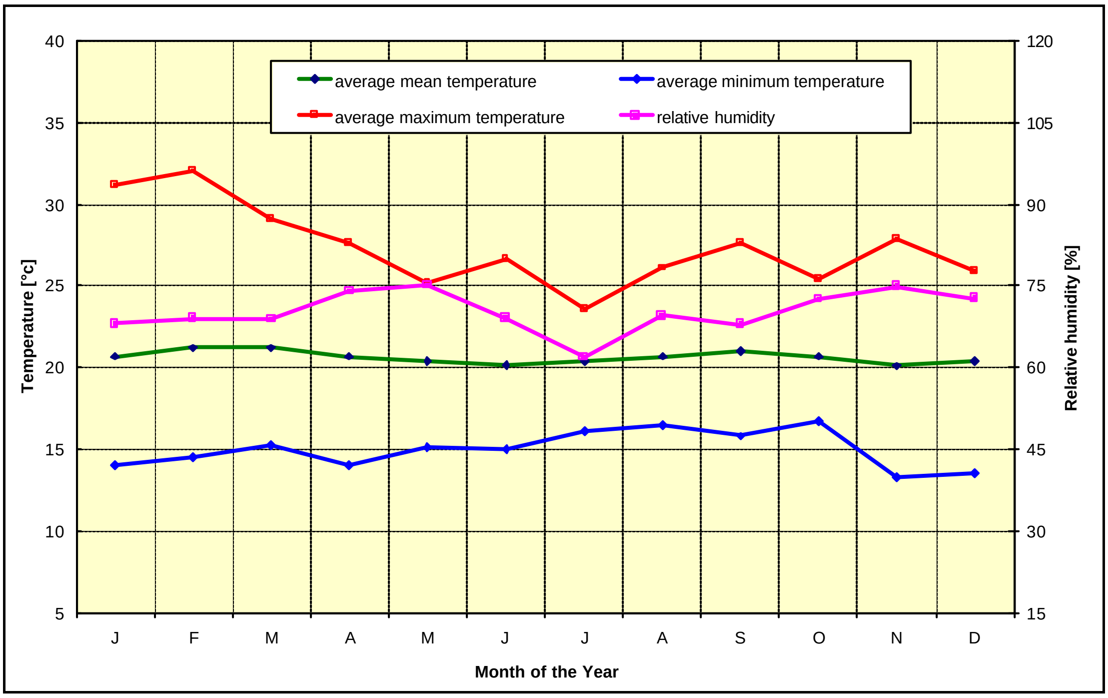
We neither took climatic measurements around Kasese nor within the building itself, but we were nevertheless able to perform the simulations using the weather data from the climatological database provided by the meteorological weather information of the computer program METEONORM. The weather information from METEONORM is widely accredited and provided us with the information for the region of Kasese, necessary to perform the simulations. This data is an average of weather information collected in a period stretching over ten years.

Several parameters which influence the thermal conditions inside the building were considered during the simulations and their impact was analysed. These parameters are:

- influence of solar radiation and orientation of the building
- the window size, type of glazing and position on the building and its orientation
- ventilation rate within the building (air movement)
- the influence of internal thermal mass: heavy and light construction
- the influence of occupants and office or domestic electrical equipment
- the effectiveness of roof projection as a sun-shading device
- the influence of night ventilation

The result of our simulations are graphically presented.

By comparing the prevailing climatic conditions outside the building with the conditions inside the building by considering the above parameters, we were able to make assumptions as to how the building might function. The prevailing weather conditions – temperature and relative humidity – were studied first.



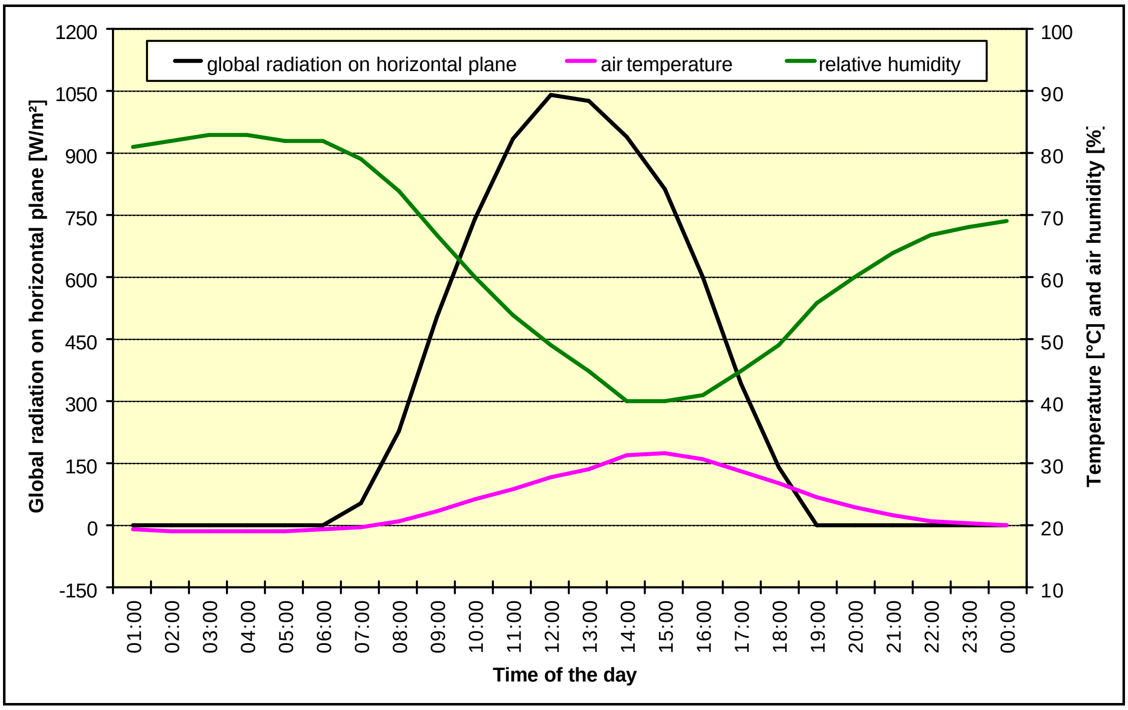

*source: METEONORM*

**Figure 3.3:** Annual temperature variations showing maximum, minimum and average values as well as relative humidity for a location at latitude 0.11°N, Kasese, Uganda

Figure 3.3 shows the annual maximum air temperature averaging 29°C, an average air temperature of 21°C and a minimum air temperature averaging 13°C.

The weather data taken from the program METEONORM shows February as one of the hottest months in the year. The temperature on one of the hottest days in the month of February shown in figure 3.4, indicates a maximum air temperature of around 32°C and a minimum air temperature of around 20°C.

The relative humidity on the same day shown in figure 3.4, is in the range of 40 - 85%. When the ambient air temperature falls to around 20°C, the relative humidity is above 70%. The relative humidity drops to around 40% when the air temperature rises above 25°C. The distribution of global radiation on a horizontal plane on a hot day (Figure 3.4) shows the highest intensity is just above 1000W/m² at around midday. Solar radiation is responsible for the rise in air temperature.




*source: METEONORM*

**Figure 3.4:** Variation of temperature, solar radiation and air humidity on a hot day in February for a location at latitude 0.11°N, Kasese, Uganda

The above climatic information is typical for bcations along the equator with some variations depending on the location's height above sea level, the proximity to the sea and the prevailing wind speed. Kasese is 959m above sea level and has no direct influence from the sea. The wind blows dominantly in the east-west direction.

### 3.1.2 The influence of solar radiation and orientation of the building on room temperature

Solar radiation reaching the building interior affects the thermal conditions inside the building by raising the room temperature. The radiant part of solar radiation falling on surfaces of objects is converted into long-wave electromagnetic radiation which raises the temperature of these objects. These objects emit heat into the surroundings which is then absorbed by the body which, if not dissipated, may upset the heat balance in the body causing discomfort.

The building was simulated without considering the influence of internal thermal mass in the form of interior walls, no obstruction to incoming solar radiation by roof projection, and no occupants and mechanical equipment or artificial lighting as extra sources of heat were taken into account.

We assumed natural ventilation of the building as an effect of opening the window depending on the room temperature. There was a constant hygienic air change rate of v=1 per hour throughout the day.

When the room temperature reached 24°C, we symbolically opened the window to allow increased air circulation within the building at a rate of v=4 per hour. This made a total air change rate of v=5 per hour. When the room temperature was below 21°C, we assumed a basic hygienic air change of v=1 per hour. Figure 3.5 shows the influence of solar radiation on the room temperature of the building in its planned state.

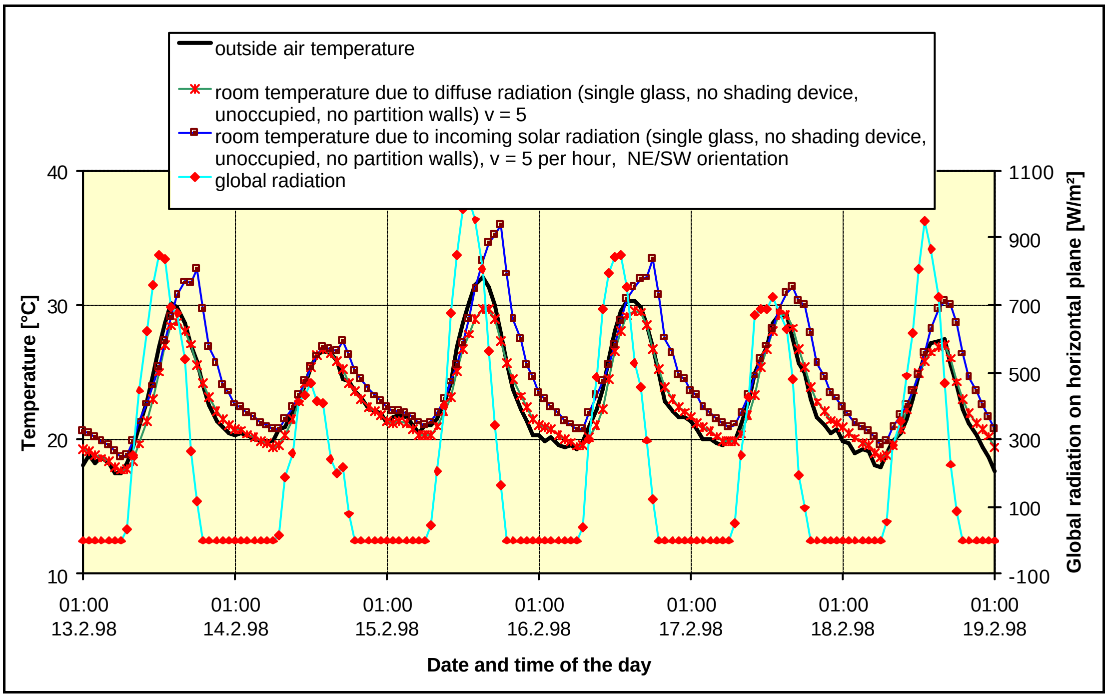



**Figure 3.5:** The influence of solar radiation on the temperature inside the building for six days in February

The building was first exposed only to diffuse radiation to study its influence on room temperature. Diffuse radiation had little impact on the temperature inside the building. The room temperature due to diffuse radiation showed minor deviations from that of the air temperature outside the building.

Total solar radiation - direct and diffuse radiation – penetrating the building, raised the room temperature by up to 6°C above outside air temperature. Direct solar radiation had the most marked impact on room temperature even though in the absence of direct radiation, that is to say under totally overcast sky conditions, diffuse radiation is responsible for any rise in room temperature.

We rotated the building 45° anti-clockwise so that the sides with the most glazed surfaces faced north and south respectively. The building was also rotated towards the east which subjected the side of the building with a proportionally large glazed area to high intensities of incoming solar radiation in the east and the west. The exposure of glazed surfaces to orientations which have higher solar radiation intensities affected the temperature inside the building. Figure 3.6 shows the comparison of room temperature as a result of the different rotations.

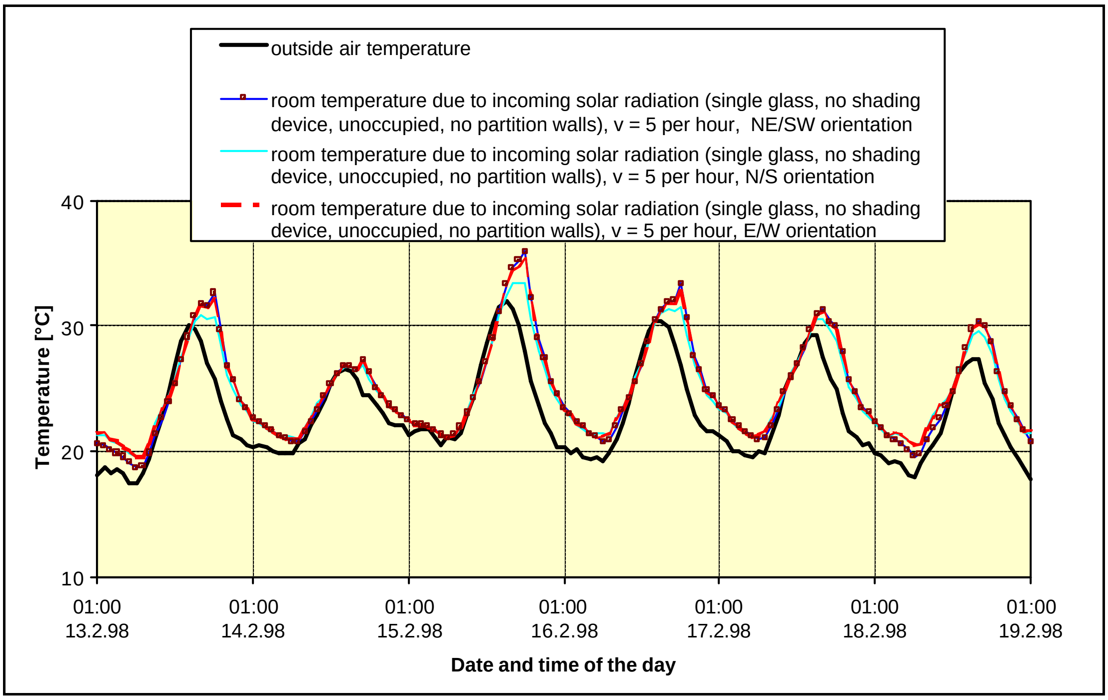



**Figure 3.6:** The influence of orientation of the building on room temperature

Rotating the building towards the north-east or the east resulted in an increase in room temperature as shown on figure 3.6. North and south orientations receive the lowest intensities of solar radiation. Both the west and the east orientations receive the highest intensities of solar radiation (Figure 5.3).

In order to avoid or minimise the consequential rise in room temperature as a result of solar radiation through glazed surfaces, the east and the west orientations of the building should have no or minimal glazed surfaces unless the situation of the building does not allow otherwise.

### 3.1.3 The influence of occupants and office equipment on room temperature

Humans constantly produce heat as a result of the biological process inside their bodies. The rate at which body heat is produced - metabolic rate - varies depending on the type of activities carried out. The produced heat must be dissipated in order to maintain a thermal balance of the body. The released heat measured in terms of MET (metabolic) may contribute to the rise in the surrounding temperature in a given environment. An example of heat produced by an individual doing office work like typing is around 1.1MET. The heat exchange between the body and the surroundings depends on the temperature of the surroundings. The human body must be able to dissipate the absorbed heat in order to maintain comfortable heat balance in the body.

Electrical equipment produces energy in form of heat which also influences room temperature. For the administration building under investigation, we assumed a total of six lightly dressed persons occupying the building and each working on a 230W personal computer (performing sedentary activities). The building was continuously occupied from 7am to 7pm and the personal computers were continuously switched on during this period. The other factors were kept unchanged.

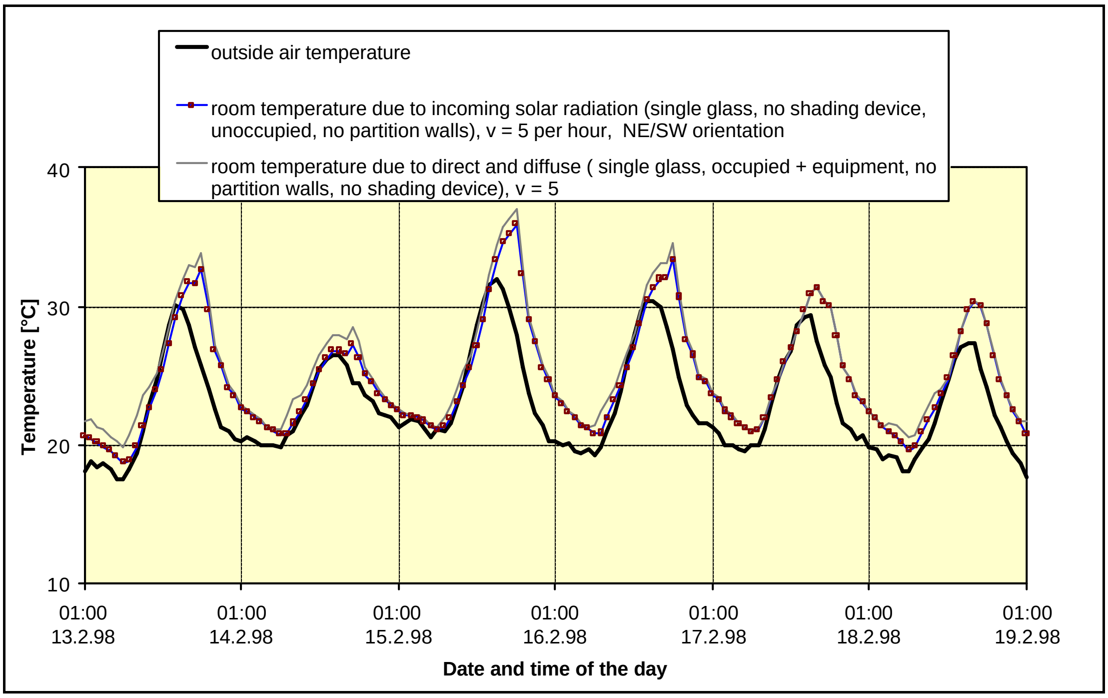



**Figure 3.7:** The influence of occupants and electrical equipment on the temperature inside the building

Figure 3.7 shows the influence of occupants and office equipment on room temperature for six days in February. The room temperature as a result of considering occupants and electrical equipment increased by around 1°C above that when only incoming solar radiation, was considered.

### 3.1.4 The influence of interior thermal mass on room temperature

We investigated the influence of thermal mass due to the internal partition walls on the temperature inside the building to find out how different materials react in an environment of fluctuating temperature. In the previously discussed cases, the simulations were carried out under the assumption that the building was just an open space enclosed by external walls.

We simulated the building by considering the interior walls as they were planned.

The interior walls were constructed out of a single brick layer 11.5cm thick plastered on both sides. The bricks have a conductivity of 1.80 KJ/hmK, a density of 1200kg/m³ and a total transmittance (U-value) of 3.093 W/m²K.

The partition walls had a total area of 308m² (total area of both surfaces) and it was assumed that both sides were directly in conductive contact to the room air. All partition walls were not directly exposed to solar radiation.

In figure 3.8, the addition of heavy partition walls with high heat capacity resulted in a drop of room temperature from a maximum of around 38°C without internal thermal mass to around 33°C during the hottest peak hours on one of the hottest days. Partition walls absorb heat when the temperature inside the building rises above that of the walls, thus lowering the air temperature of the surroundings.

The room temperature during the cool hours of the night is around 2°C warmer than that for a room without interior thermal mass. This is due to the fact that partition walls with high heat capacity absorb heat during the day when the temperature of the surrounding air is higher than that of the walls themselves which is then released when the temperature of the surroundings drops below that of the partition walls at night. The amount of heat flow into and out of the interior partition walls depends on the temperature of the surrounding environment, the thickness of the walls and also the thermal properties of the constituent materials of the wall. Thermal capacity increases with the increase in thickness of the wall. However the heat flow is not directly proportional to heat capacity or thickness of the internal walls.

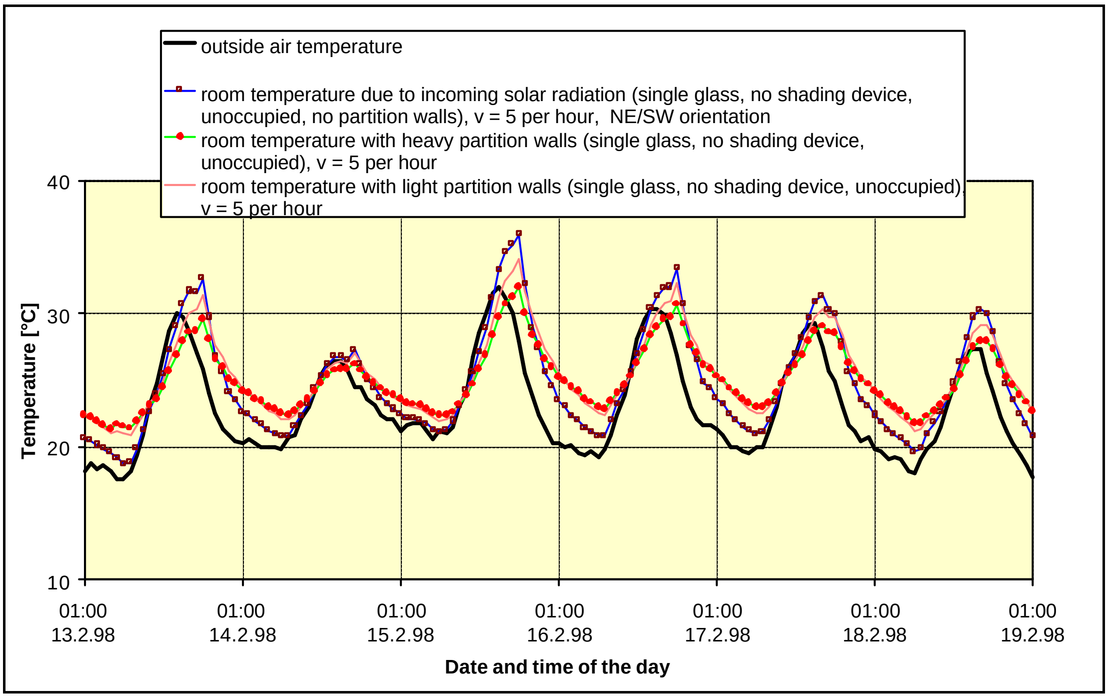



**Figure 3.8:** Influence of interior thermal mass on the temperature inside the building

We substituted the high mass walls with low mass partition walls to study the impact on room temperature. The low mass walls were 13.5cm thick with a total transmittance (U-value) of 0.204 W/m²K. The total area of the light partition walls was the same as that of heavy partition walls with both sides in direct conductive contact to the room air. All partition walls were not directly exposed to solar radiation as was the case for heavy partition walls. Replacing the high mass partition walls with low mass walls resulted in a temperature rise of up to 3°C above that with high mass partition walls at peak hours (Figure 3.8). Since the storage capacity of light walls is low, there was no significant impact on room temperature as a result of nocturnal ventilation cooling. The building with light partition walls cooled more quickly than one with heavy partition walls.

Although Kasese lies at latitude 0.11°N, its elevation above sea level of 959m qualifies it to be under the tropical highland climatic classification. While the diurnal temperature variation in hot and humid tropical climate is on average less than 7°C, tropical highland climatic zones have a diurnal temperature variation in the range of 10°C. The difference between day and night time temperature is of fundamental importance if we consider the strategy of cooling the buildings by thermal mass. Buildings in these climatic regions can be treated more or less like buildings in temperate regions regarding cooling by thermal mass.

The design strategy of cooling the building by thermal mass in humid regions poses a problem of mildew build-up as a result of moisture precipitation on the high mass. cold walls and floors and also slow cooling rate of high mass structures [4].

Generally, the diurnal temperature variations in hot and humid regions of the tropics is so minimal that the night cooling effect is negligible. Traditionally, construction materials with low thermal mass are preferable to allow a rapid cooling down at night despite the minimal temperature difference. Using materials with highly reflective surfaces, thermal separation of the roof from the living area and allowing cross-room ventilation are some of the measures which can help acquire a balanced thermal environment inside the building [1].

The strategy of constructing buildings with low mass materials, notably in modern high rise buildings in hot and humid tropical regions, may not readily be applicable.

### 3.1.5 The influence of varying air change rates (air movement) on room temperature

In all the simulations considered above, we assumed an air change rate of v=5 per hour. We then subjected the building to different air change rates of v=1 and v=10 per hour to investigate the influence on room temperature.

The simulation model to test the influence of different ventilation rates was organised such that there was a continuous and constant hygienic ventilation rate of v=1 per hour mainly due to air infiltration into the building. This is approximately 10 – 25 m³ of air per hour per person [64]. The increase in the ventilation rate depended on the room temperature.

We set the upper room temperature limit at 24°C and the lower limit at 21°C. When the room temperature reached the 24°C limit, we symbolically increased the ventilation rate by v=4 per hour making the total air change rate of v=5 per hour. When the room temperature reached the lower limit of 21°C, we reduced the ventilation rate to the basic v=1 per hour. We continued the process with varying ventilation rates.

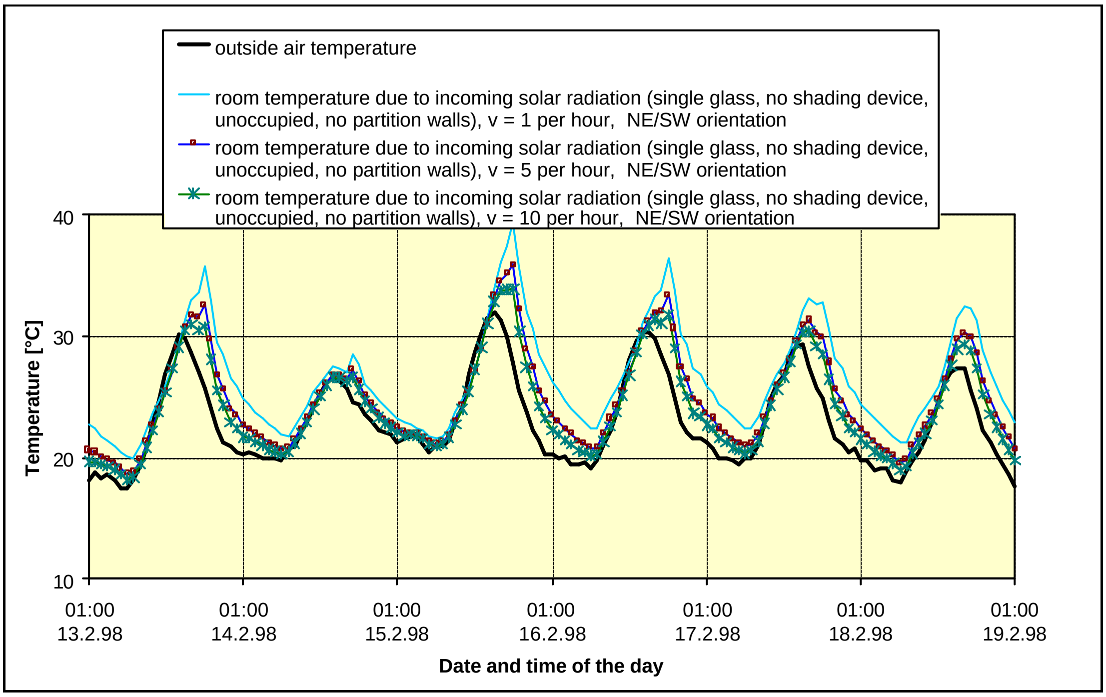



**Figure 3.9:** Temperature variation inside the building (unoccupied) as a result of different air change rates

Figure 3.9 shows the variation of room temperature as a result of varying air change rates of v=1, v=5 and v=10 per hour. Considering the results of the six hottest days - from the 13th to the 18th of February -, we made the following observations:

- The room temperature exceeds outside air temperature by up to 9K when the building is subjected to a constant air change rate of v=1 per hour. An increase of the air change rate from v=1 to v=5 per hour reduced the room temperature by up to 3°C during peak hours.
  Increasing the air change rate from v=1 per hour to v=10 per hour, reduced the room temperature by up to 5°C. An increase of the air change rate from v=5 per hour to v=10 per hour, reduced the room temperature by up to 2°C.
  Increasing the air change rate above v=10 per hour did not result in any recognisable decrease in room temperature.

- The room temperature at night was minimally influenced by the change in different air change rates.

Increased cross air movement within the building may not necessarily lead to a reduction of air temperature inside the building but will have an impact on the thermal balance of the body in two ways:

1. The temperature of the moving air will facilitate convective heat loss from the body if the skin temperature is higher than that of the surrounding air
2. Moving air facilitates evaporation depending on the humidity of the air. For regions which experience high air humidity (above 85%), the air is so saturated that moving air can not contribute significant vapour to facilitate the reduction of body temperature. The most appropriate humidity to facilitate evaporation is around 50%.

The upper limit at which air change within a building will cause discomfort is its speed but this differs depending on the different activities taking place inside the building. Wind speeds of up to 1.5 m/s may be pleasant and acceptable to many people.

### 3.1.6 The influence of night ventilation on room temperature

To analyse the influence of night ventilation on room temperature, that is to say, the air openings were closed during the day but opened only at night, the following assumptions were made during the simulation:

a) there was a continuous hygienic air change rate of v=1 per hour throughout the day
b) there was only the hygienic air change during the period form 7am to 7pm but between 7pm to 7am the air change rate was increased to a total of v=10 per hour
c) the building was assumed to be continuously occupied from 7am to 7pm and the personal computers were switched on during this period
d) heavy partition walls were considered

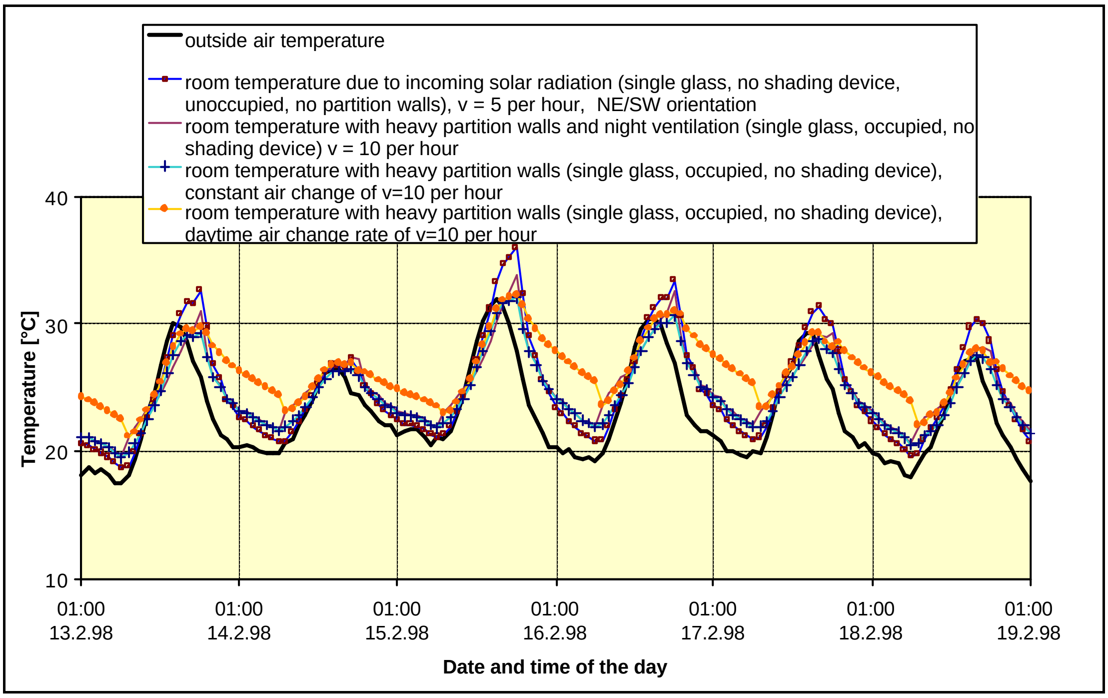



**Figure 3.10:** The effect of night ventilation on the temperature inside the building

Ventilating the building with heavy partition walls only during the night showed some impact on room temperature during the day. During the hot hours of the day, the temperature in the building exposed to increased night ventilation was around 2°C higher than that of a building continuously ventilated (v=10 per hour) as shown in figure 3.10. Increasing ventilation only during the day (v=10 per hour) resulted in a comparatively higher room temperature at night than when the building was ventilated at night. This is partly due to the temperature difference between day and night during some periods of the year.

Security considerations may outweigh the risks of opening the building for night ventilation for such minimal consequences.

### 3.1.7 The influence of roof projection on room temperature

The building as already described above has double pitch roofing on the northeast–southwest orientation. The roof as was planned extends 1.4m on the north and south orientations and 0.8m on the east and west orientations beyond the main body of the building. In all the simulation described before, it was assumed that the roof did not extend beyond the main body of the building. There were therefore no structures on the building in the form of roof projection or otherwise that obstructed incoming solar radiation from reaching the building envelope. If the side was exposed to the sun, direct solar radiation would strike the whole length of the building notably the glazed surfaces.

Depending on the orientation of the building and the time of the day - thus the altitude of the sun -, the part of the roof extending beyond the walls functions as a fixed shading system. This will be discussed in detail in chapter 6.

The protruding roof blocks some of the direct solar radiation from reaching the glazed surfaces on the walls when the solar angle is high. This significantly reduces the intensity of direct solar radiation that reaches the building façade. For the east and west façade, the solar angle is so low that the protruding roof will have no impact on the incoming solar radiation.

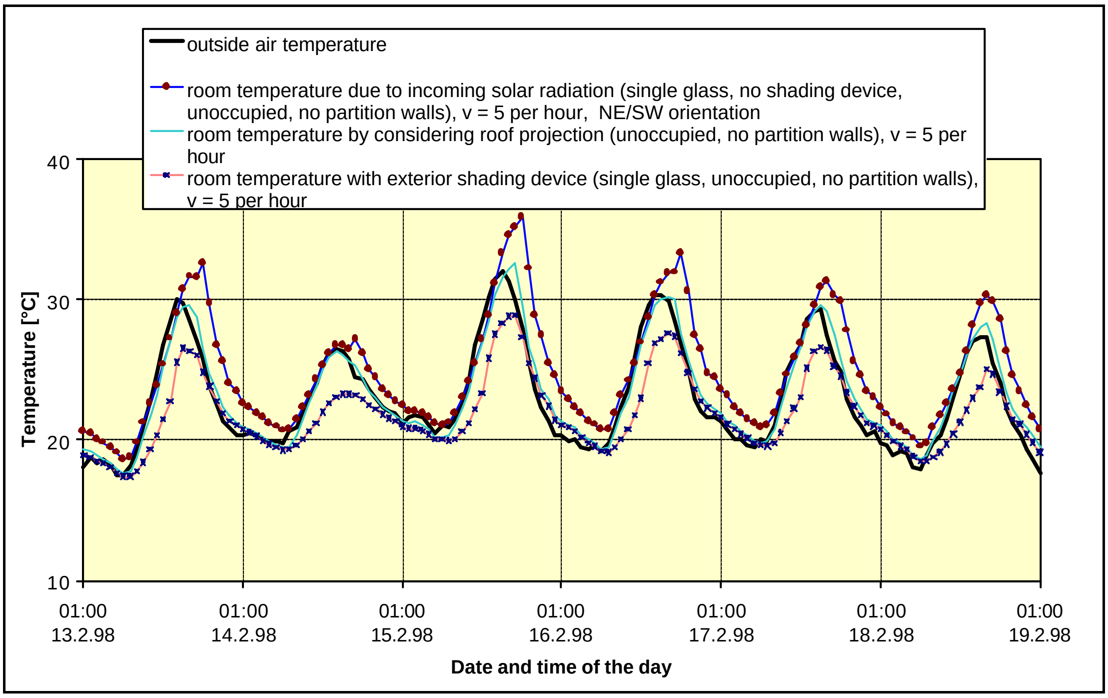



**Figure 3.11:** The effect of roof projection on room temperature

As shown in figure 3.11, roof projections or other structures extending from the main building body are effective in blocking solar radiation from entering the building, consequently reducing the room temperature. The effectiveness of such structures depends entirely on their dimensions, their position relative to the window to be shaded as well as the size of the window to be shaded. The roof projection on our prototype building was responsible for reducing the room temperature by up to 5°C below that of a building without a roof projection.

External shading devices on the window are rather more effective than a roof projection in reducing room temperature (Chapter 6).

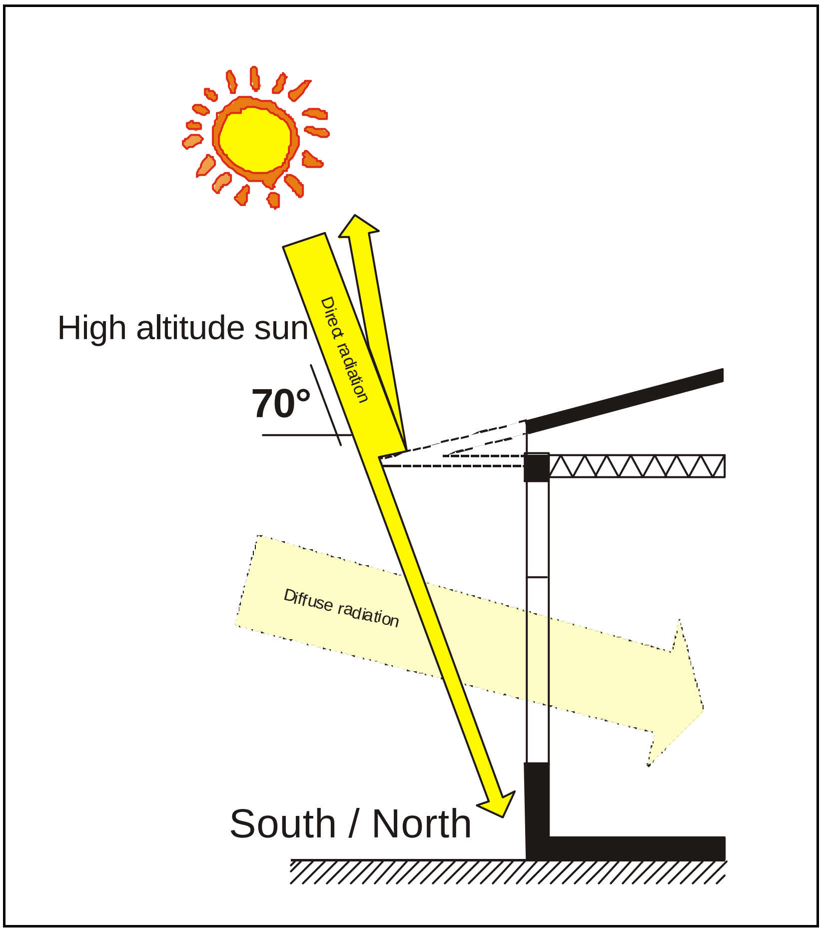



**Figure 3.12:** Schematic illustration of the effect of roof projection on incoming solar radiation

Figure 3.12 shows a schematic illustration of the protruding roof on the building and how it intercepts incoming solar radiation before it reaches the building. Direct solar radiation from the sun at an altitude of less than 40°, will penetrate the building without obstruction by the protruding roof. However, when the sun is at an altitude of above 60°, solar radiation strikes the roof projection and is partly blocked and reflected and does not directly strike the window. The length of the projection from the wall and its position from the upper limits of the window (Chapter 6), will determine whether the window will be completely protected from incoming direct solar radiation.

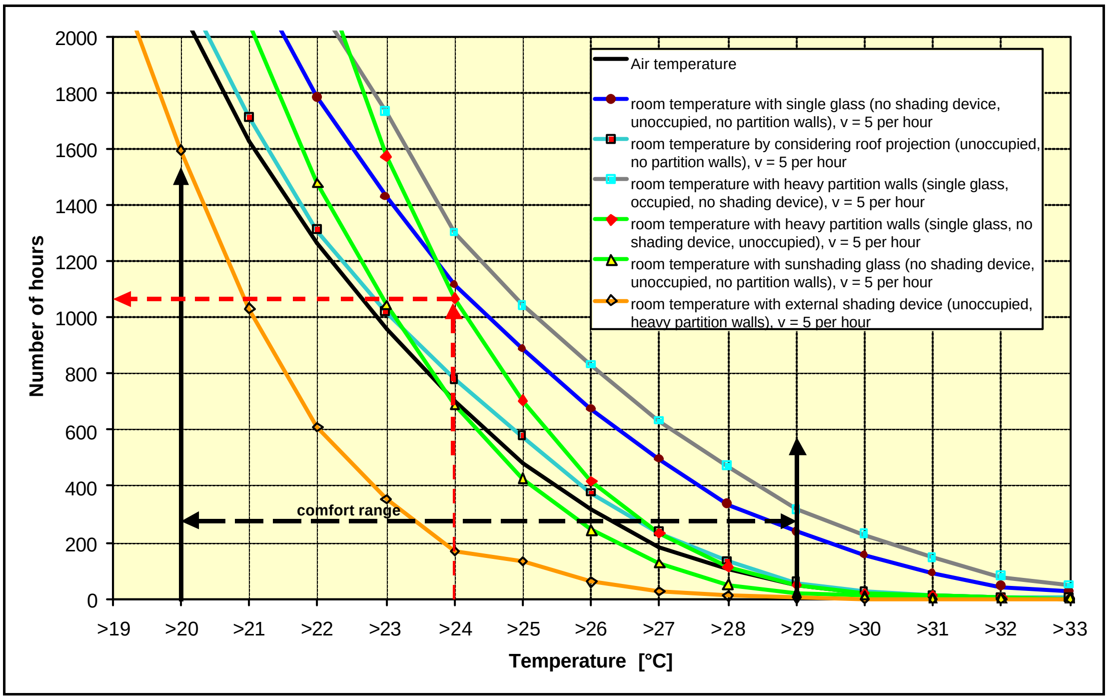



**Figure 3.13:** Comparing the number of hours in a year that exceed a given temperature for some of the measures taken to improve the thermal conditions inside the building.

In figure 3.13, the different situations considered during the simulations were compared in terms of their impact on room temperature by plotting the number of hours in a year when the temperature inside the building exceeds a certain level against the temperature inside the building. By comparing the number of hours that exceed or fall below a certain temperature for different measures which can easily be read on the graph, we can then determine the most effective alternative for reducing the temperature inside the building.

The use of an external shading device in reducing room temperature showed impressive results followed by sun-shading glass.

## 3.2 Thermal comfort; Analysis and strategies

The most noticeable response of the human body regarding different environmental factors is towards temperature. Humidity ratio of the air, movement of the air (air velocity) and solar radiation, have a direct influence on the comfort of people in a given environment. Some other factors like activity, clothing, age, sex, food and drink etc. may influence the comfort of an individual. Buildings are basically designed to keep the temperature within comfortable limits.

Deep body temperatures lie between 35°C - 40°C (normal 37°C). The skin temperature which is around 34°C (normal) is always lower than the deep body temperature. In order to guarantee heat dissipation from the deep body, the surrounding air temperature must be below that of the skin. Comfort, therefore, will be realised within a range of temperatures (comfort zone), within which there will be sufficient dissipation of heat from the body. Human comfort zone is a set of environmental conditions within which 80% of the people neither feel cold nor hot.

In order to study the potential effects of the building envelope combined with several environmental control strategies, we used our prototype building and tested through simulations several possibilities of achieving thermal comfort inside the building without resorting to the use of machines. The ambient conditions of the region of Kasese were considered as the basis. Figure 3.14 shows the variation of air temperature and relative humidity for the region of Kasese in February, the hottest month.

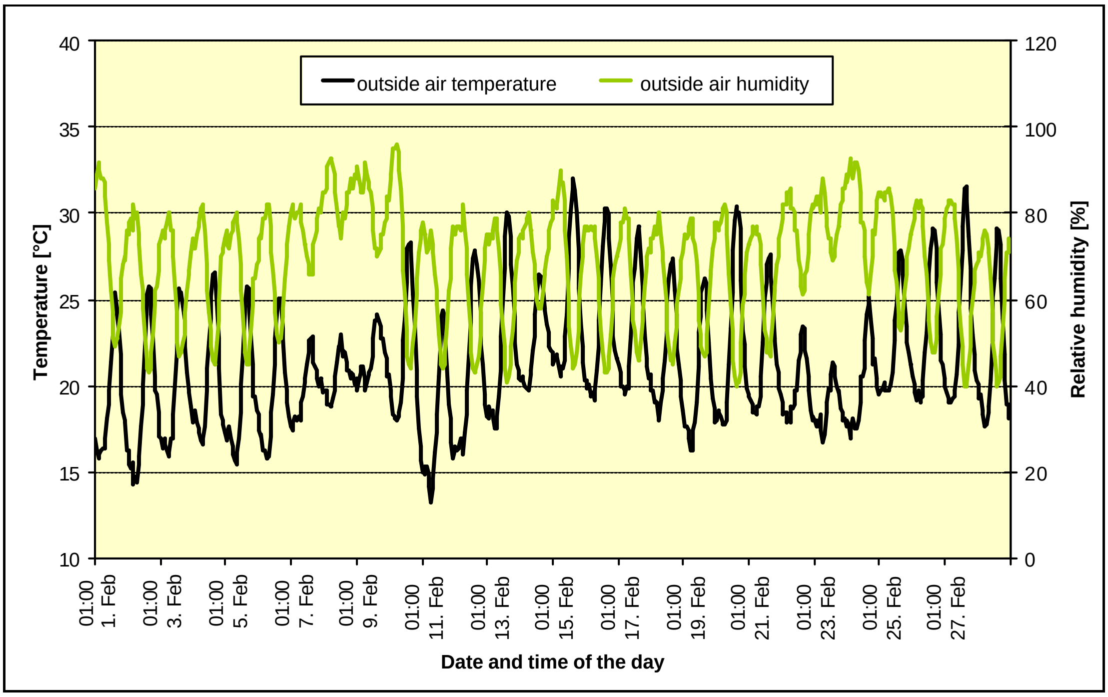



**Figure 3.14:** The variation of outside air temperature and relative humidity in February for a location at latitude 0.11°N, Kasese, Uganda

The set of conditions under which people feel comfortable slightly differs from region to region and vary from culture to culture. This slight difference in the shift of the "comfort zone" may be a result of acclimatisation whereby people in a given environment get used to some conditions which may be uncomfortable to people who are not used to them.

We defined the human comfort zones for different regions established by various researchers on a psychrometric chart. Psychrometric charts graphically represent the relationship between different environmental factors that are important elements when considering design strategies based on climate. These factors are the air temperature, relative humidity, absolute humidity, saturation humidity and enthalpy. Any change in the atmospheric conditions which affects the relationship of the above factors, can be easily recognised on the chart.
We were not able to precisely define the comfort zone for the region of Kasese or for hot and humid tropical regions in general as this was beyond the scope of this work. Comfort in buildings in tropical regions is such a complex issue that we will not be able to discuss it in detail within this work. However, we plotted comfort zones for the temperate regions of middle Europe and that of North America which were used as approximations for tropical upland climatic zones. These defined comfort zones have the following characteristics:

- the zone for middle Europe (DIN 1946) suggests a temperature of between 20°C - 26°C and a relative humidity of between 30% - 60% [67]
- the zone defined by Olgyay basically for the North American region, which suggests a temperature of between 20.6°C – 27.8°C and a relative humidity of between 30 - 65%. He further suggested temperatures of between 23°C - 29°C and relative humidity of between 30% - 70% for tropical regions [3].
- the zone for North America (approximate values) suggests a temperature of between 20°C – 26°C and a relative humidity of between 20 - 80% [4].
- the zone for the region of Kasese defined according to Peyush´s method which suggests a temperature of between 21°C – 29°C and a relative humidity of between 20 - 80% [68].

The different comfort zones plotted on the psychrometric chart are shown on figure 3.15. There is a marked variation in the different comfort zones although the general trend indicates that human comfort is within the temperature range of 20°C to 27°C and a relative humidity between 20 – 80%.

Plotting the ambient conditions on the chart can help us estimate the effect of the building envelope as well as different environmental design strategies aimed at achieving human comfort in buildings in a specified region.

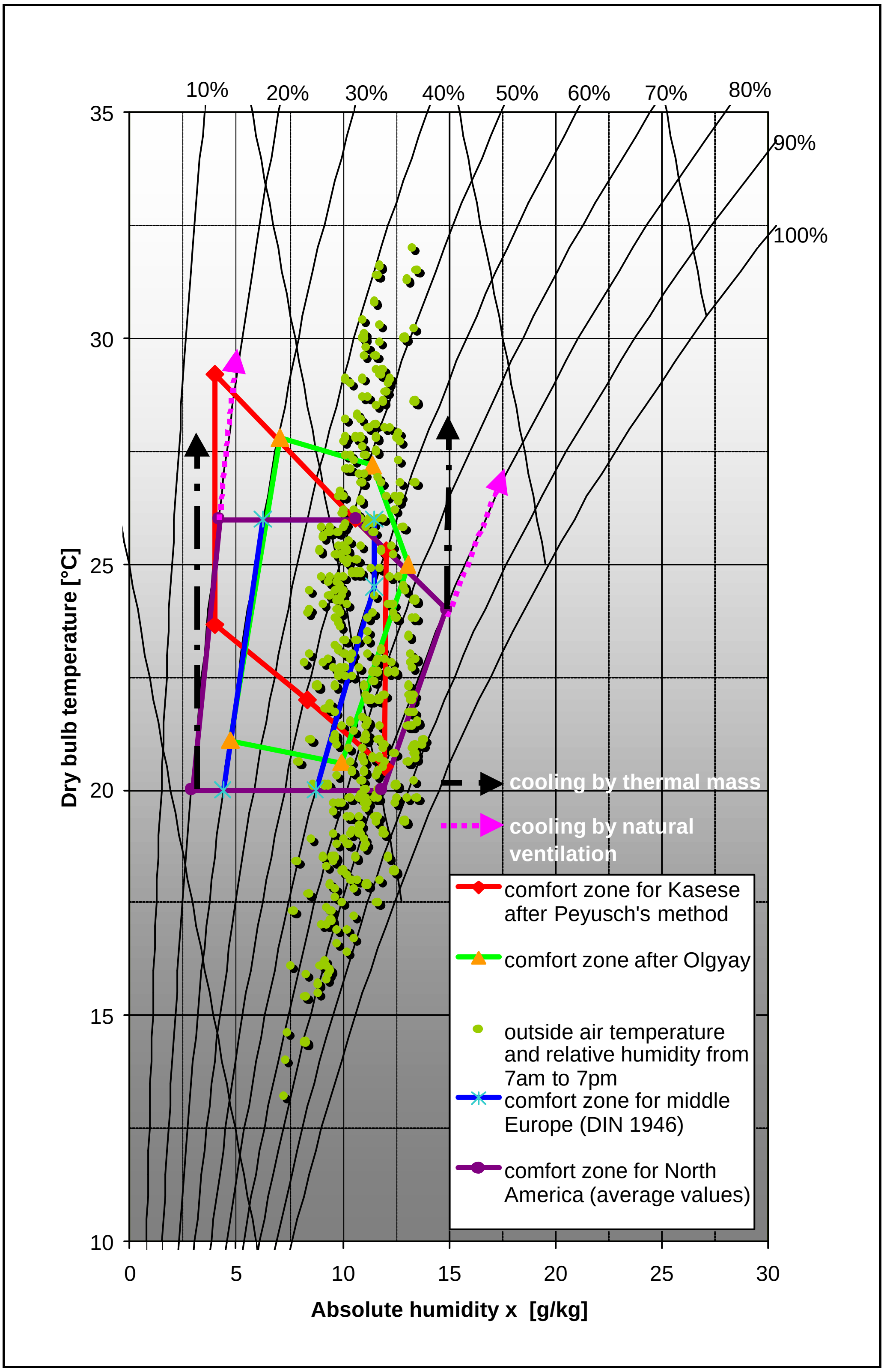



**Figure 3.15:** The variation of ambient air temperature and humidity for the month of February for the region of Kasese and the different defined comfort zones

The ambient conditions for Kasese for the month of February between the period from 7am to 7pm were plotted on the chart shown on figure 3.15. The average weather conditions (temperature and relative humidity) falls within the defined comfort zone. The defined comfort zone stretches depending on the design strategy considered. Two design strategies were considered for evaluation. The use of thermal mass and increased ventilation for cooling buildings in hot and humid regions.

The comfort zone stretches along the lines of constant moisture (dotted lines represented by cooling by thermal mass on figure 3.15) if the strategy of cooling by thermal mass is considered. Increase in thermal mass does not affect the absolute humidity i.e. moisture in the air remains constant. If the average air temperature falls within the defined comfort zone and the extreme temperature fall within the extended region, then thermal comfort can be achieved inside the building by increasing the thermal mass. Thermal mass reduces the temperature by absorbing heat during the day and releasing it after a certain period (time-lag) when the surrounding temperature falls below that of the walls (Figure 3.15). The temperature in the building is in the process kept within comfortable limits consequently enabling adequate heat dissipation from the body. The ambient conditions for the region of Kasese plotted on the psychrometric chart indicate that thermal comfort inside the building can be achieved by applying the strategy of cooling by thermal mass.

A case of increased ventilation as a design strategy for achieving thermal comfort in a building was also analysed. The considered comfort zone stretches along the lines of relative humidity (indicated by dotted lines named as cooling by natural ventilation on figure 3.15). The ambient conditions for Kasese falls within the zone where comfort in building can be acquired by increasing cross air movement through the building. The rate of air movement at which comfort is achievable depends on the activities carried out and also the nature of clothing of the occupants of the building [41].

The upper limit of the design strategy of cooling by natural ventilation is when air velocity will begin causing discomfort by disorganising things inside the building.

Comfort can as well be achieved by considering a combination of more design strategies. This can be the case whereby the extension for different design strategies plotted on the psychrometric chart overlap. In such a situation a building can be carefully designed to take advantages of both strategies. For the region of Kasese, based on the prevailing climatic conditions, the two design strategies of cooling by thermal mass and also by increased natural ventilation can be combined to achieve a comfortable environment inside the building.

The use of psychrometric chart to determine the effectiveness of different design strategies for achieving comfort in buildings, requires proper consideration of the following factors:

1. Determining the ambient climatic data of a given site
2. Establishing the “human comfort zone” for the region in which the site of the building is located. Such a measure takes into account the special characteristics of the particular region instead of the common generalisation of climatic regions to belong to either the traditional classifications of hot and humid, hot and dry, temperate or cold. Some regions may not accurately fit into these classifications as has been proved for the region of Kasese.
3. There is a need to consider several alternative design strategies for any given region. This is due to the fact that most recommended design strategies may be appropriate in traditional buildings but are not readily applicable in modern buildings. Natural ventilation for cooling and low mass constructed structures is for instance, the most appropriate design strategy for acquiring comfort in buildings in hot and humid regions. Much as this may be true especially in traditional buildings constructed out materials like straw, wood or other fibres, there are limitations to the usefulness of this strategy in modern buildings. High rise buildings in these regions can not be constructed with these materials and also the susceptibility of destruction of such materials by fire and insects makes them inappropriate construction materials in areas with a high density of buildings.
4. Design strategies may be considered individually or in combination with other strategies depending on the type of building. This will enable the maximum utilisation of natural energy techniques in acquiring comfort in buildings which can then be supplemented by other means in case of deficiencies.

It is evidently clear from the above analysis that there is a need to protect the buildings in hot regions from solar radiation in order to minimise an increase in the temperature inside the building in addition to any applied control design strategy. From figure 3.15, the temperature in Kasese can be sufficiently cold, i.e. below the comfort limit, that some form of heating may be necessary. Solar control in the building by allowing some kind of passive heating whenever it is necessary but avoiding overheating, is therefore an important element in the overall design strategy in buildings in hot and humid regions. This topic has been discussed in detail in chapter 6 of this work.

# 4 Daylighting

Daylighting refers mainly to light received on earth from the sky excluding the direct component - light that reaches earth from the sun without alteration. In regions where the sky is predominantly clear, direct sunlight contributes significantly to the amount of light received inside the building and may therefore be considered as a component of daylighting.

We will, within the scope of this work, concentrate more on how daylight behaves in buildings, advantages and disadvantages as a result of its use, and discuss methods of positively realising its potential for lighting in buildings in tropical regions, particularly in hot and humid tropical regions.

## 4.1 Definition of daylight - direct light and diffuse light and its specifications

Descending solar radiation from the extraterrestrial bodies towards the earth is affected in four major ways.

- One part get absorbed by water vapour and ozone and never reaches the earth’s atmosphere
- One part reaches us from the overcast sky. Clouds trap part of the solar radiation which is partly reflected and partly released into the atmosphere where it is scattered by air molecules, water vapour molecules and dust particles on its way to earth. This radiation is referred to as diffused radiation or light.
- Another part of solar radiation is either absorbed or scattered by air molecules, water vapour molecules and dust particles in the atmosphere
- The last part of light reaches us directly without alteration and is referred to as direct light or sunlight.

The above process practically reduces the intensity of the emitted solar radiation of around 1395 W/m² arriving at the surface of the earth’s atmosphere to a level that reaches the earth depending on the distance it has to travel (sun-earth relationship) i.e. the latitude and the time of the year.

Sunlight, infra-red and ultraviolet constitutes the direct part of solar radiation, which within the scope of this work, is radiant heat and when permitted to directly strike the building envelope or allowed to penetrate into the building, will be responsible for the increase of air temperature inside the building.

Direct light is also important for its visual amenity in that we are able to clearly identify the shape and colour of objects when direct light falls on them. Direct sunlight reaching the building interior gives people a psychological feeling of direct contact to the outside world which is very exciting. On the other hand, direct light will help plants inside the building grow tall.
Ultraviolet radiation, though comparatively minimal compared to visible light or Infra-red components, can lead to fading of materials and bleaching of colour of objects in buildings directly exposed to it.

Diffuse light is light released by the clouds which is then dispersed by air molecules and dust particles in the atmosphere. This light reaches the building interior either directly or after being reflected by objects in the vicinity or the ground. Diffused light increases the total quantity of illumination on the work performed under daylight. For good vision and identification of three dimensional objects, both direct and diffuse light is needed to create the right kind of modelling. The clarification of details of objects is greatly influenced by the amount of diffuse light that reaches the viewed object from all directions in addition to direct light falling on the surfaces of this object.

The components of solar radiation that reach the earth's atmosphere including daylight and sunlight emitted by the sun constitutes the atmospheric electromagnetic spectrum. A narrow portion of this spectrum with specified wavelength can be accommodated by our naked eyes, and thus is visible.
Visible light falls almost in the middle of the electromagnetic spectrum. This radiation spectrum comprises of components with wavelength ranging from almost a millionth of a nanometre for cosmic rays at the lower end to around a hundred kilometres for radio rays at the upper end of the spectrum. Solar radiation spectrum in the atmosphere is comprised principally of two main components: diffuse and direct radiation. For our reference, solar radiation spectrum in the atmosphere will refer to visible light as diffuse light and sunlight, ultraviolet and infra-red components.

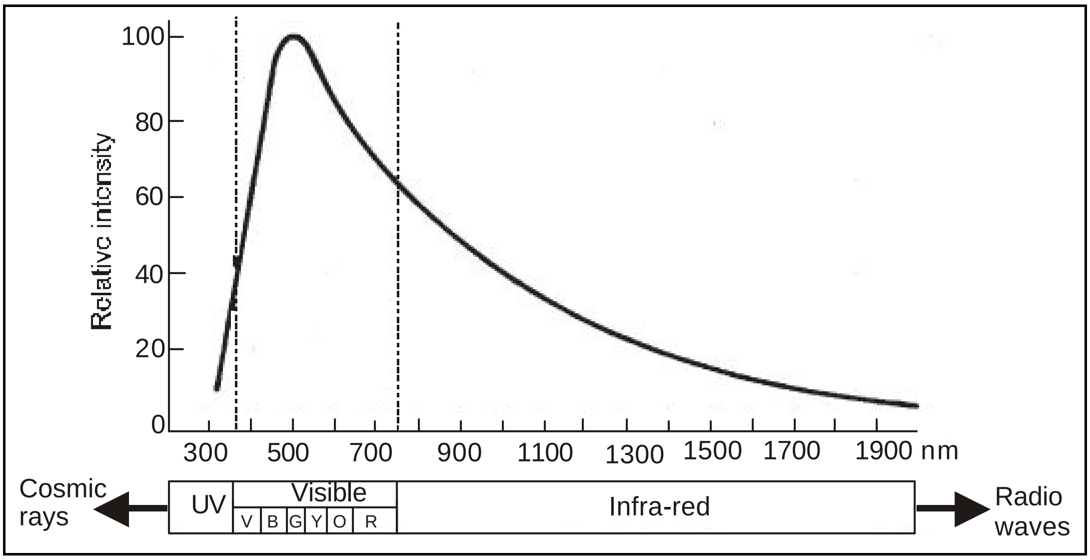



**Figure 4.1**: solar radiation spectrum

Figure 4.1 shows the solar radiation spectrum in the atmosphere where visible light has a wavelength in the range of 380 to 760 nanometres.

The term daylight will refer to the part of visible light, which we need to accomplish different visual tasks within a specified space.

### 4.1.1 Availability of daylight

Within the scope of this work, we will analyse daylight from a practical point of view. The advantages and disadvantages as a result of using daylight for illumination - visual applications - in buildings. The state of the sky, that is to say, clear, cloudy, or partly cloudy determines when and how much daylight will be available in a specified space. Daylight is an integral part of global radiation.

It is estimated that global radiation on a horizontal plane without obstructions is comprised of 4.5% ultraviolet radiation, 51.5% visible light, and 44% Infrared radiation [10]. These values may differ slightly from region to region. The percentage of daylight constituting of diffuse and partly direct radiation is difficult to estimate as it depends entirely on the changes in prevailing atmospheric conditions.

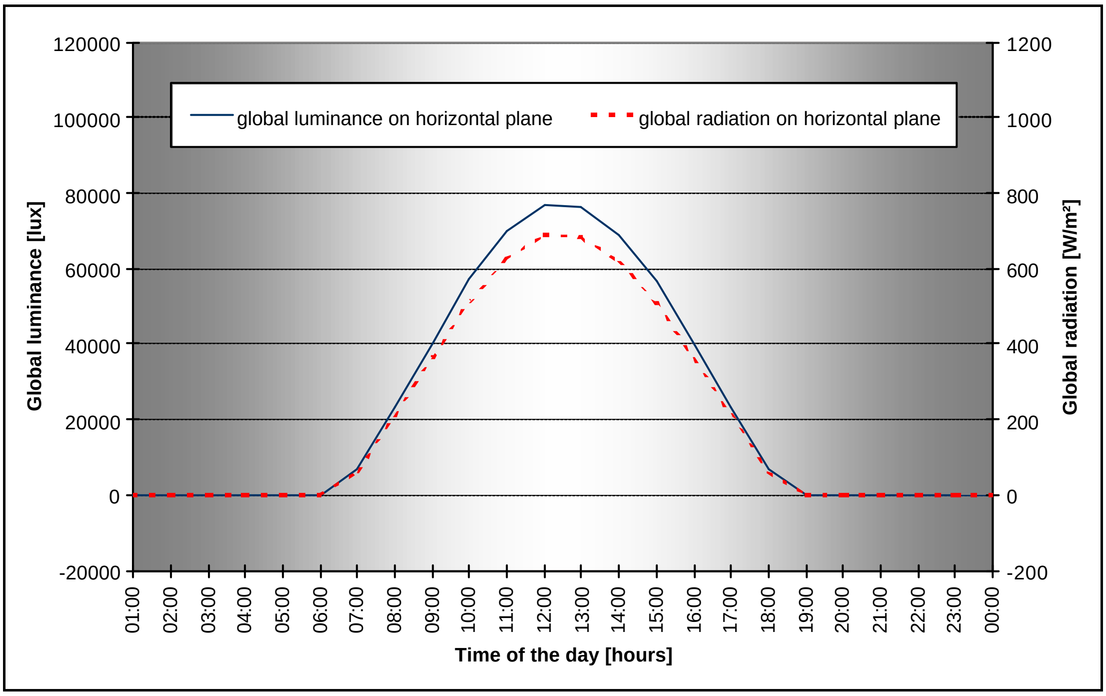



**Figure 4.2:** Average annual global luminance and global radiation on a horizontal plane for a clear sky at latitude 0.11°N, Kasese, Uganda

Figure 4.2 and figure 4.3 shows the average annual illumination and solar radiation distribution on a horizontal plane in an open space for clear and overcast sky conditions for a location at latitude 0.11°N, Kasese, Uganda. The maximum average illumination for a clear sky in a year is in the range of 80,000 lux on a horizontal plane whereas under overcast sky conditions average illumination is within a range of just over 40,000 lux around midday, which is typical for many areas in tropical regions.

The average global radiation on a horizontal plane for a clear sky is in the range of 700W/m² but will drop to below 400W/m² under overcast conditions.

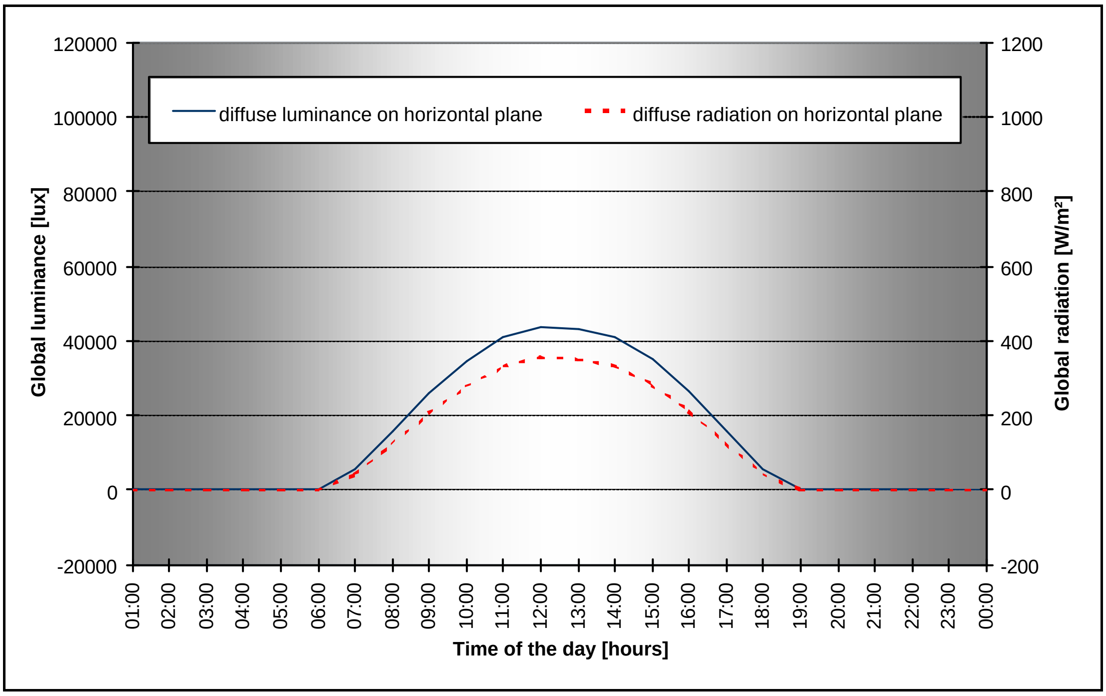



**Figure 4.3:** Average annual diffuse luminance and diffuse radiation on a horizontal plane for an overcast sky at latitude 0.11°N, Kasese, Uganda

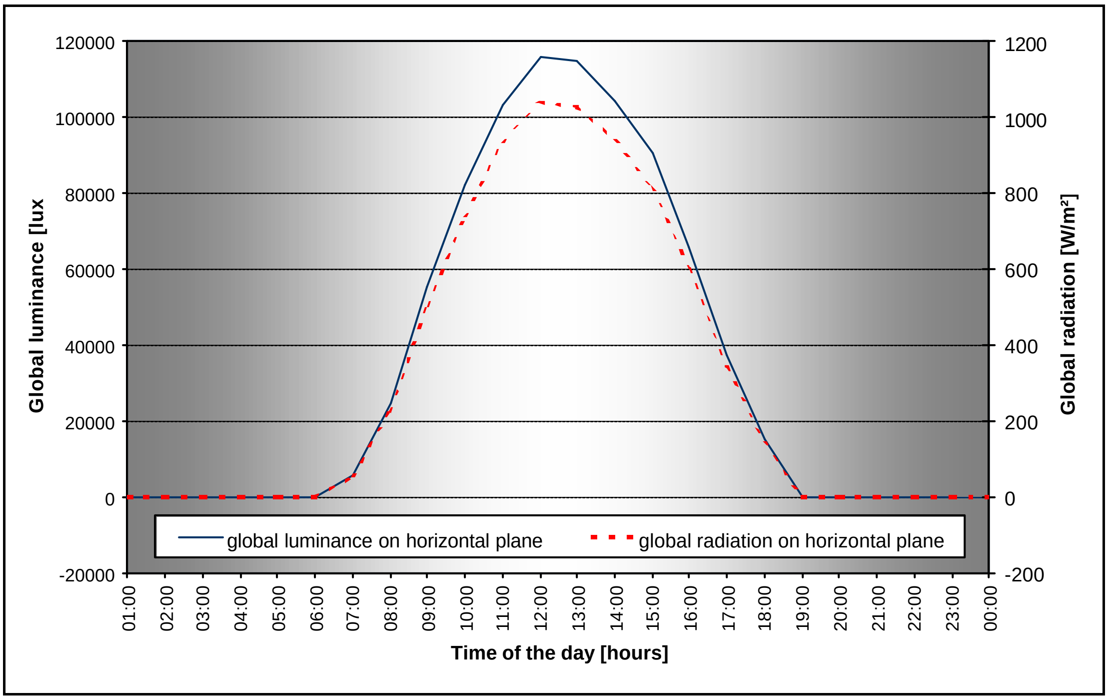



**Figure 4.4 :** Global luminance and global radiation on a horizontal plane on a clear sky day in February at latitude 0.11°N, Kasese, Uganda

Depending on the time of the year as well as the location, global luminance and radiation will vary from day to day. Figure 4.4 shows the variation of global luminance and radiation on a clear day in February. Maximum illumination is in the range of 120,000 lux at around midday whereas solar radiation on a horizontal plane is over 1000W/m².

From figure 4.2 and figure 4.4, we can clearly observe that illumination on a clear day is high and forms a smooth profile whereas on an overcast day the levels are much lower. On some days, illumination and solar radiation distribution under overcast or partly cloudy conditions indicates a fluctuating pattern. The fluctuation in the levels of illumination as demonstrated in figure 4.5 is a typical situation in many hot and humid tropical regions. Outside luminance on such a day swings between partial darkness to a maximum that barely exceeds 30,000 lux. Such a situation renders the total dependency on daylight for illumination rather difficult and unpredictable.

Figure 4.5 shows the distribution of illumination and radiation for a day under overcast sky conditions. Illumination and radiation levels fall far below that on a clear day.

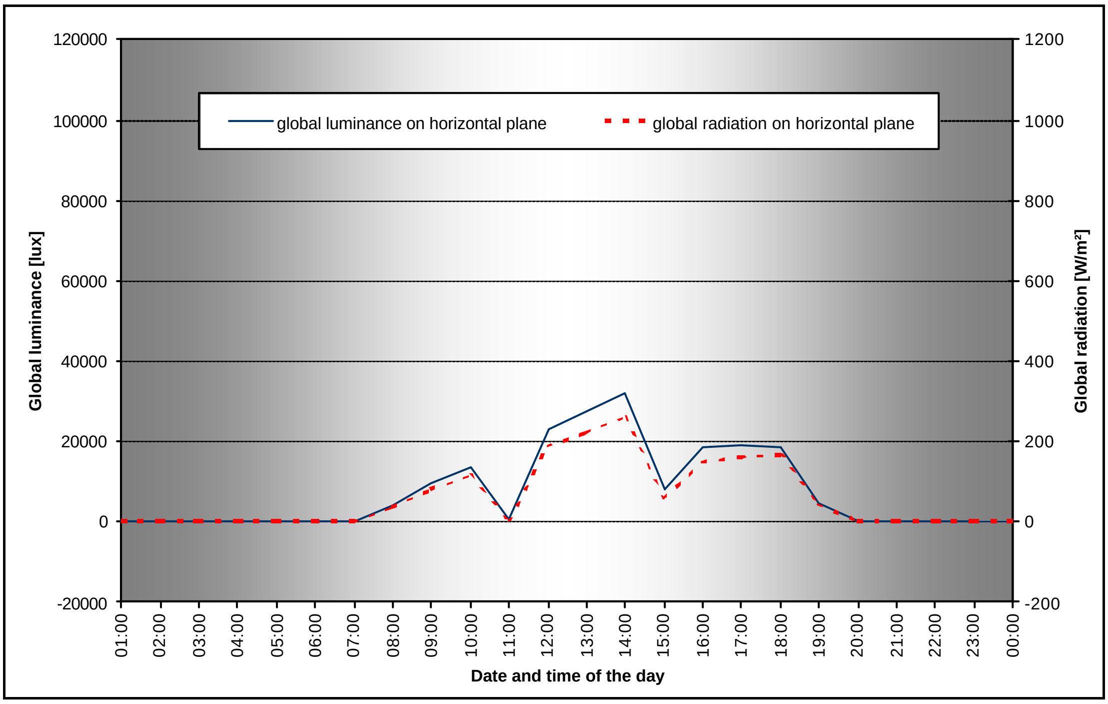



**Figure 4.5 :** Global luminance and global radiation on a horizontal plane on an overcast sky day in January at latitude 0.11°N, Kasese, Uganda

In order to determine whether there is sufficient daylight in a specified space to facilitate visual needs, we need to set a goal to determine the illumination levels within such a space. For most ambient visual tasks, we need an illumination of up to

500 lux even though some tasks may demand lower or higher illumination depending on the kind of task to be accomplished. The illumination levels in an open space are far higher than we need to accomplish most ambient visual tasks inside a building.
We need to allow a small percentage of outdoor light into a built space and the task is how to get this required amount into the building, how deep into the building, how long we can have enough daylight inside the building and also how we can reduce the negative effects that might arise by allowing daylight into the building. Each of these factors will be discussed in detail in the subsequent chapters to determine how they influence the use of daylight in buildings in tropical regions.

### 4.1.2 Estimating the daylight levels in different parts of the building

Determining the amount of daylight available at a certain point inside the building by considering sky conditions of low illumination – overcast, can substantially help us decide whether we can effectively use daylight to accomplish some visual tasks without resorting to the use of artificial lights. In dry sunny climates with a blue sky of relatively constant luminance and sunlight of predictable illumination, the quantitative specification of daylight is less difficult. This is not the case in the hot and humid climates of the tropics where the changes in cloud cover during the day is more frequent. This variability can only approximately be predicted on a statistical basis. This is rather a tedious task and demands a long monitoring process largely influenced by technical expertise and economic factors which may not be readily available in many regions of the tropics.
The amount of natural light received at a plane outdoors has three components:

- unobstructed light reaching the plane from the sky – direct component
- light reaching the plane after being diffused in the atmosphere and,
- light from the above two components after reflection by the ground and from the surrounding surfaces.

The magnitude of the above factors that determine natural light received outdoors varies with the changes in atmospheric conditions.
In temperate regions, it is widely acceptable to specify the illumination levels in terms of daylight factor. The “Daylight Factor” concept can simply be described as the ratio of the amount of daylight on a horizontal working plane of a space within a built

environment, $E_i$ , and the illumination at a horizontal plane at a point in an open space, $E_o$. Daylight factor is therefore a characteristic of the geometry of a space and is independent of the climate and site of the building. It is calculated purely under overcast conditions excluding direct sunlight.

Daylight factor is customarily expressed as a percentage:

$$\text{Daylight Factor} = \frac{E_i}{E_o} \times 100\ (\%) \qquad (1)$$

Among the advantages of the daylight factor concept is the fact that once estimated, it will almost remain constant due to the fact that under overcast conditions, the luminance of the sky is independent of the orientation of the considered space. Thus if daylight outside the building changes, the interior illumination will change relative to outside daylight changes. The average daylight factor is usually taken from a point at the geometrical centre of the considered space and measured at the level of working height.

Daylight Factor has three main components:

- The component as a result of light received from the sky after being diffused by gases in the atmosphere and water droplets in the clouds
- The component as a result of light reflected from surfaces outside the building
- The component as a result of light reflections within the built environment whose reflection coefficients are determined by the nature of the surface.

In the case of hot and humid tropical regions where the sky conditions vary unpredictably from clear to overcast, we need to find a solution to the problem of the variability of externally available light - illumination - in order to translate it into dependable interior daylight. While under an overcast sky there is uniform distribution of daylight, the situation is rather different under clear sky conditions. For a clear sky the luminance depends entirely on the position of the sun.

Because of the inconsistency of sky conditions in some tropical regions, we will produce many different light distribution patterns depicting the changes in atmospheric conditions which will render the concept of daylight factor useless. Daylight factor may therefore not be the ultimate method to estimate daylight distribution in buildings in hot and humid tropical regions due to the above reasons, although under selected overcast conditions it may serve as an alternative.

As a principle, daylight factor has very little significance in practice although it may be a very useful design criterion under average defined conditions.

Accepting illumination level as the criterion for sufficient daylight or good vision, poses a problem of special difficulty relating to the variability of available daylight in hot and humid tropical regions. Some measures have to be considered to tackle this problem and these are:

a) daylighting design around a minimum available daylight. This takes into account the situation of total overcast sky whereby during working hours there is a situation of almost partial darkness
b) daylighting design around an average sky condition
c) daylighting design such that the recommended levels of illumination are achieved in the interior during a greater part of the working hours
d) total absence of daylight, thus total dependency on artificial lighting
e) daylighting design with integrated artificial lighting as a supplement in case there is not enough daylight.

The above recommendations consider the minimum atmospheric climatic scenario of an overcast sky where, if the state of the sky changes to either partially cloudy or clear, the levels of illumination inside the building will automatically be influenced.

Figure 4.6 shows the illumination distribution inside our prototype building (described in chapter 3 of this work) at latitude 0.11°N in Kasese, Uganda, which we chose to carry out several investigations throughout this work. This figure gives information on the spatial penetration of light into the building.
This is a demonstration of illumination distribution at a given point, at a specified time, that is to say, month, day and hour of the day under overcast sky conditions. The outside illumination at the time the simulation was carried out (21$^{st}$ of September at 12 o'clock) was around 16,000 lux on a horizontal plane.
The availability of daylight at different parts of the building is not evenly distributed whereby some areas are insufficiently illuminated. Most areas receive less than 500 lux whereas areas near the window receive illumination levels of above 3000 lux, far higher than is needed to carry out most ambient visual tasks.
The nature of the glass, the position and the size of the window will, among other factors, considerably influence the distribution of daylight inside the building.

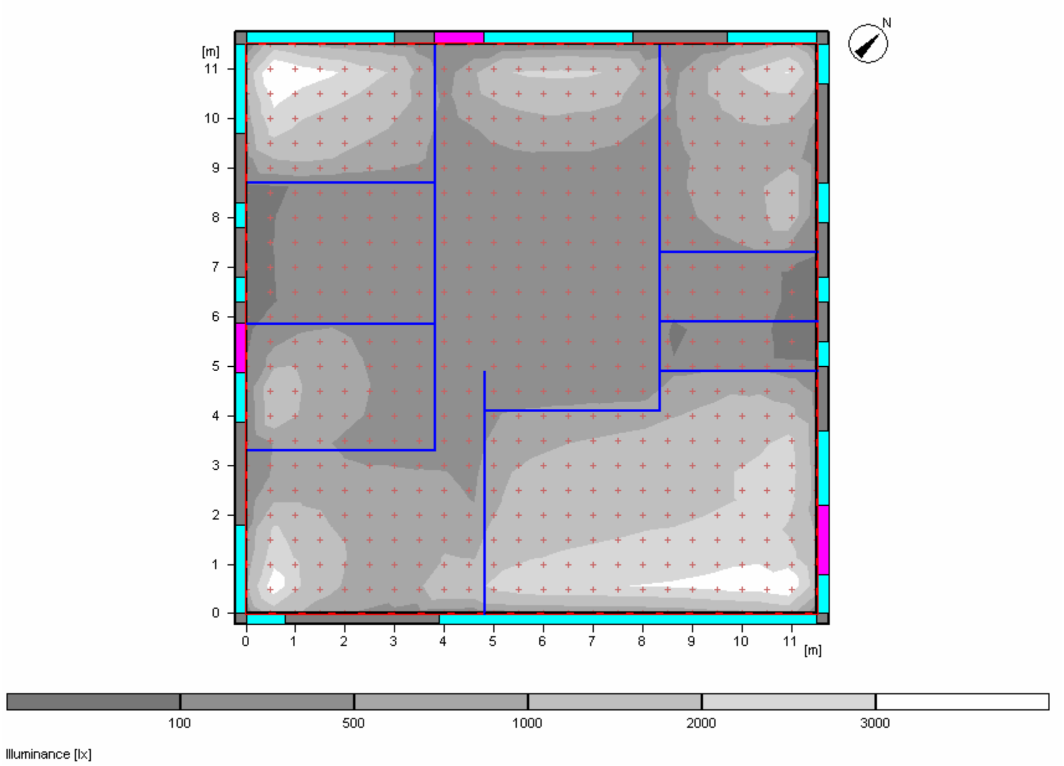



**Figure 4.6:** Two dimensional illumination distribution (isolux) in the prototype building in its planned state under overcast sky conditions at latitude0.11°N (Kasese, Uganda)

There are several methods of raising the illumination levels of the less illuminated areas of the building to relatively acceptable levels without resorting to the use of artificial lighting. Some of these methods may be:

i) using skylight (light-well) to bring light into the core area of the building
ii) increasing the size - both width and height - of windows to allow more light to penetrate the building
iii) positioning the window higher on the façade in order to bring light high into the building
iv) applying innovative methods to re-direct light deeper into the building and eventual uniform distribution
v) dimensioning the building such that the rooms are not so deep that light through the side windows can reach most areas in the building
vi) applying bright colouring on both the ceiling and the walls to enhance light reflection
vii) transporting light (daylight or sunlight) to less illuminated areas

Some of these methods will be discussed in detail to see how they influence the availability and distribution of daylight in the building.

## 4.2 Methods of allowing natural light into buildings in tropical regions; conventional and innovative methods.

For good visibility within a building, we need to get as much daylight as deep into the interior as possible. The human eye can adjust to luminance of different intensity with less discomfort thanks to the photopic and scotopic vision mechanism of the eye.
The position and size of the opening through which light enters the building in relationship to the sky plays a decisive role. The lesser inclined the openings are, the more light will get into the building [65]. Skylights will allow more light into the building than windows or clerestories on the wall despite the reflected light from the ground. We have, however, to try and control the brightness in the field of view within and outside the building to avoid excessive brightness contrast and also try to minimise conditions within the building that might cause unnecessary reflections. Building interiors, depending on their nature or function, may have direct access to natural light or in some cases the interior can be too deep or enclosed without any direct connection to the outside. This implies full dependency on artificial light for illumination. Natural light in such a case can be transported into the interior. This requires some technical knowledge and capacity.

### 4.2.1 Conventional methods

Conventionally, daylight penetrates the building through openings in the walls or on the roof of the building. Windows have several functions apart from allowing light into the building. They facilitate air circulation to and from the building, allow contact to the outside from inside the building and also permit warmth into the building. Windows can simply be referred to as the communication medium between the built environment and the outside.
Increasing the size of the glazed area will not only permit more light into the building, it will also increase the risk of raising the internal room temperature and glare by allowing more solar radiation into the building.
The task is to raise the minimum illumination levels to a level adequate to perform visual tasks in most parts of the building without resorting to using artificial lights, while minimising the risk of increasing room temperature and glare. The skylight or light well shown in figure 4.7 can improve the illumination of the areas of the building which do not receive enough light through side windows.

The amount of light through the skylight is directly proportional to the size of the skylight and the type of glass used. Buildings which have skylights as the only source of light receive shadowless and featureless light which is unpleasant. In order to improve the quality of light through the skylight it may be important to incorporate side windows whenever possible to create a shadowing effect of objects in the building [8]. Skylights are effective for single storey buildings. In multiple storey buildings it is only the upper level that will be served by a skylight. It is advisable to use highly reflective glass in order to minimise overheating in the building due to direct radiation through the skylight.

It is almost inconceivable that a window as a simple opening can simultaneously perform all the above mentioned functions to the satisfaction of the occupants of the building without some modifications. Take the example of daylight and view.

Daylight and view are thought to be inseparable but this is a wrong perception as both must not necessarily go together or be achieved through the same opening. Daylight can for instance be brought into the building by bouncing it on surfaces, thus does not necessarily need a direct route into the building whereas view must be direct.

It is therefore necessary to separate the window into two apertures for view and daylight, if possible, and to treat each separately in order to achieve the maximum advantage.

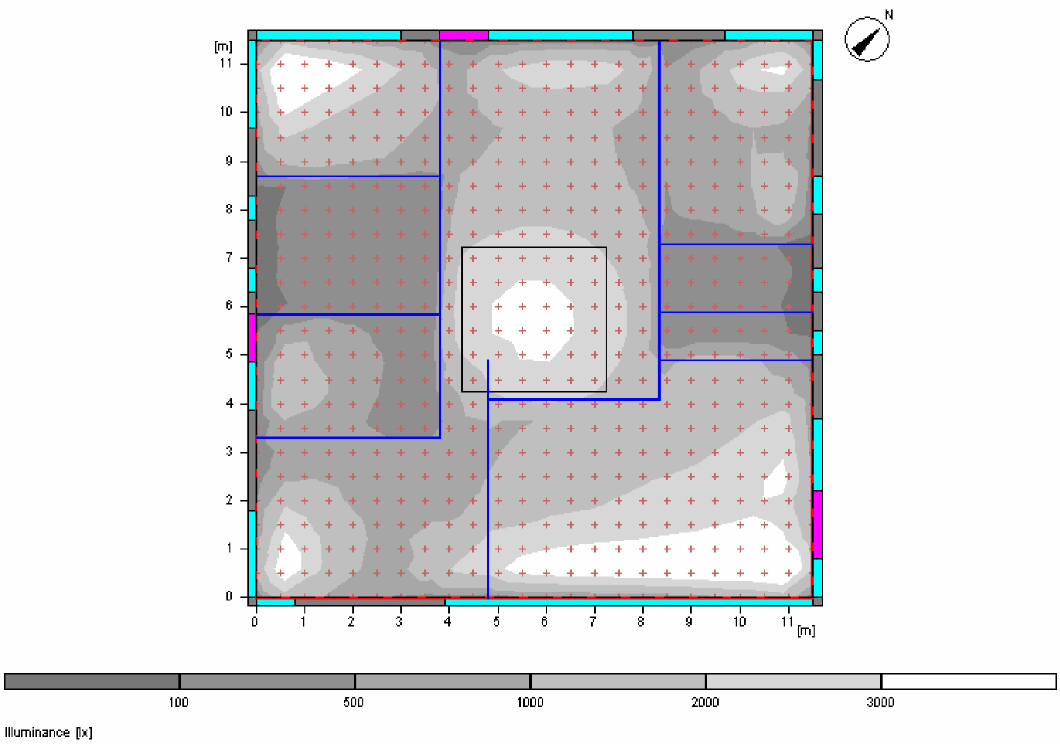



**Figure 4.7:** Demonstration of a two dimensional illumination distribution (isolux) by use of a skylight to illuminate the core of the prototype building at latitude 0.11°N, Kasese, Uganda

In most cases on many buildings, both view and daylight are achieved through the same aperture. This requires different considerations in order to achieve the full benefits of a window regarding the use of daylight in buildings. Though view and daylight can easily be achieved through the same aperture, this will automatically imply exposing the building interior to all the negative effects accompanying solar radiation reaching the building.

In tropical regions, depending on the nature of the building, some buildings may have windows and others may not. Some traditionally constructed buildings in these regions may have no windows not only because of economical reasons or lack of technical information and expertise but also due to the following reasons:

- thermal considerations
- security
- ensuring secrecy (privacy)

Such buildings may be permanent structures as may be seen in many parts in the tropics or temporary dwellings mostly preferred by nomads.
These buildings are erected for purposes of providing shelter with virtually no consideration to the benefits of using daylight for illuminating the interior.
Some buildings may have windows which are opaque. They are constructed out of materials like wood or other natural fibres like straw or bamboo with relatively low thermal mass. Such windows are preferably secure, can facilitate air circulation and allow in some daylight when opened, guarantee secrecy, comparatively reduce heat penetration due to direct solar radiation and are relatively cheaper and easy to produce and maintain. Buildings which have no windows or those with opaque windows are basically dwellings whose main function is for sleeping, or are used as shelter against rain or severe weather.

Figure 4.8 and figure 4.9 depicts some typical examples of residential buildings in hot and humid tropical regions. They clearly indicate that the factors that underline the nature of buildings are more exclusive to solar radiation rather than allowing light into the building. Stopping or reducing the radiant heat that might enter the building through windows outweighs the need to illuminate the building by daylight. In figure 4.9, diffuse radiation reflected from the ground can find its way into the building whereas direct radiation will be completely blocked out. This amount of daylight is not sufficient to meet illumination demands inside the building.

There are no daytime activities that demand extended illumination taking place inside such buildings. These openings enable limited cross air ventilation through the building for hygiene purposes and also facilitate the cooling process in the building. Lack of windows on buildings is a simplistic way of reducing the negative effects due to solar radiation reaching the building. This is neither architecturally, functionally nor psychologically acceptable in modern buildings and may be very costly if the buildings were to be artificially illuminated. Such sealed buildings may be problematic as a result of limited air circulation [64], devoid of light etc. which might be harmful to the health of the users. These problems however, will not be discussed in detail within the scope of this work.

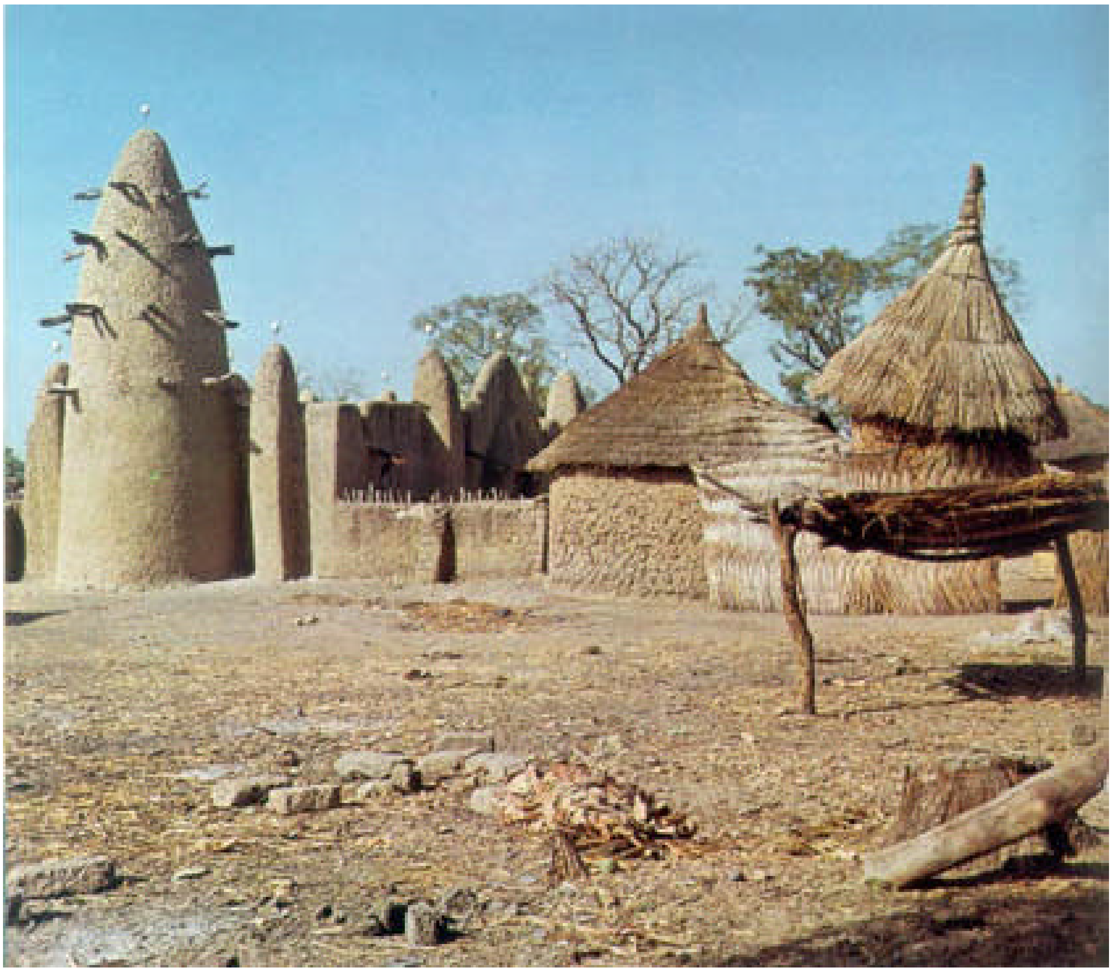


**Figure 4.8:** Dwelling buildings without windows in hot and humid tropical regions

**Figure 4.9:** Dwelling building with wooden (opaque) windows in hot and humid tropical regions

In modern buildings in tropical regions where daytime activities take place, availability of daylight inside the building is an unavoidable necessity. Such buildings include schools, hospitals, offices, residential buildings, factories, etc.

As a result of the changing lifestyles of people in tropical regions, improving living standards, increasing urban populations, growing cities, industrialisation of economies and chronicle energy shortages, the construction of new buildings has taken on a new dimension. Opaque windows have been largely replaced by transparent (glass) ones. With little or in most cases no prior consideration to the prevailing climatic conditions in these regions, many new buildings are designed focusing only on aesthetic factors whereas other aspects that make buildings comfortable habitations are completely sidelined. Some of these buildings are:

- wrongly orientated, which results in failure to maximally utilise the provisions of nature like the sun and wind,
- have large glazed areas resulting in overheating during hot periods,
- built with inappropriate materials which are costly and hazardous to the health and the environment,
- mechanically operated for cooling or lighting, rendering them so expensive in terms of energy consumption and operation

Such buildings have proved to be uneconomical, uncomfortable, and a risk to the environment.

The building envelope, the building surroundings as well as several other factors if considered during the planning phase and by undertaking appropriate consultations with experts in different disciplines, can improve on the quality and quantity of daylight inside the building.

The building envelope can be useful for attaining good daylighting inside the building if the following factors are carefully considered:

- an increase in the skin - to - volume ratio increases the floor space available for daylighting
- designing the building envelope with structures that can help block solar radiation from entering the building when it is not needed
- texture of surfaces - light surfaces reflect more light than dark surfaces

The type of glazing used for windows must also be carefully chosen. Some glazing materials like tinted glass allows clear view but considerably reduces the amount of daylight that can penetrate into the building.

Most clear glass can transmit 50% ultraviolet radiation which causes no harm to glass itself but can be destructive if it falls on objects inside the building. Clear glass is also transparent to infrared radiation which carries radiant heat. Although this heat is necessary to warm the air inside the building during cold seasons, it can become a nuisance in buildings during hot seasons by getting overheated. The amount of solar radiation that will be transmitted through single glass is proportional to the size of exposed glass and thus the magnitude of the negative effects increases as a result.

Figure 4.10 schematically illustrates a desirable type of glazing that will selectively permit enough daylight into the building but block radiant heat from entering the building and at the same time allowing unobstructed view to the outside.

This is so far a hypothetical situation and our task is to try to get closer to the above situation for ideal daylighting. This can be achieved by combining several factors which will be discussed later in this chapter.

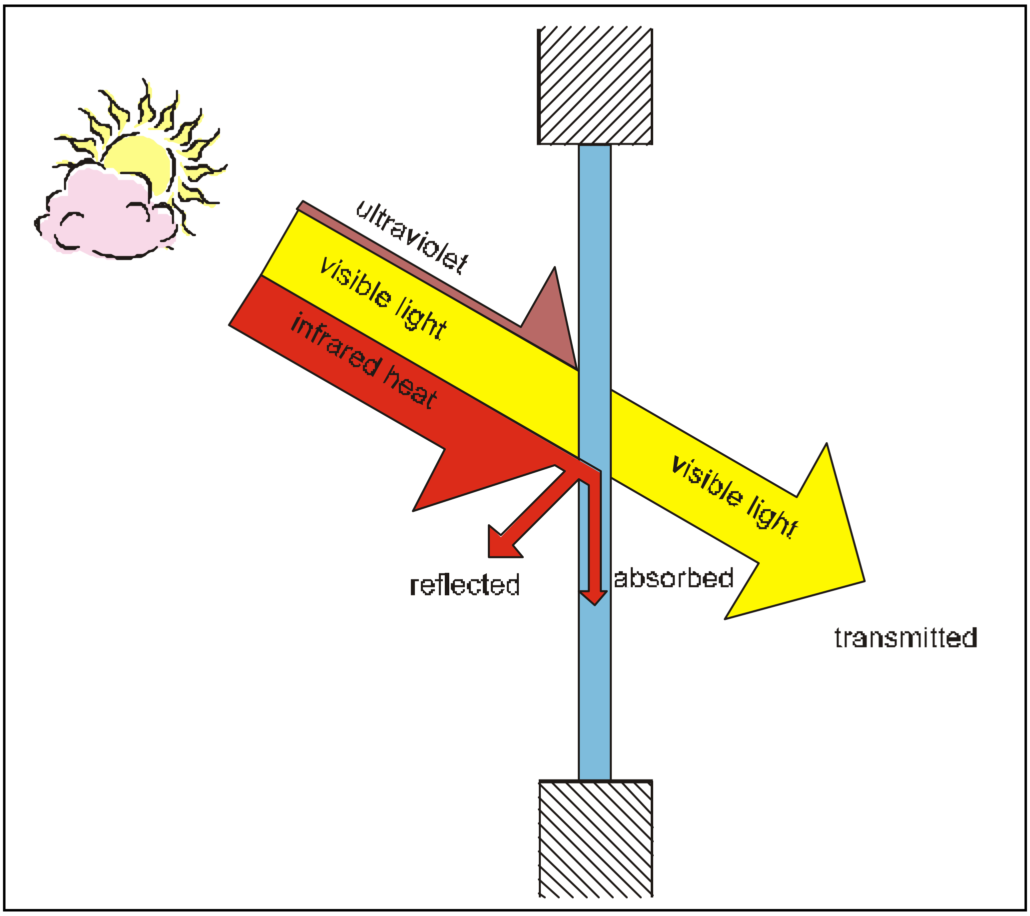



**Figure 4.10:** Schematic illustration of spectrally selective glazing ideal for good daylighting in buildings in tropical regions

In order to improve the daylighting situation inside a building by daylight through the window, the following considerations are important:

a) the higher the position of the window relative to the geometry of the room to be illuminated, the deeper the light will penetrate into the building.
b) windows should be positioned to be able to reflect light onto the ceiling which has to be light-coloured
c) separate the window into aperture for view and daylighting.
d) chose the size and shape of the window and at the same time select the type of glazing
e) incorporate solar radiation screening elements with the window and locate the window on orientations where shading is easier – south and north

Each of the above recommendations has to be considered individually taking into account the daylight demands dictated by the activities carried out within the building.

### 4.2.2 Innovative methods

Light entering the building through side windows might not be enough to meet illumination demands across the whole length of the intended space. By blocking incoming direct sunlight, we may reduce the needed daylight and also hinder view to the outside. Sunlight can be a significant subsidiary source of the required light if it is redirected or transported into the building. It is technically possible to transport or re-direct light into the building.

Applying innovative sun-lighting and daylighting systems can help us realise the following objectives:

- improvement of the uniformity and quality of light inside a building
- transportation of light to deeper areas of a room or windowless rooms
- reduction in heat penetration into the building and reduce glare influences
- the use of sunlight for illumination

We can to a certain degree separate diffuse and direct light before it enters the building. Direct radiation can then be treated in such a way that it is either prevented from reaching the building or redirected into areas of the building where it is needed, in a much softer state. Systems that can perform such functions are basically categorised as *sun-tracking systems* and *daylighting systems*.

Sun-tracking systems can provide light for illuminating areas of the building which have no access to daylight or provide supplementary light to areas of the building which do not receive sufficient daylight. Light from the sun transported through a sun-tracking system goes through several stages before it reaches the intended area of the building shown in figure 4.11. The details of each stage differs depending on the system in which they are applied.

Sun tracking systems may have the following components:

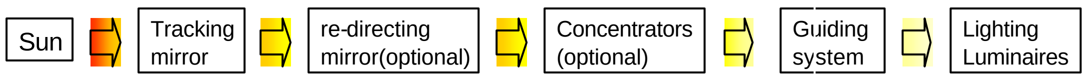



**Figure 4.11:** Components of a Sun-tracking system

The source in this case is the sun. The effectiveness of sun-tracking systems is therefore interconnected with the presence of the sun [5]. Absence of sunlight will automatically curtail their performance.

Sunlight collected by tracking mirrors may be focused on concentrating mirrors in systems which have such components. This is intended to increase the light density of the incoming sunlight. Concentrating mirrors can be focusing mirrors, lens systems or a combination of plane mirrors with either the above two cases. Some systems like rotating double prism plate system do not concentrate sunlight rather they redirect it to the guiding system.

Diverging light radiation from the concentrating mirror will be focused into a guiding system towards a distributing unit, in this case luminaires.

Some examples of guiding systems are hollow pipes whose inner surfaces may be fitted with reflecting mirrors or reflective foils for redirecting light. Other examples of guiding systems are fibre optics and liquid fibres which can carry light to more distant places than hollow light guiding systems. In some regions of the tropics, like hot and dry climates where the sky is predominantly clear for most of the day, sun-tracking systems can be very effective. In other regions of the tropics, like the hot and humid regions, the inconsistency of the state of the sky may be an obstacle.

Sun-tracking systems have the following characteristics:

- only effective in the presence of the sun
- have to be able to track the movement of the sun
- require precise optics to be able to transport light to the intended destination
- involve high Engineering costs
- require high investment for production
- require regular maintenance
- need operational energy

The amount of sunlight collected by the tracking system is directly proportional to the size of the collector. Solar heat will be channelled into the system too. It is necessary to stop this heat from reaching the building interior which might increase the cooling load. Filtering the incoming solar radiation of radiant heat might reduce the amount of light that will be transported into the building. This problem will be aggravated by the distance sunlight has to travel from the tracking component to its destination. The shorter the distance the more heat that will be transported into the building. Sunlight travelling through longer pipes will gradually dissipate most of the heat in the piping system. Light reaching the destination will therefore be almost free of solar heat.

Some examples of sun-tracking systems and their different components are shown in table 4.1.

| Components | Various types of sun-tracking systems | | | |
|---|---|---|---|---|
| | 1<br>e.g. Heliostat | 2<br>e.g. Himawari | 3<br>(under development) | 4<br>e.g. double prism plate system |
| **Tracking mirror/ collector** | + | + | + | + |
| | | | | |
| **Light re-directing mirror** | + | - | - | + |
| | | | | |
| **Concentrator** *(e.g. lens system, focusing mirror)* | + | + | + | - |
| | | | | |
| **Guiding system** *- fibre optics* | - | + | - | - |
| *- hollow light guides* | + | - | - | + |
| *- liquid fibres* | - | - | + | - |
| | | | | |
| **Distributor/ Luminaire** | + | + | + | + |

+ necessary components for the specified system
- not necessary for the specified system

**Table4.1:** Illustration of some types of sunlight transporting systems and their components

Daylighting systems on the other hand do not entirely depend on the availability of sunlight as is the case for sun-tracking systems. Daylighting systems can work well under diffused conditions. These systems are relatively easy to operate and maintain compared to sun-tracking systems. Their ability to transport light to distant areas is much more limited than is the case for sun-tracking systems. Daylighting systems range from the simple louver to more complicated within-the-window-pane integrated systems. Some examples of innovative daylighting systems which are in use today are the light shelf, reflective window sills, holograms, adjustable louvers etc. High technological methods of providing daylight are designed not only to provide the needed light but also to simultaneously protect the building from undesirable direct solar radiation and enable a view to the outside. Modified louver systems (Venetian blinds) with either simple common flat or curved lamellas, sometimes with coated reflective surfaces, have proved to be very effective daylighting systems.

The development of the intelligent string louver system used to fix the lamellas has enabled such a system to be adjustable to simultaneously shade the lower part of the window while the upper part is used to reflect light into the deeper areas of the building. A detailed illustration is given in section 4.3 of this chapter.

Some of these systems can be adjusted (manually or automatically) to allow light into the building when it is needed by redirecting it to the rear of the building, consequently maintaining high levels of daylight inside the building.

The use of innovative systems as outlined above has wide ranging advantages not only in temperate regions but also in tropical regions. However, their application and effectiveness in tropical regions poses a practical question of technical appropriation and whether they will at one time be readily available and economically viable to potential users. The duration of the availability of the sun, the seasonal changes in the year, the changing patterns of the sky and several other climatic conditions, have a direct influence on the effectiveness of innovative devices. There is therefore a need to modify these systems to match the different climatic characteristics in tropical regions. There is a proportionally bigger potential on applying these devices in tropical regions based on the longer and almost consistent sunny periods for sun-tracking systems and other innovative devices in general.

Table 7.1 shows an overview of the different daylighting and sun-shading systems showing their different characteristics and their possible application potential in tropical regions.

## 4.3 Computer method for quantification of daylight levels and energy impacts in a building

There are several methods to estimate the impact of different climatic factors in a built environment. Estimating the availability of daylight in a building is one example. Such methods can provide us with a rough estimate of the extent to which and when daylight will be available and the possible consequences as a result of allowing it into the building. These methods are particularly useful during the planning phase for the assessment of the impacts of several environmental factors before the final decisions for realising the project are made. They may help in convincing clients and also help designers to modify their strategies relating to the use of daylight and other parameters prior to construction. Some of the methods used for daylight calculation are:

- daylight calculation by hand
- scale modelling
- engineering software
- computer daylighting model

Most of these methods are very useful but differ in their application, their effectiveness to predict these effects and also the duration to give us the intended results. Some of these tools require expertise to be able to use and handle them and may be costly. We will however not be able to discuss in detail all the above mentioned methods within the scope of this work. We will only discuss the computer daylighting model method.

There are many computer programs and methods used to estimate the quantity and duration of daylight available in a building and also the assessment of the impact on both energy consumption and on the occupants of the building.

Some of these methods are so precise that apart from giving quick results, they can predict different effects with a high degree of accuracy. They require a certain level of knowledge about their applications even though we do not necessarily have to know the technicalities about their functioning.

We used the light calculating computer program SIVIEW to perform several daylight calculations in order to analyse the behaviour of daylight in our prototype building explained in chapter three. This program performs the calculations with the help of RADIANCE, a Backwards-Raytracer light calculating program, developed at Ernest Orlando Lawrence Berkeley National Laboratory in Berkeley, California. The program uses a three dimensional AutoCAD model to perform the necessary calculations. The daylight conditions of any chosen climatic region are based on the CIE sky models.

The following situations were considered for evaluation for different times of the day and different periods of the year:

a) the illumination distribution by daylight inside the building under overcast sky conditions
b) the illumination distribution by daylight inside the building as a result of solar radiation directly striking an unscreened window with single glazing
c) the effect of roof projections on illumination distribution inside the building
d) the effectiveness of a modified louver system which is adjustable (Figure 6.7) on illumination distribution within the building
e) the effectiveness of the adjustable louver system on different orientations of the building

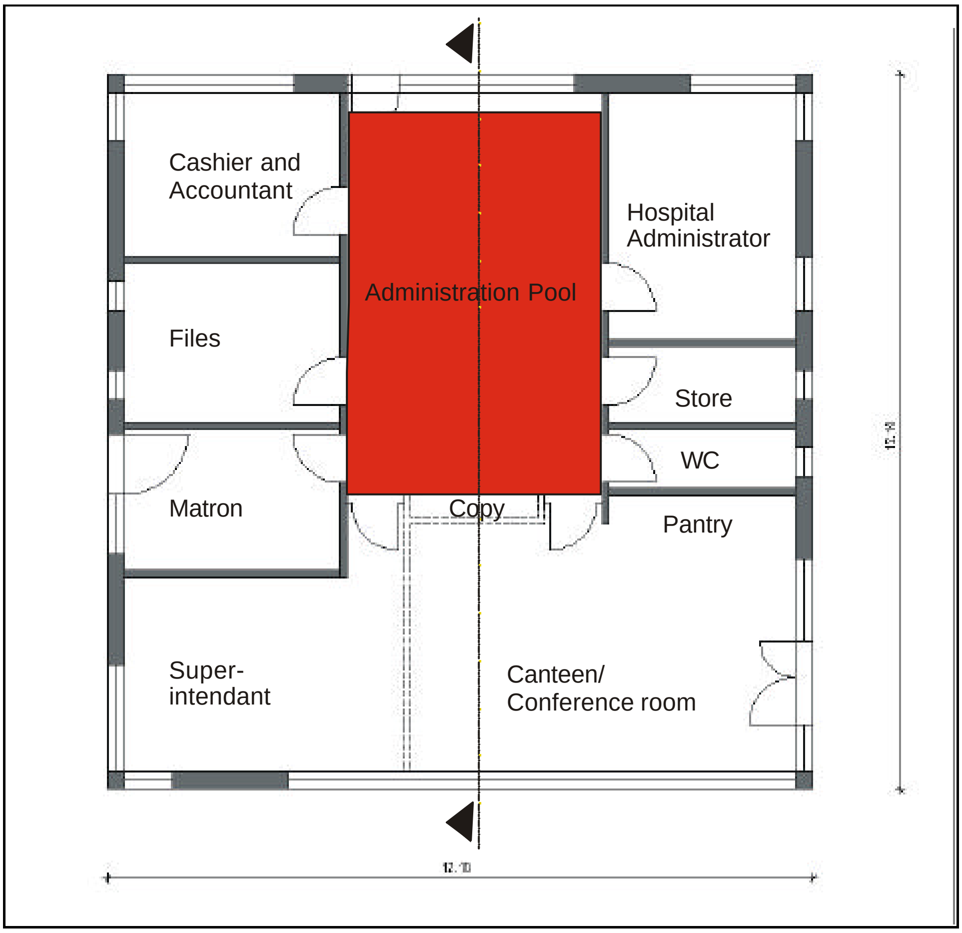



**Figure 4.12**: Plan showing the area of the building (marked red) on the north orientation considered for the simulations

For daylight calculations in this section, we assumed the building to be along the east – west axis i.e. the façades with the most glazed surfaces were facing north and south.

The following parameters were kept constant throughout the different simulations carried out:

- the reflection coefficient of the outside surroundings was 20%
- the reflection coefficient of the walls and the ceiling inside the building was 80%
- the reflection coefficient of the floor was kept at 20%
- single glazing with g-value of 0.855 was used and the area of glazed surface on all orientations was calculated as it was planned (Figure 4.12)
- it was assumed that there were no objects around the building to obstruct the incoming solar radiation

Firstly we considered the illumination inside the building under an overcast sky as was defined under CIE sky conditions. The windows were not shaded.

Under overcast conditions, average illumination on a horizontal plane generated by the light simulation program SIEVIEW for the region of Kasese was 16 772 lux. If the necessary illumination inside the building is 500 lux, this gives an average daylight factor of 3%.

Figure 4.13 shows the daylight distribution inside the building measured at a working height of 0.75m above the ground. It was expressed in terms of daylight factor. Illumination near the window is far higher compared to that deep into the building. The difference in illumination levels near the window at both sides of the building is due to the different size of the glazed area. The glazed area is larger on the south orientation than on the north.

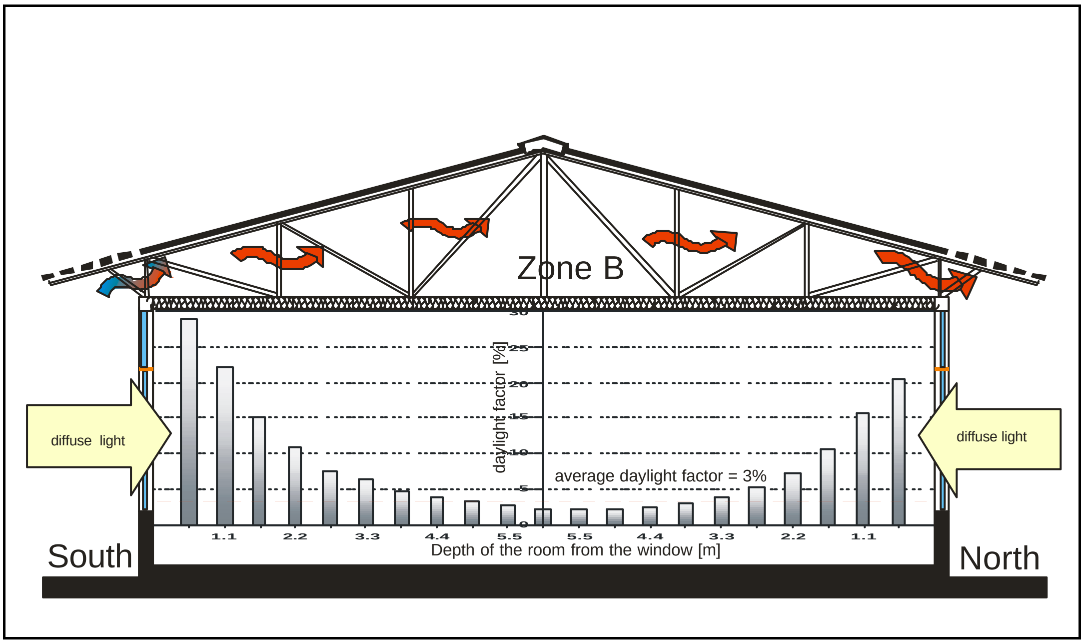



**Figure 4.13:** North – South section through the building showing illumination levels through the building due to overcast sky

Illumination at the work plane inside the building decreases as we move away from the window towards the rear of the building. Illumination for areas near the window is far higher than 500 lux, enough to carry out most ambient tasks without switching on artificial lights. Illumination around the core of the building falls far below the necessary illumination level. Over one third of the building will not be adequately illuminated by daylight while another one third will be exposed to extremely high illumination levels that might cause disability glare. The task is to reduce illumination levels near the window without further reducing the levels at the rear of the building. There are several methods of raising the illumination levels of the less illuminated areas of the building to relatively acceptable levels without resorting to the use of artificial lighting. Some of these methods have been mentioned in section 4.1.2.

We will try through simulations to analyse the effectiveness of the adjustable louver system mounted on the outer side of the window in the room facing north (marked red on figure 4.12 and shown in appendix 7) in lowering the illumination levels near the window while increasing or maintaining the levels at the core of the building.

This louver system has two parts – the lower und the upper part. Both these parts can be concurrently adjusted. The following combinations are possible:

a) We can close the lower part to block solar heat from entering the building but at the same time leave the upper part open to allow light into the building
b) We can completely open or close the whole system as a unit.
c) We can adjust the lamella such that they block incoming direct solar radiation but allow diffuse radiation through and one can still see through the gaps between them.
d) The lamella on the upper part of the system can be adjusted to such a position where they are able to reflect more light into the room by changing their angle of inclination in relation to the position of the sun.

Light falling on the surface of the blind is reflected first towards the ceiling and then deep into the building. The simulation program is capable of calculating daylight by tracing the multiple reflections taking place when light falls on the surfaces of the lamella and the consequent reflections into the building.

**Figure 4.14:** Visualisation diagram showing illumination of a room facing north under overcast sky conditions without considering solar screening device on the window

By considering the combined influence of the sun and the sky on the total illumination for the same period considered for the case of overcast sky, we got the following results.

- Illumination on the horizontal plane was 78 293 lux (clear sky)
- illumination intensities on the vertical walls were:

| | | |
|---|---|---|
| north-facing | = | 46 484 lux |
| south-facing | = | 13 083 lux |
| east-facing | = | 13 173 lux |
| west-facing | = | 32 738 lux |

For the region of Kasese at latitude 0.11° north of the equator, the sun is at an altitude of 66.66° and solar azimuth of 0.89° due north on 21 June at 1pm. For the case of our prototype building, at this time and period of the year, direct solar radiation strikes the façade facing north of the building.

If the window is not shaded, direct solar radiation will penetrate through the window into the building as shown in figure 4.15. This will automatically increase the illumination inside the building especially the side directly exposed to the sun. Similar to the case of overcast sky, illumination inside the building will be higher near the window but gradually lessen with increasing distance away from the window. The levels due to a clear sky are higher compared to that under overcast conditions for the façade that will be directly exposed to the sun (Figure 4.17).


**Figure 4.15:** Visualisation diagram showing the illumination of a room facing north under a clear sky without any obstruction of the solar radiation reaching the window


**Figure 4.16:** Visualisation diagram showing the effect of a roof projection on illumination in a room facing north under clear sky conditions without considering extra solar screening device on the window

Roof projections as shown on figure 4.16 can effectively block direct solar radiation reaching the building. Illumination levels inside the building will be reduced especially near the window directly exposed to the incoming direct radiation from the high altitude sun. The roof projection in this case will function as a fixed shading device.

The levels around the rear of the building will be slightly affected as a result of the roof projection. This clearly demonstrates that a properly dimensioned roof projection or other structures like a light-shelf above the window can effectively stop direct solar radiation from penetrating the building.

This however applies only to building orientations which receive direct solar radiation when the sun is at a higher altitude. For Kasese, which is at latitude 0.11°N, roof projection can be effective on the north and the south orientations.

The other measures for reducing the influence of solar radiation on the conditions inside the building in terms of illumination and heat transfer into the building will be discussed in chapter 6.

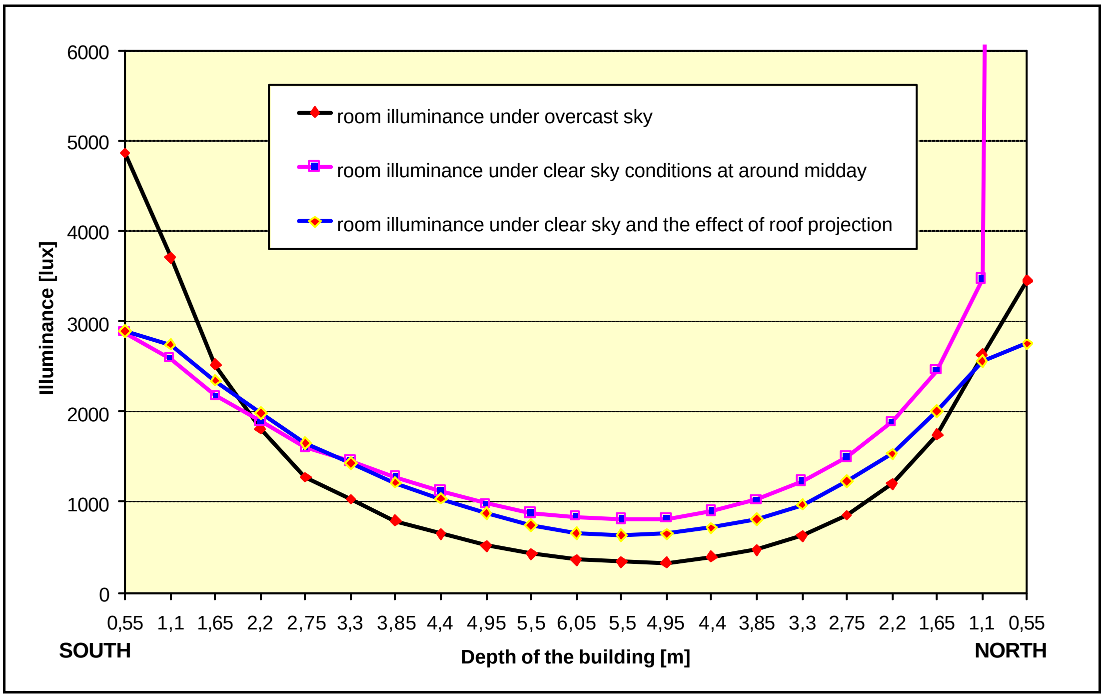



**Figure 4.17**: Illumination distribution along the north-south axis through the building by considering overcast and clear sky conditions and the effect of the roof projections

There is an uneven illumination distribution inside the building for both overcast and clear sky situations. Under overcast sky conditions, any attempt to increase illumination at the rear of the building by increasing the size of the glazed area, will consequently imply an increase of illumination near the window too. A skylight in this case will perform better though this will not mean a decrease in the high illumination levels near the window.

Under a clear sky, the minimum illumination in the building was around 800 lux which is higher than that needed to accomplish most ambient tasks but the levels under overcast sky conditions were less than 400 lux, much lower than those under clear sky (Figure 4.17). Areas near the window experience higher levels in both situations.

By allowing direct radiation to penetrate the building, we will increase the risk of increased heat transfer into the building (Chapter 5). Excessive diffuse radiation reaching the building interior can raise the room temperature too (Chapter 3).

Louvers with closed lamellas were studied to see their impact on the illumination distribution inside the building. In this state, the louver system functions like closed shutters with almost no light reaching the building interior (Figure 4.18).


**Figure 4.18:** Visualisation diagram showing illumination of a room facing north under clear sky and a solar screening device (louvers) with closed lamellas

Shutters can either be open or closed. If they are open, we get a situation similar to that shown in figure 4.15. When they are closed, then we get a situation similar to that shown in figure 4.18. Illumination levels are so low (Figure 4.20) that there is almost partial darkness inside the building. Occupants of the building will be obliged to switch on artificial lights.

Closed louvers with lamella constructed out of opaque material virtually allow no light to enter the building although some diffuse light can pass through the gaps between the lamella into the building depending on the spacing between them. Transparent lamellas can transmit some light into the building.


**Figure 4.19:** Visualisation diagram showing illumination of a room facing north without roof projection but with a modified louver screening device on the window which re-directs light to the ceiling

Louvers with adjustable lamellas were considered. These louvers are intended to simultaneously shade the lower part of the window while light falling on the lamellas on the upper part of the window is reflected into the building as shown on figure 4.19. In order for the system to optimally perform these functions, the following facts are important:

→ the size and the distance between the lamella has an impact on the amount of light that is reflected into the building

→ the angle of inclination of the lamellas relative to the position of the sun may influence the direction in which light is reflected.

→ the position of the device relative to the window - inside or outside - is decisive regarding its effectiveness in terms of solar shading and light reflection

→ the device on the lower part of the window which is characterised for vision can be designed such that direct solar radiation is stopped from entering the building whereas the possibility for diffuse light to enter the building and a view to outside is guaranteed.

There is a need for an automatic adjustment of the angle of inclination of the lamella in order to respond to the movement of the sun. Such a process will result in more light reflected into the building as well as optimising the effectiveness of the device in responding to illumination demands within the building.
For the case of our prototype building, the concave lamellas on the upper part of the system were horizontally laid whereas the lamellas on the lower part were inclined 87° towards the outside. The following observations were made and the results are shown in figure 4.20:

1) There was a reduction in the illumination near the window as a result of using the louvers. The areas at the rear of the building experienced a slight reduction in illumination as compared to a situation when there was no louvers considered.
2) Average illumination levels near the window are slightly higher than 500 lux which is enough to carry out most ambient tasks
3) Louver systems without the possibility to adjust the angle of inclination of the lamellas, permit no light or very little light into the building when they are closed.

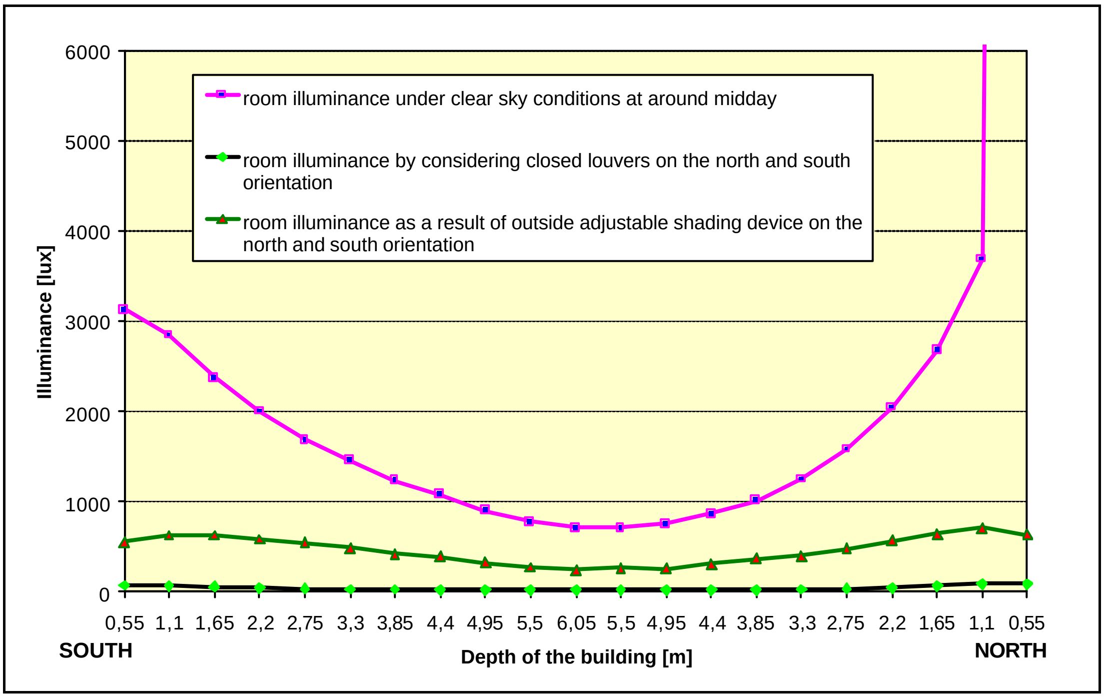



**Figure 4.20**: Illumination distribution along the north-south axis through the building due to clear sky through an unshaded window, a window shaded with closed louvers and a window shaded with adjustable louvers

In order to test the effectiveness of a similar device on different orientation of the building, we rotated the building 90°clockwise so that the tested room faced due east. Weather conditions on 21 September at 10 am were considered for the simulations carried out. On this date and time, the solar altitude was 46.83° and the solar azimuth was 89.10°. Illumination on a horizontal plane at this time was 77 493 lux.
Illumination intensity on the vertical surfaces were:

| | | |
|---|---|---|
| North-facing | = | 14 872 lux |
| South-facing | = | 14 300 lux |
| East-facing | = | 52 503 lux |
| West-facing | = | 12 704 lux |

Incoming solar radiation directly strikes the window which, when unprotected, will penetrate into the building as shown on figure 4.21.

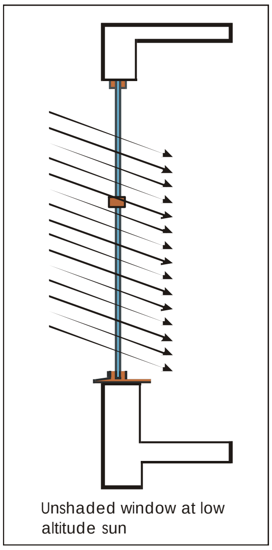




**Figure 4.21:** Visualisation diagram showing illumination of a room facing east under clear sky without considering solar screening device on the window

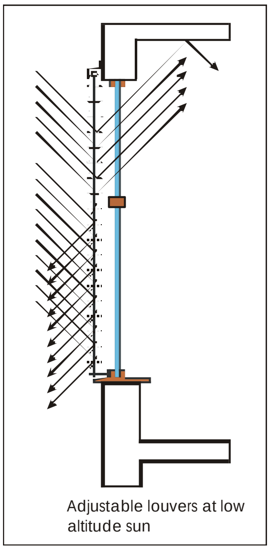




**Figure 4.22:** Visualisation diagram showing illumination of a room facing east without a roof projection but with an adjustable louver screening device on the window which redirects light to the ceiling

The effectiveness of an adjustable shading device when installed on the east orientation of the building will depend entirely on its position on the window and the time of the day, and thus the height of the sun. At a lower solar altitude, solar radiation travels almost perpendicular to the wall which renders horizontal lamella ineffective in blocking or reflecting it.

At a higher solar altitude, of for instance 45° as is the case at 10 am, horizontal lamella can effectively trap incoming solar radiation and redirect it into the building (Figure 4.22).

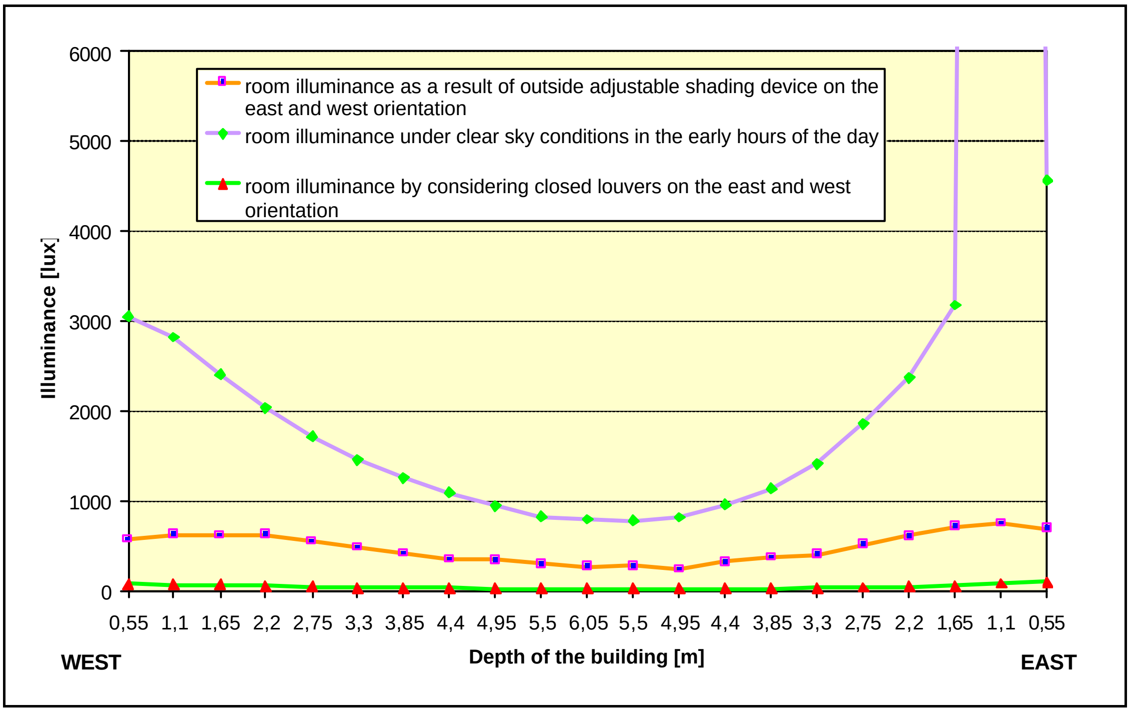



**Figure 4.23**: Illumination distribution along the east-west axis of the building due to a clear sky for a window without shade, a window shaded with closed louvers and a window shaded with adjustable louvers

In figure 4.23, three situations regarding illumination inside the building for a window without shade, with closed louvers and with adjustable louvers on the east-west axis were compared. Similar to the case on the north-south axis, illumination inside the building will be reduced to zero when the louvers are closed. There is a marked reduction in illumination levels near the window due to the effect of the adjustable louvers compared to that when no louvers were considered. Light falling on the lamellas on the upper part of the system is reflected onto the ceiling and later into the room. There is sufficient illumination of slightly above 500 lux up to a distance of 3m from the window which then decreases as we get deeper into the building. Light redirected into the building by lamella contributed to a slight increase in illumination levels to areas not further than 1.5m from the window. Illumination levels further away from the window slightly decreased as a result of applying adjustable louvers.

Figure 4.24 compares the effectiveness of the adjustable shading device on the north and east orientation of the building.

A case whereby the lamellas on the upper part of the system were inclined 15° towards the building was also studied. It showed no marked impact on the illumination levels inside the building as shown in figure 4.24.

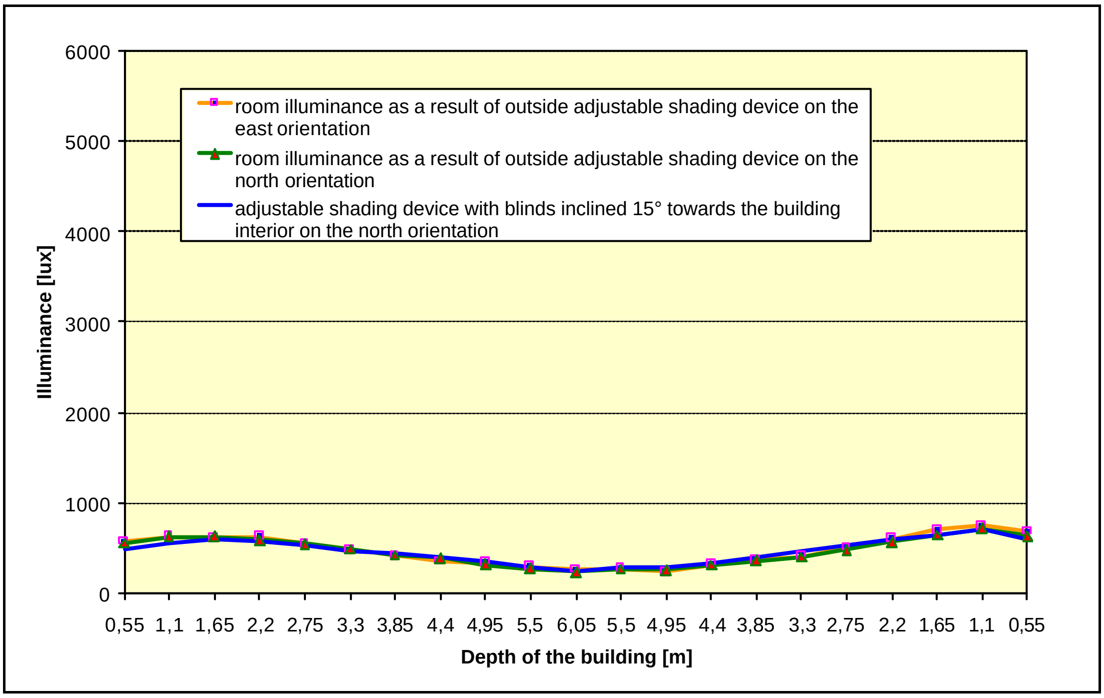



**Figure 4.24**: Comparing the effect of adjustable louver system on Illumination distribution inside the building in a room facing north and after turning the building 90° to the east

The effects of an adjustable louver system are equally good for both orientations of the building though the performance of such louvers can be enhanced by taking the following measures:

- proper positioning of the system at an appropriate height in order to capture and reflect more light into the building.
- the effectiveness of the system may be improved if the lamellas are automatically adjustable i.e. reacting to the illumination demands inside the building as well as the movement of the sun.
- a combination of such a system with artificial lighting may be advisable where the switching on of an artificial light will only be as a supplement to daylight.

## 4.4 Daylight in hospitals - demands and problems

It is easy to erect walls over a space and cover them with roofing, install windows and doors, partition the space and furnish it for both patients and nursing personnel. This alone however, does not make this structure a place (hospital) where patients can comfortably spend the time they need to recover or for the nurses to perform their duties efficiently. Several factors have to be considered to make this place (hospital) comfortable for the inhabitants. One of these factors is the use of daylight which we will discuss in this section.

Hospitals are such complex places where, when we consider using daylight for illuminating the buildings, we have to take a rather different approach and give more special consideration than is the case for other buildings. Such an approach may encompass solutions applicable in other buildings but must be either modified or completely changed to meet the special demands in hospitals. Hospitals are places for living, working, performing critical tasks and also providing room for relaxation.

It is widely believed that natural light plays a significant role, psychological and physiological, for the well-being of people. This has even more meaning when considering sick people who need to be as near to nature as their recovery process may demand. Availability of daylight in their daily living environment plays a very significant role.

There are different sections in a hospital that require different lighting levels. These sections can be categorised into three parts:

One part comprises of the areas where some critical tasks are carried out for example diagnostic centres, examination rooms, recovery rooms and operating theatres. There is the part occupied by patients – sick wards, day space and also areas for visitors. The third part is for laboratories, administration, staff space, kitchens, laundries and sterilisation. Visual requirements in these areas are different and have to be examined individually based on the activities performed there. The activities taking place in the three mentioned parts of a hospital can be accomplished using a combination of natural and artificial lighting for illumination or only artificial lighting, which is not the main issue of this work.

We will try to analyse the effects of using daylight for illumination to effectively carry out the necessary activities. Some activities are of a critical nature – for instance in operating theatres – where the tasks are characteristically of low contrast and small size – which demands a higher level of illumination ranging between 10 000 lux to over 30 000 lux. Such a concentration is unlikely to be achieved by daylight reaching the building interior whenever it is desirable and without very serious negative effects. In such cases where ambient lighting is needed - for instance for movement, observation, and orientation, daylight can be a very useful alternative. In tropical regions, there is sufficient daylight to meet illumination demands for ambient tasks for a greater part of the day. In administration and nurses' rooms, the situation can be considered as in an office building. Our concern here is the wards which have to be treated like living areas but with some special considerations.

In sick wards special attention has to be paid to the needs of patients to facilitate their recovery process and also for the nurses to be able to monitor the patients and carry on their activities efficiently. Patients on the other hand need sufficient light to enable them to read, sew, and engage in other activities without disturbing other patients. This is however not an easy task and may create some psychological problems due to the fact that patients in a ward may be in different stages of recovery, and therefore have different illumination demands. In relatively big hospitals and where the conditions are conducive, it is possible to separate patients according to their degree of recovery and needs. Unfortunately, this is not the case for many hospitals in different parts of the developing world including in the tropics. Some areas in these regions have virtually no access to electricity of any form or if at all then generators have to be installed. Power produced by such generators is not sufficient to meet all the energy demands in hospitals. Hospitals in these regions have to depend on daylight for illumination. Different illumination needs can be satisfactorily met by daylight supplemented by a small artificial light source usually controlled by the patient.

In a sick ward occupied by more patients, illumination by daylight may be complicated by the different needs of the occupants which can not be met simultaneously through the window. Some may want to let solar radiation into the room by opening the curtains to provide some warmth in the early hours whereas the others may prefer to have the curtains closed for them to sleep a bit longer. This can create problems and some misunderstanding between the patients. This conflict can be minimised if the window and the accompanying shading devices are automatically adjusted and are not influenced by the patients. This will nevertheless not meet the demands of patients all the time but will guarantee a balanced availability of daylight in the ward.
It is worth mentioning at this point that the automatic control of daylight in the ward seems to be a fair solution but may have the following consequences:

- the process does not necessarily ensure patients will receive their illumination demands
- the process will need extra operational costs in terms of energy consumption
- the process may not be fully appreciated by the patients
- the process is entirely dependent on the effectiveness of the mechanics involved and any malfunctioning will have very negative consequences for the patients.

In order to achieve comfortable daylighting conditions, the windows have to be designed with considerable care. A permanent glare protection device has to be built into the window in order to reduce the amount of visible sky by patients occupying beds near the window. Other solar radiation protecting devices should be chosen on the criterion that they will not be adjusted by patients or nurses. Devices like adjustable Venetian blinds are effective in many buildings, but when applied in hospitals the nurses may not have the time to adjust them and the patients may not be able to adjust them themselves. They should therefore be automatically operated.

# 5 Problems

The physical environment consists of elements interrelated with each other in a very complex way. These elements can be summed up as climate, space, light, sound, animate.

All these elements act on the human body which either accepts or tries to counteract them. In the process to counteract the elements unacceptable to our bodies, we search for conditions which make us feel comfortable. These conditions slightly differ from region to region, culture to culture and may be acceptable to people in a specific region but not to others. For centuries man has put up shelters in which some of the requirements for comfort are achieved, thus minimising the amount of energy spent in search for comfort. These shelters have evolved from pre-historical structures like caves to modern buildings. The search for a biological balance in our bodies may result in physiological and psychological reactions which, if not properly controlled, can be dangerous to human life.

Depending on the type and functions of the shelter, there is always a task to regulate the above mentioned environmental elements to achieve the desired comfort. This process is cumbersome and can have negative effects on both our lives and the environment. Within this chapter we will restrict ourselves to the analysis of the negative effects of daylight as a constituent element of climate regarding its use in buildings in tropical regions.

## 5.1 Problems due to the use of daylight in buildings in tropical regions

To better understand the problems that may occur as a result of allowing daylight into the building, we have to first analyse the path of light from its source to the building envelope and later into the building. The anatomy of the building will either stop or allow light to penetrate the building.

In chapter 4, we clearly indicated the different transformation that takes place at different stages as light descends from its source to earth. In this chapter however, we will concentrate on the consequences of solar radiation on striking the building envelope and the eventual penetration into the building interior.

Figure 5.1 schematically illustrates how solar radiation transcends from its source to earth and the different transformations that take place along the way.

When solar radiation reaches the surface of the earth, part of diffuse radiation is reflected, long wave radiation is re-emitted, water molecules heat up and evaporate, convection and heat conduction takes place too. Part of the radiation is absorbed into the ground. The situation is rather different when solar radiation strikes the building envelope. Solar radiation, on reaching the building envelope (point B on Figure 5.1) is partially reflected, absorbed, or transmitted depending on the nature of the material on which it falls.

The magnitude of solar radiation that will be reflected, absorbed or transmitted by the building envelope depends on the nature, the orientation, the angle of inclination of the surface of the building envelope, time of the day as well as the sky conditions. The percentage of solar radiation that will reach point C, figure 5.1, is the part that will influence the thermal conditions inside the building.

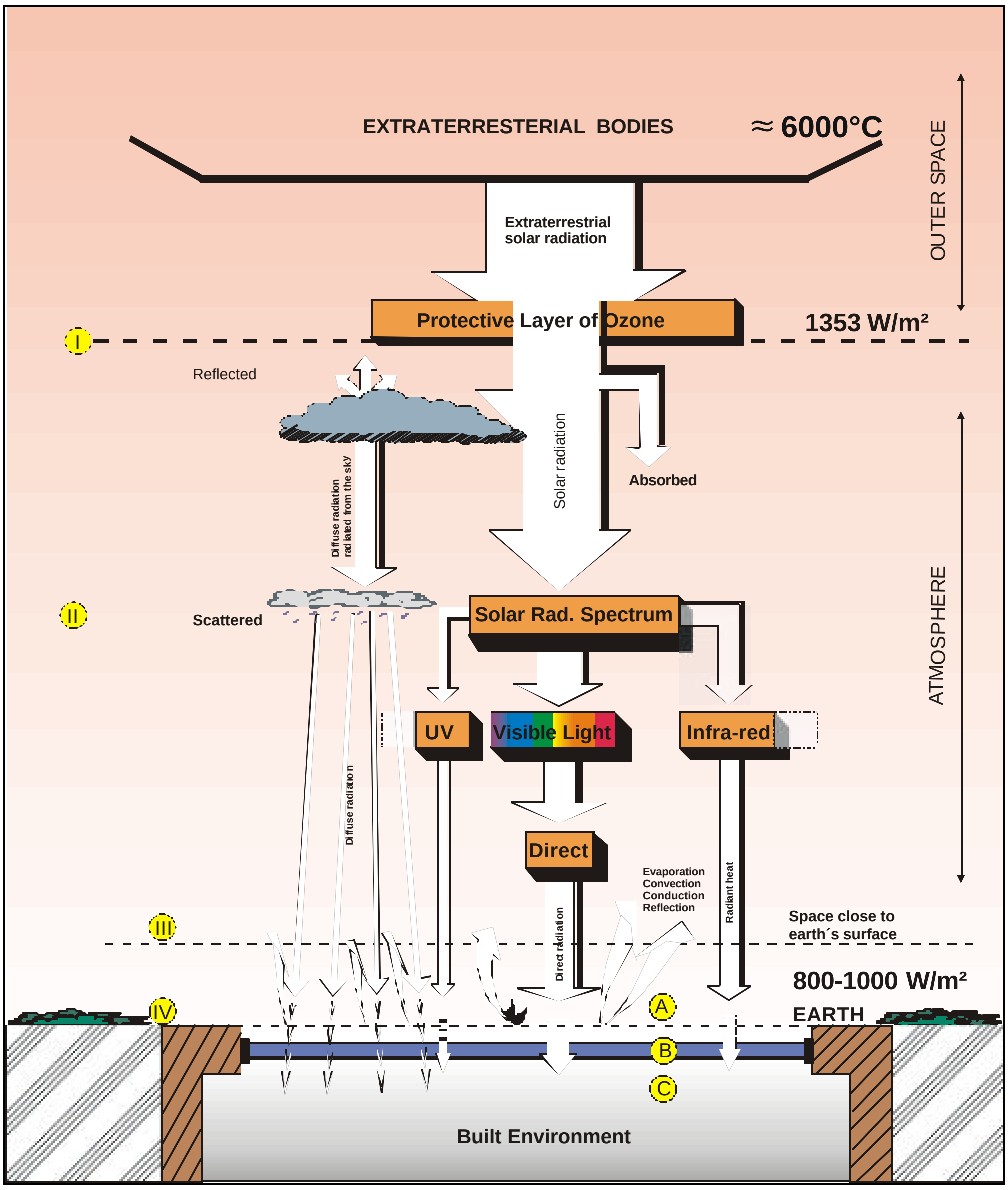



**Figure 5.1 :** Schematic illustration of the movement of solar radiation from the Sun to Earth.

Point A on figure 5.1 represents the area before the building envelope, point B, the building envelope and point C represents the enclosed space in the built environment. The roof is more exposed to incoming solar radiation than the walls. Glazed windows on the roof, or skylights, are the areas of the building that will allow more light and heat into the building. Skylights should therefore be fitted with materials that can repel direct solar radiation but allow the easy passage of diffuse radiation.

Problems of daylighting in buildings are partly due to the nature of daylight itself and also from the fact that windows, apart from their main function of admitting light into the building, provide the necessary view to the outside and guarantee the visual contact to the outside world from within the building. Glazed windows on the walls contribute significantly to the heat gain inside the building despite the incidence angle at which the incoming solar radiation will strike it. It is difficult to protect the roof from solar radiation though the roof can be structurally constructed such that the heat gain due to solar radiation reaching it does not penetrate the working or living areas of the building.

We will concentrate on the heat gain through the window as a result of allowing daylight through the window into the building interior.

### 5.1.1 Solar heat gain through glazed windows

The thermal performance of a building is determined by the rate of ventilation, internal gains, solar heat gain and relative humidity within the building. Some of these factors have been discussed in chapter 3. In this section we will discuss, in detail, solar heat gain through glazed windows and its impact on the thermal conditions inside the building. Windows are the most dynamic and critical part of the building as far as energy use and comfort in buildings is concerned.

For buildings in tropical regions there is a net heat gain to the interior of the building as a result of radiant heat of the sun striking the building envelope throughout the day. Solar heat gain through a unit area of a window with single glazing can be many times higher than that through the same unit area of opaque wall or roof.

In buildings which inadequately deflect or block direct solar radiation from entering the building, the part that reaches the building interior will consequently raise the room temperature.

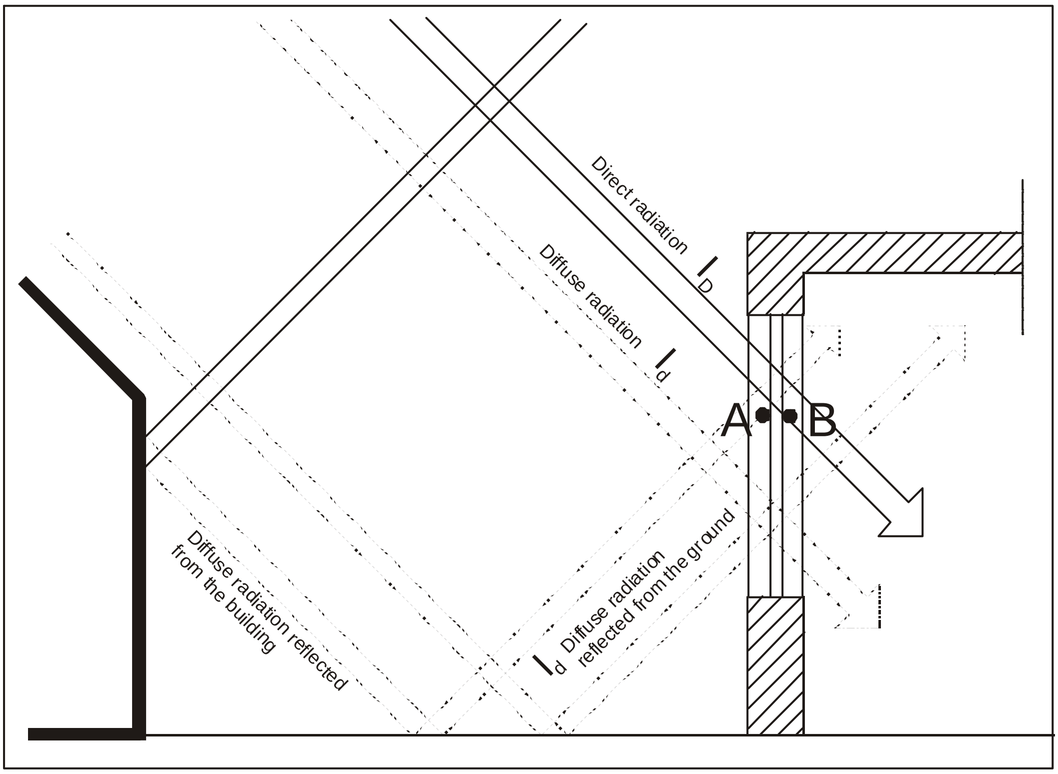



**Figure 5.2**: Direct and diffuse solar radiation reaching the building envelope

Figure 5.2 illustrates how solar radiation will reach the building envelope. The total solar radiation intensity at the surface of the building envelope as at point A on figure 5.2, represented by $Q_A$, is the sum of both incident direct radiation $I_D$ and diffuse radiation $I_d$ expressed in equation 5.1.

$$Q_A = I_D + I_d \quad \text{.........} \quad (5.1)$$

The intensity of solar radiation on inclined surfaces is comparatively smaller than the intensity on horizontal surfaces due to the incidence angle.

The heat gain at point B inside the building, represented by $Q_B$, illustrated on figure 5.2, has two principal components:

i) heat conducted through glazed area A, with thermal transmittance U due to the temperature difference between outside and inside air, referred to as $\theta_t$

ii) solar heat gain through glazed area A as a result of incident direct and diffuse solar radiation, by considering the transmissivity of glass $\tau$, referred to as $\theta_s$

Case i and ii can be calculated using the following equations:

$$\theta_t = UA(T_{out} - T_{in}) \qquad (5.2)$$

$$\theta_s = (I_D A_S \tau_1 + I_d A \tau_2) \qquad (5.3)$$

The fractional composition of direct and diffuse radiation is entirely dependent on the state of the sky. Direct radiation is the dominant component under clear sky conditions. The diffuse component under clear sky conditions is estimated to be in the order 20-30% [10].

Solar heat gain at point B on figure 5.2 is the total of $\theta_t$ and $\theta_s$ and can be calculated using the formula:

$$Q_B = UA(T_{out} - T_{in}) + (I_D A_S \tau_1 + I_d A \tau_2) \qquad (5.4)$$

Under overcast sky conditions, solar heat gain inside the building will be as a result of diffuse radiation entering the building. This is obvious in regions where the sky conditions are constantly changing, ranging from overcast to clear, as is the case in hot and humid tropical regions.

Depending on the location of the building – for our case at latitude 0.11°N, south and north orientations will receive almost equal intensities of solar radiation while the east and west will have the most but also almost of equal intensity.

Glass absorbs some of the solar radiation which is then partly re-emitted to either side of the glass. The contribution of the re-emitted heat into the room to the total heat gain inside the building is very minimal. $Q_B$ as calculated in equation 5.4, does not take into account the part of re-emitted heat.

The equation however, considers the area of glass that will be exposed to direct solar radiation $A_S$ at any given time throughout the day.

If the windows are constructed out of opaque materials rather than glass, as is the case on many buildings in tropical regions, the situation is rather different. Such materials like wood or plastic absorb more solar radiation and when released contribute significantly to the total solar heat gain inside the building.

Solar radiation absorbed by non-transparent windows will in this case be considered in the same way as other opaque structures on the building like walls or roof where the absorbed solar radiation is calculated using the sol-air temperature concept [10], [63].

For buildings which inadequately deflect or reject the incoming solar radiation, there will be an unavoidable use of energy for cooling the building in order to achieve an acceptable interior comfort.

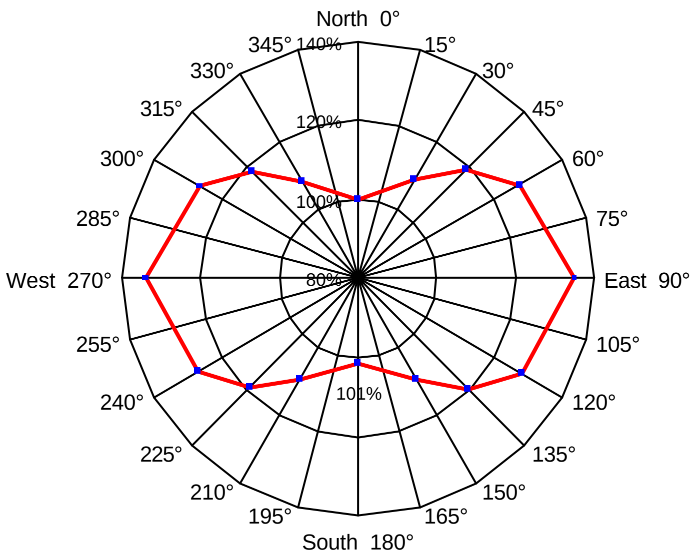



**Figure 5.3:** Relative magnitude of solar heat gain on different orientations of the building for latitude 0.11°N, Kasese, Uganda

Figure 5.3 illustrates the average annual solar heat gain on a unit area of a vertical wall for different orientations on a building at latitude 0.11°N. This is as a result of both diffuse and direct radiation reaching the building envelope throughout the day shown in figure 5.2.

The intensity of solar radiation under cloudy conditions is variable and depends entirely on the degree of cloudiness. Solar radiation under such conditions is hard to predict though it can roughly be estimated on statistical basis.

All orientations of the building receive direct radiation at different times throughout the day. Under clear sky conditions, for façades which will not be exposed to direct solar radiation, the diffuse component will in this case vary from being a percentage of the total solar radiant heat load received to representing the total solar radiant heat received shown in figure 3.5.

From figures 5.3, it is evidently clear that buildings in tropical regions should have less if any, glazed surfaces on the west and east orientations. Unless there are planning constraints, windows should be placed on either the north or the south orientations which receive lower solar intensities than the east or west.

### 5.1.2 Glare inside buildings and its causes

The human eye can accommodate a wide range of intensity levels without discomfort. It readily adjusts to the light source, and is able to alter the perception of colour in order to match the spectral composition of light. It is generally believed that the more light available the better we can see, although contrasts between outside illumination and that in the built environment can cause visual discomfort.

This variation of illumination as a result of the changes in the state of the sky and the consequent visual contrast of the visible sky, the ground or reflective objects in the line of view from a built environment, is a major cause of visual discomfort. This phenomenon is referred to as glare.

Glare can therefore be defined as an effect of contrast between the sky or ground luminance and the luminance of the building interior, especially at work places.

Glare, which is unwanted luminous energy, is a function of the luminance of the sky or the ground and the size of the visible sky patch or ground. The greater the luminance of the interior surroundings, the less the effects of glare. The luminance of very light reflective surfaces may exceed 25 000 candela per square metre, the threshold beyond which absolute glare becomes unpleasant [2].

Glare can be recognised in two distinct aspects. These are disability glare and discomfort glare.

Disability glare refers to the situation whereby there is reduction in ability to see objects in the visual field as a result of the difference between the levels of illumination of the surroundings of the viewer and the viewed objects. Disability glare is therefore a visual performance effect. This situation mainly occurs when viewing a bright sky from a poorly lit interior. An increase in interior illumination can drastically reduce this problem.

Discomfort glare on the other hand is a result of light from a bright sky or from other objects in the line of vision bouncing straight in the eyes of people inside a building.

Such light can cause pain, distraction and dazzle. Discomfort glare effects are therefore both comfort and health.

Both these aspects of glare can be reduced if the source of the excessive bright light in the line of view is either removed or screened.

### 5.1.3 Glare control in buildings

By using the "Glare index" concept [8], we can estimate the intensity of the glare problem. The causes of glare may be the same irrespective of the region but the source of external illumination differs from region to region. While the sky for instance is the main source of bright light in warm and humid tropical regions, the horizon is rather the focus point in hot and dry regions. The screening method will therefore be relative [69].

Figure 5.4 shows a comparison of the relationship between sky luminance and angular altitude in hot-and-arid and warm-and-humid tropical regions. Identifying the source of external luminance can help us position windows such that the part of the sky or horizon viewed from inside the building is minimised, thus reducing the contrast in luminance which is the main cause of glare.

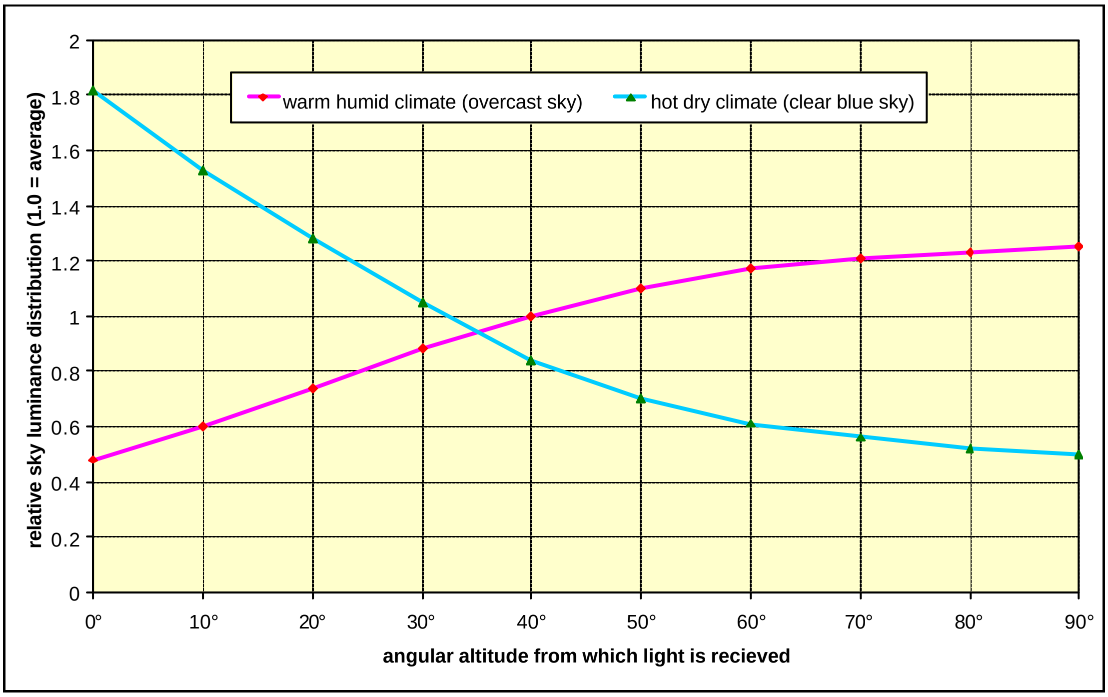



**Figure 5.4:** The relationship of sky luminance and angular solar altitude in tropical regions [2]

The size of the window opening and its position on the building or the use of tinted low-transmission glass on conventional windows, can minimise the effects of glare. However, this effect will drastically reduce the amount of light reaching the building interior, prompting the switching on of artificial lights.
Vegetation can be helpful in reducing the brightness of the ground when direct sunlight from the sky or high illumination from the sky reaches the ground.

In order to easily control glare and heat penetration into the building, it is necessary to design the window with separate apertures for daylight and for view as illustrated in figure 5.5. This will guarantee the shading of the lower part of the window from unwanted solar radiation and glare without obstructing daylight penetration into the building.
The aperture for view can then be treated to allow diffuse radiation into the building, relatively good view to the outside and also treated to minimise direct view of the sources of external illumination like sky or horizon. This will drastically reduce the threats of glare for occupants inside the building.

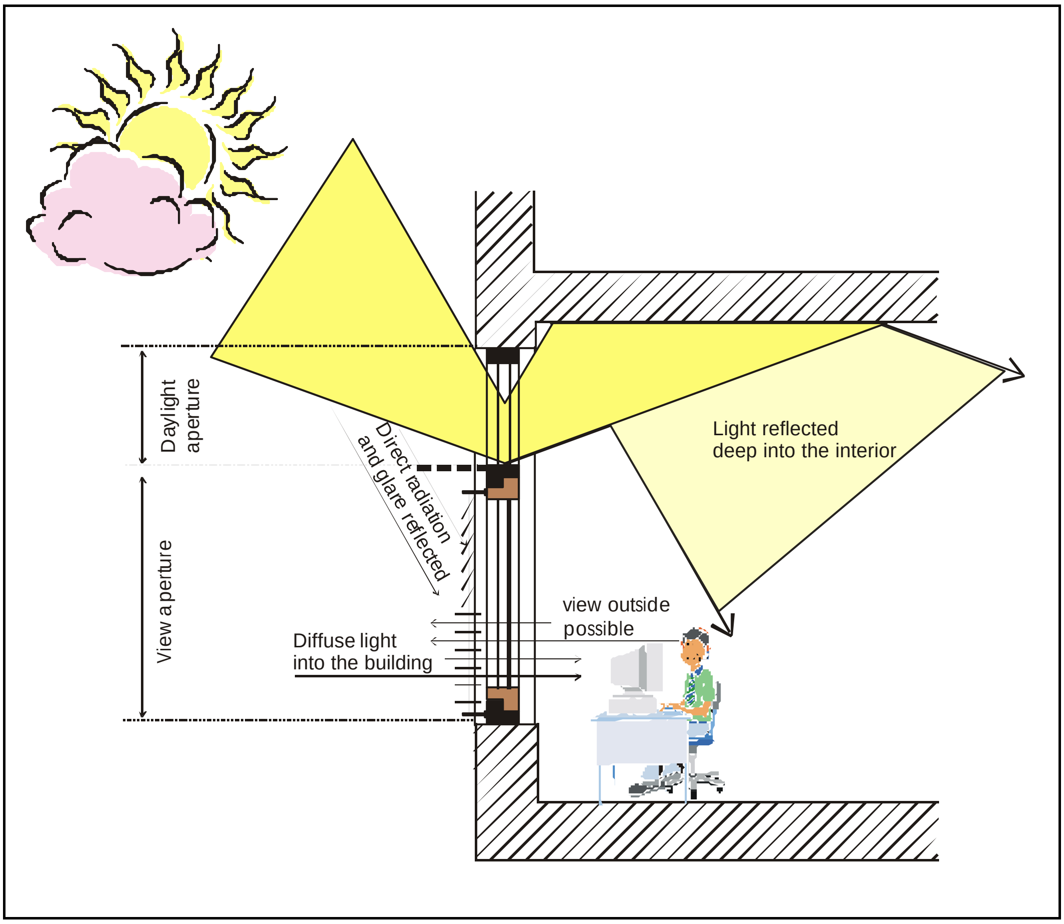



**Figure 5.5:** Illustration of separated aperture for view and daylight on a window

Installing glare screening devices on the lower part of the window can also contribute to the reduction of glare threats to the occupants in the building. Such devices can be transparent to allow light and continuous view to the outside when they are closed as shown in figure 5.6.

**Figure 5.6:** Transparent glare screening device installed on the inner side of the window

In the case of tropical regions, the following methods can improve on the use of daylight and simultaneously reduce glare threats in buildings:

- the orientation of the building and the proper designing and dimensioning of windows to minimise the contrast between outside and inside illumination of the building.
- application of innovative methods which can protect the window from direct solar radiation and glare while allowing daylight into the building (chapter 5). This can be in the form of using louvers with adjustable lamellas as an example.
- installation of transparent glare screening devices on the window, which when closed can greatly reduce glare effects while allowing light into the building and a relatively good view to the outside.

## 5.2 The effects of direct solar radiation on different materials and humans

Solar radiation is responsible for stimulating plant growth thus sustaining life on earth. Whereas there is a need to exclude this direct radiation from the building, there is a necessity to controllably allow it reach the plants growing inside the building.

When direct solar radiation which carries radiant heat is permitted to directly strike the building envelope or allowed to penetrate into the building, it will not only be responsible for increasing internal temperatures within the building, it may also cause some other negative consequences.

The percentage of ultraviolet radiation, though comparatively minimal compared to visible light or infra-red components of the solar radiation spectrum, can lead to fading of materials and bleaching of colour of objects in buildings if permitted to directly fall on them. This radiation causes deterioration partly by heightening temperatures on the exposed surfaces and partly by photo-chemical action of the rays intensified by the enhanced ultraviolet component in the electromagnetic spectrum.

It is also believed that this radiation can cause some health hazards like sun-burn which can lead to eventual development of skin cancer.

## 5.3 Problems due to the use of artificial lighting in buildings

In many buildings, depending on their dimensions, daylight may not be able to meet all the illumination needs even on very sunny days. This is even so in regions where there is a need to minimise the area of glazing on the building for reasons mentioned before. In such cases daylight can not be the substitute for artificial light.

Artificial lighting is necessary, among other reasons, to provide supplementary illumination to areas within the building which are insufficiently illuminated by daylight, illuminate the building and spaces at night for safety reasons and also provide highly concentrated light for special visual tasks. The need for artificial lighting is not only commercial but rather a necessity to get some visual tasks accomplished which can not be fulfilled by using daylight.

Areas of the building which do not receive sufficient daylight have the following characteristics:

- rooms without windows
- deeper rooms with fenestration on one side
- rooms with proportionally small windows compared to the size of the room to be lit
- areas of the building where critical activities which demand high illumination levels are carried out

In order to raise illumination levels within buildings with the above characteristics, it may be necessary to resort to artificial light.
We shall, within the scope of this work, make only a brief reference to artificial light as it is not the main theme of this work. Since daylight as explained above may not in some circumstances cover all the illumination demands in the building, a mention about artificial light as a supplement will not be misplaced.
In many regions where there are no provisions for electric power supply, lack of artificial lighting is a problem of grave concern. Power generators or the increasing use of solar and wind energy can be a substitute.
We will refer to regions of the tropics which have access to electricity. Artificial light in buildings in these regions has not only advantages, but also several disadvantages of which the following are more common:

→ artificial lighting can significantly increase the cooling load in a building (figure 5.7)
→ artificial lights may negatively influence decisions which demand critical visual judgements involving colours
→ full dependency on artificial lighting may lead to wrong perception of time
→ people with glimmering or glittering visual effects can be negatively affected with the substitution of daylight by artificial lights
→ costs of running buildings may increase not only due to increased energy consumption but also due to the necessary regular maintenance costs.

In many buildings in tropical regions, artificial light is switched on as soon as one enters the office and switched off when one leaves the office [Appendixes 9 and 10]. This is done irrespective of the illumination by daylight in the building that might be sufficient to carry out several activities. This unconscious and irresponsible turning on of lights not only increases the costs of electricity itself, cooling costs are raised as well. Electric lamps – incandescent and fluorescent - emit radiation which carry heat. This heat is responsible for the rise of temperature of the room air and also of the objects inside the building, which will consequently increase the cooling load.

To test the impact of prolonged switching on of artificial lights on room temperature, we simulated our prototype building by making the following assumptions:

- the building was occupied by six persons from 7am to 7pm everyday
- the occupants of the building carried on normal office activities like typing on personal computer
- we assumed a total heat gain of 10W/m² due to artificial light throughout the whole period the building was occupied.

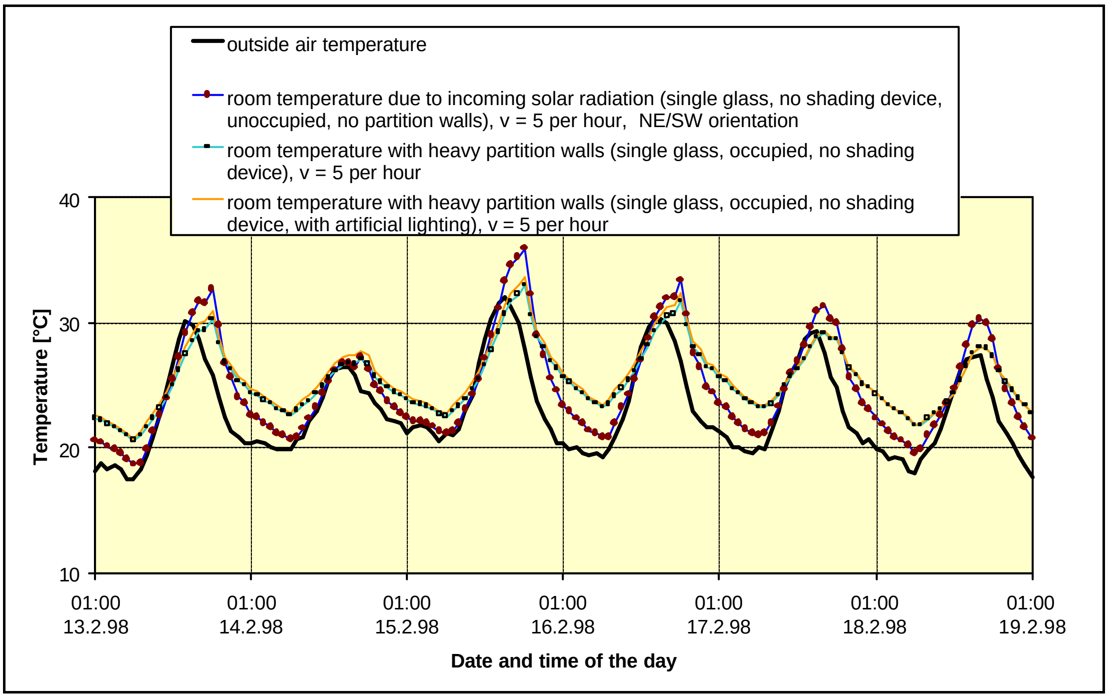



**Figure 5.7:** The impacts of continuous switching on of artificial lights on the temperature inside the building

The results shown in figure 5.7 indicate a temperature rise of between 0.5°C to 1°C above that when artificial lights were not switched on. The amount of heat radiated depends on the number and type of lamps switched on. Automatic switching on of artificial lights can be useful in this case.

# 6 Sun-shading

The sun is the main source of natural light and solar energy received on earth. The intensity of solar energy reaching the surface of the earth depends entirely on the time of the day, the season of the year and also on the altitude of the location considered.

In Uganda, Kasese in particular, which is at the altitude of 0.11°N, average insolation on a horizontal plane is about 700W/m² but can exceed 1000W/m² on warm days. A significant percentage of solar energy that reaches the building envelope will penetrate the building through glazed surfaces if not screened. The problem of screening the building from solar radiation has been aggravated by the new trends in modern architecture. The traditional methods of constructing buildings using massive bearing walls – thick mud walls in some tropical regions - with limited openings to allow air circulation and daylight into the building have been replaced by the modern skeletal structural construction with the building skin covered with materials like glass or transparent plastic panels, which readily permit solar radiation transmission. The developments in glass technology leading to the manufacturing of reinforced glass or double glass, has given way to the construction of buildings with large glazed areas. The building skin plays a great role in the utilisation or the control of solar radiation.

In some tropical regions, traditionally constructed building have virtually no openings to allow direct solar radiation penetration (chapter 4). This may be essential in some situations but it is too simplistic to be accepted architecturally or functionally and may well be accompanied with psychological problems and other shortcomings. There is little necessity for direct solar control in this case.

In situations where there are openings on the building to allow daylight into the building, solar control is an absolute necessity in order to minimise the negative effects. Daylight and solar screening in buildings offers us a challenge in search of a balance between the two. The task is to allow enough daylight into the building while blocking solar radiation that might cause overheating and glare inside the building.

Air, light, heat, cold, odours, and sound are abundant in an open environment but can be filtered by the building envelope to a level necessary to maintain a comfortable environment inside a building. The physical composition of these elements determines whether they can be effectively controlled before their impact on the building are realised. Whereas light is easy to control inside the building (chapter 4), sound and air can easily be contained within the building skin. Heat radiation, wind and odour, can easily be controlled before the building envelope.

Heat radiation control is of the utmost importance in buildings in tropical regions and is the main focus in this chapter.

## 6.1 Shading devices

The solar radiation spectrum in the atmosphere, as discussed in chapter 4, comprises of three main parts. Visible light which covers the greater percentage followed by infra-red and ultraviolet respectively. These percentages directly represent the amount of solar energy carried by the radiation in either category. This implies that most energy is in the visible light area.

An effective shading device should therefore be able to filter the unwanted solar heat but allow the needed daylight to reach the building interior. Conventional shading devices can block solar radiation from penetrating the building but can not selectively block the undesired radiation alone. Innovative devices perform better in this respect as will be discussed later in this chapter.

Shading devices should allow diffuse light to reach the building interior without obstruction and either block the direct light component or re-direct it into the building.

Depending on the time of the day, some parts of the building are exposed to more solar heat radiation than others. Throughout the day, the roof receives the greatest percentage of solar radiation followed by the walls. This is more evident in the tropical regions where the sun is almost overhead the greater part of the day. Buildings in tropical regions should be constructed in such a way that heat absorbed by the roof is dissipated before reaching the living or working areas of the building. Shading the roof can drastically reduce the amount of heat penetrating the building. Glazed apertures on the roof and windows on the walls are the most vulnerable areas of the building which, when unprotected from solar radiation, will permit the most heat into the building.

For regions along the equator, shading of buildings offers a big challenge as compared to regions further away in either the northern or southern hemispheres. Whereas in regions along the equator both the south and north sides of the building will have almost equal intensities of solar radiation reaching them, figure 5.3, deeper in the northern hemisphere, the south facing façade will receive more than the north facing façade while in the southern hemisphere the north facing façade will take in more than the one facing south. In all cases, the east and west facing façades have the greatest amount of solar radiation reaching them.

Shading the east and west façades is more problematic than the north or south because of the lower solar altitude. It is therefore more advisable to have fewer or no openings on these sides.

Shading devices differ in their nature, degree of effectiveness, cost and characteristics. These devices must be able to perform some functions in order to qualify as shading devices. The nature of the building, the activities carried out in the building, the orientation and location of the building all influence the choice of the device. Shading devices should be able to perform some of these functions:

- stop solar radiation from penetrating the building during hot periods
- allow solar radiation penetration into the building interiors during cooler periods to provide warmth – passive heating.
- should allow view (contact) to the outside from inside the building
- should allow daylight into the building
- provide some privacy whenever desired
- be used to improve the quality and quantity of incoming light at the rear areas and eventual even distribution within the building
- be able to shield the occupants of the building from glare
- should not interfere with air circulation through the openings
- should not influence the daylight colour composition

It is not possible for a shading device to effectively perform all these functions even though adjustable shading devices may respond to more demands than fixed ones. A device should therefore be chosen after identifying the functions it is to perform.

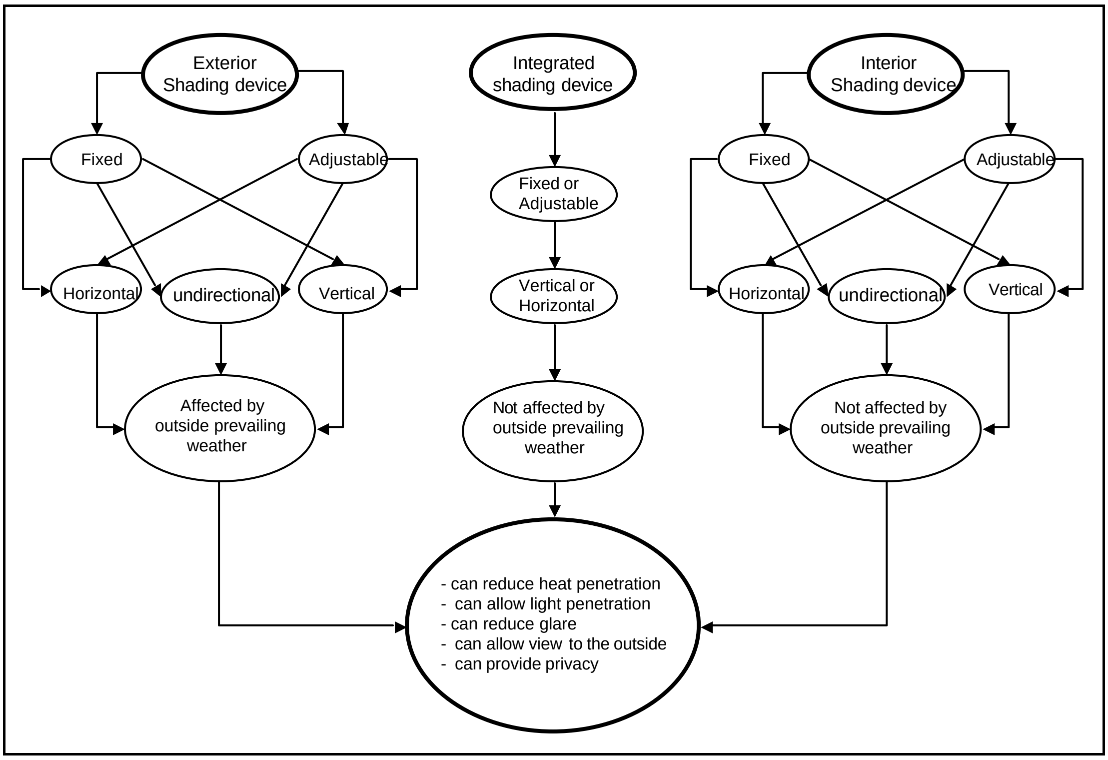



**Figure 6.1:** Main categories of shading devices

The position of a shading device relative to the building envelope can be a considerable criteria in categorising them. This can help us analyse different shading devices in order to test their effectiveness and other characteristics.
Shading devices can be mounted outside, within or inside the building envelope as illustrated in figure 6.1.

### 6.1.1 Exterior shading devices

Shading devices mounted on the outer side of the building envelope will be referred to as exterior shading devices throughout this work. Such devices are basically horizontally or vertically installed. Unidirectional devices as well as diagonal shading devices are also in use. They can be either fixed (static) or adjustable. Roof overhang, shutters, venetian blinds, awnings and curtains are notable examples in this category.

External devices trap solar radiation before it reaches the building envelope. Their position relative to the area to be shaded enhances their effectiveness. Depending on the nature of the shading device, there is a tendency of heat build-up in the space between the device and the building envelope as a result of heat released by the device itself. Part of this heat may penetrate the building through glazed surfaces.
Air circulation between the device and the building envelope can drastically reduce this heat build up and thus the amount that will enter the building interior. Since external devices are exposed to prevailing weather conditions, their duration may be greatly reduced and may demand regular maintenance and replacement.
From the architectural point of view, outside shading devices may influence the general appearance of the building façade. Their colour, form, and shape have to be considered during the planning phase to avoid the negative influences on the building appearance. A schematic illustration of some forms of exterior shading devices is shown in figure 6.2.

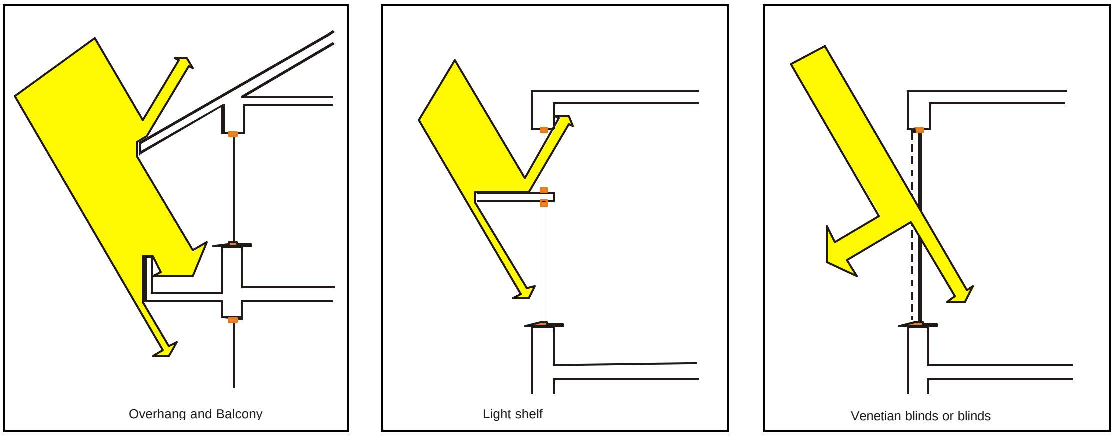



**Figure 6.2**: Schematic illustration of some examples of exterior shading devices

The distance between the device and the building envelope depends on the type of the device. There are some disadvantages in using external shading devices among them are the following:

- some devices mounted on the outer surface of the building envelope can be washed away by heavy winds if they are not properly fixed.
- some devices like venetian blinds can produce unpleasant noise and movement (rattle) when they get in touch with gusting winds.
- some devices made of materials whose surfaces are coated with reflective elements may reflect light towards neighbouring buildings and can distract the occupants of these buildings.
- some devices may be damaged by prevailing atmospheric conditions like rainfall, moisture etc. In tropical regions, devices constructed out of materials like wood can be attacked by insects or algae leading to an eventual break down.
- they require regular maintenance

### 6.1.2 Integrated shading devices

Shading devices may be integrated within the window system by mounting them between the panes of glass. Notable examples of such devices are louvers and curtains. Louvers can be adjustable and are either horizontally or vertically mounted whereas curtains are normally unidirectionally fixed. Apart from shading the building, they can also be used to redirect light deep into the interior.

Their physical characteristics are not influenced by prevailing atmospheric conditions and can easily be integrated in the overall façade design. They do not require any maintenance though they may cause problems in case of malfunction or replacement. An example of such a device is schematically illustrated in figure 6.3.

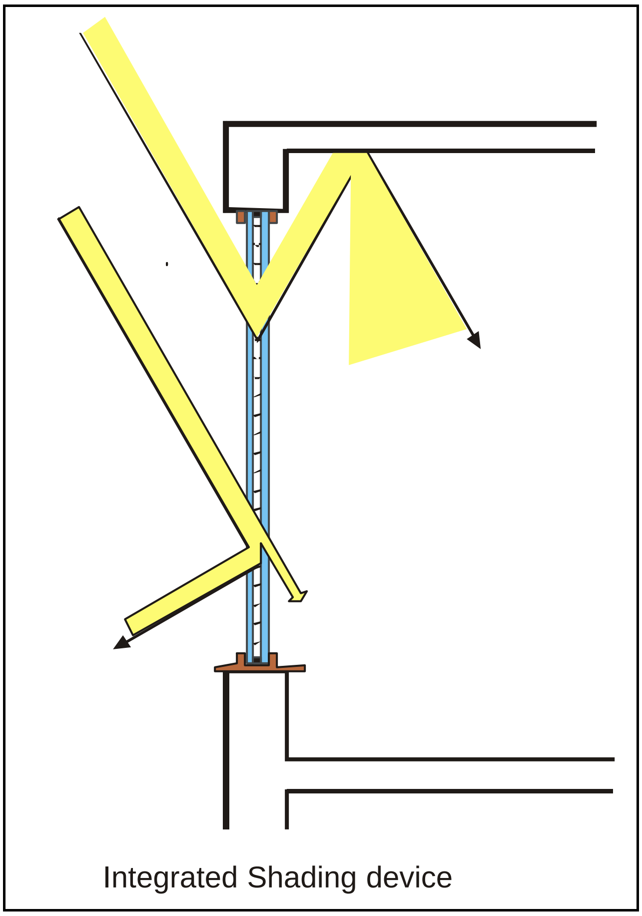



**Figure 6.3**: Illustration of an integrated shading system

Installing windows with integrated devices has to be properly planned during the early phases of the building design in order to avoid other building parts like construction beams from obstructing their effectiveness. It is also advisable to separate the window into parts for view and for daylight in case such a device is to be used.

### 6.1.3 Interior shading devices

Shading devices mounted on the inner side of the building envelope will be referred to as interior shading devices throughout this work. Such devices can either be fixed - like interior light shelves or adjustable like louvers, curtains, etc. They can be horizontally, vertically or unidirectionally mounted.

There is no direct influence of the prevailing atmospheric conditions on interior shading devices. However, the effectiveness of interior shading devices in reducing solar heat gain inside the building may be highly reduced due to the fact that they intercept the solar radiation inside the building. Figure 6.4 shows a schematic illustration of an interior shading device which demonstrates the behaviour of solar radiation on reaching the device.

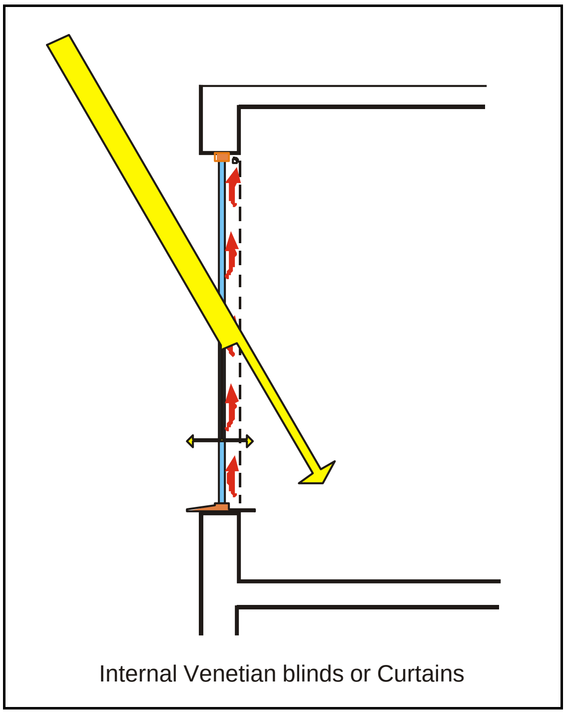



**Figure 6.4:** Illustration of Internal shading devices

Short wave solar radiation can easily penetrate through normal glass into the building. It is then trapped and absorbed by the interior shading device or other opaque object consequently transforming it into heat. There is a gradual accumulation of heat between the glass and the shading device and eventually into the space of the building interior. This will effectively raise the room temperature, a process commonly referred to as the “green house effect”.

Objects inside the building will absorb this heat, heat-up and then re-emit long wave radiation carrying heat in all directions depending on the temperature of the surroundings. Part of the emitted heat that re-strikes the glass pane is first absorbed but later re-emitted to either side of the glass. Long wave radiation barely passes through glass.

The dissipation of the accumulated heat inside the building can be achieved by cross air ventilation or by sucking the accumulating warm air between the glass and the shading device.

To test the influence of the position of a shading device on room temperature, we carried out simulations of the building with a device installed outside the building envelope (exterior device) and one installed inside the building (interior device) with specifications shown in table 6.1. We used our prototype building to carry out the simulations. The following assumptions were made during the simulations:

- single pane of glass with thermal transmittance of 5.8W/m²K and a solar gain factor of 0.885 was considered for all glazed surfaces
- there was no internal thermal mass considered and the building was not occupied
- there was a constant hygienic air change of v=1 per hour
- there was no obstruction to the radiation reaching the window in form of roof projection or other objects around the building

The tested shading devices on the inner and outer (interior and exterior) side of the façade had the following technical specifications (transmission, reflection and absorption)

| Device | Solar radiation transmission, $T_s$ , [%] | Solar radiation reflection, $R_s$ , [%] | Solar radiation absorption, $A_s$ , [%] |
|---|---|---|---|
| Exterior | 4 | 25 | 71 |
| Interior | 19 | 35 | 46 |

**Table 6.1:** Technical specifications of the tested shading devices

A period of five days in February with the highest recorded air temperature was analysed. The temperature inside the building rose up to 38°C as a result of solar radiation penetrating through unprotected glass. This was 5°C above the temperature outside the building. By installing an interior shading device, there was a reduction of around 4°C below that when no shading device was considered. It was not possible to remove accumulated warm air between the device and glass in our model, which might have enhanced the performance of the interior device. Cross-room ventilation can be helpful in such a situation.

Exterior shading devices showed the best results as illustrated in figure 6.5. The replacement of an interior shading device by an exterior device under similar conditions reduced the room temperature by up to 10°C below that of a room without shading device.

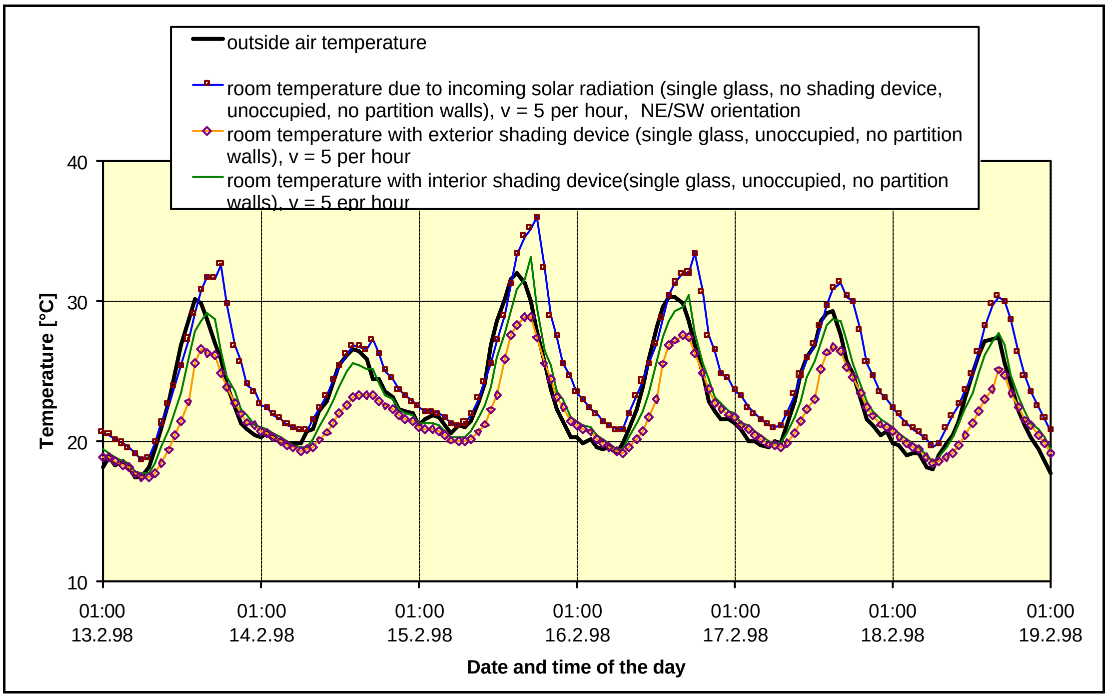



**Figure 6.5:** Comparing the influence of external and internal shading devices on room temperature

Intercepting incoming solar radiation before it reaches the building interior, as is the case for external shading devices, showed a more positive effect in terms of reducing room temperature than is the case for interior devices which trap the radiation inside the building.

### 6.1.4 Fixed Shading devices

Fixed shading devices are parts of the building or extra structures (or elements) mounted on the building façade, designed to shade apertures on the building through which solar radiation penetrates the building. They can be external or internal structures. Such devices are static and do not react to the movement of the sun. Overhangs, egg-crate and light shelves are good examples of fixed shading devices.

The effectiveness of fixed shading devices does not only depend on their dimension but also on the orientation and the size of the aperture they are intended to screen. Fixed devices can be horizontally or vertically mounted.

Horizontal devices are effective only when the sun altitude is high. This is the case for the north and south orientations for buildings along the equator.

Buildings further north of the equator, the south facing façade is better protected by horizontally fixed devices whereas for buildings further in the southern hemisphere, it is the northern façade which is effectively protected.

Because of the low solar altitude on the east and west orientations of the building, horizontally fixed devices are practically ineffective since solar radiation will travel almost parallel to the device. A combination of vertically and horizontally fixed devices can perform comparatively better. Egg crate structures are good examples.

Egg crates are structurally horizontal and vertical elements, which to a certain extent take into account the changing altitude of the sun.

Before deciding on the construction of the fixed shading device (horizontal or vertical) it is important to first determine the dimension of the device by calculating the period when the intended aperture will be shaded by the device. This can be done by constructing shading masks using sun path diagrams and shadow angle protractors to help us know the horizontal and vertical shadow angles which will indicate period when the intended aperture will be shaded [10], [64].

Alternatively, determining the proportions and dimensions of a shading device after deciding the orientation and size of the window on the building, basically involves the calculation of the cut-off angle which is simply the horizontal shadow angle $\gamma$, for a vertical device expressed in equation 6.2 and involves the calculation of the vertical shadow angle $\theta$, for a horizontal device expressed in equation 6.1. The cut-off angle concept is illustrated in figure 6.6.

After calculating the cut-off angle, we can then use the shadow angle protractor to determine exactly when direct radiation will fall on the glazed surface.

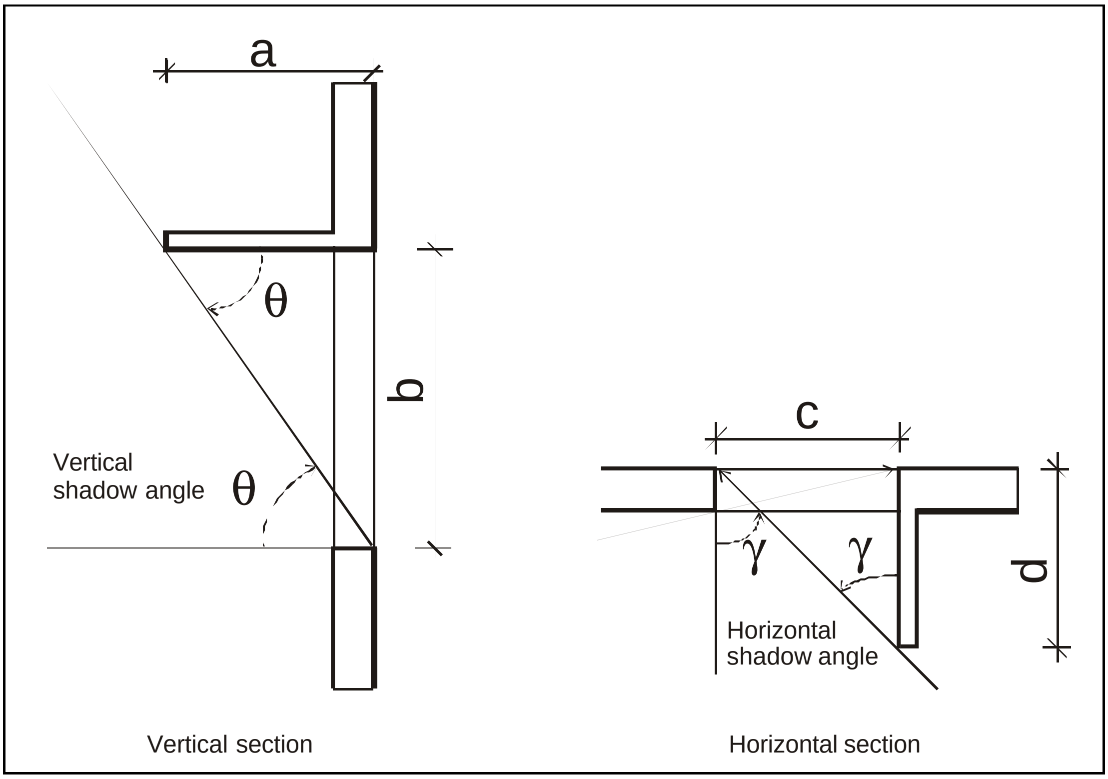



**Figure 6.6:** Illustration of vertical and horizontal shadow angles

The dimension of the shading device needed to completely shade the aperture is a relationship between the height of the opening ***b*** and the projection of the device ***a*** for a horizontal shading device whereas for a vertical shading device, the projection of the device ***d*** and the length of the window ***c*** must be considered.

for horizontal shading device............................ $\tan(q) = \frac{b}{a}$ (6.1)

for vertical shading device................................ $\tan(g) = \frac{c}{d}$ (6.2)

Depending on the dimension, inclination and design of the device, the effectiveness of the device is determined by the changes in solar altitude. They can block light when it is needed, or allow in solar radiation when it is not needed. There is therefore a need to adjust the position of shading devices in order to accommodate the changes of the position of the sun. This can be realised by using adjustable devices.

### 6.1.5 Adjustable shading devices

For regions of the tropics with a long heating period, adjustable shading devices are necessary in order to cope with the changing solar seasons. This is mainly to offer total shading of the windows to minimise solar heat gain inside the building but also allow enough daylight into the building.

Adjustable devices are useful mostly for the east and west orientations even though they function equally well for the north and south orientations too. Examples of adjustable devices are venetian blinds, curtains, awnings, etc.

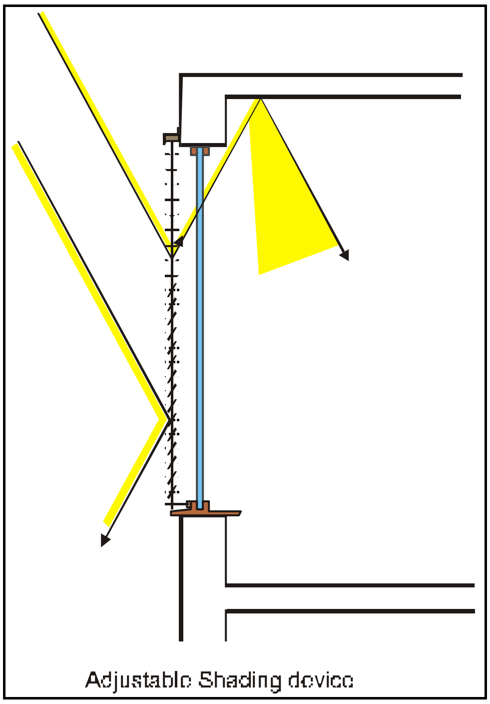
Adjustable devices function basically by changing the cut-off angle (figure 6.6) to accommodate the changing solar altitude as a result of the movement of the sun. These devices can be manually or automatically adjusted.

Manual control is a demanding exercise as one has to operate the control mechanism from time to time to respond to the needs of occupants inside the building.

This however, may create conflicts between occupants of the buildings if their demands are different at a certain point of time.

Adjustable devices can however be automatically operated, responding to set conditions within or outside the building. Such conditions may be room temperature, illumination intensity at a reference point inside the building, global illumination or the time of the day. This may be the basis for regulating energy consumption in a building. The effectiveness of adjustable devices was discussed in chapter 5.

a)




b)

**Figure 6.7a and b:** Illustration of adjustable shading devices

Figure 6.7b schematically illustrates how adjustable shading devices may function if applied on buildings. Depending on the angle of inclination of the blinds, they can completely block incoming solar radiation by reflecting it away from the building, selectively reflect direct and diffuse solar radiation into the building interior by first bouncing it on the ceiling and then deeper into the building. They are capable of being adjusted to allow diffuse light into the building and enabling a view to outside from the building.

## 6.2 Glass and solar heat control in buildings in tropical regions

Glass is increasingly being used as a building material not only in temperate regions but also in tropical regions too. Its transparency or translucent characteristics renders it appropriate for use in buildings as a bridge between the inside and the outside of the building.

Solar radiation on reaching glass surface can be partly reflected, absorbed or transmitted. The percentage of the radiation that will be repelled, absorbed or transmitted depends on the nature of the glass itself. The thickness of glass, surface coating, the number of glass layers used, among other factors, determines its reaction towards incoming radiation. Clear glass which is 4mm thick for instance, has a light transmittance of almost 90%.

Tinted glass on the other hand which can effectively reduce the influence of glare inside buildings has got a comparatively lower light transmittance compared to clear glass. The light transmittances of such glass ranges between 20 – 60%. Some tinted glass effectively reduce light transmission more than heat, implying that by installing such glass, illumination inside the building will be reduced and might force occupants to switch on artificial lights.

We carried out simulations in order to determine the influence of glass type on room temperature inside our prototype building.

Table 6.2 shows the different types of glass and their specifications which were considered for our simulation. These different types of glass were tested through simulations under similar conditions to compare their effect on room temperature.

| Type of glass | Layers | Thermal transmittance (U-value), W/m²K | Solar gain factor, g-value | Light Transmission [%] |
|---|---|---|---|---|
| Single glass | 1 | 5.8 | 0.855 | 89 |
| Insulating or double glass | 2 | 2.8 | 0.755 | 81 |
| Heat protection or Thermal insulating glass filled with Argon | 2 | 1.4 | 0.589 | 76 |
| Sun-shading glass with silver coating | 2 | 1.3 | 0.298 | 50 |

**Table 6.2:** Used glass and their specifications

Simulations were carried out under the following conditions:

- it was assumed that there was no shading of any kind to obstruct the solar radiation reaching the building envelope and in particular glazed surfaces
- there were neither internal thermal mass in form of interior walls nor other sources of heat in the form of occupants or electrical appliances was considered.
- there was a constant hygienic air exchange rate of v=1 per hour inside the building
- the glazed area was the same for all the simulations

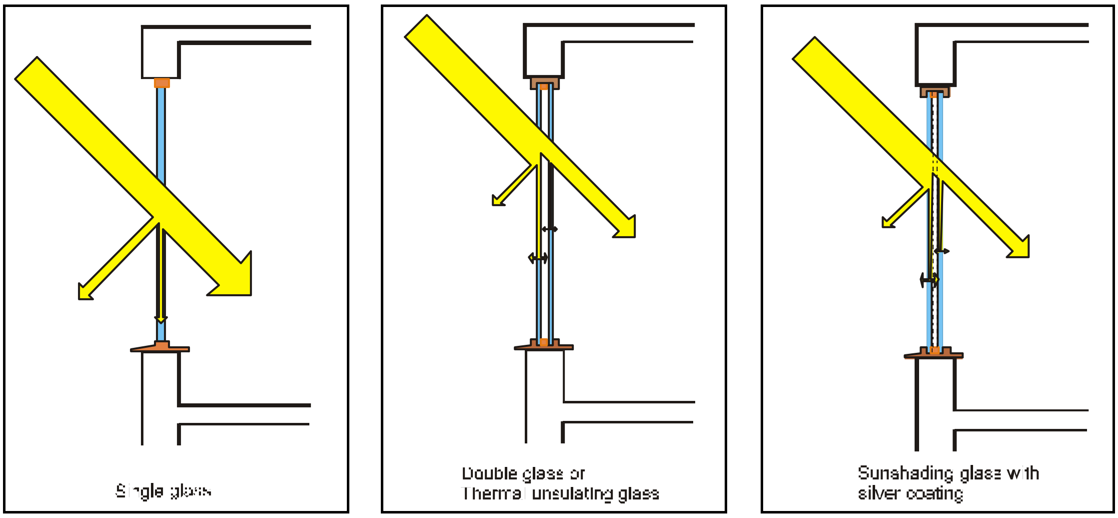



**Figure 6.8:** schematic illustration of the different glass types showing their behaviour towards solar radiation

The proportion of solar radiation that will reach the building interior depends on the following factors:

- type of glass used (thickness, coating and filling)
- the incident angle of the incoming sun rays
- the area of the exposed glass
- the orientation of glass on the building

Solar radiation absorbed by glass is re-emitted to either side of the glass depending on the prevailing air temperature of the surroundings. Its contribution to the rise of internal temperature is minimal though not insignificant.

Transmitted radiation trapped in the building will partly be absorbed, reflected or re-transmitted by objects like walls, the floor or furniture depending on the nature of the surface of the object on which it falls. The radiation that reaches the interior of the building will be responsible for the rise in room temperature.

Transmission through glass decreases with increase in incident angle, whereas reflection by glass increases with increasing angle of incidence. Because of the lengthened optical path, absorption will first increase but later decrease as a result of increasing incident angle. For this reason, skylights which are at a lower incident angle will transmit more solar radiation (light and heat) than a proportionally similar window on a vertical wall though the same window will reflect more solar radiation than a skylight of the same area. Solar heat gain through glazed surfaces can therefore be attributed to these two situations.

Five days in February with some of the highest recorded air temperatures in the year for the region of Kasese, Uganda, were analysed. The results of our simulation showing the temperature inside the prototype building as a result of using different glass types for this period are shown in figure 6.9.

There is a noticeable rise in room temperature as a result of solar heat through glass. Insulating glass, single glass and low emissive (heat-protecting) glass showed the least performance in terms of blocking solar heat penetration in buildings in tropical regions. During the hottest hours of the day, the room temperature rose by over 3°C above the outside air temperature as a result of using these types of glass.

Sun-shading glass with a silver coating showed convincing results. The reflecting effects of the silver coatings intercepts the incoming solar radiation on striking the glass surface and reflects it before reaching the building interior. This process effectively minimises the heat gain in the building which keeps the room temperature in the range of the prevailing outside air temperature.

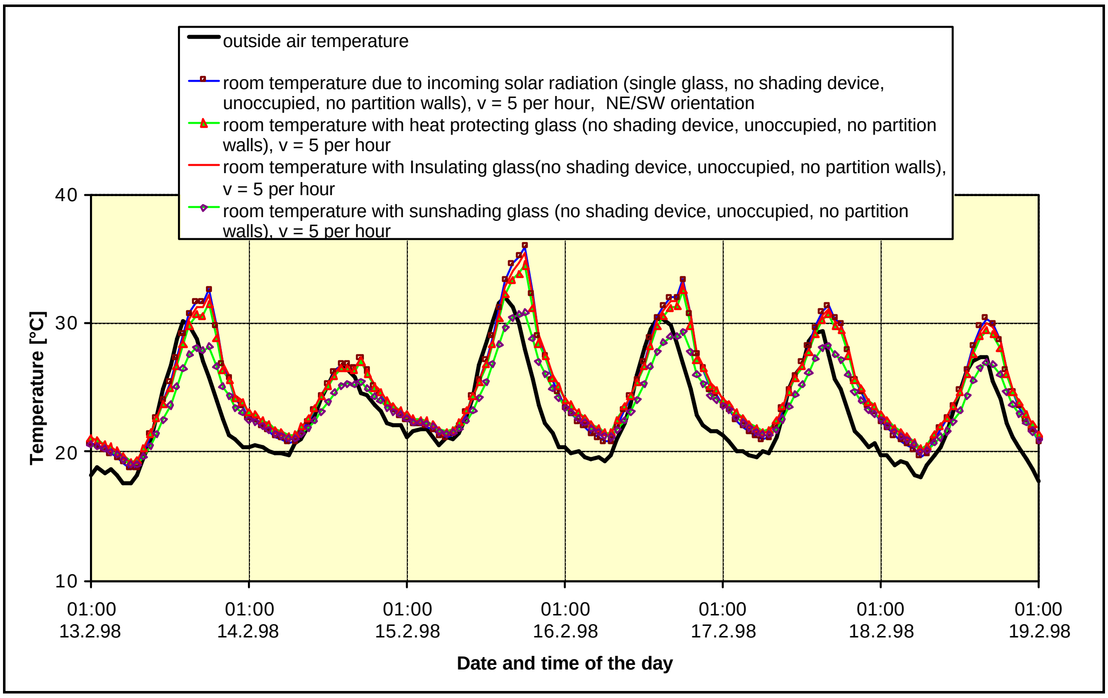



**Figure 6.9:** The effect of different glass types on room temperature

The choice of glass does not only depend on its effectiveness to reduce solar heat gain but also on other factors like availability and cost. In many tropical regions, single glass is the most common and widely used glass type in both domestic and many public buildings despite its vulnerability to solar heat penetration. Therefore, the need to shade the building in these regions is even more important than in regions where there is the possibility and capability to use different types of glass which can minimise solar heat gain in the building.

## 6.3 Traditional methods of shading buildings in tropical regions

Shading of buildings in tropical regions is basically an attempt to minimise the overheating problem inside the building. Traditionally, buildings in these regions are constructed in such a way that incoming solar radiation is not permitted to directly reach the building interior. The form and shape of the buildings differ from one sub-region to another. Forms adapted in hot and arid tropical regions may not necessarily suit the conditions in hot and humid regions. In hot and arid regions, the sky is dominantly clear and its luminance is much lower than at the horizon.

In hot and humid regions however, the sky is dominantly cloudy with a comparatively higher luminance than the horizon. The design of windows on buildings must take into account this fact as a control mechanism in order to minimise the exposure of the glazed area to direct solar radiation and also to reduce excessive luminance contrast which might cause disability glare.

Buildings which have small or at times no openings at all as described in chapter 4, can be very effective in reducing these effects.

Some traditional buildings in hot and humid tropical regions adapted a circular building body form with a cone-shaped roof protruding beyond the walls. The inclined cone-roofed shape reduces the roof area exposed to the sun at higher altitudes and consequently the amount of heat absorbed by the roof.

Figure 6.10 shows an example of a typical dwelling in hot and humid tropical regions. These buildings are constructed using light materials like straw and wood with a low thermal capacity and readily allow the diffusion of air to and from the building. The entrance is also used as the main inlet for fresh air and outlet for waste air which also diffuses out of the building through the gaps created by the different construction layers of the roof.

Figure 6.11 shows an illustration of the air circulation system in such buildings.

**Figure 6.10:** Dwelling in a hot and humid region

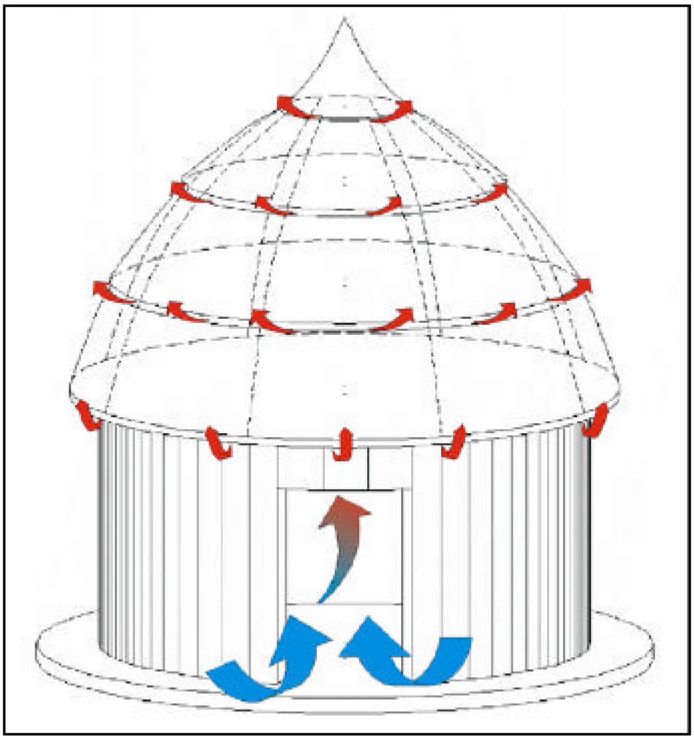


**Figure 6.11:** Schematic illustration of the ventilation concept in a dwelling house

These buildings are constructed so close to one another that they themselves cast shadows on neighbouring buildings as a remedy for stopping direct solar radiation from reaching them. There is however, enough space between the buildings to allow air movement. These buildings form a compound within which trees are planted to provide further shading. This creates a friendly natural environment in which the shape of the buildings communicates and tries to merge with nature [3]. Figure 6.12 shows an example of a typical dwelling in the hot and humid tropical regions of west Africa.

**Figure 6.12:** Dwellings in a West African village

The principle of constructing buildings with only a narrow space separating them as a means of providing shade is also widely applied in the conceptual planning of towns in tropical regions. In this particular case, the streets are so narrow that the buildings themselves cast a shadow on the streets for most of the day. In order to achieve total shading of the streets, the relationship of the distance between the buildings and the height of the building shown in figure 6.13 has to be properly considered.
Streets are basically used by pedestrians and facilitate air circulation and also serve as escape routes in case of catastrophes. The principles of narrow streets in town planning can be seen across the whole tropical regions and even beyond. In modern cities, the streets may be wider but are then planted with trees and vegetation which provide the needed shade, cast by their canopies, for both pedestrians and parts of the buildings.

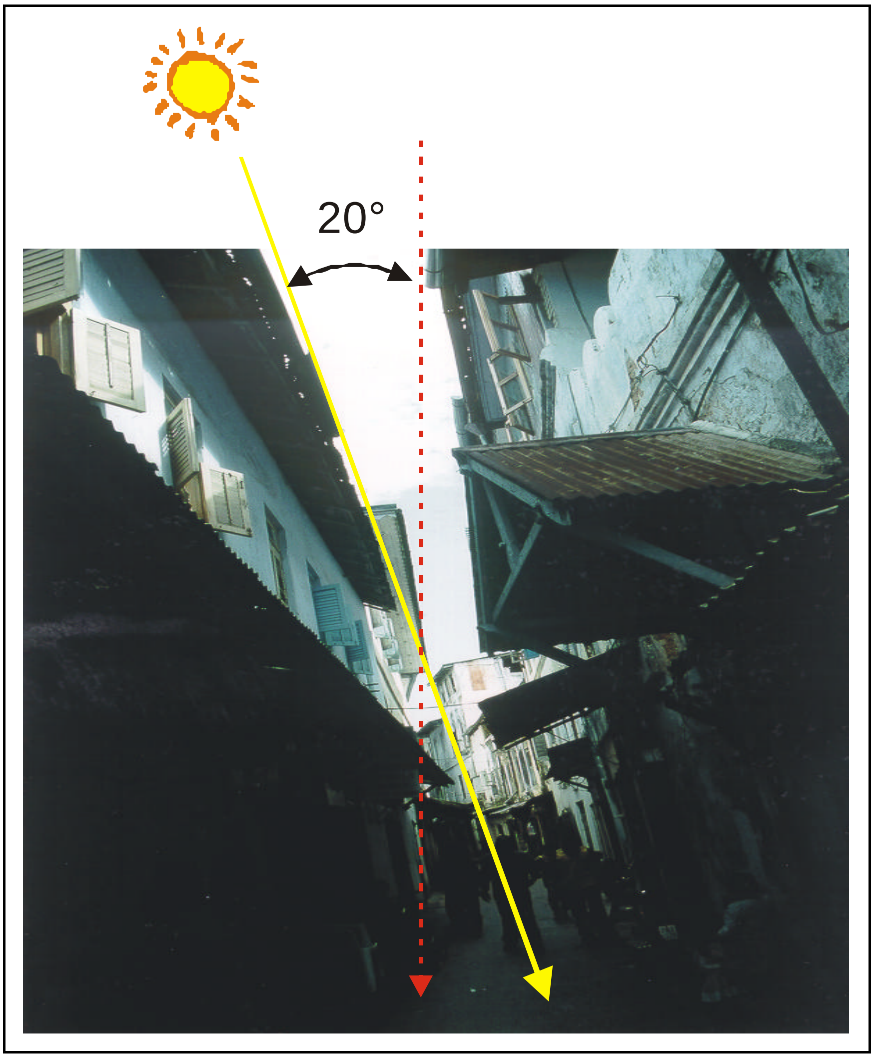



**Figure 6.13:** Illustration of shadowing in narrow streets in Zanzibar

In tropical regions buildings and cities in general tend to develop along the east-west axis wherever possible. This implies that in order to minimise solar heat gains in the building, the south and north façades are more exposed to incoming solar radiation than the east and west façades which is more advantageous in terms of energy efficiency. The area of the building in the east or west orientation which experiences the highest solar radiation intensities is less than that on the north or south orientation with lower solar radiation intensities.

Traditional building forms and methods no longer play a dominant role in the planning and construction of modern cities which are designed to accommodate more people in small spaces and meet the challenges of the changing lifestyles of people in these regions. Some traditional construction principles, however, are still applied in some modern buildings to achieve comfort.

## 6.4 Integration of topography and vegetation in the concept of shading a building

Landscapes can offer us an opportunity to construct buildings which at a certain time of the day will be shaded as a result of the surrounding land levels. Integrating topography into the overall concept for the shading of a building requires a thorough consideration of the tilt of the land and the orientation of the building in relation to the movement of the sun.

The shadow cast on the building will take place at a given time of the day when the angle of inclination of the landscape is higher than the altitude angle of the sun in relation to the building to be shaded. Since both the building and the landscape are fixed structures, it is very important to design a building knowing that the shaded part of the building will always be shaded at a particular time in a given season of the year. Figure 6.14 shows the effect of topography on solar radiation reaching the building at a low solar altitude.

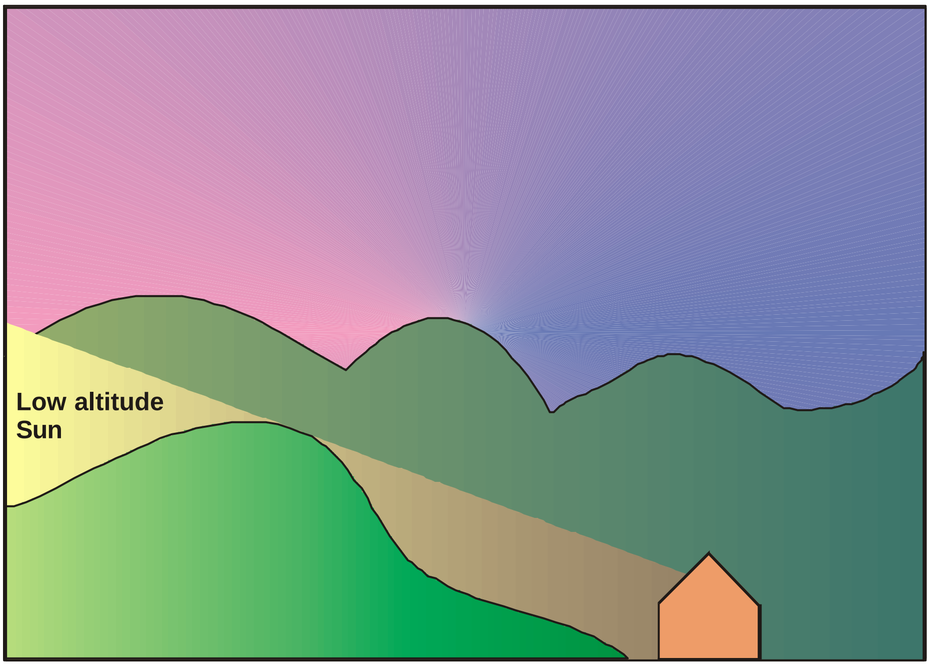



**Figure 6.14:** schematic illustration of shading using topography

Vegetation has similar effects as topography. It can both block or channel wind, necessary for cooling, towards the building. Trees planted to provide shading to buildings have to be properly chosen. They should be able to cast shadows on the building but at the same time permit solar radiation to reach the building at times when it is needed. The effectiveness of vegetation for shading depends entirely on the type of trees, the size, and the distance from the building to be shaded. Shading is a result of the leaves blocking direct solar radiation from reaching the building envelope. Since some trees shed their leaves sometime during the year, choosing the right tree that will not shed its leaves during the hot season may be one of the most important criteria.

Even though solar radiation may lead to a rise in room temperature, there are times when the temperatures are too low that some sort of heating may be desirable in buildings in tropical regions.

This may be the case in the early hours of the day or during some seasons. This kind of passive heating of the building should not be curtailed by the presence of trees.

Vegetation can also absorb large quantities of solar radiation while the effects of evapotranspiration of plants may help reduce surrounding temperatures. The appropriate dimensions of the vegetation that can provide adequate shading and at the right time can easily be estimated [10], [42].

Figure 6.15 shows how trees can be used to shade the building. A combination of vegetation with other forms of shading mechanism can produce good results.

**Figure 6.15:** Trees providing additional shade to the administration building at the University of Dar es salaam

## 6.5 The application of innovative shading methods in buildings in tropical regions

Traditional construction methods of buildings in tropical regions are a result of experience accumulated over a long time. These methods, despite their simplistic nature, evolved with time and were being adapted as the most appropriate alternatives for creating a comfortable living environment for people in these regions until the present time. Some of these methods have been scientifically proved to be suitable for the regions in which they are applied. However, with increasing modernisation of societies and the changing living habits of people in these regions, there is a need to adapt new ideas to meet the needs of the time.

Development of modern cities, different working habits, improving living standards, use of modern transportation, all demand a new approach.

In cities, buildings are no longer being used only as dwellings but increasingly as offices, schools, hospitals, factories and for other activities.

They can no longer be built without windows as is the case in many traditional buildings, but are increasingly being built with transparent windows to allow the use of daylight. City streets have to be wider as they are no longer only used by pedestrians but also by vehicles. Different building materials are being used for constructing high rise buildings. Traditional building materials like straw or other natural fibres, because of their susceptibility to easy destruction by fire and insects and limitations to construct massive structures, have been largely replaced by new building materials.

There are chronic shortages of energy essential for cooling and illuminating buildings, especially in tropical regions. In cases where mechanical cooling or artificial lighting of buildings is necessary there are diverse negative impacts on the environment as a result. All these factors demand different considerations in order to achieve healthy and comfortable conditions inside the buildings. The main cause of uncomfortable conditions in buildings in tropical regions is overheating and glare. Complete shading of the building will trigger the switching on of artificial lights for illumination. Regarding the use of daylight in most buildings the situation has always been either daylight and overheating in buildings or no overheating and thus no daylight. This can be partly seen as traditional methods contra modernisation. Innovative daylighting and shading methods try to tackle this dilemma. Such systems not only enable the use of daylight but also reduce the negative consequences as a result of solar radiation entering the buildings. Innovative daylighting methods have been discussed in chapter 4.

Innovative shading methods are designed to shade the building from incoming solar radiation but also allow a considerable amount of natural light into the building as well as maintaining contact to the outside of the building.

Innovative shading devices have the following characteristics:

- can stop heat penetration into the building
- can reduce glare influences
- can allow view to the outside from the building
- can allow a certain degree of daylight to enter the building

These shading devices can either be fixed or adjustable. Examples of innovative fixed devices are the different types of sun shading glass like Electro-chrome, Thermo-chrome, Gazo-chrome and Thermotropic glass.

Some of these new types of glass have already been installed in buildings whereas others are currently being tested. Their application may suppress the need to use extra shading devices. The effectiveness of these glasses, their acceptance by users, cost and applicability in different climatic regions are issues of great interest. The technical details about these high-tech glasses, however, will not be dealt with within the scope of this work.

Examples of other innovative shading devices are modified adjustable louver systems which can be opened or closed whenever there is need (section 4.3).

The use of innovative shading systems, as is the case for innovative daylighting systems, may have wide ranging advantages in tropical regions.

There is nevertheless a need to modify these systems to meet the different climatic characteristics in tropical regions in order to achieve maximum benefits once they are installed. Some examples of innovative shading devices and their characteristics are listed in table 7.1.

## 6.6 The contribution of solar screening to urban microclimate

In a congested urban environment there is a marked rise of the air temperature compared to the surrounding areas. This results in the formation of a micro-climatic zone within the general regional climate seen on a wider perspective. Dissipated heat from the buildings as a result of mechanical cooling, is mostly released into the atmosphere which contributes to the warming of the surrounding air.

Several other factors contribute to this phenomenon and among them are the following:

- increased density of buildings and the topography of the area that can reduce airflow and humidity
- the use of building materials that increase the absorption of incoming solar radiation but can not readily dissipate accumulating heat inside the buildings
- increased air pollution that might block the path of incoming solar radiation
- heat released by vehicles and industries
- heat repelled by shading devices installed on buildings

Each of the above factors contributes to the formation of an urban microclimate. We will, within the scope of this thesis, try to analyse the role played by shading devices on buildings in the formation of this microclimate.

Most shading devices are repellents of the unwanted solar radiation. The repelled solar radiation by shading devices bounces back into the nearby atmosphere carrying the radiant heat with it. Because of the congested nature of buildings, there is insufficient air movement to drive this dissipated heat away which leads to a build up of a heat blanket in the atmosphere, which in turn leads to a significant rise of the surrounding air temperature. This situation happens in almost all urban environments but is aggravated by the climatic conditions in tropical regions. Ranging from the sky scrapers of Hong Kong to slums of many cities in tropical Africa, the effects of micro-climates are experienced everywhere.

Shading devices could effectively be used to reduce their contribution if they were designed to trap the heat-carrying solar radiation and then transform it into useful energy. Research in developing an intelligent building envelope that can transform solar heat into another kind of useful energy are under way, which will hopefully change shading devices from being repellents to being transformers of solar heat into profitable energy.

Alternatively, cities have to be designed with provisions of open spaces most probably planted with trees and vegetation which can absorb some of the dissipated heat from the buildings and other pollutants. This will create a form of a cool island to counterbalance the accumulating heat in the surroundings.

# 7 Integrated solutions for optimising daylight and sun-shading in buildings in tropical regions

Optimal use of daylight for lighting buildings in tropical regions while protecting the building from overheating and glare, may demand solutions other than the conventional methods applied in many buildings. Solutions have to be decided case by case taking into account the different lighting demands for each building. A combination of measures like supplementing daylight with artificial light, installing of daylighting, sun-shading systems or designing the building with provisions of improving the use of daylight like skylights might be inevitable. Some of the different sun-shading and daylighting systems that can be used to improve the use of daylight are listed in table 7.1. Modifications on the administration building to improve the use of daylight will also be discussed later in this chapter.

## 7.1 Examples of different sun-shading devices and daylighting systems and their characteristics

Different sun-shading devices and daylighting systems can be identified from the various characteristics, which determine their performances under different conditions. The importance for both illuminating a building with daylight and protecting the building from solar heat and glare effects especially in tropical regions are simultaneous processes which have to be handled with care in order to achieve the benefits of the former while minimising the negative effects of the latter.

By allowing daylight into the building without blocking the heat and glare that will come with it, will not only upset the thermal balance inside the building, it will be very costly to try to regain the necessary comfort in the building. Shading the building to stop heat penetration and glare effects while completely blocking daylight from entering the building will force the occupants to resort to artificial lighting, which will result in an increase in both energy and the operational costs of the building.

Systems that are strategically designed to perform a particular function without considering other demands have shown many deficiencies in that they have to be combined with other systems in order to produce good results.

Choosing a good system should be based on the following criteria:

→ ability to allow light into the building
→ ability to protect the building from heat penetration
→ ability to protect the occupants of the building against glare
→ ability to allow contact to the outside
→ compatibility (control) and possibility to integrate the system in the overall architecture of the building
→ availability and costs

Innovative daylighting systems apart from their main function of allowing and improving daylight distribution within a building, can to a certain degree block solar heat from entering the building and reduce glare effects. Some of these systems are adjustable in order to meet several demands at different times. They can allow view to the outside without compromising the other functions.

Innovative sun-shading devices on the other hand, do not only block the unwanted solar heat, they can allow some daylight into the building and view to the outside. It is not possible to have a system that can optimally perform all these functions simultaneously. In many cases, daylighting and sun-shading systems have to be combined to get the required results.

In table 7.1, we have listed some of the systems (daylighting and sun-shading), indicating their potentials and deficiencies by systematically identifying their special characteristics. It should be mentioned at this point that our judgement of the systems listed in table 7.1 are rough estimates as the efficiencies of these systems can be influenced by the detailed planning of each individual system. It is a hard task choosing a system that will meet all the requirements of a building. The first step however, is to define the objectives of a chosen system, then identify the system according to its abilities. By comparing the characteristics of the different systems it might be easy to chose a system that might be appropriate for the objectives one might need to accomplish.

## 7.2 Proposed modifications of the administrative building in order to optimise the use of daylight in the building

Buildings can be planned to optimally utilise daylight for illumination. This may involve the right dimensioning of, not only the rooms, but also the openings through which light enters the building. The orientation of the building has to be set which, in case there are no constraints, should be along the east-west axis. Orientations of the building with large glazed areas should face north or south. For single storey buildings, it may be important to plan for a skylight if side windows are not sufficient to allow enough daylight for illuminating all areas of the building. Figure 7.1 shows a plan of the administration building with some modifications (architectural and constructive) intended to improve the use of daylight but with minimal negative effects.

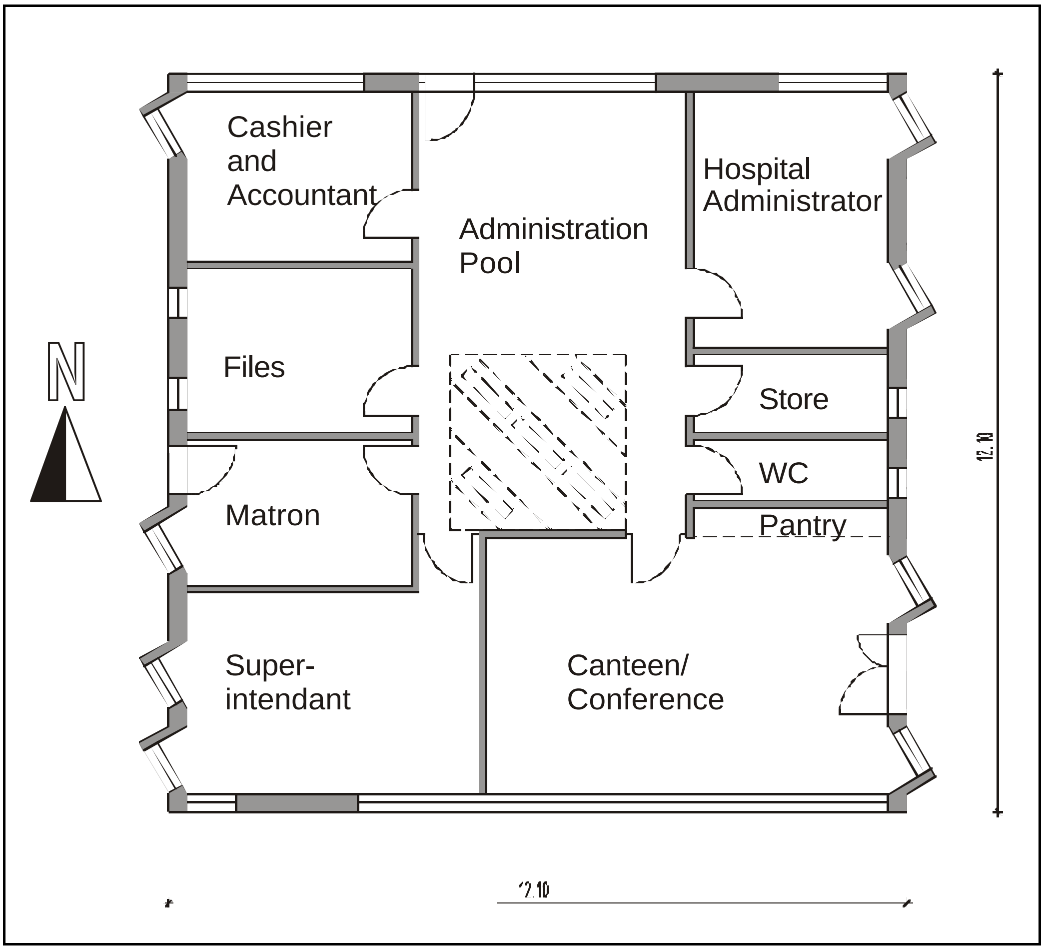



**Figure 7.1:** Floor plan of the administration building at Virika hospital with modified windows on the east and west façades and a skylight in the middle of the building.

By rotating the building 45° anti-clockwise, the façades with the most glazed area will face north and south which is more favourable as far as solar heat gain inside the building is concerned. This in effect reduces solar heat gain inside the building (Figure 3.6).

The construction measures considered to minimise solar heat gain and increase daylight inside the administration building were:

1. The windows on the east and west side of the building were turned to create a form of bay window. On the east façade, the glazed surface faced due north whereas the glazed surface on the west façade faced due south (Figure 7.1). This measure reduced the glazed surface directly facing east or west directions which receive the most solar intensities. In both cases direct solar radiation will be blocked by the wall perpendicular to the window and will not be able to directly strike the window, whereas diffuse radiation will continue to find its way into the building. The effectiveness of this measure is determined by the orientation of the building. The orientations of the bay windows has to be due east and west respectively as shown in figure 7.1. Any alteration of the orientation of the building as in figure 3.1, will render this measure ineffective.
2. The skylight allows more light into the building and improves illumination at the rear of the building, which receives less light from side windows. In order to minimise solar heat that might penetrate the building through the skylight, highly reflective glass that reflects direct solar radiation but allows diffuse light into the building may be used as well as a system like louvers or egg-crate on the lower part of the skylight to reduce direct exposure of occupants of the building to the sky. The skylight extends above the roof to provide space for openings to allow exit for waste air out of the building (facilitating cooling through natural ventilation) as an additional measure to reduce the heat build-up as a result of solar heat through the skylight.

Figure 7.2 shows a schematic illustration of the effect of a skylight for illumination and air circulation in the building.

The windows, if opened, will allow fresh air into the building which on warming will rise up the tubular skylight and escape through the openings on the sides at the upper part of the skylight. This continuous process will create a chimney effect which will reduce the heat build-up inside the building. The heat that is collected by the roof is blocked by the insulation layer between the roof and the lower part of the building before it reaches the working area of the building. This heat will then be removed by the air sweeping through the air space separating the roof and the lower part of the building.

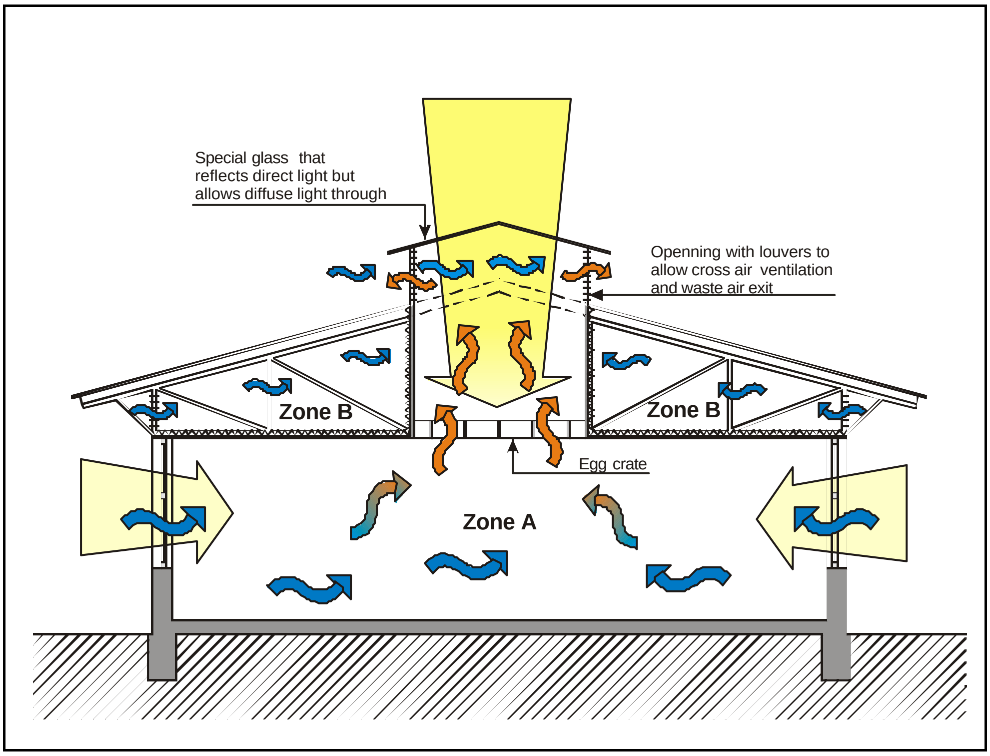



**Figure 7.2:** Schematic illustration of the effects of the skylight on both lighting and ventilation

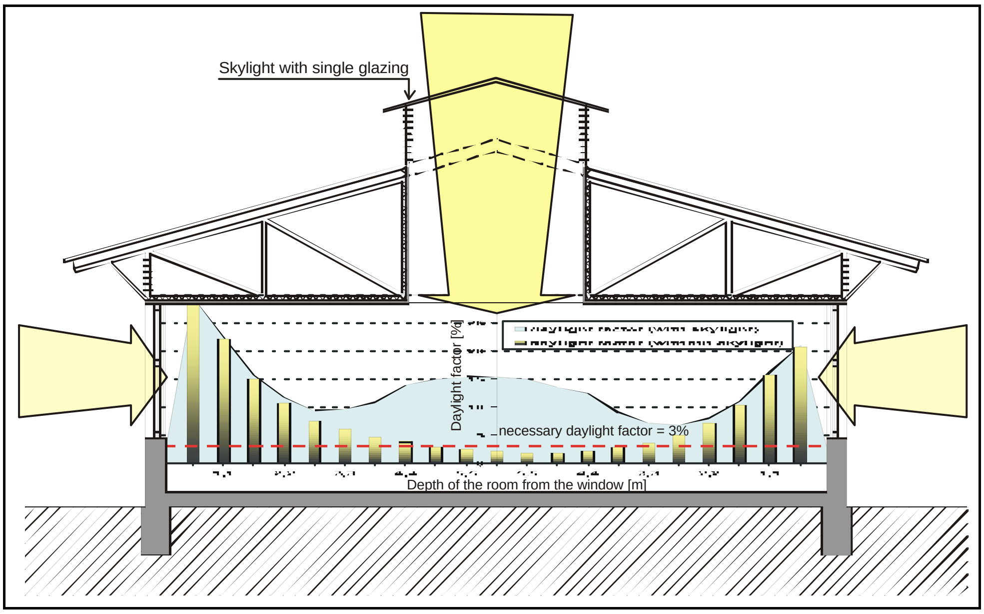



**Figure 7.3:** Comparing the daylight factor inside the building for a case with only side windows and one with additional skylight under overcast conditions.

We simulated the building with and without a skylight under overcast sky conditions to compare the illumination inside the building. We assumed that the skylight was constructed with single glazing. The effects of the louvers (egg-crate) below the skylight were not considered during the simulation.

Light through the skylight increased the illumination in the core of the building as shown on figure 7.3. There is however marked variations in the illumination distribution in the building. The areas near the window and at the rear of the building receives illumination levels far higher than that needed to accomplish most ambient visual tasks. Some measures have to be taken to reduce these illumination levels which might cause glare. Some of the measures have been discussed throughout this work.

The temperature inside the building with and without a skylight was compared. Despite the increase in solar radiation penetrating the building through the skylight (single glass), the anticipated increase in room temperature is suppressed by the increased rate of air movement facilitated by a combination of simultaneous opening of the windows and the openings on the top of the skylight (chimney effect). The room temperature in the building with a skylight is in the range of 1°C below that when no skylight was considered (Figure 7.4).

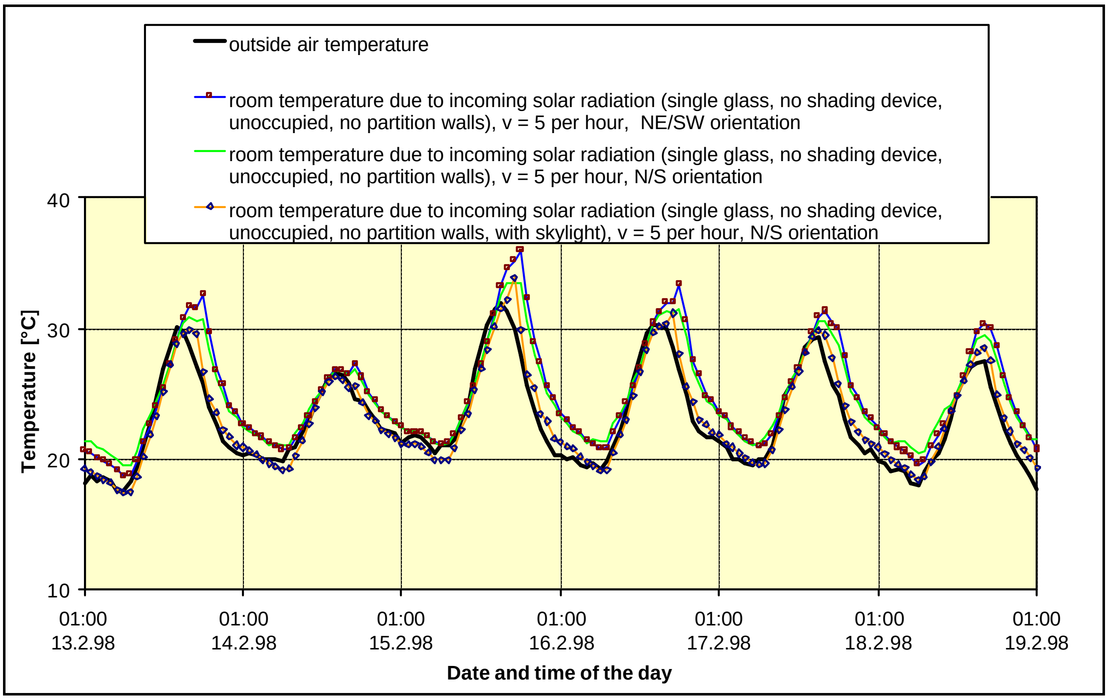



**Figure 7.4:** Comparing the temperature inside the building for a case with only side windows and one with additional skylight for the month of February

We were not able to quantify both the effect of the louvers or egg-crate below the skylight on the intensity of light entering the building through the skylight and substituting single glass with reflective glass on the temperature inside the building.

# 8 The economy of using daylight in buildings in tropical regions.

The usefulness of daylight in a building can be measured by considering three major aspects: The quality of the space lit by daylight, the percentage of the building adequately lit by daylight and the duration such a space will be adequately lit. This "*time - and - space"* relationship is the basis of determining how economical and useful lighting a building with daylight can be. Daylight can be a useful source of light in buildings if the "*time - and - space"* relationship is carefully balanced. Building designers have to consider, at the very beginning of the design process several factors discussed in this work, in order to optimise the usefulness of using daylight in buildings. We used the administration building at Virika hospital to analyse the economic efficiency of using daylight in a building. In order to have adequate and qualitative daylight inside a building for a long period, some costs have to be incurred. These costs are for:

→ the construction of daylighting structures like skylights, which are complicated and costly
→ the installation of daylighting systems designed to increase the amount of daylight inside the building
→ the need for maintenance in the form of regular cleaning of the daylighting structures like skylight and windows, in order to allow more light into the building
→ minimising the effects of overheating and glare as a result of allowing more daylight into the building by installing solar and glare screening devices
→ ensuring security in buildings with large glazed surfaces in which the risks are higher (a case for the developing world).

The controversies of the use of daylight in buildings and the accompanying problems have already been discussed. It is now evident that adequately illuminating a building with daylight is not free. Where conditions allow, the use of daylight has to be supplemented with artificial light. In such a case, we can use daylight to the limits of its usefulness and then supplement it.

Illumination in the administration building (current state) is as a result of light through the side windows. The estimated illumination level necessary to carry on many ambient visual tasks in the building is 500 lux. The average outside illumination on a horizontal plane for the region of Kasese under an overcast sky generated by the light simulation program SIVIEW is 16 772 lux. This gives an average daylight factor of 3%. These figures constantly change depending on the state of the sky. The building was symbolically divided into zones A and B according to the illumination distribution in the building shown in figure 8.1. The areas near the window receive enough daylight while those at the rear of the building do not. The case of illuminating the rear areas of the building through the skylight was also considered.

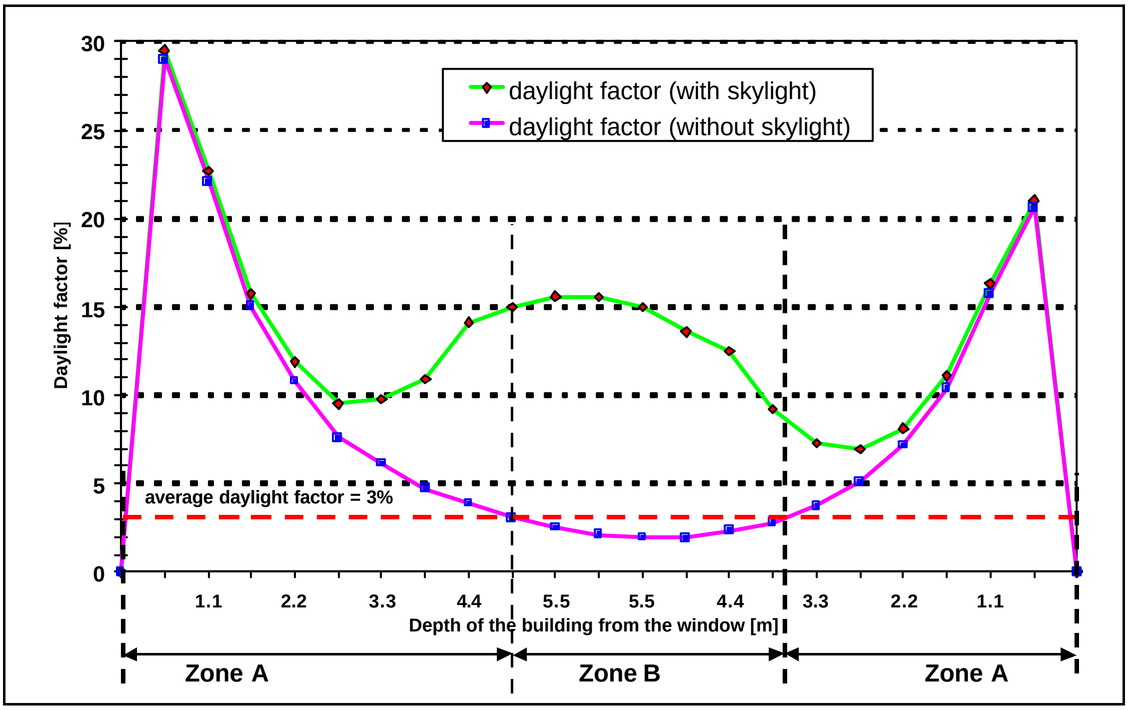



**Figure 8.1:** Illumination distribution as a result of daylight into the building with and without skylight

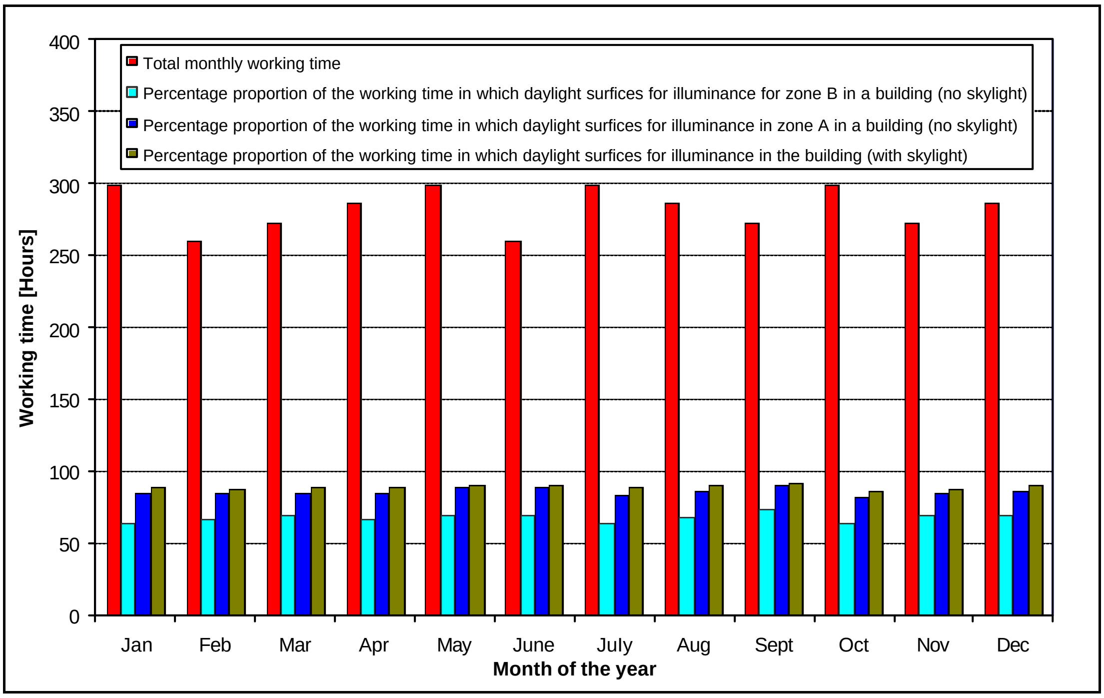



**Figure 8.2:** The total working time in a month and the percentage proportion of the time when daylight will be sufficient for illumination in the building

There is a total of 3394 working hours in a year for the period Monday to Friday from 7am to 7pm (without considering holidays). Depending on the time of the year, the number of working hours when daylight will be sufficient to illuminate the building varies with the state of the sky (cloudy or clear). Figure 8.2 shows the total number of working hours for every month and the time when daylight will be sufficient for illumination expressed as a percentage of the total monthly working time. The building with and without a skylight was considered. Artificial light has to be used to cover the period not adequately illuminated by daylight.

There are 14 luminaires installed in the reference building schematically shown in figure 8.3. These luminaires are manually controlled such that once they are switched on, they continue to burn irrespective of the illumination levels inside the building until they are switched off (Appendix 10). A case whereby these simple luminaires were connected to light sensors to control their switching on and off depending on the illumination level in the building was considered.

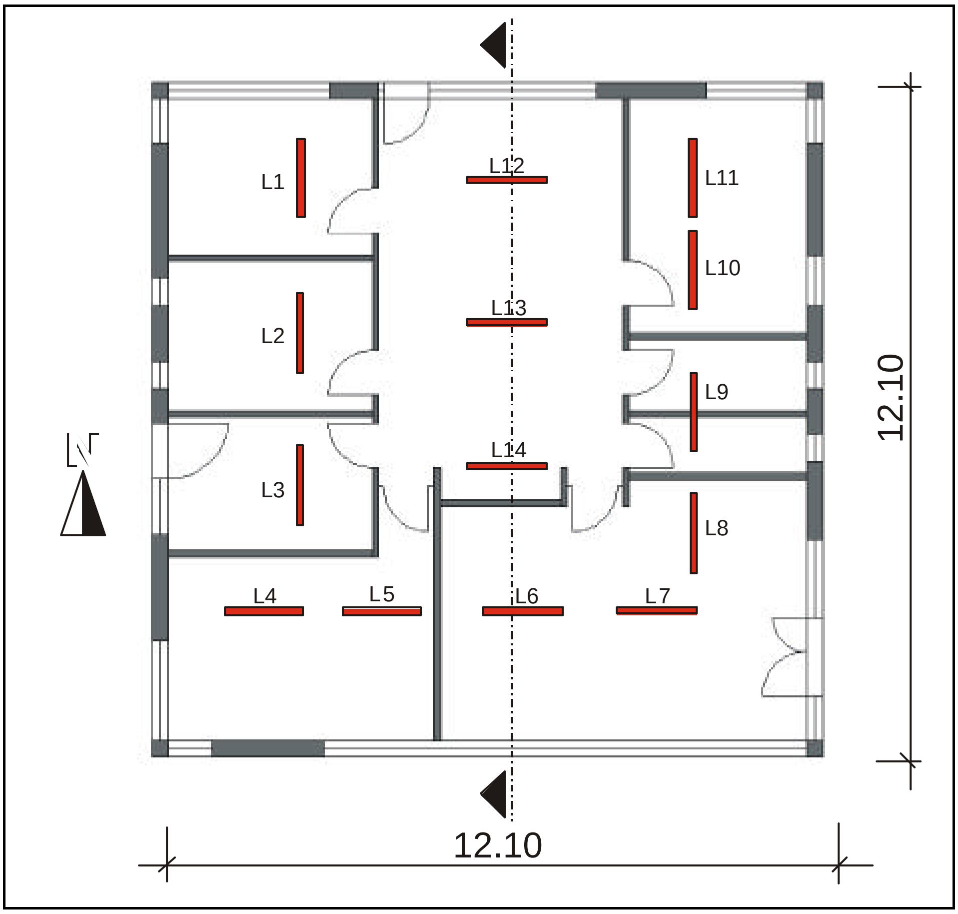



**Figure 8.3:** Schematic illustration of the position of the luminaires installed in the administration building

For the switching on of the luminaires, the following assumptions were made:

1. All luminaires were manually switched on at the beginning of the working day and switched off at the end i.e. from 7am to 7pm (current situation)
2. Luminairies in zone A i.e. (L1 - L11) and those in zone B i.e. (L12 – L14) were controlled in two separate groups. Each group was connected to one light sensor which monitored the illumination level in the particular zone. If the average illumination level in either zone was less than 500 lux on the working plane, the luminairies in that zone were automatically switched on and if the levels were 500 lux and above, they were switched off.

The sky condition for the region of Kasese i.e. how oft the sky was overcast or clear during the working period and the average luminance for every month is shown in table 8.1. Luminance under both overcast and clear sky varies from month to month.

| Month | Total monthly working time | The time when the sky is overcast during the working time | The time when the sky is clear during the working time | Average luminance on overcast days | Average luminance on clear days |
|---|---|---|---|---|---|
| | [Hours] | [Hours] | [Hours] | [lx] | [lx] |
| January | 299 | 205 | 94 | 22045 | 41203 |
| February | 260 | 189 | 71 | 25535 | 41971 |
| March | 273 | 220 | 53 | 27313 | 45332 |
| April | 286 | 223 | 63 | 24904 | 39506 |
| May | 299 | 196 | 103 | 24046 | 41604 |
| June | 260 | 173 | 87 | 22281 | 37256 |
| July | 299 | 231 | 68 | 23783 | 33050 |
| August | 286 | 211 | 75 | 24486 | 41436 |
| September | 273 | 197 | 76 | 26893 | 38671 |
| October | 299 | 195 | 104 | 21079 | 46982 |
| November | 273 | 185 | 88 | 24690 | 37994 |
| December | 287 | 178 | 109 | 22953 | 46629 |

**Table 8.1:** The total monthly working time and the sky condition during this period for the region of Kasese, Uganda

In order to establish the economic advantages of illuminating the building with daylight, several variations of the building were considered. The building in its current state was the basis of the evaluation. By setting the minimum illumination level inside the building at 500 lux, we were able to calculate the time when daylight was sufficient for lighting the building during the working period Monday to Friday from 7am to 7pm. The time when artificial light was necessary could also be easily established. The influence of the skylight and adjustable louvers on the amount of daylight in the building and also the replacement of the simple luminaires with upgraded ones were also considered. The following variations were considered for the evaluation:

## Variation 1

Considers the building in its current state i.e. light into the building is through side windows (without a skylight and sun-shading device) shown in figure 8.1.

Zone A receives enough light through the side windows under average overcast sky conditions. The average daylight factor in this zone is 9%. This implies that for zone A we need a minimum outside illumination of 5556 lux on a horizontal plane in order to acquire the necessary 500 lux in this zone. There are 2839 working hours in a year when illumination in zone A will be satisfied with light through the side window under both overcast and clear sky conditions. The remaining 555 hours will not be adequately illuminated with daylight such that artificial light will have to be switched on.

Zone B will not be adequately lit by daylight under average sky conditions. The average daylight factor in zone B is 2.4%. We need a minimum outside illumination of 20 833 lux on a horizontal plane in order to acquire the necessary 500 lux in this zone. There are 2031 working hours in a year when illumination in zone B will be satisfied with light through side windows. Artificial light will have to be switched on for the remaining 1363 hours in order to acquire the necessary illumination level in this zone (Table 8.2). By using artificial light, the following alternatives were considered:

a) simple luminaires
b) simple luminaires with light sensor (separate control for zone A and B)
c) upgraded luminaires with electronic ballast integrated with light sensor (separate control for zone A and B)
d) simple luminaires with light sensor and adjustable louvers (separate control for zone A and B)

| Month | Total monthly working time | The time when the sky is overcast during the working time | The time when the sky is clear during the working time | The time when daylight is sufficient for illumination in the reference building | | | | Total time when daylight is not sufficient for illumination | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Zone A | | Zone B | | Zone A | | Zone B | |
| | | | | overcast sky | clear sky | overcast sky | clear sky | overcast sky | clear sky | overcast sky | clear sky |
| | [Hours] | [Hours] | [Hours] | [Hours] | [Hours] | [Hours] | [Hours] | [Hours] | [Hours] | [Hours] | [Hours] |
| January | 299 | 205 | 94 | 158 | 90 | 97 | 76 | 47 | 4 | 108 | 18 |
| February | 260 | 189 | 71 | 147 | 68 | 102 | 54 | 42 | 3 | 87 | 17 |
| March | 273 | 220 | 53 | 177 | 53 | 125 | 49 | 43 | 0 | 95 | 4 |
| April | 286 | 223 | 63 | 180 | 61 | 113 | 53 | 43 | 2 | 110 | 10 |
| May | 299 | 196 | 103 | 153 | 96 | 98 | 84 | 43 | 7 | 98 | 19 |
| June | 260 | 173 | 87 | 137 | 82 | 84 | 71 | 36 | 5 | 89 | 16 |
| July | 299 | 231 | 68 | 177 | 63 | 114 | 54 | 54 | 5 | 117 | 14 |
| August | 286 | 211 | 75 | 171 | 75 | 108 | 61 | 40 | 0 | 103 | 14 |
| September | 273 | 197 | 76 | 165 | 74 | 110 | 62 | 32 | 2 | 87 | 14 |
| October | 299 | 195 | 104 | 141 | 102 | 86 | 88 | 54 | 2 | 109 | 16 |
| November | 273 | 185 | 88 | 141 | 87 | 101 | 71 | 44 | 1 | 84 | 17 |
| December | 287 | 178 | 109 | 139 | 102 | 84 | 86 | 39 | 7 | 94 | 23 |

**Table 8.2:** The monthly time when daylight is sufficient and when it is not sufficient for illumination in the reference building under overcast and clear sky conditions

**Variation 2**

Considers the building lit from side windows and through the skylight. Under average sky conditions, the building (both zone A and B) will be adequately lit. The average illumination level in the building is 13% (Figure 8.1). In order to have the minimum illumination level of 500 lx in the building, we need a minimum outside illumination on a horizontal plane of 3846 lux. There are 3004 working hours in a year when illumination in the building (zone A and B) will be satisfied with light through the side window and the skylight for both overcast and clear sky conditions. Artificial light will have to be switched on for the remaining 390 hours in order to adequately illuminate the building (Table 8.3).

By using artificial light, the following alternatives were considered:

a) simple luminaires
b) simple luminaires with light sensor (single control for zone A and B)
c) upgraded luminaires with electronic ballast integrated with light sensor (single control for zone A and B)
d) simple luminaires with light sensor and adjustable louvers (single control for zone A and B)

| Month | Total monthly working time | The time when the sky is overcast during the working time | The time when the sky is clear during the working time | The time when daylight is sufficient for illumination in the reference building with skylight | | Total time when daylight is not sufficient for illumination in the building with skylight | |
|---|---|---|---|---|---|---|---|
| | | | | Zone A and B | | Zone A and B | |
| | | | | overcast sky | clear sky | overcast sky | clear sky |
| | [Hours] | [Hours] | [Hours] | [Hours] | [Hours] | [Hours] | [Hours] |
| January | 299 | 205 | 94 | 171 | 93 | 34 | 1 |
| February | 260 | 189 | 71 | 156 | 71 | 33 | 0 |
| March | 273 | 220 | 53 | 191 | 53 | 29 | 0 |
| April | 286 | 223 | 63 | 191 | 61 | 32 | 2 |
| May | 299 | 196 | 103 | 167 | 98 | 29 | 5 |
| June | 260 | 173 | 87 | 147 | 83 | 26 | 4 |
| July | 299 | 231 | 68 | 195 | 65 | 36 | 3 |
| August | 286 | 211 | 75 | 183 | 75 | 28 | 0 |
| September | 273 | 197 | 76 | 174 | 76 | 23 | 0 |
| October | 299 | 195 | 104 | 154 | 104 | 41 | 0 |
| November | 273 | 185 | 88 | 154 | 88 | 31 | 0 |
| December | 287 | 178 | 109 | 150 | 104 | 28 | 5 |

**Table 8.3:** The monthly time when daylight is sufficient and when it is not sufficient for illumination in the building with skylight under overcast and clear sky conditions

The time when daylight will be sufficient for illumination in the building drastically increases if the additional light through the skylight is considered. Zone B of the reference building which does not receive enough light from the side windows will benefit more from light through the skylight (Figure 8.1), which will reduce the need to use artificial light for illumination. Figure 8.4 shows a graphic in which the time when light will be sufficient for illumination in the reference building with and without the skylight is compared. The time when daylight will not be sufficient is also represented.


**Figure 8.4:** The time when light will be sufficient for illumination in a building with and without a skylight.

Table 8.4 shows the parameters which were considered for the calculation of the cost of electric energy consumed in the building.

| Building | Total area [m²] | Total glazed area (single glass) [m²] | Total area of the skylight [m²] | Number of Luminaire | Cost of electricity [€/kWh] | Total annual working time [Hours] |
|---|---|---|---|---|---|---|
| Administration block | 147 | 53 | 9 | 14 | 0.1 | 3394 |

**Table 8.4:** Different parameters considered for the evaluation of the economic efficiency of using daylight in the administration building

The cost of electricity for illuminating the building for variation 1 (current state of the building) where the lights are left on for the whole working time and also the costs when illumination is only used when daylight is not sufficient in both zone A and B are shown in table 8.5. The costs do not include the investment for controlling the switching on of the lamps and maintenance.

| Month | Total monthly working time | Electricity consumed by using 14 luminaires with a total output of 50W each | Cost of electricity required for lighting [0.1€/kWh] | Total time when artificial light is required in the reference building (no skylight) | | Electricity consumed by using 14 luminaires with a total output of 50W each | | Cost of electricity required for lighting [0.1€/kWh] | | Total cost of electricity required |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Zone A | Zone B | Zone A (11 luminaires) | Zone B (3 luminaires) | Zone A | Zone B | Zone A and B |
| | [Hours] | [kWh] | [€] | [Hours] | [Hours] | [kWh] | [kWh] | [€] | [€] | [€] |
| January | 299 | 209.3 | 20.93 | 51 | 126 | 28.05 | 18.9 | 2.81 | 1.89 | 4.7 |
| February | 260 | 182 | 18.20 | 45 | 104 | 24.75 | 15.6 | 2.48 | 1.56 | 4.04 |
| March | 273 | 191.1 | 19.11 | 43 | 99 | 23.65 | 14.85 | 2.37 | 1.49 | 3.86 |
| April | 286 | 200.2 | 20.02 | 45 | 120 | 24.75 | 18 | 2.48 | 1.8 | 4.28 |
| May | 299 | 209.3 | 20.93 | 50 | 117 | 27.5 | 17.55 | 2.75 | 1.76 | 4.51 |
| June | 260 | 182 | 18.20 | 41 | 105 | 22.55 | 15.75 | 2.26 | 1.58 | 3.84 |
| July | 299 | 209.3 | 20.93 | 59 | 131 | 32.45 | 19.65 | 3.25 | 1.97 | 5.22 |
| August | 286 | 200.2 | 20.02 | 40 | 117 | 22 | 17.55 | 2.2 | 1.76 | 3.96 |
| September | 273 | 191.1 | 19.11 | 34 | 101 | 18.7 | 15.15 | 1.87 | 1.52 | 3.39 |
| October | 299 | 209.3 | 20.93 | 56 | 125 | 30.8 | 18.75 | 3.08 | 1.88 | 4.96 |
| November | 273 | 191.1 | 19.11 | 45 | 101 | 24.75 | 15.15 | 2.48 | 1.52 | 4 |
| December | 287 | 200.9 | 20.09 | 46 | 117 | 25.3 | 17.55 | 2.53 | 1.76 | 4.29 |
| | | | | | | | | | | |
| Total | 3394 | 2375.8 | 237.58 | 555 | 1363 | 305.25 | 204.45 | 30.53 | 20.49 | 51.02 |

**Table 8.5:** The total cost of electricity in the reference building when artificial light is used throughout the working period and when it is only used when daylight was not sufficient

| Month | Total monthly working time | Electricity consumed by using 14 luminaires with a total output of 50W each | Cost of needed electricity for lighting [0.1€/kWh] | Total time when artificial light is required in the reference building (with skylight) | Electricity consumed by using 14 luminaires with a total output of 50W each | Total cost of electricity required for lighting [0.1€/kWh] |
|---|---|---|---|---|---|---|
| | | | | Zone A and B | Zone A and B | Zone A and B |
| | [Hours] | [kWh] | [€] | [Hours] | [kWh] | [€] |
| January | 299 | 209.3 | 20.93 | 35 | 24.5 | 2.45 |
| February | 260 | 182 | 18.20 | 33 | 23.1 | 2.31 |
| March | 273 | 191.1 | 19.11 | 29 | 20.3 | 2.03 |
| April | 286 | 200.2 | 20.02 | 34 | 23.8 | 2.38 |
| May | 299 | 209.3 | 20.93 | 34 | 23.8 | 2.38 |
| June | 260 | 182 | 18.20 | 30 | 21 | 2.10 |
| July | 299 | 209.3 | 20.93 | 39 | 27.3 | 2.73 |
| August | 286 | 200.2 | 20.02 | 28 | 19.6 | 1.96 |
| September | 273 | 191.1 | 19.11 | 23 | 16.1 | 1.61 |
| October | 299 | 209.3 | 20.93 | 41 | 28.7 | 2.87 |
| November | 273 | 191.1 | 19.11 | 31 | 21.7 | 2.17 |
| December | 287 | 200.9 | 20.09 | 33 | 23.1 | 2.31 |
| | | | | | | |
| Total | 3394 | 2375.8 | 237.58 | 390 | 273 | 27.3 |

**Table8.6:** The total cost of electricity in the building with a skylight when artificial light is used throughout the working period and when it is only used when daylight was not sufficient

Table 8.6 shows the cost of electricity in the building with a skylight. The costs are exclusive of the construction and maintenance costs of the skylight as well as for the control mechanism for the switching on of the luminaires.

Figure 8.5 shows the graphic representation of the total annual cost of electricity needed to illuminate the building for variations 1 and 2 without considering the additional cost of luminairies, a controller, louvers and for the construction of the skylight. The cost of electricity will be reduced by 78.6% for variation 1 and by 88.7% for variation 2 if artificial light is only switched on when daylight is not sufficient for illumination.

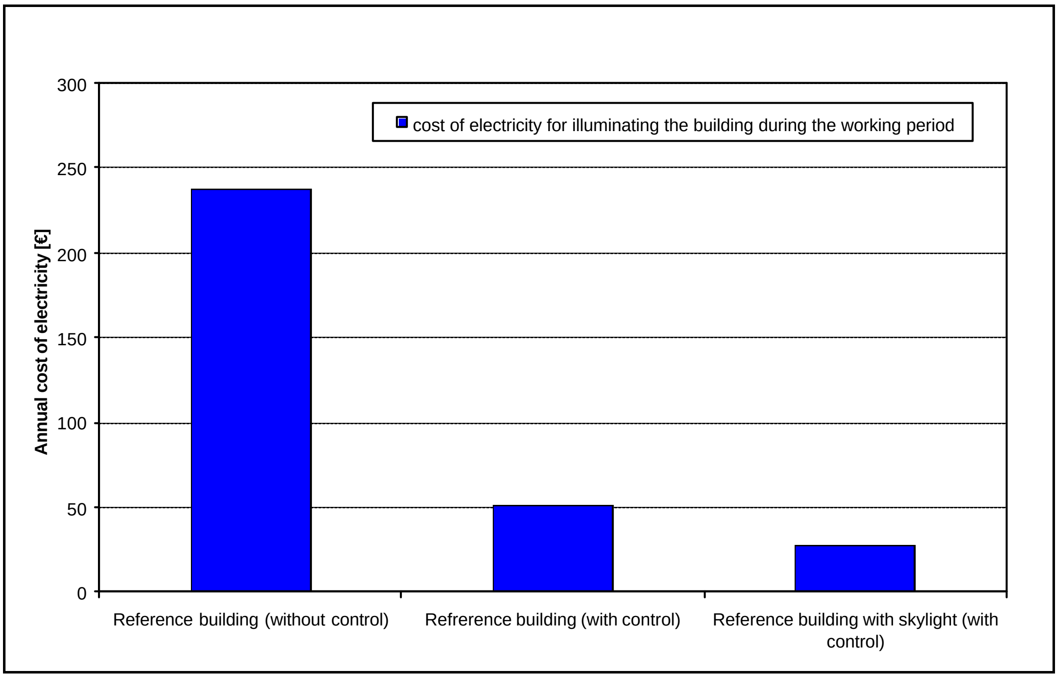



**Figure 8.5:** The cost of electricity in a year needed to illuminate the building with and without a skylight.

The cost of electricity for illuminating the building during the working period for variations 1 and 2 including the investment costs of the different components was analysed. The following alternatives were considered for the evaluation:

a) The cost of constructing the skylight to improve illumination of the rear area of the building

b) The cost of the shading device used to stop solar heat from entering the building but can allow some light into the building (Figures 4.19 and 4.20)

c) The cost of high efficiency luminaires with electronic ballast which consumes less energy and minimises thermal output

Table 8.7 outlines the components for the different alternatives considered for variations 1 and 2. The total cost of the components and electricity consumed annually for the different variations is shown in figure 8.6.

A case of when the cost of the extra component for each of the different variations was divided over a period of 12 years was considered. The total annual cost of electricity and the components is shown in figure 8.7.

| Variation | Alternative | Total time in a year when daylight is not adequate | | Cost of different components and electricity: Simple luminaire with a total output of (50W) 20€/piece* | | Simple luminaires (50W) controlled by two light sensors (20€/piece* + 40€/sensor *) | | Luminaires with electronic ballast (36W) controlled by two light sensors (150€/piece* + 40€/sensor *) | | Skylight | Adjustable Louvers | Total cost of all the used components |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Zone A | Zone B | Zone A (11 luminaires) | Zone B (3 luminaires) | Zone A (11 luminaires) | Zone B (3 luminaires) | Zone A (11 luminaires) | Zone B (3 luminaires) | 75€/m² * | 100€/m² * | |
| | | [Hours] | [Hours] | [€] | [€] | [€] | [€] | [€] | [€] | [€] | [€] | [€] |
| 1a | Reference building (current state) | 555 | 1363 | 220 | 60 | - | - | - | - | - | - | 280 |
| 1b | Reference building with simple luminaires | 555 | 1363 | - | - | 240 | 100 | - | - | - | - | 340 |
| 1c | Reference building with upgraded luminaires | 555 | 1363 | - | - | - | - | 1690 | 340 | - | - | 2030 |
| 1d | Reference building with simple luminaires (controlled) + | 555 | 1363 | - | - | 240 | 100 | - | - | - | 2000 | 2340 |
| | | Zone A and B | | Zone A and B | | Zone A and B | | Zone A and B | | | | |
| 2a | Reference building with skylight | 390 | | 280 | | - | | - | | 900 | - | 1180 |
| 2b | Reference building with skylight + simple luminaires (controlled) | 390 | | - | | 320 | | - | | 900 | - | 1220 |
| 2c | Reference building with skylight + upgraded luminaires (controlled) | 390 | | - | | - | | 2140 | | 900 | - | 3040 |
| 2d | Reference building with skylight + simple luminaires (controlled) + adjustable louvers | 390 | | - | | 320 | | - | | 900 | 2000 | 3220 |

* Estimated preis on the Ugandan market

**Table 8.7:** The cost of the components for the different alternatives for variations 1 and 2

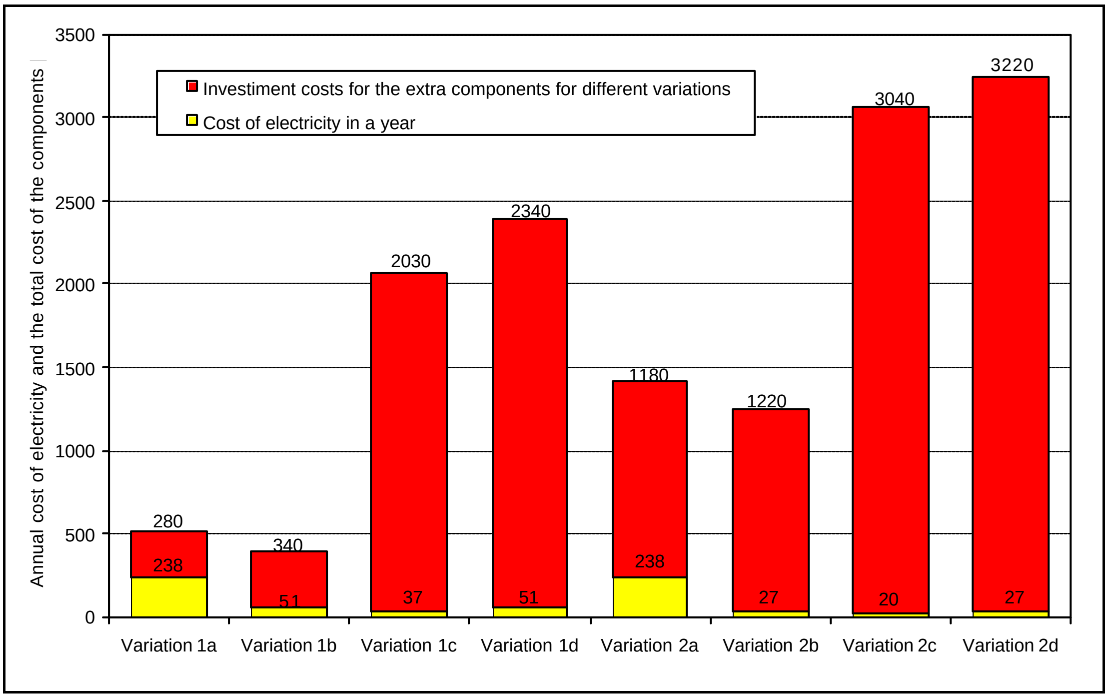



**Figure 8.6:** Comparing the cost of electricity in one year and the components for different variations of the building

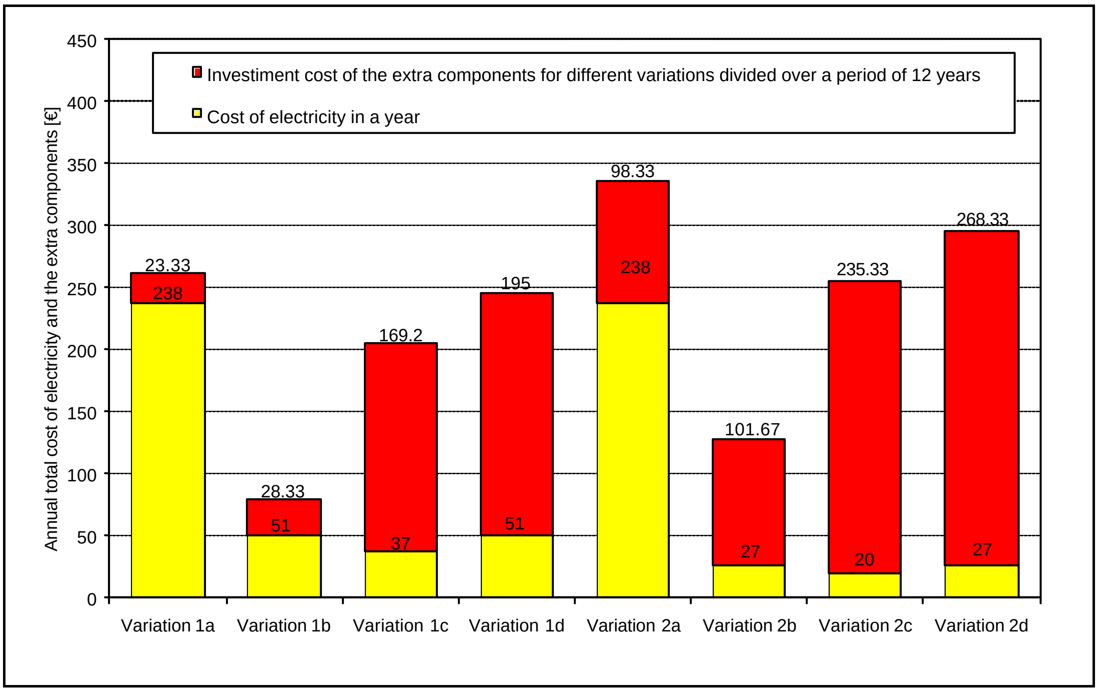



**Figure 8.7:** Comparing the total annual cost of electricity and the components for different variations of the building when the investment cost of the components is divided over a period of 12 years

The following analysis was made for the different variations:

***Variation 1a:*** The annual energy consumption in the reference building is high although the cost of the used luminairies is low. This is due to the fact that some areas of the building particularly the rear areas, are not adequately lit with light from side windows during the working period meaning that artificial lighting will have to be switched on for a long period. The simple luminaires installed in the building are manually controlled. People tend to switch them on at the beginning of work and only switch them off at the end of their working time although at some time of the day, artificial light is not necessary. This results in an increase of electricity consumption.

***Variation 1b:*** Using light sensors to monitor the illumination levels in the building and control the switching on of artificial light, will drastically reduce the amount of energy needed for lighting. Artificial light will only be switched on only when daylight is not sufficient. There is a slight increase in investment costs (for the light sensors) as compared to variation 1 but the annual cost of electricity would be reduced by 78.6%.

***Variation 1c:*** Replacing the simple luminaires with upgraded ones (with electronic ballast) which are automatically controlled as in variation 2, will further reduce the cost of energy consumed by 6% below that of simple luminairies. The investment costs will be six times higher than that in variation 2.

***Variation 1d:*** The adjustable louvers are assumed to be opened when the sky is overcast and closed when the sky is clear to block direct radiation especially on the orientations of the building which will be directly exposed to the sun (Figure 4.15 and 4.21). When the louvers are closed, the areas near the window will nevertheless receive enough light (Figure 4.20) that artificial lighting will not need to be switched on. Artificial lighting in this case will be switched on as in variation 1b. The louvers are used to reduce heat penetration into the building while allowing a view to the outside. The cost of such louvers is high.

***Variation 2a:*** Light through the skylight increases illumination at the rear area of the building which increases the time when daylight will be sufficient for illumination in the building (Figure 8.4). If simple luminaires which are manually controlled are used, the electricity consumed will be as much as that in variation 1a despite the increase in daylight. The investment cost for the construction of the skylight are relatively high.

***Variation 2b:*** Controlling the switching on of the luminaires in the building will reduce the total cost of electricity used by 88.7% below that in variation 1a and 2a. This is also 10% lower than that of the building under similar conditions but without a skylight (variation 1b). The extra cost of constructing the skylight will be compensated for by the low cost of electricity and the other advantages discussed in chapter 7.

***Variation 2c:*** Replacing the simple luminaires with upgraded ones will result in a further reduction in the total cost of electricity by 3% below that of simple luminaires but the investment costs will be three times higher.

***Variation 2d:*** As the case in variation 1d, the adjustable louvers when closed, will block direct light from entering the building through side windows. The areas near the window will receive enough light whereas the rear areas of the building will be lit with light through the skylight. The total cost of electricity will be the same as in variation 2b. A combination of the skylight and the louvers offers the best alternative for using daylight in the building while minimising the negative effects of overheating and glare. However, the investment costs for the skylight and the louvers is very high. This will in effect increase the payback time which might render the use of daylight very expensive.

By dividing the cost of the components over a period of 12 years (Figure 8.7) indicates that by controlling the switching on of the simple luminaires (variation 1b) will have overriding advantages over the other variation in terms of total annual cost of electricity and components. This variation however, does not take into account the negative effects of allowing uncontrolled solar radiation into the building which will result in overheating and glare as discussed before.

Variation 2b (skylight with automatically controlled simple luminaires) offers a relatively good and affordable alternative. The skylight will not only increase the amount of light in the building, there are also other advantages discussed in chapter 7 which will positively contribute to the improvement of the working situation in the building.

The high solar intensity through the side window can be reduced by using glare screening devices (Figure 5.10), which can also block some heat from entering the building. These devices are comparatively cheaper than adjustable louvers. The effectiveness of the glare screening device in reducing solar heat gain in the building is not as good as when louvers are used. Their application in this case, is a result of financial constraints as far as the cost of the adjustable shading device is concerned.

# 9 Summary of the results of this dissertation thesis and outlook

There is a growing demand world-wide for alternative energy sources which are less destructive to the environment but also affordable. Affordable energy is also the basis for sustainable development. This is even more the case in regions which do not have fossil energy resources or the ability to make use of alternative energy sources like wind or solar. We need to systematically identify the areas which consume more energy and look for solutions based on the demands for each individual case. Energy consumption, in buildings for instance, is basically for lighting, cooling in the case of hot regions and running electrical equipment and appliances. We can, in this case, develop concepts to meet these different energy needs in buildings individually or collectively. The main aim of this work was to try to assess the extent to which daylight can be used for lighting in buildings in tropical regions particularly hot and humid ones, with minimal negative consequences. The conclusions below are made from the different building simulations of the newly constructed administration building of Virika hospital complex, Kasese, Uganda which were carried out throughout this work.

**Improve the quality of room illumination**

Because of the varying climatic conditions in tropical regions and the varying nature of the buildings, daylighting in a building must be considered separately for every individual case. Conditions that may be conducive for the use of daylight in one building may not necessarily be appropriate for other buildings. The use of daylight has to be considered during the planning process of the building. This will ensure adequate amounts of daylight in the building which will not cause visual stress and overheating due to excess solar radiation entering the building.

**Reduce the amount of energy needed to illuminate the building**

Based on the climatic conditions for the region of Kasese, Uganda, illumination in an open space during daytime working hours (7am to 7pm) is so high that we only need to allow a small percentage of light into the building (Figures 4.2 and 4.3) to meet lighting demands for most ambient tasks. If the building is properly planned for the use of daylight (Chapter 7), daylight can meet up to 80% of the illumination demands in the building as shown in figure 8.4. This will ensure a reduction in the need to use artificial light in the building.

**Increased costs for the construction of daylighting systems**

There is a marked increase in the total construction cost of the building if the additional cost for daylight structures like skylight or daylighting systems is considered. Such structures, however, increases the amount of daylight in the building which will in effect reduce the need to illuminate the building with artificial light (Figure 8.4). The investment costs will be compensated for by the reduction in the cost of electricity in addition to other benefits identifiable for the particular system used (Table 7.1). If for instance a skylight is properly designed, apart from improving illumination in the building, they can facilitate air circulation in the building necessary to keep the building cool. These structures (systems) however, must be carefully chosen in order to shorten the payback period.

**Reduce the operating costs in a building**

The more daylight we can bring into the building, the more we will reduce the dependence on artificial energy. However, daylight can not meet all the illumination demands in the building all the time (Figure 8.2). In order to minimise the cost of artificial light, we need to use luminaires, integrated with a control mechanism, capable of reacting to the illumination levels inside the building. Such luminaires have to be automatically controlled. Compared to the simple luminaires which are manually controlled, luminaires with integrated control mechanism are slightly more expensive although the annual cost of electricity consumed will be reduced by up to 78%. This will not only reduce the cost of electricity but also the working life of the luminaires will be prolonged.

**Reduce heat gain resulting from the use of artificial lights inside buildings**

Uncontrolled use of artificial lights does not only increase the energy costs, it emits heat that influences the thermal balance in the building as shown in figure 5.11. This will raise the cooling load and effectively increase the operational costs of the building. There is therefore a need to control the use of artificial light by either using energy efficient lamps with low thermal output or to apply control mechanisms for the switching on and off of the simple luminaries in order to reduce the increase in room temperature as a result of heat released by the luminaires.

**Limitation of flexibility in planning of buildings (e.g. the depth of the rooms)**

In order to have enough daylight in the building, we need to carefully consider several factors during the planning phase so that light can be allowed into the building when it is required, to areas where it is needed and in quantities that does not cause visual stress. These factors are the proper dimensioning of the space inside the building to be lit by daylight, choosing the right texture (colour) for the surfaces of the interior space, the size, position and orientation of the window and the type of glazing (section 4.1.2). Considering all the above mentioned factors will curtail the freedom to design the building as one might wish. Buildings in tropical regions which are designed without considering the above factors will have to be artificially lit or mechanically cooled. Such buildings are highly uneconomical and should be avoided if possible.

**Increase in solar heat gain and glare threats inside the building**

Permitting solar radiation into the building will result in an increase in solar heat gain in the building (Figure 3.5). The problem is aggravated by increasing the area of the glazed surface in order to allow more light into the building or if there are large glazed surfaces on the west or east orientations of the building (Figure 3.6). To be able to increase the illumination levels inside the building while minimising the increase in solar heat gain and glare, the following recommendations are very helpful:

a) The window can be designed with separated apertures for light and view so that the lower part can be treated to allow view to outside while blocking solar heat from entering the building whereas the upper part can be used for daylighting (Figure 5.9).
b) Any skylights should be built with highly reflective glass that allows enough light but blocks solar heat into the building. They should be constructed to facilitate air circulation in the building which is necessary to reduce the room temperature.
c) The use of innovative daylighting and sun-shading systems (Figures 4.19, 4.22) can reduce the increase in solar heat gain in the building while allowing enough light into the building. However, innovative daylighting and sun-shading systems should be chosen after carefully analysing their characteristics (Table 7.1). Some of these systems are so expensive that their ability to enhance the use of daylight in buildings will not be economical compared to more simplistic systems. For buildings in tropical regions, systems that allow daylight into the building but do not block solar heat or which block solar heat but do not allow light into the building, should not have the first priority.

The method of simulating buildings using the modern computer technology to assess their functioning is a very useful tool which is widely applied in the developed world. Such simulations can give designers reliable information about different aspects of the building prior to construction. Whole buildings or a part of a building can be simulated during the planning phase, which can give designers an opportunity to undertake the necessary modifications to optimise the use of energy in the building. These computer programmes must have the correct weather information for the location of the building to be simulated in order to give reliable results. Some of these programmes are designed to use the CIE sky model, which may not accurately reflect the climatic conditions for some regions of the world especially tropical regions with wide ranging climate variations, leading to incorrect information regarding the performance of the building. In such a case, there is therefore a need to develop a “tropical sky model” which will take into account the climatic conditions in tropical regions.

In addition to using computer models to assess the functioning of a building, physical measurements of the conditions inside the building (which is common in the developed world), must be undertaken to help us to test the efficiency of computer programmes by comparing the measured and the simulated results. This will enable us to adopt the appropriate technology suitable for use in tropical regions.

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# 11 Appendix


*Appendix 1:* View of the Main Entrance, Virika Hospital

*Appendix 2:* View of the roofed walk way connecting different buildings of the private wing

*Appendix 3:* Elevation of the east side of the administration building (refer to figure 3.1)

*Appendix 4:* Perspective showing the west and south side of the administration building (refer to figure 3.1)

*Appendix 5:* Elevation of the west side of the administration building (refer to figure 3.1)

*Appendix 6:* Perspective showing the Entrance (north side) of the administration building (refer to figure 3.1)


*Appendix 7:* View of the reception area of the administration building (window facing north which we used for daylight calculation)


*Appendix 8:* View of the waiting area (patients waiting to see the Doctor)

*Appendix 9:* View of the Nurses´ Station

*Appendix 10:* View into the patients´ ward (note the burning lights despite the glazed window that brings in enough daylight)

Table 7: Sequency of determining the necessity, abilities and compatibility of different daylighting and sun-shading systems in buildings

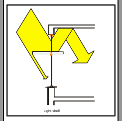
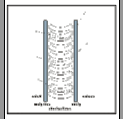
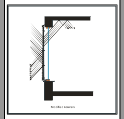
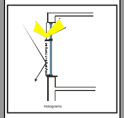
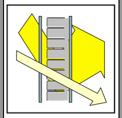
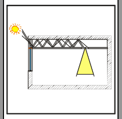
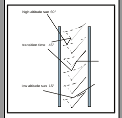
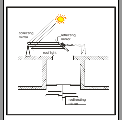
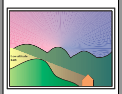
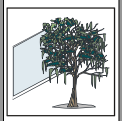
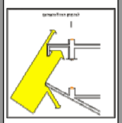
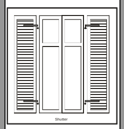
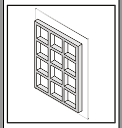
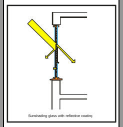
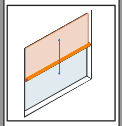
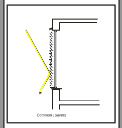
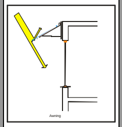
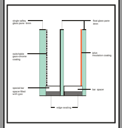
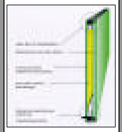
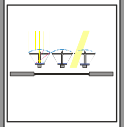
| EXAMPLES | SCHEMATIC ILLUSTRATION | TYPE OF PLACING | ABILITIES | | | | | | | | | METHOD OF CONTROL | DURABILITY | USERS ACCEPTANCE | EFFECTIVENESS AS PER REGION | | | | | | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | TEMPERATE REGIONS | | | TROPICAL REGIONS | | | |
| | | | increasing core illuminance | reducing solar heat gain | allowing view to outside | integration into facade planning | glare control | providing privacy | mounting | maintenance | air circulation | | | | Conditions | Availability | Costs | Conditions | Availability | Costs | |
| light-shelf |  | both sides of the facade | good | good | excellent | excellent | good | poor | easy | necessary | excellent | not necessary | long | good | depends on the orientation | readily available | affordable | depends on the orientation | readily available | affordable | - effective only for high solar altitude<br>- the shading effect and glare protection is depends on the dimensions (the longer the device, the bigger the part of the window to be shaded)<br>- inner light shelf is more effective for protecting against glare |
| lumitop (reflecting glass) |  | between two glass pane, on the facade | good | good | poor | excellent | good | good | easy | necessary | poor | not necessary | long | good | should be mounted on the part of the window not used for view | readily available | expensive | should be mounted on the part of the wondow not used for view | not readily available | X | - have to be kept free from dust and other particles that may curtail their effectiveness<br>- should be adjusted to accomodate the high altitude sun in tropical regions<br>- assembling requires expertise<br>- there is no maintenance necessary though repair due to mulfunctioning can be complicated<br>- must be mounted on the part of the window not used for view |
| modified louvers (adjustable) |  | on either side of the facade | good | excellent | good | excellent | good | excellent | easy | necessary | good | manual / automatic | long | good | functions for the solar altitude in the range of 40°- 65° | readily available | expensive | functions for the solar altitude in the range of 40°- 65° | not readily available | X | - more effective if it is automatically adjustable taking into account the position of the sun<br>- the spacing of the blinds and nature of their surfaces should be carefully chosen in order to achieve maximum effectiveness<br>- have to be kept free from dust and other particles that may curtail their effectiveness |
| holograms |  | on facade and roof | good | not good | good | excellent | good | good | easy | necessary | XO | not necessary | long | good | need to be precisely assembled to guarantee good effectiveness | readily available | expensive | need to be precisely assembled to guarantee good effectiveness | not readily available | X | - can be used for decoration purposes<br>- have to be precisely installed in order to achieve maximum effectiveness<br>- have to be kept free from dust and other particles that may curtail their effectiveness |
| laser cut panels |  | on facade | excellent | poor | poor | good | good | good | easy | necessary | poor | not necessary | long | good | should be mounted on the part of the window not used for view | available | expensive | should be mounted on the part of the window not used for view | not readily available | X | - should be adjusted to accomodate the high altitude sun in tropical regions<br>- must be mounted on the part of the window not used for view<br>- there is no maintenance necessary though repair due to mulfunctioning can be complicated<br>- have to be kept free from dust and other particles that may curtail their effectiveness |
| luminous ceiling |  | in the ceiling | good | good | excellent | good | good | poor | not easy | not necessary | excellent | not necessary | long | X | effective only under sunny conditions | available | expensive | effective only under sunny conditions | not readily available | X | - it functions only under sunny conditions<br>- increased hieght of the rooms to create space for installation<br>- requires technical expertise |
| reflective mirror profiles integrated in glass pane |  | between two glass pane, on the facade | good | poor | poor | good | good | poor | easy | necessary | poor | not necessary | long | good | must be properly fixed to take into account the different solar altitudes | available | expensive | must be properly fixed to take into account the different solar altitudes | not readily available | X | - redirects light for low altitude sun<br>- their effectiveness depends on the angle at which the profiles are fixed<br>- requires regular maintenance<br>- has to be kept free from dust and other particles that may curtail their effectiveness |
| heliostat with light pipe |  | depends on the type | good | good | poor | XO | XO | XO | not easy | necessary | XO | automatic | XO | XO | only functional under sunny conditions | not readily available | expensive | only functional under sunny conditions | not readily available | X | - regular maintenance is necessary<br>- requires technical expertise<br>- not siutable for cloudy sky conditions |
| topology |  | should not block the wind movement | poor | good | excellent | XOX | poor | XOX | XOX | XOX | excellent | not necessary | long | excellent | depends on the tilt of the land | readily available | XOX | depends on the tilt of the land | readily available | XOX | - can be effective in reducing the influence of direct solar radiation on buildings |
| vegetation |  | on all sides of the building | poor | good | good | excellent | good | good | XOX | necessary | excellent | not necessary | XOX | excellent | must be proportionally spaced from the building | readily available | XOX | must be proportionally spaced from the building | readily available | XOX | - depends on the size, type, distance from the building<br>- more effective when combined with other shading facilities |
| roof projection, balconies, protruding edge beams |  | on all facades especially north and south | poor | good | excellent | excellent | good | good | easy | necessary | excellent | not necessary | long | good | higher altitude sun | readiy available | affordable | higher altitude sun | readily available | affordable | - depends on the dimension (length and position relative to the window)<br>- not so effective for low altitude sun on the east and west orientation |
| shutter |  | on facade | poor | excellent | poor | good | good | excellent | easy | not necessary | good | manual | long | good | has to be manually openned or closed | readily available though not commonly used | cheap | has to be manually openned or closed | readily available | affordable | - affected by prevailing weather conditions<br>- influences the appearance of the facade |

Table 7: Sequency of determining the necessity, abilities and compatibility of different daylighting and sun-shading systems in buildings (**continued...**)

| EXAMPLES | SCHEMATIC ILLUSTRATION | TYPE OF PLACING | ABILITIES | | | | | | | | | METHOD OF CONTROL | DURABILITY | USERS ACCEPTANCE | EFFECTIVENESS AS PER REGION | | | | | | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | TEMPERATE REGIONS | | | TROPICAL REGIONS | | | |
| | | | increasing core illuminance | reducing solar heat gain | allowing view to outside | integration into facade planning | glare control | providing privacy | mounting | maintenance | air circulation | | | | Conditions | Availability | Costs | Conditions | Availability | Costs | |
| egg crate, moucharabia |  | on facade | poor | good | excellent | good | good | good | easy | not necessary | good | not necessary | long | good | must be properly dimensioned to guarantee effective shading and good view | readily available though not commonly used | X | must be properly dimensioned to guarantee effective shading and good view | readily available | affordable | - functions like combined vertical and horizontal fixed shading devices<br>- their effectiveness depends on the length and spacing of the projections<br>- should be spaced from the main facade to allow air circulation |
| sunshading glass |  | on facade and on the roof | poor | excellent | good** | excellent | good | good** | easy | necessary | poor | not necessary | long | excellent | the type of coating plays a big role | readily available | expensive | the type of coating plays a big role | available | expensive | - effectiveness depends on the coating material<br>- reflective surfaces may reflect sunlight to neighbouring buildings<br>- *may increase the cooling load in buildings*<br>- sunshading glasses depending on the coating may reduce light levels inside the building |
| curtains |  | on facade and roof (both sides) | poor | excellent | poor | excellent | good | excellent | easy | necessary | good | manual / automatic | long | excellent | more effective as external shading device | readily available | cheap | more effective as external shading device | available | affordable | - should be spaced from the facade to allow air circulation<br>- outside installed curtains are more effective than inside ones<br>- curtains out of materials with high light transmission coefficients can allow some light into the building<br>- external devices need regular maintenance and their duration is shorter than those mounted inside the building |
| common louvers vertical / horizontal) |  | on facade and on the roof (both sides) | poor | excellent | poor | good | good | excellent | easy | necessary | excellent | manual / automatic | long | good | more effective as external shading device | readily available | cheap | more effective as external shading device | available | affordable | - vertical louvers are effective on east and west orientations whereas horizontal louvers are effective on the north/south orientations<br>- louvers mounted on the outer side of the window are more effective in protecting against solar heat than those on the interior side<br>- inside louvers are more durable than outide ones<br>- outside louvers are affected by prevailing weather conditions |
| awning |  | on facade | poor | good | excellent | good | good | poor | easy | necessary | excellent | manual / automatic | long | good | effective only against high altitude sun | readily available | cheap | effective only against high altitude sun | available | cheap | - effective on orientations which recieve direct radiation from high altitude sun<br>- the part of the window to be shaded depends on the dimension of the awning<br>- affected by prevailing weather conditions |
| thermotropic glass | under development | on facade | OX | OX | OX | OX | OX | OX | OX | OX | OX | OX | OX | OX | OX | not readily available | OX | OX | OX | OX | - under development |
| gazo-chrome glass |  | on facade | OX | OX | OX | OX | OX | OX | OX | OX | OX | OX | OX | OX | OX | available | expensive | OX | not readily available | OX | - under development |
| electro-chrome glass |  | on facade | poor | excellent | good | excelent | poor | good | good | necessary | poor | manual / automatic | X | X | | available | expensive | - | not readily available | X | - requires technical expertise<br>- under development |
| holographic optical elements (HOE) |  | on facade | poor | excellent | excellent | poor | poor | good | not easy | necessary | good | automatic | X | X | must be able to track the sun | available | expensive | must be able to track the sun | not readily available | X | - has to be precisely installed in order to achieve maximum effectiveness<br>- offers a possibility co combine it with Photovoltaic elements to produce electricity<br>- requires technical expertise<br>- requires regular maintenance |

**X** no information available
**OX** under development
**XO** evaluation is being carried out
**XOX** no evaluation data available
****** the type of coating plays a decisive role

# 12 List of Tables

# 13 List of Figures

# Curriculum vitae

| | |
|---|---|
| Name : | Ssengooba – Kasule |
| Date of birth : | 9 October 1962 |
| Place of birth : | Bulyakamu |
| Country : | Uganda |
| Nationality : | Ugandan |
| Marital status : | Married, 2 children |

Education

**1968 – 1974**
Kamengo Primary School

**1975 – 1976**
Kakoma Primary School

**1977 – 1980**
Kakoma Secondary School

**1981 – 1983**
Kampala High School

University

**1986 – 1987**
Beijing Language Institute – China
1 Year Intensive course Chinese Language

**1987 – 1991**
Tianjin University - Architectural Studies

**1991**
Graduation – Bachelors degree of Architecture with Honours

**1992 – 1993**
German Language course at the Volkshochschule in Aachen and RWTH Aachen

**1993 – 1995**
Upgrading course in Architectural studies at the RWTH Aachen and at the Fachhochschule Aachen

**1995**
Diplom Examination at the Fachhochschule Aachen

**1996 – 1999**
Upgrading Course in Architecture at the University of Dortmund

**1999**
Diplom Examination

| | |
|---|---|
| Working experience: | **1991-1992**<br>Architectural office - Loseck und Partner in Jülich, Germany |
| | **1993**<br>Architectural office - Kahlen und Partner in Aachen, Germany |
| | **1993-1995**<br>Architectural office - Clemenz und Partner in Herzogenrath, Germany (Division: Institute for Regional planning, IRP) |
| | **1997**<br>Design Office - Lang Ladenbau in Dortmund, Germany |
| | **Since 1999**<br>Research fellow at the Department of Environmental Architecture and Building Physics, University of Dortmund.<br>Head of department: Prof. Dr. -Ing. Helmut F. O. Mueller |