PASSIVE TECHNIQUES FOR ENERGY EFFICIENCY OF BUILDINGS IN SRI LANKA

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Master of Philosophy

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Declaration

I, Asitha Indika Jayawardena, hereby declare that the content of the thesis is the original work carried out over a period of 2 ½ years at the Department of Civil Engineering, University of Moratuwa. Whenever others' work is included in this thesis, it is appropriately acknowledged as a reference.

Abstract

Rising demand for electricity is a major contributory factor to the energy crisis that Sri Lanka is now facing. One potential candidate for energy conservation is the domestic sector. By way of adopting an environment-friendly solution (i.e. a passive solution), there remains a potential to achieve indoor thermal comfort in houses, thus reducing, or sometimes even totally eliminating, the need for active means such as fans.

The main objective of this study is to conserve electricity in the domestic sector of Sri Lanka, by developing a set of guidelines for the achievement of indoor thermal comfort at houses in the low altitudes of Sri Lanka through passive means, which are energy-efficient and environment-friendly.

In order to achieve the above objective, the following methodology was adopted in the study. A comprehensive literature survey was conducted to determine the passive concepts and techniques desirable to warm humid climatic conditions prevailing in the low altitudes of Sri Lanka. Then, in order to identify the undesirable features of the building envelope with respect to thermal comfort and the indoor temperatures that occur in reality, a series of thermal and comfort surveys was conducted at several existing buildings, mostly houses. In order to identify the current situation with respect to thermal comfort and their preferences which would be crucial in developing a solution, a pilot questionnaire survey was conducted among a group of adults. A series of computer simulations was carried out using the software DEROB-LTH on a simple model to determine the effect of various features of the buildings envelope on indoor thermal comfort since such simulation software is quite good in predicting the trends.

Using the findings of the literature survey and the results of thermal surveys, comfort surveys and computer simulations, a comprehensive set of desirable and undesirable features with respect to indoor thermal comfort was prepared. Incorporating desirable features and eliminating the undesirable ones whenever possible, a set of conceptual house plans of various floor areas and catering to the requirements identified from the questionnaire survey, was developed. A set of land subdivision guidelines suitable to develop a passive housing scheme was developed, highlighting the need for an integrated approach for energy conservation. In addition, two sets of guidelines for the enhancement of indoor thermal comfort were developed for a house being planned and for an existing house.

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CONTENTS

List of tables

List of figures

List of charts

Chapter 1

INTRODUCTION

1.1 General

Economic growth has caused urbanization and urbanization has further promoted economic growth around the world. The congested living resulting from urbanization has adversely affected human health and environment. The degraded environment in turn has further intensified the health problems. The undesirable levels of indoor comfort resulting from the degraded environment have increased the use of energy for active means used for the achievement of indoor comfort. This has further degraded the environment. In the developing world, architecture and indoor thermal standards incompatible to the local climate have further promoted the use of active means for thermal comfort. Moreover, since economic growth has made expensive active means affordable to a wider population, energy use has further increased.

However, realizing the gravity of the energy crisis and environmental degradation, many countries – especially developing countries – have initiated various measures to explore an energy-efficient and environment-friendly alternative for the achievement of indoor thermal comfort. Climatic design of buildings has found to be one of the effective solutions.

The inter-related crisis of energy and environment has affected Sri Lanka as well, perhaps more severely than most other developing nations. The demand for electricity is on the increase while the supply is unable to accommodate a corresponding increase without a drastic rise in the price of electricity. Therefore, in a local context, energy conservation by way of climatic design is of paramount importance. For this, the domestic sector is a potential candidate not only because of its high share in electricity consumption but also of its flexibility in accommodating passive concepts and techniques.

1.2 Energy crisis in Sri Lanka and the domestic sector for energy conservation

Sri Lanka is experiencing rapid urbanization, with Colombo and its suburbs as the region of attraction. For example the population density of Colombo is 3253 persons/km^2 whereas it is as low as 300 persons/km^2 for the entire country (Central Bank of Sri Lanka, 1998).

In Sri Lanka, the demand for electricity is rapidly increasing. In 1998/99 the percentage increase in the electricity sales was 6.4 %. The corresponding figure for 1999/2000 was 9.3 %. The increase in the number of consumer accounts was 10.8 % and 10.2 % for 1998/1999 and 1999/2000, respectively (Statistical Digests, 1999 & 2000). The increase of the growth of demand for electricity is expected to continue for the foreseeable future with added impetus (Leelaratne, 1997).

National demand for energy is increasing due to two reasons. Firstly, more energy is required for the increased population. Secondly, standard of living of the masses is gradually increasing. The percentage of households provided with electricity has increased from 16% in 1983 to 45% in 1996. People returning from overseas employment are bringing electrical appliances. Number of motor vehicles, hotels and large scale industries has increased. All these will need more energy (Joseph, 1997).

For supply of this electricity demand, Sri Lanka primarily depends on hydropower and fossil fuel, and to a marginal extent on wind power.

Although hydropower is renewable, it is not reliable. Dry spells of weather now experienced more often than in the past especially due to increased deforestation, have reduced its capacity for power generation. Hydropower has reached its economical potential. Of the total estimated hydropower potential of 2000 MW (Kariyawasam, 1999), about 1150 MW has already been harnessed (Statistical Digest, 2000). The potential of the remaining hydro-resources, economic exploitation seems to be very limited (Fernando & Ratnasiri, 1997). Therefore, attempts to develop new hydropower projects are unlikely to be economical or may cause severe adverse effects on the environment. In fact, the increased concern for the environment has caused stiff public resistance to the proposed Upper Kotmale Hydropower Project and therefore it was to be at least delayed if not abandoned. Any other proposal to a new development of such magnitude is also likely to suffer a similar fate.

Therefore, hydropower is not a sustainable solution to the increasing demand for electricity not only because new developments are unlikely but also due to its drop in the capacity during dry seasons. As highlighted by Leelaratne (1997), the vulnerability of the weak commercial energy supply system and awesome economic and social impact of an energy scarcity were amply demonstrated during 1995-96 (and also 2001-2002) as the whole country plunged into darkness, in cyclic fashion, when severe drought forced curtailment of electrical power generation by hydro beyond tolerable limits

In Sri Lanka, petroleum is used for the generation of thermal power. It is non renewable and the reserves around the world, as shown by their relatively short life indices, are depleting fast. The life index is the number of years a resource will last if the current rate of production prevails. The life index for petroleum and natural gas in 1991 were 40 and 60 years respectively. Coal reserves, however, are expected to last about 300-400 years (Der-Petrossian & Johansson, 2000). Therefore, the world market price can be expected to go up in the future, especially that of petroleum.

Unfortunately, Sri Lanka has to import all its petroleum requirement and therefore will have little control over the world market price. Therefore, the Ceylon Electricity Board is confronted with the increased cost of thermal power generation. This is reflected in the average fuel cost per unit (i.e. Rs/kWh) for thermal generation. The figures corresponding to 1998, 1999 and 2000 are Rs. 2.10, Rs. 2.41 and Rs. 4.17 respectively. Therefore the percentage increases in 1998/99 and 1999/2000 are 14.5 % and 73.1 %, respectively (Statistical Digests, 1999 & 2000).

Besides, electricity generation using petroleum, as is the case at present in Sri Lanka, can be the most expensive of all fossil fuel types. However, introduction of coal has become a serious problem due to public resistance to the location of coal power plants on environmental grounds. The issue of the proposed coal power plant at

Norochcholai can be cited as an example. Therefore, whatever the world market price is, the only option to cater to the increasing electricity demand seems to be thermal power generated from a relatively more expensive option, i.e. petroleum. Therefore, Fernando & Ratnasiri (1997) state that thermal based-power generation is likely to meet future demand for electricity in Sri Lanka, and warn that such fuel combustion activities will lead to increased emission of greenhouse gases requiring concern for introduction of mitigation measures.

The shift of the main role of electricity generation from renewable hydropower to non-renewable petroleum is not a desirable development for a developing country like Sri Lanka. However, this has already happened, as shown in Figure 1.1. The contribution from another renewable source of energy, i.e. wind power, still remains at an insignificant level of less than 0.1 %.

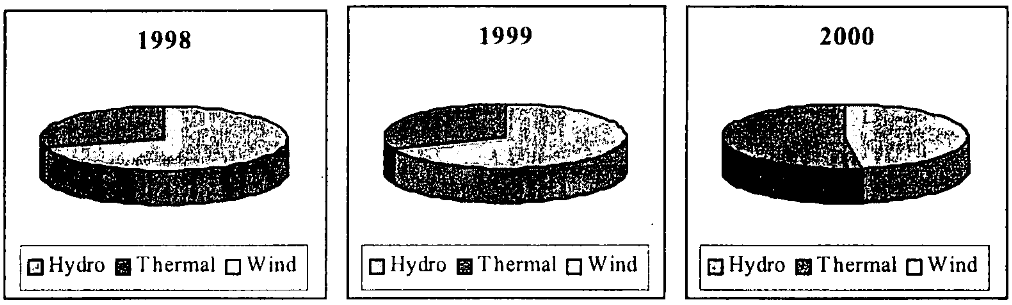


Figure 1.1 Electricity generation in Sri Lanka by type
(Statistical Digest, 1999 & 2000)

Besides, the situation is bound to worsen in the coming years because the reliability of the country's meager hydropower resources has apparently begun to dwindle due to the recurring drought, year after year (Leelaratne, 1997).

The expansion of the energy sector to meet the growing demand is a pressing need (Joseph, 1997), and in bridging the gap between the supply and demand for commercial energy, Sri Lanka will face a great challenge (Leelaratne, 1997).

Sri Lanka desperately needs a sustainable solution to the energy crisis and environmental degradation. Falling in line with the global regional trend, energy conservation can be considered as a remedial measure because a unit of electricity saved is as good as an extra unit generated.

In actively exploring a passive solution, the domestic consumption can be considered as a sector with high potential for energy conservation. Of the total electricity sales by the CEB in 2000, the share of the domestic sector was 32.3 %. However, the total share of the domestic sector could be even higher, around 40 %, when the bulk electricity sales to the Lanka Electricity Company is considered because more than half of that is resold to houses (Statistical Digest, 2000). A large portion of the power consumed in the residential sector is being used for lighting. Refrigeration and electric motors such as fans also seem to consume a substantial portion of power (Fernando & Ratnasiri, 1997).

Warm outdoors cause warm indoors. To inhibit the resulting thermal discomfort, occupants of both single unit houses as well as apartments are resorting to active techniques such as fans. A pilot questionnaire survey carried out in this study using 179 adults revealed that 72.7 % of those surveyed usually use at least two fans in their houses (Chart 4.9). Although air-conditioning is not so widely adopted in the domestic sector, economic growth has paved the way for the demand of higher living standards and therefore air conditioning is gradually becoming more a requirement than a luxury. For example, most of the luxury apartments recently built and being built in and around Colombo depend on air-conditioning.

Fans can provide thermal comfort by means of physiological cooling. However, circulation of indoor air would not be very effective if the indoor temperature is high. On the other hand, if the outdoor air temperature is also high (i.e. for example, over 31°C as is the case in the afternoon in March and April in Colombo), comfort conditions may not be achievable by sucking outdoor air into the indoor environment. Therefore, fans, though costly they are, may not be as effective as expected in providing thermally comfortable indoors of houses.

Although air-conditioning could achieve any practical desirable indoor condition, the cost would be comparatively very high. The capital cost of the air conditioning plant, the operating cost in the form of electricity charges and the maintenance cost of the plant make this option unaffordable to most house owners. From an environmental point of view as well, it is undesirable as the waste heat from air conditioning units drives up the air temperature in the neighbourhood, requiring in turn larger cooling loads for the buildings (Takakura et al., 2000). Therefore, air conditioning is not a sustainable solution because it is not environment-friendly.

The climatic conditions of the low altitudes (i.e. below 300 m) of Sri Lanka are not extreme. For example, in the afternoon when the outdoor temperature rises to a maximum (i.e. around 14.00 hours), the outdoor environment under a shady tree would be thermally comfortable. Therefore, means should be investigated to extract the maximum benefits of the desirable outdoor climate to achieve thermally comfortable conditions indoors. This is possible by way of passive means, which can be considered as an effective way of utilising the "invisible" energy source, i.e. energy efficiency.

The basis of passive option is to work with the environment to achieve thermally comfortable indoors. Therefore, it can be perceived as environmentally friendly. Its basic strategies can be listed as minimisation of undesirable elements such as the roof, provision of proper orientation for the building and its openings, provision of shading for openings, strategic location of activity spaces according to their use and frequency of use, use of proper building and insulating materials, use of desirable colours for the surfaces, and enhancement of the neighbourhood by promoting vegetation in order to create a desirable microclimate.

Passive techniques offer benefits both at individual user level and national level. A passive house can reduce the operating cost by saving electricity that would otherwise be spent for inhibiting the resulting thermal discomfort indoors. The tariff structure of the Ceylon Electricity Board, where the unit rate increases with the usage, would further reduce the electricity bill. In addition to the normal electricity charges, the

CEB introduces during the dry periods a temporary fuel adjustment charge of 25% on all units consumed by all electricity consumers in order to recover the expenses incurred due to the generation of electricity with the use of petroleum fuel (The Gazette of the Democratic Socialist Republic of Sri Lanka, 2001). By minimising the total number of units consumed, this additional charge can be minimised too. Since passive techniques do not require energy consuming mechanical plant, savings are also possible in capital, operating and maintenance costs.

The benefits of passive houses at the national level, though not as significant as those at the user level, could be magnified if a significant slice of the population adopts them. The energy saved by the use of passive means could be channelled to the industrial sector, paving the way for economic growth. By resorting to passive techniques, the number of fans as well as the duration for which they are used in houses could be minimised, or fans may be eliminated altogether. Such development would make air conditioning, which is more energy intensive than fans and more undesirable to the environment, a remote option in the domestic sector. A reduction in the rate of electricity demand would save foreign exchange that would otherwise be needed for importing petroleum for thermal power plants. Also beneficial to the nation is the mitigated need for the development of new power plants because it would minimise possible adverse effects on the environment. The environment is already threatened by the diminishing forest cover and the adverse climatic changes due to the massive artificial reservoirs catering to the hydropower plants.

1.3 Objective of the study

The main objectives of the study is to conserve electricity in the domestic sector of Sri Lanka, by developing a set of guidelines for the achievement of indoor thermal comfort at houses in the low altitudes of Sri Lanka through passive means, which are energy-efficient and environment-friendly.

1.4 Methodology

In order to achieve the above objective, the following methodology was adopted in the study:

1. A comprehensive literature survey was conducted to determine the passive concepts and techniques desirable to warm humid climatic conditions prevailing in the low altitudes of Sri Lanka

2 A series of thermal and comfort surveys was conducted at several existing buildings, mostly houses, in order to identify the undesirable features of the building envelope with respect to thermal comfort and the indoor temperatures that occur in reality

3 A pilot questionnaire survey was conducted among adult residents in order to identify the current situation with respect to thermal comfort and their preferences which would be crucial in developing a solution

4 A series of computer simulations was carried out using the software DEROB-LTH on a simple model to determine the effect of various features of the building

envelope on indoor thermal comfort since such simulation software is quite good in predicting the trends.

5 Using the findings of the literature survey and the results of thermal surveys, comfort surveys and computer simulations, a comprehensive set of desirable and undesirable features with respect to indoor thermal comfort was prepared

6 Incorporating desirable features and eliminating the undesirable ones whenever possible, a set of conceptual house plans of various floor areas and catering to the requirements identified from the questionnaire survey, was developed

7 A set of land subdivision guidelines suitable to locate the passive houses was developed highlighting the need for an integrated approach for energy conservation.

1.5 Main findings of the study

The main findings of this study can be categorized into the following:

1 General findings
2 Recommendations

General findings

- Thermal and visual discomfort occur in houses, and the measures people resort to inhibit them are active means, contributing to electricity consumption

- Passive concepts and techniques can be adopted for warm humid climatic conditions in order to achieve indoor thermal comfort

- A multi-storey house possesses an inherent superior passive performance over an equivalent single-storey house

Recommendations

- A set of passive guidelines for planning a housing scheme: This includes access roads along east-west with trees along the sides, a seven perch plot measuring 11m by 16m, a set of compatible passive house plans, and storm water detention pits on the sidewalks.

- A set of passive guidelines for planning a house: This includes multi-storey construction, strategic allocation of spaces (e.g., depending on the frequency of use), front of house facing north or south, shaded openings facing north or south, short openings facing east or west shaded by external blinds, strategic location of trees, courtyard, light colour exterior and interior surfaces, avoidance of exposed roof terraces, skylights and tinted glazing, preference of clay tiles to cement fibre sheets for roof, ceiling with a reflective foil, growing shrubbery or grass in front of openings and ivy on the exterior surface of external walls.

- A set of passive guidelines for an existing house: This includes vegetation, light colour exterior and interior surfaces, ceiling, overhangs to shade north or south facing openings, external blinds to shade east or west facing openings, and keeping windows open late into night.

1.6 An overview of chapters

A brief overview of the Chapters could be presented as following:

- Chapter 1 gives an introduction, highlighting the problem
- Chapter 2 presents the findings of literature review carried out for this study.
- Chapter 3 describes the thermal and comfort surveys conducted for this study
- Chapter 4 describes the questionnaire survey conducted for this study
- Chapter 5 presents the desirable passive concepts and techniques
- Chapter 6 discusses the development of passive guidelines in this study
- Chapter 7 gives the findings and recommendations

Chapter 2

LITERATURE REVIEW

2.1 General

A comprehensive literature survey was carried out in order to determine the following:

1. The emerging global trends in the face of environmental degradation and energy crisis
2. Theoretical basis of comfort – thermal and, to a lesser degree, visual
3. The concepts behind climatic design of buildings
4. Thermal comfort requirement of Sri Lankans
5. Passive concepts and techniques applicable to warm humid climatic conditions

It was found that the emerging global trend, especially in Asia, is energy conservation. In buildings this is achieved through climatic design. Certain countries have taken steps to develop their own thermal standard to cater to the local people rather than adopting western standards that cause high levels of energy consumption.

2.2 Energy and environment: Global crisis and emerging trends

The proportion of the world's population that lives in urban areas is constantly increasing (Grundstrom et al., 1999). During the last 150 years, the global urban population has increased from a mere 3% in the 1850s to more than 45% in 1955. While global population has increased only six times during the last 200 years, urban population has grown 128 times. Even though the global population growth rates seem to abate somewhat, global urbanization shows no sign of retreat (Emmanual, 1999). The fastest urbanization is now occurring in Africa and Asia, and it is believed that by about the year 2015, most of the population in developing countries will live in towns (Grundstrom et al., 1999).

The rapid global urbanization has brought in its wake many hitherto unknown changes to humans, other life forms and the physical environment (Emmanual, 1999):

- To humans: Diseases associated with crowding, air-pollution related illnesses, and physiological and emotional disorders.
- To other life forms: Physiological changes in urban flora and fauna and their diversity, and growth retardation in vegetation.
- To physical environment: Degraded air and water quality, and microclimate.

The last factor, i.e. the effect on the environment, is the worst. Temperatures in big cities are higher than those in rural vicinities throughout the year, and this is called 'heat island' phenomenon (Takakura et al., 2000). The phenomenon of 'urban heat island' increases urban air temperatures, creating differences 1 to 2°C during daytime and normally 3 to 5°C at night, but there can be extremes of up to 10 °C (Rosenlund, 2000).

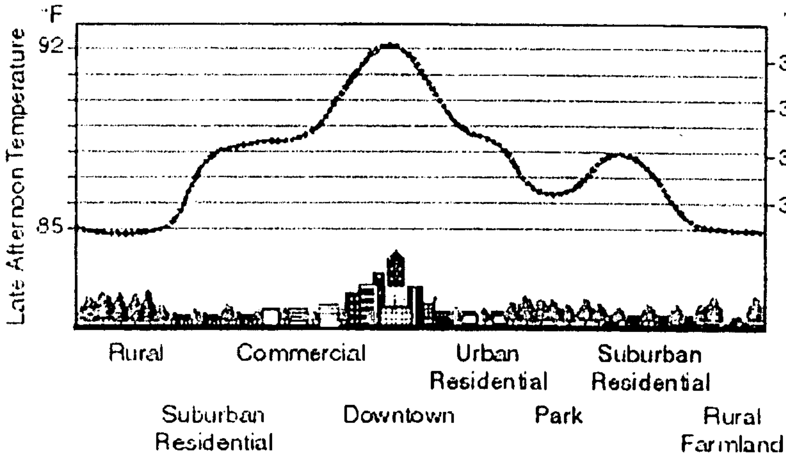


Figure 2.1. Schematic representation of urban heat island (Akbari et al., 1992)

Over the years, various studies have identified the causes of the phenomenon of the heat island. Rosenfeld et al. (1995 and 1998) illustrate the case for down town Los Angeles over the period 1882-1984. With increasing irrigation and orchards, the city of Los Angeles cooled by 2°C until the 1930s. Since then, as asphalt replaced trees, the city warmed by 3°C. In 1966, one of the earliest equatorial urban microclimatic studies was conducted in Singapore. It found out that the city was appreciably warmer (3-3.5°C) and drier (relative humidity up to 20% lower) than the rural setting. Another study in early seventies found out that City Country Temperature Difference (CCTD) was related to cloud cover. On clear days it was 4.4-5.0°C; on cloudy days 2.0-2.2°C. It attributed CCTD to surface characteristics of city (more dark colour surfaces), and lack of vertical air mixing, resulting in hot air being trapped at body level (Emmanual, 1993).

Although early causative studies attempted to link the Urban Heat Island to city size, recent research has shown that canyon geometry and surface thermal properties of urban buildings are the most important causes. Moreover, the following factors are said to augment urban microclimatic modifications (Emmanual, 1999):

- Anthropogenic heat, i.e. heat waste from combustion and matabolism
- Urban greenhouse effect, i.e. increased incoming longwave radiation from polluted urban atmosphere.
- Evaporation loss (reduction in green areas in cities leads to more sensible than latent heat transfer).
- Wind shelter, i.e. reduced ability of wind to carry heat (turbulent transfer) either as sensible or latent heat.

Rosenlund (2000) considers the main factors generating the heat island as:

- Lower heat radiation loss during the night, due to the geometry of the city.
- Heat storage in the building mass
- Heat generating activities (transportation, industry etc)
- Lower evaporation due to less vegetation and different surface structures
- Heating and cooling of buildings both of which generate heat to the urban environment

For settlement of people and for provision of infrastructure facilities, vegetation is cleared. Forests are an important natural resource-base, which play a crucial role in the conservation of watersheds, prevention of soil erosion and balancing the eco-system (Der-Petrossian & Johansson, 2000). Vegetation can be considered as natural air conditioners because, in the process of evapotranspiration, they convert large amounts of solar radiation incident on them into latent heat, which does not cause a rise in air temperature (Takakura et al., 2000). As a result of urbanisation, most green areas in urban and suburban centres are replaced by man made structures such as buildings, roads and paved areas. When exposed to the sun, these surfaces absorb heat and in turn increase the air temperature in the surroundings. Such undesirable changes to the microclimate will make urban and suburban regions warmer.

Ca et al. (1998) explain the causes in detail. Development of cities significantly changes the climate of cities and surrounding areas. Increase in impervious portion of ground surface in the urban area caused by pavements, roads and buildings significantly reduces evaporation from ground surface, and consequently increases underground heat storage. This underground heat storage makes ground surface temperature higher than that of previously vegetated surface, thus increasing sensible heat exchange between ground surface and atmosphere, and upward long wave radiation. On the other hand, tall buildings with shading effect in the ground/wall surfaces may cause a reduction in air temperature at noon. However, even with shading effect, in many cases, heat released from hot surfaces together with anthropogenic heat released from industry and human activity make air temperature in urban areas significantly higher than that in surrounding rural areas, causing the so-called 'urban heat island'.

As urbanization progresses, the "heat island" problem is expected to aggravate mainly because of reduced density of green vegetation in urban development (Shashua–Bar & Hoffman, 2000).

Urbanization results in congested living, health problems and environmental degradation. Urbanization, due to its increased thermal capacity, lack of water for evapotranspiration, and above all due to the "canyon effect", tends to aggravate an already stressful climate (Emmanual, 1993). As reported by Acioly & Davidson (1996) studies in Guinea-Bissau have revealed a strong correlation between high population densities and ill health. This could be attributed to both the degraded environment and congested living as could be found in an urban context.

All these problems cause provision of housing for urban population a challenging task. For example, Hong Kong has faced many challenges in tackling the housing needs of its urban population. A large number of urban and suburban building projects have been developed to meet the ever increasing demand. Most of the building developments are located in high-density residential areas. In order to maximize the space from the finite resources of land, most residential buildings are highrise apartment blocks built close to each other resulting in severe sky obstructions. Hence the amount of natural light entering the building interiors may be restricted, particularly for flats on the lower floors. Habitation rooms may face large external obstructions, adversely affecting their daylighting performance (Li et al., 1999)

Energy is at the heart of contemporary living. Energy is needed not only for basic needs such as cooking food but also for industry, commerce, recreation, education, communication etc. Since it is the center of "development", an adequate energy capacity is an essential requirement for the economic development of any country (Joseph, 1997).

Industrialized countries consume large amounts of fossil fuel per capita. Since the energy crisis in the 1970s, the per capita, as well as the total, consumption has been fairly constant. The major increase during the last decades was in developing countries, although most of this is due to population growth. Nonetheless, the consumption per capita is rising as a result of industrialization, urbanization and improved economy. In 2010 developing countries are expected to account for 40% of the world's energy consumption (Der-Petrossian & Johansson, 2000).

The energy consumed for environmental control in buildings represents an important sector of the gross energy consumption, especially in developed countries (El-Asfouriet al., 1988). In many countries, especially in the industrialized world, buildings account directly for over 50% of total energy consumption, and even more when one includes what it costs to manufacture the materials required for construction (Rosenlund, 2000). In subtropical Hong Kong, air-conditioning during hot summer months accounts for one third of the total electricity consumption in the residential sector (Li et al., 1999).

Excessive use of energy degrades the environment and this degraded environment in turn increases the requirement of energy for climate control of buildings. For example, in big cities, a vicious circle is created because waste heat from air-conditioning units to cool buildings drives up city temperature which then requires larger cooling load for buildings (Takakura et al., 2000).

Mechanical ventilation in combination with air-conditioning of buildings consumes a large amount of non-renewable fossil based energy in the world, particularly in developed countries where buildings are responsible for half of all energy consumption. Therefore, increased use of fossil fuels can lead to atmospheric pollution and possible climatic changes (Gan, 2000).

Energy production and consumption patterns of the world heavily rely on combustion of fossil fuels. This has become a key factor for the unprecedented increase of levels of carbon dioxide in the atmosphere – recognized as a major contribution to global warming (Fernando & Ratnasiri, 1997). Although not toxic, carbon dioxide is the major greenhouse gas and thus contributes to global warming (Der-Petrossian & Johansson, 2000). Fortunately, policies at international level have recognized the problem of climate change and environmental problems associated with the use of energy (Fernando & Ratnasiri, 1997).

Urbanization gives rise to great social and economic changes, such as economic growth, which in turn results in higher energy use for e.g. cooling and heating buildings (Grundstrom et al., 1999). Rosenlund (2000), too, adopts a similar view. As living standards rise, people want to install heating and/or cooling equipment to improve thermal comfort. For buildings not adapted to the climate, the amount of energy to run the equipment, and its cost, will be excessively high, and it will have a negative impact of the environment. A good, or at least acceptable, indoor climate can often be achieved with little or no extra input of energy.

Unfortunately, for indoor climate control of buildings located in developing countries, energy is unnecessarily over-used, or even could be termed "wasted" basically due to two reasons. Firstly, the indoor comfort conditions achieved by way of energy intensive active means are not the comfort conditions desired by the people. Secondly, the planning and design of buildings are not compatible to the local climate, requiring increased involvement of active techniques for thermal comfort.

Like many other developing countries, a country that suffers from incompatible thermal comfort standards is Malaysia, where indoor comfort conditions in buildings conform to ASHRAE standards. However, Malaysians bring extra clothing to air conditioned work places, to seminars or conferences in hotels, fearing excessive cold (Rahman & Kannan, 1997). The reason is that, like most other thermal standards, ASHRAE comfort standards adopted are derived from models calibrated with experimental results of people acclimatized to temperate climates; therefore, the Malaysians, being acclimatized to warm humid climatic conditions, encounter cold discomfort under the conditions which are supposed to be comfortable to them.

Buildings in developing countries are often designed without taking sufficient account of the climate. Factors such as the urban surroundings or site characteristics, orientation and architectural design of the building, choice of building materials etc. are not given enough importance. Consequently, buildings often have a poor indoor climate, which affects comfort, health and efficiency (Rosenlund, 2000).

There are several reasons for this. One is historical. Planning and design in the twentieth century were drastically altered by a number of factors: need for rapid and massive housing solutions by the end of World War II, industrialization of construction, modern communication, mass media, cheap and fast means of transportation. All these factors brought forth the "internationalization" of design and planning. "Internationalized" necessarily meant "not local", and this in turn, led to an abstraction of the design process and product. Lack of connection between the design product and the local climate, socio-economic background etc, soon caused the destruction of the traditional patterns, often without replacement by successful alternatives. In many cases, monotonous urban environments evolved from the new theories, proving to be climatically and socially unsuitable (Meir, 1989).

Architectural standards throughout the world have declined as a result of the advent of air conditioning and they have been abetted in this by the use of temperature standards which can only be met using air conditioning. The fact that any building can be made to 'work' with the use of air conditioning has militated against those design buildings which work with the climate rather than fighting it (Nicol & Roaf, 1996).

Another reason why buildings are poorly adapted to the climate is lack of knowledge among architects, planners and engineers. The knowledge from traditional construction, which was fairly well adapted to the climate, is often lost or difficult to translate to modern techniques and society (Rosenlund, 2000). For example, designs of most of the houses in Bangkok, Thailand, are under the influence of the western "modern" architecture. For example, houses located in Europe are designed for storage heat and the ceiling design under the roof is a closed system for preventing heat from spreading out. In addition the roof is made of dark colour tiles (red, blue, orange) to enhance the absorption of solar radiation. The design should be reversed for houses in hot humid regions. However, Thai architects often use western models to design houses, leading to overheating of the air under the roof structure as no air vents are provided. Therefore, heat will be transmitted to the interior of the residence through the ceiling during daytime, which in turn will force the residents to use air-conditioners with a high cooling load (Khedari et al., 2000).

Overemphasis on aesthetical considerations can also be cited as a reason as it has not only resulted in undesirable lighting qualities in interiors but also poor efficiency in the usage of energy (Ranasinghe & Perera, 1997). Buildings with a modern appearance are characterized by the widespread use of glass on building facades. This could cause overheating problems even in a temperate climate (Jorge et al., 1993). For example, nowadays, houses in Bangkok, Thailand, have various modern styles based on western architecture with much more emphasis on the beauty of the outside than of the local Thai residents' thermal comfort, requiring active means for thermal comfort (Khedari et al., 2000).

Neglect of environment when planning and designing buildings could also be cited as a contributory factor to excessive use of energy for buildings. As shown by Aynsley (1979), people engage specialist consultants to design a building and its internal spaces. No one seems to design the odd leftover public spaces around the building. While the interior of the buildings is carefully air-conditioned for summer comfort, the extracted heat is dumped in surrounding public spaces.

One such "selfish" measure is the use of heat reflective solar control glazing. Architects and engineers often advocate its use to reduce heat loads on the air-conditioning, without giving enough thought to the environmental problems. Employing a layer of metallic particles under the surface of the glass, or by adhering a reflective film to the back, the reflective glazing protects the interior of buildings from unwanted radiation by reflecting it as heat and glare into public spaces and neighboring buildings. Therefore, a neighboring building with normal clear glazing could be adversely affected. Moreover, the reflected radiation may alter the balance of heat and glare loads in the microclimate around the buildings, resulting in warmer outdoors (Aynsley, 1979).

In many countries energy use, and consequently air pollution, due to heating and/or cooling of buildings is very high. To some extent this is unavoidable, since the indoor climate would otherwise become unbearable, but energy use could be much lower if buildings were better adapted to the outdoor climate (Der-Petrossian & Johansson, 2000).

Today's technology can be used to provide any desired thermal state, irrespective of building form or location, but economic penalty is high. Limitations of conventional energy sources, in terms of costs and availability, and an increased awareness of environmental issues, have led to renewed interest in passive building design (Barozzi et al., 1992).

Various countries have already launched initiatives to conserve energy. For example, in the commercial sector of Thailand, a major portion of energy is spent for air-conditioning. In the face of energy and economic crises, Thailand is looking for solutions to reduce electricity demand in both commercial and industrial sectors (Khedari et al., 2000).

In the moderate South African climate, where cooling is a problem, large air-conditioning systems are often unnecessarily used to cool non-residential buildings, mainly due to bad design. Since these systems are expensive in capital and running costs, the Department of Finance initiated a project to establish minimum cooling requirements to provide thermal comfort in new state-funded office buildings in different climates of South Africa (Kruger & Mathews, 1992).

Realising that an increasing important fraction of energy used by buildings in Pakistan is used by air conditioning systems, and that energy cost of air conditioning is affected by indoor air temperature standards, ENERCON (National Energy Conservation Centre in Pakistan) commissioned Oxford Brookes University to advise on setting of appropriate indoor temperatures in different climatic regions in Pakistan (Nicol & Raja, 1997).

2.3 Indoor comfort

Indoor comfort can be two-fold: thermal and visual. This study is mainly concerned with the former while the latter is also considered as it has an effect on the overall comfort though not as significantly as the former.

2.3.1 Thermal comfort

Indoor thermal comfort is simply defined as the "state of mind which expresses satisfaction with thermal environment" (Watson & Labs, 1983). However, there are more elaborate definitions and descriptions, citing the associated parameters as well.

Khedari et al. (2000) state that, world wide, thermal comfort is recognized not as an exact concept nor it occurs at an exact temperature. Apart from common quantifiable factors such as temperature and humidity, air velocity, activity, etc, the state comfort depends on a wide range of factors which are "not quantifiable" such as mental states, habits, education, etc.

Barozzi et al., (1992) view indoor thermal comfort as a function of temperature, air flow, relative humidity and radiation. They further emphasize that the methods of controlling or modifying these parameters must be taken into consideration throughout the useful life of a building.

According to ANSI/ASHRAE (1981), thermal comfort is a sensation of complete physical and mental well being; it is a subjective quantity resulting from internal environmental variables such as dry bulb temperature, mean radiative temperature, humidity and air velocity. It is also affected by personal variables such as activity level and clothing level of the occupants. Thermal comfort could be achieved for several combinations of the above mentioned environmental and personal parameters. These combinations of parameters form the basis of a "comfort zone" on the standard psychrometric chart.

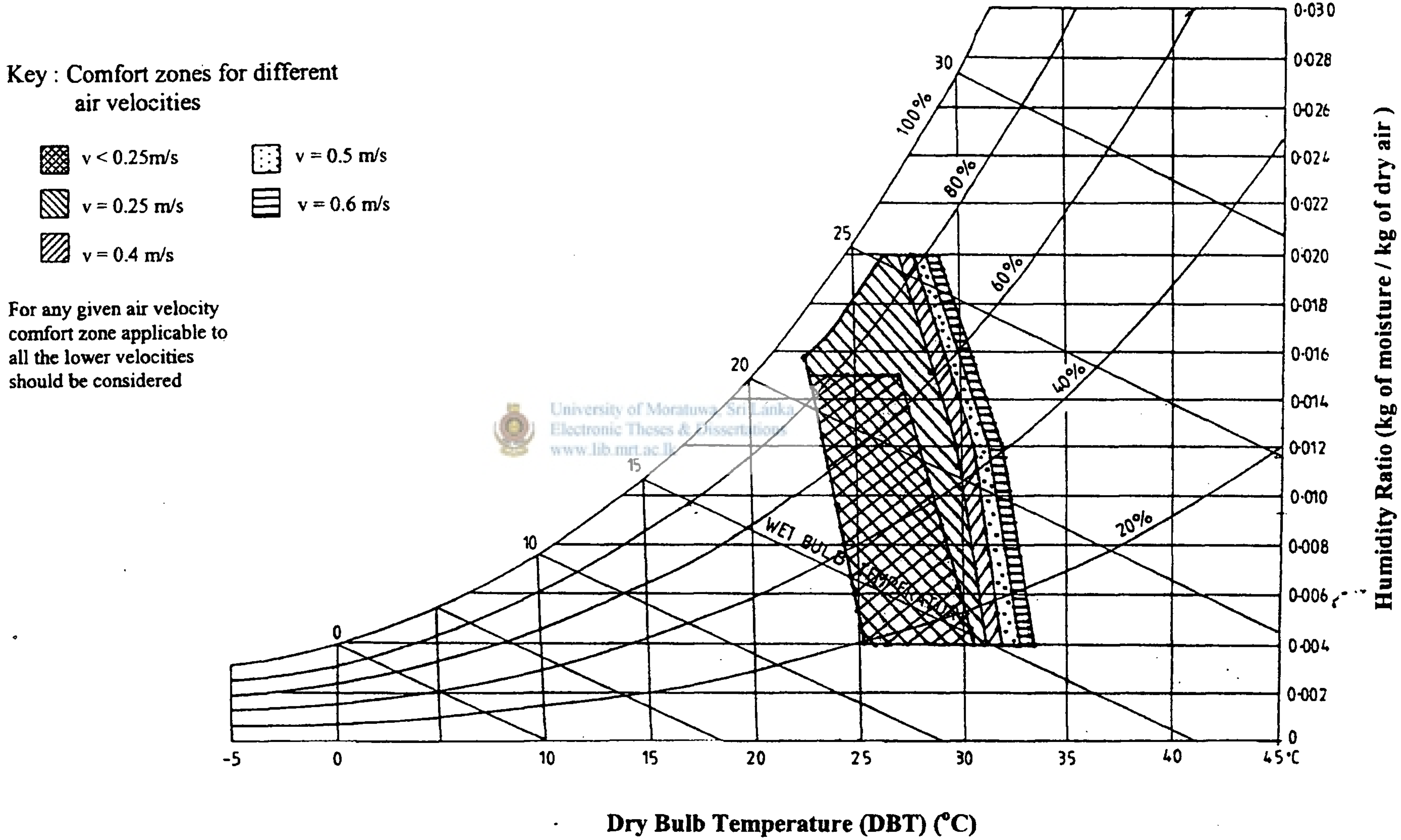


Figure 2.2 Psychrometric chart

Maintenance of thermal comfort is a problem of heat balance between body and its surroundings (Watson & Labs, 1983). The human body, like other bodies, exchanges heat with its environment through conduction (by direct contact), convection (transported by air), radiation (mainly short-wave visual light and long-wave heat) and evaporation/condensation (heat released through change of state of water, also called latent heat). Factors influencing the heat balance are environmental (air and mean radiant temperatures, vapour pressure and air motion) and individual (metabolic rate and clothing). The thermal equilibrium must be maintained within narrow limits for survival, and the range of comfort is even narrower (Rosenlund, 2000).

Activity	Metabolic rate (W)
Sleeping	75
Reclining	85
Sitting	105
Standing, relaxed	125
Typing	125-145
Cooking	170-210
Housecleaning	210-350
Walking (level, 3-6 km/h)	210-400
Dancing, gymnastics	250-460
Heavy machine work	370-470
Pick and shovel work	420-500

Table 2.1 Metabolic rate of different activities (Rosenlund, 2000)

Clothing	Clo value (clo)
Nude	0
Shorts	0.1
Walking shorts + short-sleeve shirt	0.4
Knee-length skirt + short-sleeve shirt	0.5
Trousers + shirt	0.6
Sweat pants + sweat shirt	0.7
Trousers + shirt + jacket	1.0
Knee-length skirt + long-sleeve shirt + half slip + long sleeve sweater or jacket	1.0-1.1
Men's heavy three-piece business suit	1.5
Men's heavy suit + woolen overcoat	2.0-2.5

Note: Unit clo is equal to $0.155 m^2K/W$

Table 2.2 Clo values for various clothing (Rosenlund, 2000)

Processes through which body exchanges heat with its environment are given as (Watson & Labs, 1983):

1. Conduction (contact)
2. Conduction-convection (air movement)
3. Evaporation-convection of skin moisture

4. Radiation (solar and thermal)

The corresponding factors governing the rate of heat exchange and, consequently sense of comfort, comprise (Watson & Labs, 1983):

1. Thermal resistance of clothing and temperature of surfaces in contact with body
2. Thermal resistance of clothing, air temperature and speed of air movement
3. vapour (water) pressure of air
4. temperature of surrounding surfaces (and area of body exposed)

The modes of heat exchange between the human body and the environment is graphically presented in Rosenlund (2000) as following:

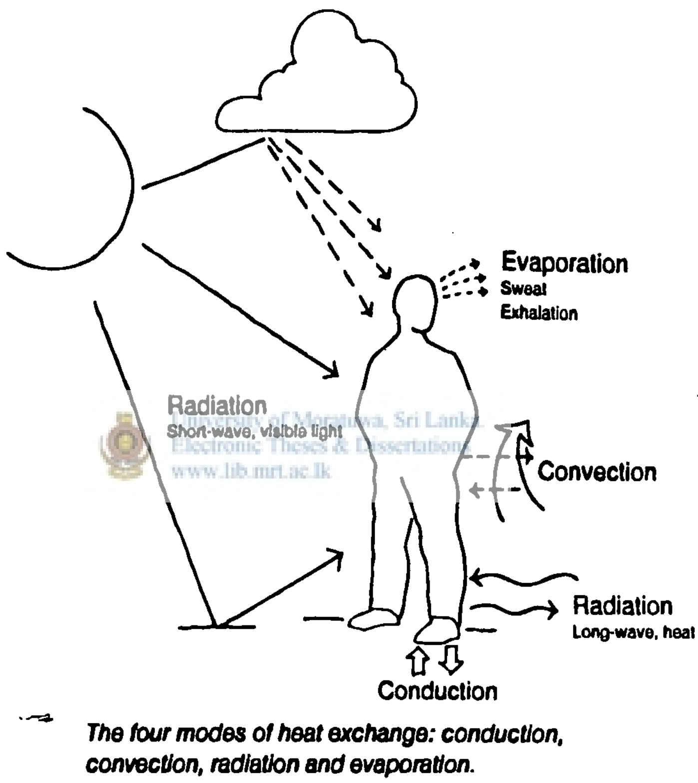


Figure 2.3 Modes of heat exchange between human body and the environment (Rosenlund, 2000)

2.3.1.1 Psychrometric chart and comfort zone

The word "psychrometry" refers to the study of air and water vapour mixtures and their changes. As shown in Figure 2.2, the psychrometric chart has two main axes: Dry Bulb Temperature or DBT (i.e. air temperature) and Humidity ratio (i.e. kg of moisture per kg of dry air). Saturation Humidity refers to the maximum amount of moisture that air can support at any given temperature. Plot of this against DBT forms the basis of the psychrometric chart. In the psychrometric chart, the curved lines give the Relative Humidity, which is an expression of the moisture content of a given atmosphere as a percentage of the saturation humidity at the same temperature. The sloping lines refer to the Wet Bulb Temperature, which can be used to determine the relative humidity when the corresponding DBT is known (Szokolay, 1991).

Comfort is a subjective experience, and not all people agree about optimal comfort. To handle comfort, it was necessary to define some kind of index, or a 'comfort zone' where the majority of the people experiences well-being (Rosenlund, 2000).

On the psychrometric chart, it is possible to mark a zone within which a majority of the people will be thermally comfortable. The center point of the comfort zone is the Neutrality Temperature, i.e. preferred temperature. It is shown by Humphrey (1978) that annual mean outdoor temperature of a particular region could be related to its neutrality temperature. This relationship as well as the equations for the determination of the boundaries of the comfort zone are given in Szokolay (1991).

The combination of the two environmental variables, the dry bulb temperature and the humidity of internal air, which forms the conditions so that at least *70%* of the population finds the whole body thermally comfortable is considered as the comfort zone. However, the standard comfort zone implicitly considers sedentary activity level (*1.2* met = *69.6* W/m^2) with light to medium clothing (around 0.8 clo), internal air velocity less than 0.25m/s and without any asymmetrical radiation from surrounding surfaces (ANSI/ASHRAE, 1981). Nevertheless, local thermal discomfort may be present on one or particular parts of the body caused by unwanted heating or cooling, head to feet temperature gradient, radiation asymmetry and draughts (Achard & Gicquel, 1986).

2.3.1.2 Standard methods of developing the comfort zone

The comfort zone is established using the neutrality temperature which is considered as the centre point of the comfort zone. The neutrality temperature is calculated based on the meteorological data obtained over a number of years, for example, about 10 years. The neutrality temperature is given by the following equation (Szokolay, 1991):

$$T_n = 17.6 + 0.31\ T_o \qquad \text{Equation 2.1}$$

where T_o is the annual mean dry bulb temperature at a selected locality.

The boundaries of the comfort zone are determined using a set of lines called Standard Effective Temperatures (SET), which represents the combined effects of temperatures, humidity, radiation and air movement, for an internal space.

SET lines can be approximately found by calculating the base line intercept for temperature T on the psychrometric chart (Szokolay, 1991), where

$$T_{intercept} = T + 23\ (T - 14)\ HR_T \qquad \text{Equation 2.2}$$

where HR_T is the humidity ratio in kg_w/kg_a at temperature T and 50% relative humidity (RH).

When the wind velocity is less than *0.25 m/s*, the comfort zone can be developed using the following steps:

1. Calculate the neutral temperature using the meteorological data.

2. Locate this point on the *50%* relative humidity (RH) curve of the chart.
3. The boundaries of the standard comfort zone consist of two SET lines corresponding to $T_1 = T_n - 2\,^oC$ and $T_2 = T_n + 2\,^oC$ points on the *50%* RH curve.
4. The top and bottom boundaries will be at *0.012* and *0.004* humidity ratio levels.

2.3.1.3 Modification of comfort zone for different air velocities

When natural or artificial ventilation is available, people will feel comfortable even outside the standard comfort zone. The air movement produces a physiological cooling effect. Thus to take account of this effect, the boundaries of the comfort zone should be modified according to the air velocity. It is common to consider the following limits:

1. Air movement less than *0.25 m/s* where the comfort zone is established.
2. Air movement between *0.25 m/s* and *1.0 m/s*.
3. Air movement greater that *1.0 m/s*.

The physiological cooling effect of air movement is taken into account in the psychrometric chart by using the following modifications, where the value of T_2 is modified (Szokolay, 1991):

$dT = 6v - v^2\ (^oC)$ for air velocities up to 3.0 m/s — Equation 2.3

$T_3 = T_2 + dT$ — Equation 2.4

The SET line corresponding to T_3 is drawn up to 90% relative humidity and the upper boundary of the comfort zone is now considered as 90% relative humidity line. In very low humidities experienced in hot dry climates, evaporation from skin is not restricted even with still air, so the improvement due to ventilation is much less. It is taken into account by halving the base line intercept below a humidity ratio of 0.012.

2.3.2 Visual comfort

Although thermal comfort can be described as the crucial element in the sense of overall indoor comfort, it cannot be considered alone. Visual comfort should also be considered – at least qualitatively. The findings of a study by Neeman (1977) conclude:

- Both visual and thermal comfort conditions should be satisfied before overall comfort in the environment is achieved.
- Glare from visual tasks seems to be the most significant response for the evaluation of visual comfort.
- Quantity of sunlight penetration into a room is the key variable for both visual and thermal comfort assessments in the space. The quantity of sunlight, in this respect, is mainly determined by the depth of penetration, rather than by the measured intensity of direct sunshine.
- Not only due to thermal reaction, but also because of visual requirements, people do not like the sun to shine in their close vicinity. They are particularly keen to avoid the sun falling on their working area and from falling on their eyes.

According to Numan (1979), control of the solar irradiance field by artificial mechanical means, constructional and added design features, adds considerably to the initial and running costs of buildings and the consumption of energy. This may not be justified, he argues, in terms of meagre financial and energy resources of the developing countries. It is conceivable, he states, that a practical and natural control of the thermal and visual built environment and the factors determining it may be achieved by manipulating the form, spacing, orientation and physical properties of buildings.

2.4 Design for comfort

The main purpose of buildings is to give shelter – for privacy and for thermal comfort. Privacy includes elements of social, psychological and religious character, but is physically created by enclosing a space by an envelope, sizing and positioning the openings towards the surroundings, and providing acoustic insulation. For thermal comfort, the building must act as a barrier, transforming the outdoor climate to conditions suitable for indoor activities. (Rosenlund, 2000). Wang (1992), too, identifies that the provision of a comfortable indoor environment is one of the most important functions of a building. If the building concerned fails in that, the users of the building tend to use active techniques such as fans and air-conditioning for achievement desirable indoor conditions, resulting in energy consumption.

However, in the face of ever-expanding energy crisis and environmental degradation, climatic design has emerged as a potential sustainable solution. Therefore, traditional architecture, which seems to have climatic design as the basis, has received increased attention of architects and engineers.

Mazouz & Zelouala (1999) observe that an important number of designers in some arid and topical regions, seeking passive and climatically cheap solutions, are turning back to the architectural inheritance of the past. Rosenlund (2000) states that a newly awakened interest for passive climatization should have a great deal to learn from the past, but purely traditional solutions assuming continuity of lifestyles and kinds of work seem rather unlikely. Therefore, he concludes that combining traditional knowledge and advanced technology is necessary.

2.4.1 Traditional architecture

Wang (1992) describes the main aims of the owner of a traditional residential building as convenience, comfort and economical construction, and the main factors that affect the architecture of traditional dwellings as cultural influences and the local climate. The traditional concentration on comfort is highlighted by Rosenlund (2000). He states that traditional buildings often mitigated the exterior climate, even if 'comfort' was not always achieved at all times of the day or in all seasons.

Traditional building elements employed for achievement of thermal comfort are (De Waal, 1993):

- Roof spray and roof paved systems
- Earth air tunnel system
- Earth sheltered building
- Covering roof with small closely packed inverted earthen pots
- Movable shutters of the roof for insulation by day and rapid cooling by night

On the other hand, modern housing developments often show very little regard for the local culture, climate and geographical resources. New buildings, therefore, consume large amounts of energy to maintain indoor thermal comfort. However, the traditional architecture based on local climate conditions and resources offers natural space conditioning inside buildings. It is therefore, imperative to adopt relevant and positive aspects of the traditional architecture for conservation of energy and improvement of thermal comfort (Ahamed et al., 1985).

Ahamed et al. (1985) cite an example in Ghadames in the western part of Libya. There, the traditional architecture has combined compactness, and achieved minimum exposure to the sun providing privacy to the family. Clay mixed with organic matter is the main building material while palm trunks and leaves are used for roofs. In a study conducted by them using a modern house and a traditional house, the summer ambient temperature varied from 20 to 40°C with an average of about 31°C. The average indoor temperature in the new house was 35°C (ranging from 34 and 39°C) while that of the traditional house was only 28°C (staying fairly constant for the week long period of observation). The results show that traditional house can provide an indoor environment comfortable throughout the year while the modern house, in spite of some visual similarities with the old, is unable to provide indoor comfort both in summer and in winter.

In Greece, too, vernacular buildings respond well to seasonal changes because they are adapted to the microclimate of the area. Contemporary housing, however, usually totally ignores the climate, resulting in undesirable indoor conditions (Kolokotroni & Ykoung, 1990).

However, there are exceptional cases as well. For example, in a study conducted during the cool season of the tropical upland climate of Zambia, both types of houses –traditional as well as contemporary houses–were found to be uncomfortable, and the traditional house was more uncomfortable than the contemporary house (Malama & Sharples, 1997).

2.4.2 Climatic design

For a building to be energy efficient, it is necessary to control the input of energy through regulatory (i.e. active) systems and/or through 'passive' techniques (i.e. by way of climatic design). The former requires sophisticated equipment and depends on their smooth functioning and energy supply. The latter normally requires more interaction, monitoring and knowledge by the user, and is therefore more sensitive to human factors, though technically simpler and more reliable (Rosenlund, 2000).

There are three main considerations influencing architectural design in the tropics (Fry & Drew, 1982):

1. people and their needs
2. climate and its attendant ills
3. materials and the means of construction

As the first two indicate, a building should cater to its users in a friendly manner while providing a comfortable indoor environment by interacting with the climate.

2.4.2.1 Adaptive approach

An approach that takes into consideration not only climate but also culture is "Adoptive approach" (Rahuman & Kannan, 1997). Adaptive approach to thermal comfort, developed from comparisons between results of field surveys, was suggested in early 1970s and is based on Adaptive Principle: "If a change occurs in the thermal environment such as to produce discomfort, people react in ways will tend to restore the their comfort." This means that in an environment with changing temperatures such as a building with no heating or cooling, people will take actions such as changing their clothing, posture of position in the room which allow them to remain comfortable. They will also make use of controls at their disposal (windows, fans, heaters etc) to change environment to then liking. It has been found that by adopting such strategies people remain comfortable over a wide range of temperatures (Nicol & Raja, 1997).

Such responses given in Watson & Labs (1983) are:

- Increasing metabolic heat production
- Ingesting hot or cold food or liquid
- Add or subtract clothing
- Seek a different environment

Fritch et al. (1990) give various factors influencing window opening:

- External factors: Outdoor temperature, solar radiation, wind speed and direction, rain, noise, odours and pollutants
- Internal factors: Indoor temperature, odours and contaminants, humidity
- "Human" parameters: Type of activities, habits

2.4.2.2 Acclimatization

Comfort preferences of people in different location vary in terms of acclimatization to a particular climate. Long term experience of several generations of a humid and warmer climate may result to tolerance of people of that environment to higher temperatures as compared with people in colder regions (Khedari et al., 2000).

This has been demonstrated in several developing countries that are using western thermal comfort standards. In Bangladesh, where ASHRAE standard is adopted, comfort zone was found to be larger than that of the ASHRAE one, covering higher air temperatures and higher velocities (Mallick, 1996). A recent study conducted in Pakistan concluded that the ASHRAE standard does not apply in practice as climatic variation is very large (Khedari et al., 2000). In Thailand, two studies conducted on thermal comfort showed that thermal acceptability exists over a broad range of temperature, pushing summer comfort outward by a few degrees Celsius (Khedari et al., 2000). Another study conducted by Khedari et al. (2000) using Thai subjects has found that thermal acceptability is a few degrees Celsius beyond common comfort zone defined by ASHRAE and ISO7730 for warm boundary of summer comfort. This demonstrates that Thai people have a tolerance to higher temperatures.

The important role played by acclimatization in achievement of thermal comfort is highlighted in a study conducted by Rahman and Kannan (1997), using Malaysian college students attending lectures conducted in naturally ventilated classrooms. The neutral temperature predicted for these students by ASHRAE was between 19.9 and 25.4°C and that predicted by ISO 7730 was 24.6°C. However, this study comprising subjective assessment and simultaneous physical measurements of indoor environment concluded the neutral temperature as 27.4°C. This shows that models derived from studies using people acclimatized to temperate climates cannot predict comfort requirements of people acclimatized to hot and humid climates such as found in Malaysia. The Malaysians can withstand higher temperatures and thus do not require such lower temperatures to be comfortable. This argument is further strengthened by the fact that the neutral temperature for college-age Malaysians is higher than that for college-age Americans (25.6°C), Danes (25.7) and Japanese (26.3).

Therefore, Rahman & Kannan (1997) emphasize that it is important for developing countries to develop thermal comfort standards that take into account and represent true subjective feeling of people under their own natural environment.

2.4.2.3 Climatic design of buildings for local people

Building design is the first "line of defence" against the stress of outdoor climate (Watson & Labs, 1983). Each building site offers its own conditions for a good climatic design, and it is the task of the designer to exploit the positive and avoid the negative. Climatic design helps the building take advantage of the climate when it is advantageous, and protects the building from the climate when it is not (Rosenlund, 2000). It can substantially reduce the energy cost of a building (Watson & Labs, 1983; El-Asfouri et al., 1988) and is therefore a good investment in the long run (Watson & Labs, 1983).

As the terminology implies, climatic design is an approach to reduce energy cost of a building by using "natural energy" available at the site for provision of indoor thermal comfort. Sources of natural heating and cooling are the sun, wind, precipitation, and resulting temperatures in the air and stored in the ground (Watson & Labs, 1983). The sun may be described as the 'engine' of the climate since it supplies a large amount of energy to the earth. The sun's path is regular and depends on the latitude and the time of the year (Rosenlund, 2000).

The generic concepts of climatic design can be listed as (Watson & Labs, 1983):

- Plants and water (site planning)
- Indoor/outdoor rooms (building massing)
- Earth sheltering (building massing)
- Sun shading (building openings)
- Natural ventilation (building openings)

Most passive techniques are no-cost ones while the others can be easily incorporated into conventional construction (Watson & Labs, 1983). Usually the passive system is an integral part of the structure and has multiple uses. One example is an ordinary window, which can provide view, light, ventilation and solar gain (Rosenlund, 2000).

There are now technical means that would allow building design to ignore the climate; but while this is technically possible, there are still good reasons to adopt passive techniques, not only economic, but also to promote environmental sustainability at both local and global levels (Rosenlund, 2000).

Early stage requirement

According to Mathews et al. (1992), the foundation for a good thermal design is laid during the sketch design phase. A similar view is expressed by Szokolay (1983), who suggests that "climatic design" may contribute to help the architect in the process of form generation, not simply as an evaluation tool, which intervenes after an architectural solution has been found, but as a tool which may be used in the initial stages of the design process, through the preparation of "climatically sound solutions" as conjectures.

Another instance is reported by Rosenlund (2000). The climatic design process requires special attention. Already in 1974 the Building Research Establishment in the UK applied a systems approach by stating: *It is not practical to plan a building exclusively on economic, functional or formal grounds and expect a few minor adjustments to give a good indoor climate. Climate must be taken into account when deciding on the overall concept of a project, on the layout and orientation of buildings, on the shape and character of structures , on the spaces to be enclosed and last but by no mean least, the spaces between buildings. In other words climate must be considered at the early design stage.*

Building heat transfer

Building energy is primarily governed by three mechanisms of heat transfer conduction, ration and convection (Barozzi et al., 1992). Bansal et al., (1992) further describes the heat transfer modes, stating that heat enters a room in several different modes, namely by conduction and convection through walls, roof and floor, by convection in form of ventilation and infiltration; and by direct gain through glazed area of window.

According to Watson & Labs (1983), energy flows in and out of a building – through walls, roofs, openings, floors, and what the designer should do is identify these "hows" and build in controls of heat flow. They also state that the building envelope is the device through which heat exchange between exterior and interior environment is controlled. It intercedes with external climate, creating a new interior microclimatic zone.

Fundamental control options are (Watson & Labs, 1983):

- Admitting, or excluding heat gain from external energy sources
- Containing, or rejecting heat energy present in interior

Most these manifestations are static (e.g., area and orientation of glazing) while the others are dynamic (e.g., adjustable sun shading devices) (Watson & Labs, 1983).

Another factor that affects the processes of heat transfer is the thermal properties of the materials of the building envelope. According to Rosenlund (2000), thermal resistance and thermal capacity are more or less antonyms, but all building materials possess both of them in different proportions. He also gives three factors influencing these properties:

1. The density plays a great role for the thermal properties: the lighter the material the more insulation and the heavier the more heat storing.
2. The conductivity (W/mK) describes the ability to conduct heat. Insulation materials have low conductivity.
3. The specific heat (Wh/kgK) indicates how much energy can be stored in the material. High specific heat means good thermal, that is heat storing, capacity.

The combination of thermal properties has influence of the time lag and the attenuation of building elements. The time lag is the time from outside to inside maximum surface temperature, and the attenuation is the proportion of inside to outside temperature amplitude (swing). These properties strongly affect the indoor climate (Rosenlund, 2000).

Passive cooling

Passive solar heating has been widely examined, passive solar cooling, however, remains largely unexplored. Need for passive cooling strategies is greatest in developing countries, where hot annual temperatures are predominant. Constrained by extreme environmental conditions, poor building technology, and limited financial resources, these countries have had little opportunity to establish good standards of thermal comfort in buildings. In many instances indigenous architecture has been superseded by imported modern building design. Compounded by cost of foreign made materials and components, increased fuel consumption required to keep these buildings cool has invariably contributed to financial ruin. A collective effort is therefore required to develop new passive building technologies for the Third World. Use of low-cost, readily available building materials, and simple construction methods should be encouraged, and passive means of cooling buildings must be utilized (Barozzi et al., 1992).

Passive cooling techniques present a very important alternative to conventional air-conditioning of buildings (Geros et al.,1990). The principles of passive cooling include: shading, reflection, insulation, reduction of internal gains, and ventilation. Heat reduction is best achieved by excluding unwanted heat rather than removing it later, often by air-conditioning. Passive cooling sources can be listed as the sky, the atmosphere, and the earth – all natural heat sinks. The sky acts exclusively by radiation, the earth and the atmosphere by convection and latent energy processes (evaporation) (Rosenlund, 2000).

Generally, building design should be passive as far as possible to minimize the need for energy input. If this solution is not fully satisfactory, complementary hybrid or active systems may be used. 'Passive' has in fact changed its meaning to include what are called hybrid systems, i.e. limited use of low energy equipment such as ceiling or table fans if their coefficient of performance (the relation between energy output and input) is high. However, these systems should by simple and cheap to build, operate and maintain, integrated as far as possible in the building structure, and they should meet any user requirements (Rosenlund, 2000).

2.4.3 Daylight design

Daylighting is an important factor in interior design affecting the functional arrangement of spaces, occupant comfort (visual and thermal), structure, and energy use in buildings. It gives a sense of cheeriness and brightness that can have a significant positive impact on the people (Li et al., 1999). Maitreya (1977) also report that preference for natural light is well established by scientific research and experience.

Natural illumination is an economical means of lighting for a building. In recent years, greater recognition has been given to the contribution that daylight can make to energy conservation in buildings. For example, in Hong Kong, in terms of luminous efficacy (i.e. the amount of light provided per unit heat gain), daylight (100-200 lm/W) is much better than the 16-40 lm/W for fluorescent lamps that are commonly installed at homes because less heat is introduced to achieve the same lighting level and less cooling will be required (Li et al., 1999).

Distribution of daylight is graphically presented in Nayak et al. (1999) as follows:

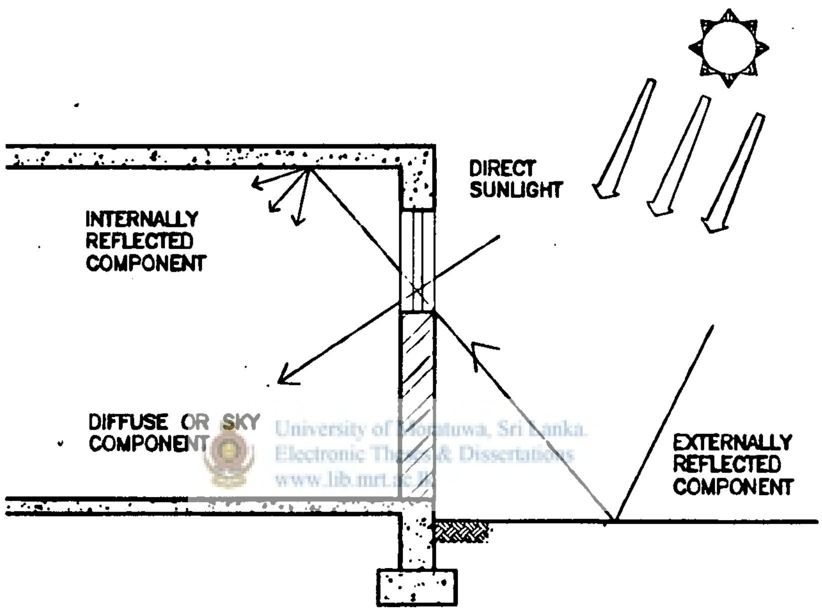


Figure 2.4 Distribution of daylight (Nayak et al., 1999)

The amount of daylight entering a building is mainly through window openings which provide the dual function not only of admitting light for indoor environment, but also allowing people to maintain visual contact with the outside world (Li et al., 1999).

Key building variables affecting daylighting designs (Li et al., 1999):

- Glass type: Glass type controls indoor daylight availability in terms of light transmittance. In Hong Kong most buildings use single glazing. Clear and tinted glasses with typical light transmittance values of 0.85 and 0.5 are commonly used for residential buildings. The majority is clear glass. Tinted glass is usually installed for luxury buildings in fashionable residential zones.

- Window area: For a given glazing type, the critical factor determining the daylight entering a building is the window area.

- Shading: Shading devices shade the window from direct sun penetration but allow diffuse daylight to be admitted. Exterior shading devices frequently found in Hong Kong include overhangs, side fins and balconies. Among them, the first is the most popular.

- External obstructions: Depends on the amount of daylight being obstructed, depending on height of neighboring buildings and separations. When buildings are located close to each other, blockage of natural light can be severe, particularly for the units on lower floors

2.5 Thermal comfort for Sri Lankans

Sri Lanka is an island of about 65,000 km^2 located at latitude 5°55'-9°51'N and longitude 79°43'-82°53'E (Central Bank of Sri Lanka, 1999). The low altitudes of Sri Lanka experience equatorial warm humid climatic conditions.

2.5.1 Climate of low altitudes of Sri Lanka

The primary characteristic of the equatorial climate is its almost unchanging weather patterns. Unlike other climates, daily weather patterns dominate over seasonal weather – all seasons occurring within one day. There are cool mornings, warm early day, hot and humid daytime and almost unbearably damp afternoons, all within the day, repeating perpetually. While no single climatic parameter is excessively high, the combination and the time of occurrence make equatorial climates unbearable. Thus a combination of air temperature at 30-31°C coupled with a relative humidity of 80% or more, occurring with 0.1m/s or less air movement, is extremely oppressive (Emmanual, 1993).

The climate of the low altitudes of Sri Lanka is predominantly warm humid. Rosenlund (2000) describes a warm humid climate as one with a fairly constant temperature, both over the day and over the year. Humidity and cloudiness make diffuse solar radiation important, and the potential for radiative sky cooling is lower. Seasons are often determined by rainfall and winds.

Sri Lanka comprises three climatic zones, namely wet zone, dry zone and hill country; the wet and dry zones belong to low country. In low country, the annual average minimum and maximum temperatures are 24.6 and 32.4°C respectively; in hill country the corresponding figures are 17.8 and 26.8°C (Central Bank of Sri Lanka, 1999). Early in the morning, relative humidity can be as high as 90 to 100% whereas it drops to 60 to 70% in the afternoon. Distinct seasonal changes are not evident, and the general requirement in the low altitudes throughout the year is cooling. The climatic data given in Table 2.3 is applicable to Colombo (latitude 6°54'N, longitude 79°43'E, altitude < 10m).

Month	Sunshine (hours per day)	Average Rainfall (mm/month)	Mean daily temperature(°C)		Relative humidity(%), temperature(°C)		Minimum & maximum relative humidity(%)*	
			Max (around 14.00 hours)	Min (around 6.00 hours)	8.30 hours	17.30 hours	Min (around 14.00 hours)	Max (around 6.00 hours)
Jan	7.5	87.9	30.3	22.2	81, 24.5	70, 27.6	58	90
Feb	8.2	96.0	30.6	22.3	82, 24.9	72, 28.1	59	92
Mar	8.8	117.6	31.0	23.3	83, 26.4	72, 28.8	64	94
Apr	7.9	259.8	31.1	24.3	84, 27.3	74, 29.1	68	95
May	6.2	352.6	30.6	25.3	83, 27.8	78, 28.7	72	92
Jun	6.6	211.6	29.6	25.2	82, 27.5	78, 28.0	73	93
Jul	6.1	139.7	29.3	24.9	82, 26.9	78, 27.6	70	90
Aug	6.5	123.7	29.4	25.0	81, 27.1	77, 27.6	65	90
Sep	6.4	153.4	29.6	24.7	81, 26.9	77, 27.5	67	91
Oct	6.2	354.1	29.4	23.8	83, 26.5	78, 27.2	70	92
Nov	6.8	324.4	29.6	22.9	83, 26.8	77, 27.1	67	93
Dec	6.9	174.8	29.8	22.4	81, 26.1	74, 27.1	61	91

*These are calculated using the psychrometric chart assuming that the moisture content remains the same. Minimum relative humidity corresponds to maximum temperature and maximum relative humidity corresponds to minimum temperature.

Table 2.3 Climatic data for Colombo

As shown in Table 2.3, the maximum outdoor temperature, which occurs around 14.00 hours, lies between 29.3°C (July) and 31.1°C (April). Although the sun path lies directly over Colombo in April, March can be considered as the most undesirable month with respect to thermal comfort because the average sunshine hours it experiences is the highest. This could be attributed to the higher average rainfall experienced in April, resulting in cloudy weather obstructing the sun. The minimum outdoor temperature, which occurs around 6.00 hours is as low as 22.2°C in January and as high as 25.3°C in May.

The minimum relative humidity occurs when the outdoor temperature is maximum, and the value lies generally between 60 and 75%. The maximum relative humidity, which occurs when the outdoor temperature is minimum is generally about 90%.

2.5.2 Comfort zone developed for Sri Lanka

Comfort preferences of people in different locations vary in terms of acclimatization to a particular climate. Long term several generations experience of a warm humid climate may result in tolerance of people of that environment to higher temperatures as compared with people in cold regions (Khedari et al., 2000). This has been demonstrated in several developing countries such as Bangladesh (Mallick, 1996), Pakistan (Khedari et al., 2000) and Thailand (Khedari et al., 2000).

Research in this regard has been carried out in Sri Lanka as well. It is shown by Jayasinghe & Attalage (1997) that, for Sri Lanka, a single neutral temperature of 26°C can be used to obtain the standard comfort zone for any part of the country where the altitude is less than 300m. Above 300m up to 900m, a value of 25°C can be used. It is also possible to enlarge the standard comfort zone to suit Sri Lanka by using a higher humidity ratio of 0.015 as the upper boundary. When the internal air velocity is greater than 0.25m/s, the standard comfort zone can be modified to take account of the physiological effects of cooling. For these modifications, a humidity ratio of 0.020 has been suggested as an upper boundary when used with a neutral temperature of 26°C.

For low altitudes of Sri Lanka, the standard comfort zone and the modified zones for different internal air velocities are given in Figure 2.1. This shows that, when involved in sedentary activity levels such as desk work, Sri Lankans can be thermally comfortable at temperatures as high as 30°C in presence of air movement indoors. (Jayasinghe & Attalage, 1999a). This conforms to the statement by Watson & Labs (1983) that, within certain conditions, effect of increased air movement is to extend upper limit of comfort zone to higher temperatures.

This important finding could be effectively employed along with passive techniques to achieve indoor thermal comfort of houses in Sri Lanka, thus reducing the energy use and environmental degradation.

In low altitudes of Sri Lanka (i.e. below 300m), the general requirement throughout the year is cooling. Therefore, the designers should aim to minimise the heat gains while maximising the natural ventilation and structural cooling (Jayasinghe & Attalage, 1999b). The external gains occur through the building envelope; the internal gains are generated indoors. The strategy should be to resist radiant and conductive heat gains and to minimise internal heat gains.

Natural ventilation is very important for the warm humid climatic conditions. It promotes conduction-convection heat loss from the human body, evaporation of skin moisture from the human body (i.e. physiological cooling effect), and night time cooling and structural cooling, which allows a cooler structure at the beginning of the day.

2.6 Passive concepts and techniques for warm humid climates

The passive concepts and techniques for the warm humid climatic conditions prevailing in low altitudes of Sri Lanka where thermal discomfort is a major problem presented.

2.6.1 Microclimate

The surroundings of a building have great influence on its indoor climate, whether it is in a city or in the countryside. Topography, surrounding buildings, vegetation and water are elements that transform the regional climate into a specific microclimate, which is the input for the indoor climate of the individual building (Rosenlund, 2000).

With increasing urbanization, the phenomenon "urban heat island" is expected to affect a larger number of urban residents. Thus in areas where there is thermal stress, it makes sense to develop ecological approaches to mitigation (Ca et al., 1998). A study by Rosenfeld et al. (1995) on alleviating the heat island problem, suggests a three pronged strategies beyond microclimate below trees: (a) cool roofs, (b) cool pavements, and (c) vegetation for evapotranspiration. Therefore, vegetation can be used for the creation of a desirable microclimate, by way of shading and evapotranspiration.

Cool surfaces

In a green area with trees, cooling effect is determined by amount of canopy shading. Different levels of shading will produce different levels of shading effect. Canopy shading is determined by factors such as canopy shape and depth and leaf area distribution, spacing of trees, and growth factors such as cultivation and irrigation regime (Shashua–Bar & Hoffman, 2000).

Another important factor is that vegetation surfaces show lower radiative temperatures than other inanimate ones of the same colour. The difference in maximum temperature may exceed 20°C (Shashua–Bar & Hoffman, 2000). Therefore, exposed non-vegetative surfaces should be minimized by proper planning as reported in De Waal (1993), where subsurface parking is recommended as the combination of asphalt and cars can lead to high urban air temperatures.

Evapotranspiration

Evapotranspiration can be useful in two ways. By evapotranspiration, large amounts of solar radiation can be converted into latent heat which does not cause temperature to rise (Takakura et al., 2000). With presence of a vegetated surface, evapotranspiration can transform a larger portion of incoming solar radiation to the surface, which otherwise would contribute to underground heat storage, into latent heat and makes ground surface cooler. Thus in making a development plan of a city, effect of vegetation on urban thermal climate should be studied carefully (Ca et al., 1998).

Macro-level application of vegetation

In macro, one of the effective control measures suggested against heat island is vegetation. Various studies have found that large green areas such as parks located in urban areas affect air temperature above them and thus improve the thermal environment of the urban area (Shashua – Bar & Hoffman, 2000). For example, Jauregui (1990) found that, in Chapultepec Park (500 ha in extent) in Mexico City, Mexico, effect of the park on air temperature was noticeable at a radius of 2 km, about the same as its width.

A study conducted by Ca et al. (1998) at many locations inside a park and its neighbourhood in the Tama New Town in Japan, to investigate possibilities of reduction of air conditioning energy, has indicated that vegetation could significantly alter the climate in the town. The park, extending to 0.6 km^2, could reduce by up to 1.5°C the air temperature in a busy commercial area 1 km down wind at noon. It was also found that, by lowering outdoor air temperature from 33.5 to 31.5°C, a saving of almost 15% in electricity spent for air-conditioning was possible at noon.

Micro-level application of vegetation

In micro, effect of vegetation on thermal environment of its surrounding area is rather small but still significant (Shashua–Bar & Hoffman, 2000). Saito et al. (1990) & Rosenfeld et al. (1995) have found that even a single tree can affect air temperature of the immediate surrounding environment.

Various studies have shown the cooling potential of small sites. The cooling effect of Haifa's Biniamin Park (0.5 ha in extent) in Israel was found to be noticeable 20 to 150m outside it (Shashua–Bar & Hoffman, 2000). In Japan, Hunjo & Takakura (1990), using a numerical model, have shown a cooling range effective 200m in the direction of wind when the width of green area is in the range 300 to 700m.

To determine the summer cooling effects of small urban green wooded sites of various geometric configurations, Shashua–Bar & Hoffman (2000) have experimentally studied eleven different wooded sites in the Tel–Aviv urban complex in Israel. They comprised two gardens, four avenues, one green square, two courtyards, and two streets – width between 20 and 60m. The average cooling effect in all sites was about 2.8°C, ranging from as low as 1°C in a street with heavy traffic to as high as 4°C in the smaller garden (0.15 ha).

Further, based on a statistical analysis carried out on 714 experimental observations gathered each hour from the sites, an empirical model was developed for the prediction of cooling effect inside sites. The following effects, which can be of special interest for design of small urban green habitats, were found to be statistically significant (Shashua–Bar & Hoffman, 2000):

- Background effect: Cooling effect in a wooded site was found to depend, among other factors, on air temperature of its background site. The higher this temperature the stronger the cooling effect. For example, a stronger cooling effect of 6°C is expected in a typical garden in south Israel (say Eilat) as against 2.8°C in Tel Aviv region because Eilat is 10°C hotter in summer than Tel Aviv.

- Tree shading coverage: In the studied sites, shading in summer is provided by trees, and it is estimated that, on average, about 80% of cooling effect was contributed by tree shading. Besides, the shading coverage factor is a control variable. It can be regulated by cultivation regime and by pruning, and in new sites by proper choice and placement of shade trees.

- Effect of trees in street: Shading effect of trees in streets was found to have the same magnitude of cooling effect as in other sites.

- Cooling effect on site surroundings: Range of cooling effect was found to be rather narrow and is perceivable up to 100 m from site boundary. This fact corroborates earlier studies.

Overall conclusion that can be drawn from this study by Shashua–Bar & Hoffman (2000) is that the cooling effects of small green areas though local are significant. Based on this, the following policy measures have been proposed for alleviating the heat island effect in urban environment:

- Range of cooling effect being perceivable up to 100m suggests small gardens, 200m apart. These gardens can be designed to accommodate recreational needs of young children & senior citizens.

- Cooling effect of trees in streets was found to be significant. In a street with trees, with heavy traffic, the cooling effect reaches about 1°C. Since the streets constitute more than 25 % of urban city area, this policy measure, properly designed, is most effective in reducing traffic heating effects. Besides the cost is minimal.

- At least one shade tree per eligible house is recommended to offset some of car's parking effect in courtyard.

Small green sites at intervals instead of one large green site have been preferred by other researchers as well.

One of the characteristics of the equatorial tropics is the weak temperature variation, both diurnal and seasonal. Larger climate modifying agents like lakes are of little use to particular outdoor stretches if micro level enhancements are not provided. For thermal comfort in equatorial tropics, it is necessary to provide smaller comfort-enhancing elements in each urban block. Thus, rather than a large park, many smaller but climatically viable parks will ameliorate the microclimate over a wider area Emmanual (1993).

In the study by Hunjo & Takakura (1990), the simulation results indicate that range of cooling effects is a function of green area scale and intervals between green areas. Therefore, they suggest that smaller green areas at sufficient intervals are preferable for effective cooling of surroundings to lumped larger green areas.

To improve urban climate to a moderate extant, Landsberg (1981) has recommended that many small areas of vegetation are better than one large park.

2.6.2 Building form and elements

In the tropical region with warm humid climatic conditions, resisting solar radiation and promoting ventilation are important for the achievement of indoor thermal comfort. For resisting solar gains, compact construction and roof insulation have been proposed; for ventilation, open structure is recommended.

De Waal (1993) reports that compact high-rise buildings perform substantially better than low rise buildings. This could be attributed to reduced exposure to solar radiation.

Rosenlund (2000) states that ceilings, moderately insulated if possible, in combination with ventilated attic spaces help protect from solar heating through the roof. The roofing sheets should be light coloured and the inside should be shiny to decrease heat emission downwards. However, oxidization often rapidly decreases this effect.

Rosenlund (2000) further suggests that, in the tropics, buildings should be of open structure with large openings providing cross ventilation. Pitched roofs with wide overhangs or verandahs create shade and rain protection.

2.6.3 Orientation and shading

The solar heat flow through glazed fenestration is a major item which has a strong impact on both the instantaneous demand and the integrated consumption of energy requirement for environmental control (El-Asfouri et al., 1988). Ranasinghe & Perera (1997) share this view stating that direct sunlight on glazing contributes to excessive heat gain.

Therefore, in climatic design, proper orientation of and shading for openings is very important.

For high solar altitudes as experienced in the equatorial tropics, De Waal (1993) recommends north-south orientation for large building facades. Besides, the orientation of a window determines quality, quantity and character of lighting within a space (Ranasinghe & Perera, 1997).

Proper and improper orientation is given in Nayak et al. (1999).

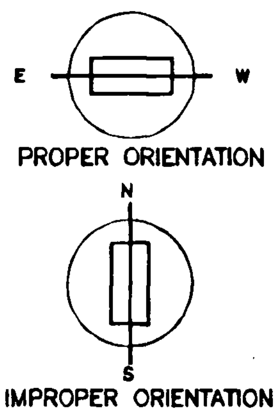


Figure 2.5 Proper and improper orientation (Nayak et al., 1999)

In the tropics, shading of openings is one of the most important factors for comfort thermal as well as visual comfort (Rosenlund, 2000). Fortunately, in this region, the sun is closer to the azimuth most of the year, and therefore sun control of individual buildings is relatively easy (Emmanual, 1993).

External arrangement of shading devices is much more effective than internal arrangement, and their efficiency also depends on orientation. (Jorge et al., 1993).

There are various shading devices. They are given in Nayak et al. (1999).

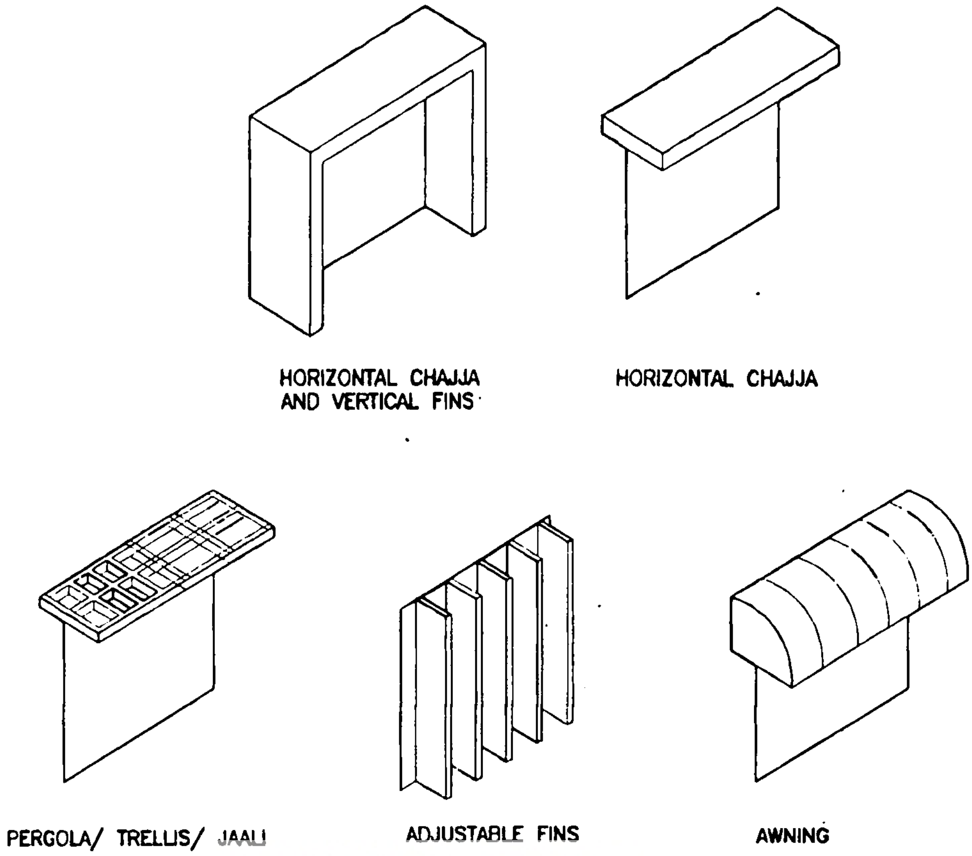


Figure 2.6 Shading devices (Nayak et al., 1999)

For a building in Sri Lanka, Jayasinghe & Attalage (1999b) have shown that an overhang making a horizontal angle of 60° will be sufficient for the protection of a north or south facing opening throughout the year.

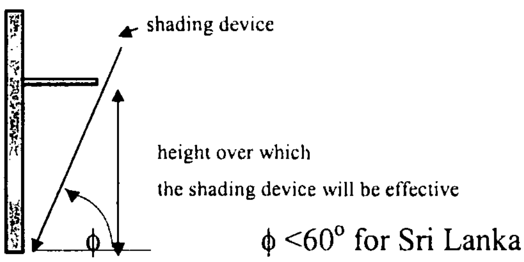


Figure 2.7 Overhang for a north or south facing opening of a Sri Lankan building

Shading devices is one method adopted to counter glare, i.e. the excessive brightness in the field of vision. Another method is use of tinted glass or mirrored glass, which is characterized in contemporary architectural trends (Ranasinghe & Perera, 1997). However, the former adversely affects the visual comfort indoors while the latter heats the surroundings by intense reflection.

2.6.4 Ventilation

There are various purposes of ventilation. Rosenlund (2000) lists them as thermal comfort, structural heating/cooling, health and moisture removal from the skin. Gan (2000) states that effective distribution of fresh air within an occupied space is of considerable importance in securing thermal comfort and good indoor air quality, and could also be used for energy conservation.

Chand et al (1989) emphasizes its role of increased importance in the design of buildings in the tropics. This view is shared by Kindangen et al. (1997). According to them, especially in regions where the climate is hot humid, natural ventilation proves to be a realistic alternative as an energy conserving design strategy aimed at reducing cooling loads of buildings and improving indoor thermal comfort. Although a lot of advancement has been made in technology of mechanical systems of ventilation, tendency among building designers to give prime importance to provision of natural ventilation still persists (Chand et al., 1989).

The design principle recommended by Nayak et al. (1999) for warm humid climates further reinforces the importance of ventilation.

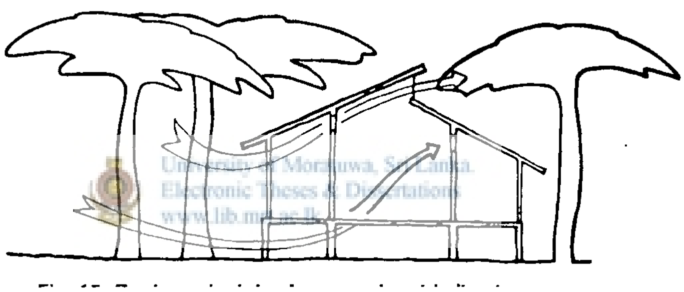


Figure 2.8 Design principle for warm humid climates (Nayak et al., 1999)

Thermal comfort can be created by increasing air speed through cross ventilation, which promotes evaporative cooling of moist skin (Rosenlund, 2000). Natural ventilation can be in form of single sided or cross flow. Cross ventilation is generally more effective in promoting room air movement than single-sided ventilation (Gan, 2000). Placement of openings for inlet and outlet of air is essential for directing the air current to the occupation zone (Rosenlund, 2000).

The shape of buildings, particularly around windward openings, can have a significant effect on air flow through buildings. Typical building shapings used to enhance air flow through windward openings includes projecting eaves; recessing windows into the wall; rounding the edges of the openings; projecting wing walls on the leeward edges of windows on walls inclined to the prevailing wind. When prevailing winds come from either side of normal to the wall, a vertical fin at the center of the window can be effective in increasing air flow through the windows (Aynsley, 1999). An example, a baffle wall, is given in Nayak et al. (1999)

Rosenlund (2000) recommends ventilated attic spaces, preferably with some ceiling insulation, to reduce radiative heat transfer from the roof sheeting, thus enhancing indoor thermal comfort.

Night ventilation techniques are based on the use of cool ambient air as a heat sink, to decrease indoor air temperate as well as temperature of building's structure. Recent research has shown that night ventilation techniques, especially when applied to massive buildings, can significantly reduce cooling loads of air-conditioning buildings and increase thermal comfort levels of non-air conditioned buildings (Geros et al., 1990).

The problem in using ventilation for achievement of thermal comfort is its unpredictability both in occurrence and direction. Therefore, it is prudent to consider that the wind direction could be anything. As shown by Aynsley (1999), openings in the leeward side of the building are usually in suction regions so shaping of the openings has little effect; however, in some locations, the direction of prevailing winds can shift through 180° so any wall can be a windward wall.

Besides, as reported by Emmanual (1993), cooling effect of wind movement, which is proportional to the difference between skin temperature and air temperature, is of little value in the equatorial tropics, since both these temperatures are almost equal.

2.6.5 Courtyard

The prime objective of a central courtyard is to trap cool air during night and to keep walls of surrounding rooms cool during daytime. Courtyards also facilitate provision of indoors on opposite walls of rooms for achieving cross ventilation through them. An example of use of this can be found in traditional Tamil houses in India (Chand et al., 1989).

2.6.6 Exterior surface

Surface characteristics have been cited as one of the causes of the urban heat island. This, however, is not a serious urban design problem. Simple guidelines could be incorporated into urban ordinances that encourage/prevent certain building materials in particular land uses. Effectiveness of such guidelines would perhaps be enhanced if they are applied over a larger area (say an entire city) (Emmanual, 1993).

Surface properties of building materials are absorptance, which is the ability to absorb short-wave, visible light, and emittance, correspondingly to long-wave, heat radiation. Absorptance relates to colour, and values between 20% for white paint and 95% for black surfaces are normal. Emittance relates more to surface structure, and is normally about 85-95% for building materials, except shiny metal surfaces, which may have 10-30% emittance. Consequently, a white painted rendering reflects most of the solar radiation but may emit a great deal of heat, e.g. to a clear night sky (Rosenlund, 2000).

Material		Absorptance (%)	Emittance (%)
Aluminium sheet	New	20-40	10
	Oxidized	30-50	20-30
Burnt clay brick	Cream	30-50	85-95
	Yellow	55	90
	Red	65-80	85-95
Concrete	Light	45-70	85-95
	Dark	90	90
Earth		80	90
Grass, leaves		75-80	85-95
Paint	White	20-30	85-95
	Light grey	30	90
	Light green	50-60	90
	Medium grey, yellow, orange	55	90
	Light brown, grey, red	65-70	90
	Dark brown, red, green	80-90	85-95
	Black	85-95	85-95
Steel sheet	Galvanized, new	30-65	15-30
	Galvanized, oxidized	80	20-40
	Rusty	60-85	60-90
Stone	White marble	50	85-95
	Limestone	60	85-95
	Yellow	50-70	85-95
	Red	65-80	85-95
Tatch		60-70	85-95
White-wash	New	10-15	20-30
	Weathered	20-30	20-40
Wood	Pine	60	90-95

Table 2.4 Absorptance and emittance of some building materials (Rosenlund, 2000)

Surface colour

Colour of outside surface of a building envelope is expected to influence the thermal performance of a building significantly as it determines the amount of absorbed solar radiation and, therefore, its inward transmission into the building (Givoni, 1976). Various studies have shown that there is an effect.

Experimental measurements reported for two colours, namely white and grey, showed a difference of 3°C in room air temperature when measured 0.1m below the ceiling, while it remained only 1°C when measured 1.2 m above the floor. Temperatures, as expected, were higher for grey-coloured enclosure (Bansal et al. 1992).

Givoni (1976) states that effect of external colour on room air temperature depends on various other parameters also, particularly heat resistance and heat capacity of building. For example, for a low U value building with high thermal capacity (heavy construction), effect of external colour is not so significant as for low thermal resistance (high U value) and low heat capacity building.

As reported by Bansal et al. (1992) effect of external surface colour on room temperature inside a building will also depend on the rate of air ventilation in building and the direct solar radiation gain into building.

Bansal et al. (1992) have conducted a study using two identical enclosures, one painted black and the other painted white on four walls and the roof, with a detachable overhang capable of completely shading the glazed window. The black painted enclosure showed higher temperatures than white painted one during day time, maximum difference being the case when no ventilation was allowed and no direct radiation came through window. During night time, air temperature inside both enclosures were the same and equal to ambient temperature. This could be attributed to the negligible heat capacity of enclosures made from 25-mm thick plywood boards.

A basic fact which comes out from the measurements is that effect of external surface colour gets diluted if ventilation is maintained in building and if direct radiation is allowed to penetrate into building (Bansal et al., 1992).

It is evident that external colour of a building envelope affects thermal performance of building (Bansal et al., 1992). This is in contrast to earlier belief that exterior surface colour will have a minor to negligible influence on both heating and cooling performance of buildings (Sodha et al., 1984). However, the effect is diluted by more influential parameters like ventilation and direct solar gain inside building.

Besides a white painted normal sized room is shown to record 6°C lower temperature during hot summer months than a corresponding black painted room even when air exchanges up to 3 are allowed in room (Bansal et al., 1992).

Greenery cover over surface

One way to increase evapotranspiration surface area in big cities is to cover buildings with vegetative greenery. Greenery cover over a building has a cooling effect on surroundings and also reduces cooling loads inside buildings. Preliminary experiments show rather large cooling effects of roof top greenery. Energy savings produced by various greenery coverings are reported to have varied widely due to weather and vegetating differences (Takakura et al., 2000).

Takakura et al., (2000) have investigated the cooling effect of various kinds of greenery cover by both experimental model and computer simulation, using four concrete roof models with different coverings: bare concrete, soil layer, soil layer with turf and soil layer with ivy. According to the results, for the ivy covered roof, indoor air temperatures were very steady throughout day - lowest 22°C and highest 25°C. However, the inside air temperatures under base concrete roof rose to almost 40°C during day and fell to below 20°C at night.

2.7 Summary

The findings of the literature survey can be summarized as follows:

1. The emerging global trends in the face of environmental degradation and energy crisis is energy conservation. In buildings, this is achieved by climatic design for achieving thermal comfort, which is an environment friendly strategy.

2. Having realized the negative effects of the blind adoption of western architecture and western thermal standards, Asian countries like Pakistan and Thailand have resorted to climatic design, including development of their own thermal standards.

3. Thermal comfort depends on various parameters, and their combinations at which the majority feel comfortable form the basis of the comfort zone, which is plotted on a psychrometric chart. Taking effects of physiological cooling, the comfort zone could be enlarged when air movement is present.

4. Climatic design takes into account the climate and the requirements of the local people. By way of various control options, the passive building manipulates the heat exchange to achieve indoor thermal comfort. This is the basis of traditional architecture round the world.

5. Acclimatized to warm humid climatic conditions for generations, Sri Lankans feel thermally comfortable at temperatures as high as 29°C or even 30°C, especially when some air movement is present.

6. Passive concepts and techniques suitable to warm humid climatic conditions can be listed as the following:

    - Microclimate rich in vegetation
    - Proper building form and elements
    - Proper orientation and shading for openings
    - Ventilation
    - Courtyard
    - Proper external surface

In this thesis, the adoption of all these trends and techniques to Sri Lanka for developing passive residential buildings was explored utilising the climatic data applicable to Colombo the business capital of Sri Lanka.

Chapter 3

THERMAL AND COMFORT SURVEYS

3.1 General

Under this study, thermal and comfort surveys were conducted at several existing buildings located in the Western Province of Sri Lanka at different times of the year. These actual measurements validated the comfort requirements of the Sri Lankans already identified by previous research, assessed the thermal performance of the surveyed buildings, and determined the effect of various passive concepts and techniques on indoor temperature. The seven buildings surveyed constitued a single-storey house, four two-storey houses, a three-storey hostel building, and a lecture room at the top floor of a three-storey university building.

3.2 Objectives

The objectives of the thermal and comfort surveys were the following:

1. To validate thermal comfort requirements of Sri Lankans already identified by previous research
2. To assess thermal performance of several typical existing buildings
3. To identify the effect of various passive concepts and techniques on indoor temperature

3.3 Methodology

To reach the above objectives, the following methodology was adopted:

1. Passive concepts and techniques desirable to achieve indoor thermal comfort under warm humid climatic conditions were identified through a literature survey
2. Thermal surveys, sometimes along with comfort surveys, were carried out at several typical existing buildings in the Western Province of Sri Lanka, using a hygrometer (i.e. wet and dry bulb thermometer)
3. The results of the surveys were analyzed

3.4 Case studies

Thermal and comfort surveys were conducted at different times of the year in seven existing buildings – mostly houses – located in the Western Province of Sri Lanka (Figure 3.1). An overview of the case studies is given in Table 3.1.

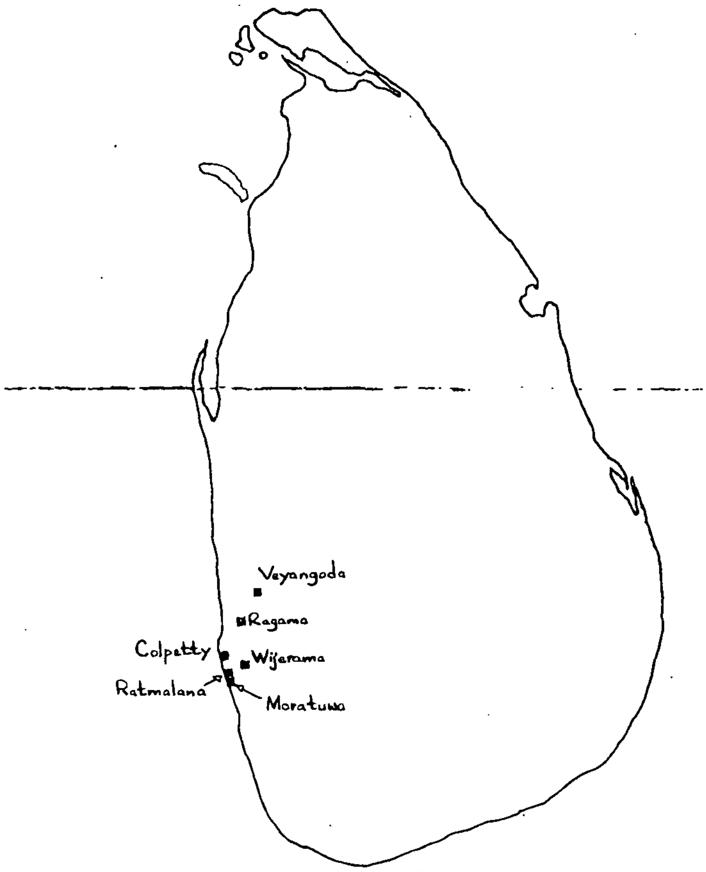


Figure 3.1 Locations of thermal and comfort surveys

Case No	Location	Use of building	Type of building	Thermal survey	Comfort survey	Month
1	Veyangoda	House	Single-storey	Yes	Yes	August
2	Ragama	House	Two-storey	Yes	Yes	June, July
3	Ratmalana	House	Two-storey	Yes	Yes	July
4	Wijerama	House	Two-storey	Yes	No	August
5	Colpetty	House	Two-storey	Yes	No	July
6	Moratuwa	Hostel	Three-storey	Yes	Yes	August
7	Moratuwa	Lecture room	Top floor of three-storey	Yes	No	July

Table 3.1 Cases of thermal and comfort surveys

Each case is described below in detail.

3.4.1 Case 1: Single-storey house in Veyangoda

Case 1 is a single-storey house located in the outskirts of Veyangoda town. The floor plan is given in Figure 3.2.

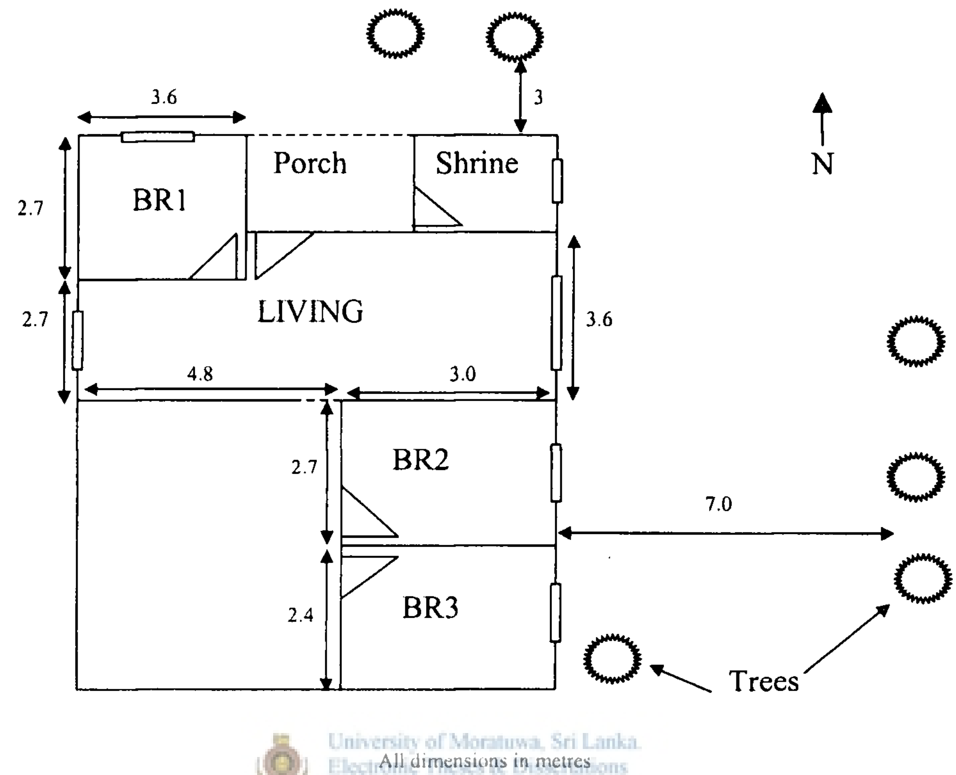
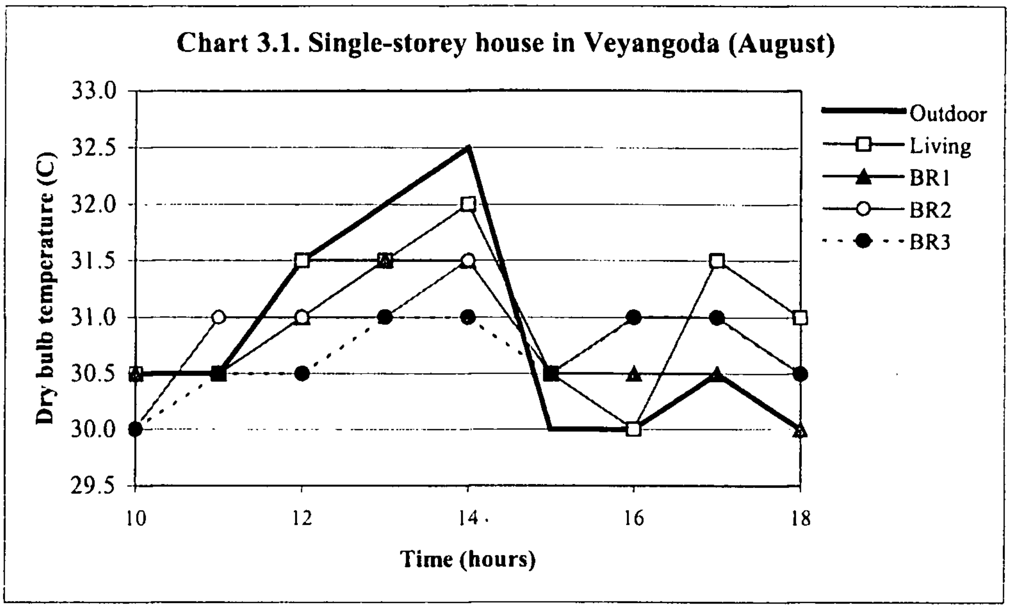


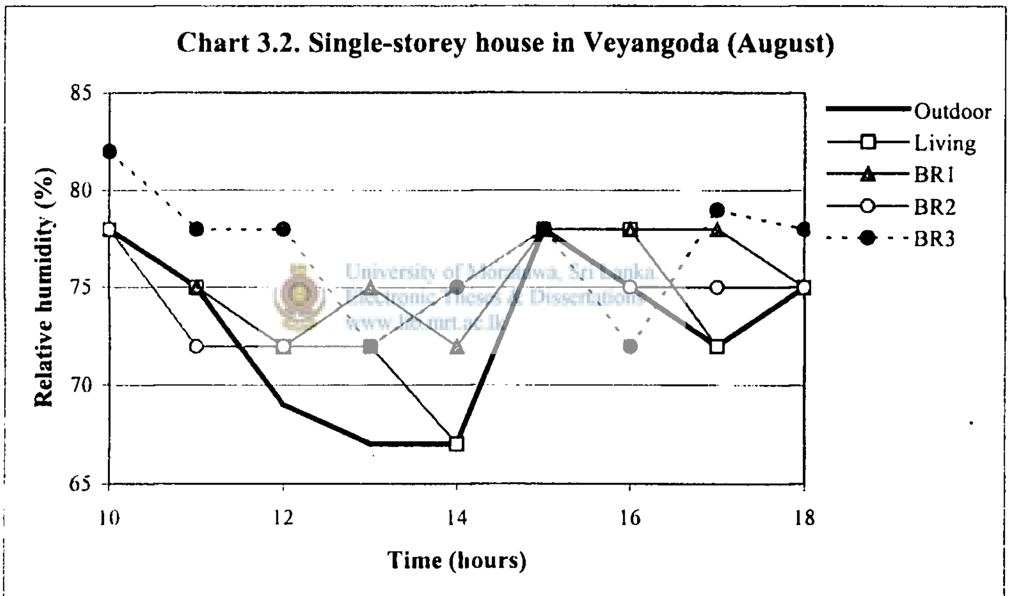
Figure 3.2 Floor plan of house in Veyangoda

The orientation of the house is given in Figure 3.2. The roof covering was of cement fibre sheets; the ceiling was a flat cement fibre ceiling. The wall material was brickwork. The colour of the exterior surface of the house was off-white. The windows had no shading devices. The garden had several trees and shrubbery. The ground was predominantly covered with grass.

A thermal survey, along with a comfort survey, was carried out on a hot day in August in four living spaces, namely combined space of living/dining (marked LIVING in Figure 3.2) and three bedrooms (BR1, BR2 and BR3). During the survey, no fans were used and the windows remained open.

Charts 3.1 and 3.2 present the variation of dry bulb temperature and relative humidity on this particular day. Table 3.2 highlights the maximum dry bulb temperature in each space and the time it was recorded.





	Maximum temperature (C)	Time of occurrence (hours)
Outdoor	32.5	14
Living	32.0	14
BR1	31.5	13,14
BR2	31.5	14
BR3	31.0	13,14,16,17

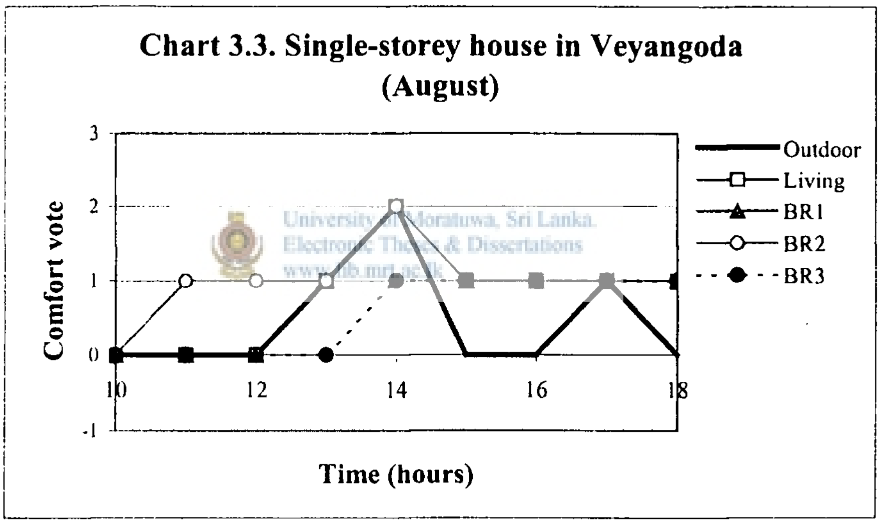
Table 3.2 Maximum temperature and time of occurrence in Veyangoda house in August

This house had several windows with undesirable orientation, i.e. facing east or west. However, although the outdoor temperature rose to 32.5°C on this day, indoor temperature remained within 32°C. This could be attributed to the line of *Pihimbiya* trees located 7m away from the eastern edge of the house. These trees protected the east facing windows from the morning sunlight.

LIVING recorded a maximum indoor temperature of 32°C around 14.00 hours, slightly higher than the other volumes surveyed. One reason could be that it had a comparatively large area of glazing. Its indoor temperature rose again to 31.5°C around 17.00 hours. This was probably due to the solar radiation it received across the west-facing window.

Bedrooms BR2 and BR3 were of comparable dimensions, and their windows were also similar. The only significant difference with respect to thermal comfort was the small tree that provided cover from the sun for the window of BR3. It is likely that this resulted in a slightly lower maximum indoor temperature in BR3 (i.e. 31°C against 31.5°C of BR2).

On this hot day, most of the daytime, the indoor temperature of the volumes surveyed remained above 30.5°C, which is above the thermally desirable value. As Chart 3.3 of the comfort survey indicates, the indoor conditions were generally warm. This could be even worse if not for the breeze that was available due to the adjacent paddy field.



The following observation can be made from the surveys:

1. On a hot day, it is difficult to achieve indoor thermal comfort in a single-storey house even when a ceiling is provided to reduce the undesirable effects of the roof.
2. Protection of east or west-facing windows is a problem since overhangs would be ineffective. However, trees planted at a distance in front of such a window could be effective to a certain extent but fails to achieve desirable comfort levels.
3. West-facing windows contribute to an increase in the indoor temperature in the evening, due to exposure to afternoon sunlight. Windows facing west should be avoided especially in Living rooms since the glazed area tends to be large due to aesthetical considerations.

3.4.2 Case 2: Two-storey house in Ragama

Case 2 is a two-storey house located in the outskirts of Ragama town. The floor plan is given in Figure 3.3a and 3.3b.

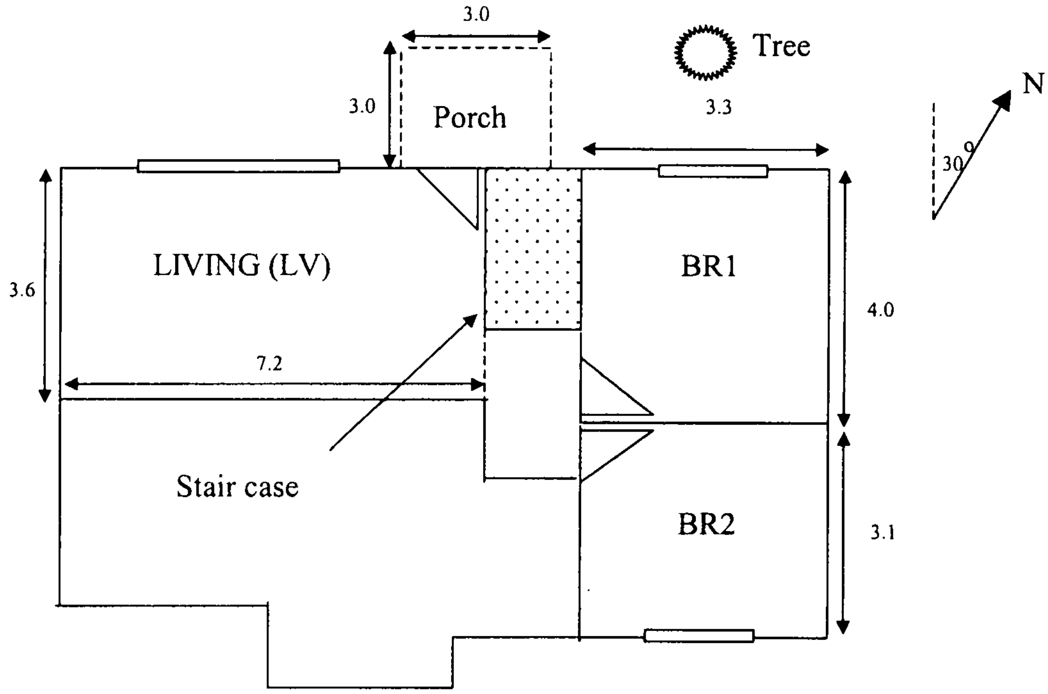
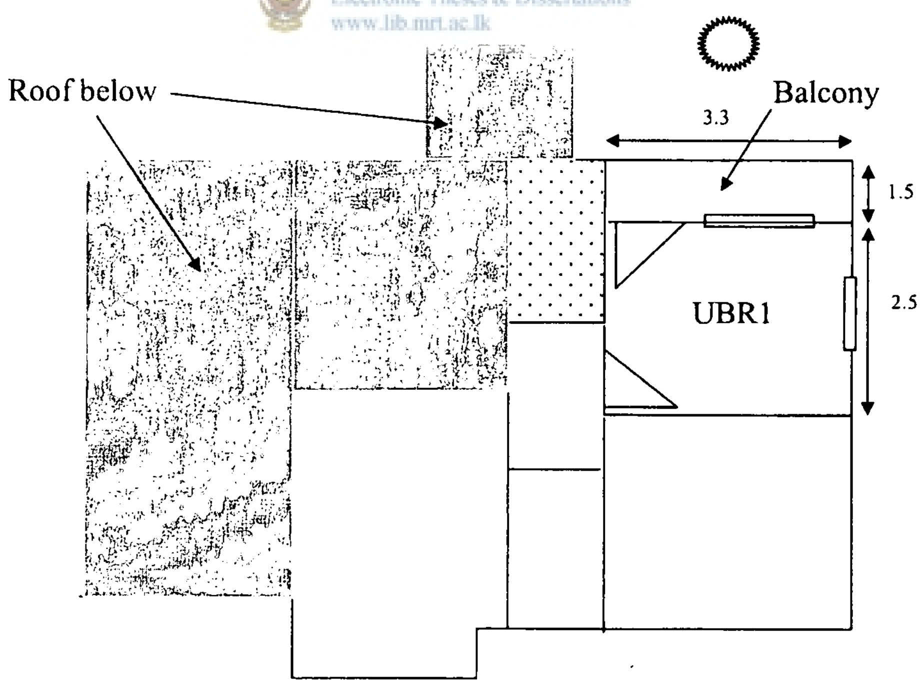


Figure 3.3a Ground floor plan of house in Ragama



Dimensions in metres

Figure 3.3b Upper floor plan of house in Ragama

The front of the house approximately faced north. The exact orientation is given in Figure 3.3a. The roof covering was of clay tiles. The ceiling of LIVING was a flat cement fibre ceiling; the upstairs had no ceiling. The wall material was of solid cement sand blockwork. The colour of the exterior surface of the house was light brown. The windows had no shading devices. The garden was very small and has only one tree, but there were several small trees on the boundary, which was a line of shrubbery. The ground was predominantly bare.

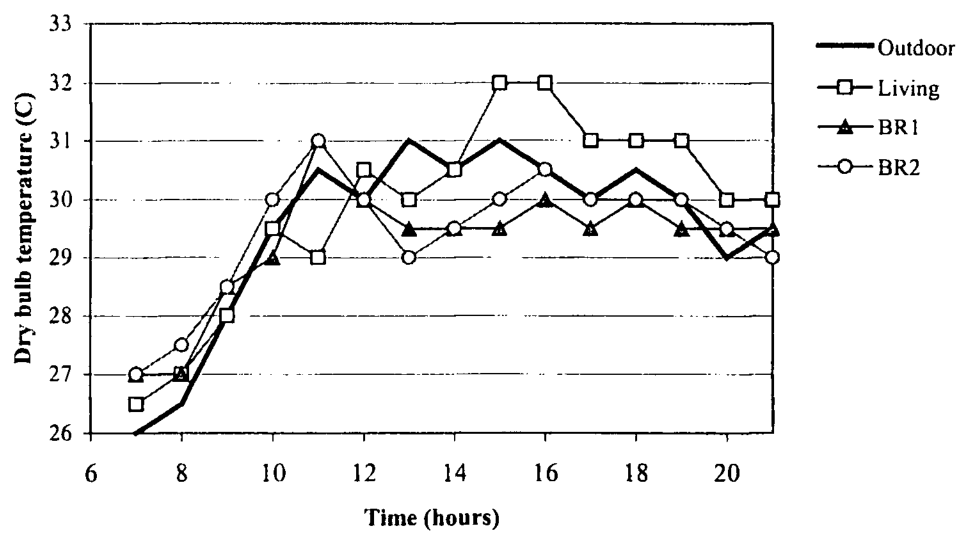
In this house thermal and comfort surveys were carried out in the months of June and July. The spaces studied were Living (LV), two bedrooms downstairs (BR1 and BR2), and a bedroom upstairs (UBR1). The front opening of UBR1 was "brick" type, and was covered up to half height with a polythene sheet.

Case 2a: Ragama in June

On a warm day in June, a thermal survey was conducted in LV, BR1 and BR2. Charts 3.4 and 3.5 present the variation of the dry bulb temperature and relative humidity, respectively. Table 3.3 highlights the maximum temperature of each space and the time it was recorded.

On this particular day of the survey, the outdoor maximum temperature was 31°C. Bedrooms BR1 and BR2 were sheltered volumes, and their maximum also was 31°C. It is however interesting to note that this maximum occurred around 11.00 hours. This could be due to the light brown colour wall approximately facing north-east. Its absorptance is higher than an equivalent off-white colour wall. Besides, the blind wall downstairs was totally exposed to the morning sun because the next house was a single-storey and beyond that was a paddy field. The fact that in June the sun path is at its northmost location must have also contributed to this early maximum.

Chart 3.4. Two-storey house in Ragama (June)



Maximum indoor temperature in the Living room was 32°C. Such a higher value could be due to the thermally undesirable effects of the roof. Another contributory factor could be the tall window without a shading device. Besides it faced north-west, making the window vulnerable to intense afternoon sunlight.

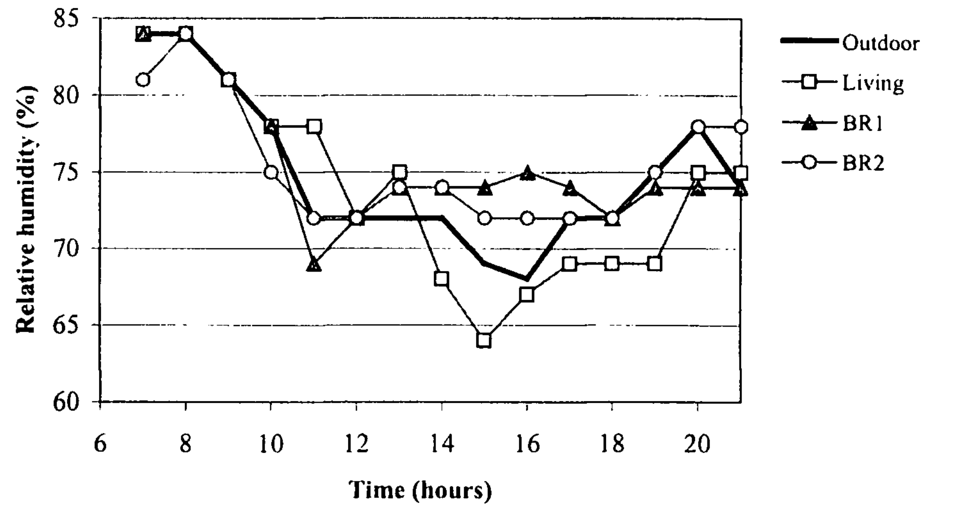


Chart 3.5. Two-storey house in Ragama (June)

	Maximum temperature (C)	Time of occurrence (hours)
Outdoor	31.0	13,15
Living	32.0	15,16
BR1	31.0	11
BR2	31.0	11

Table 3.3 Maximum temperature and time of occurrence in Ragama house in June

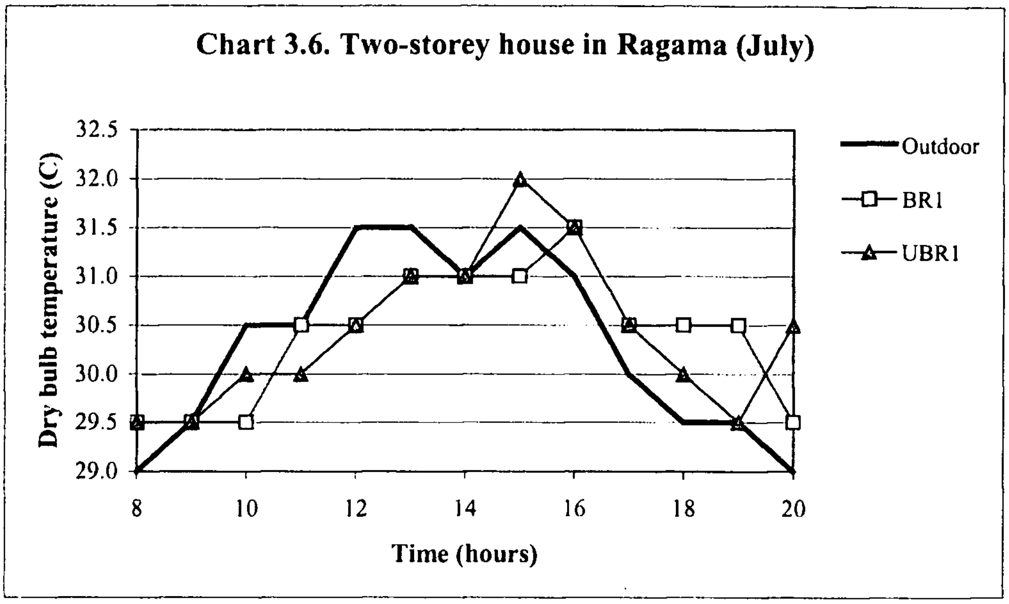
The following observations can be made from the thermal survey:

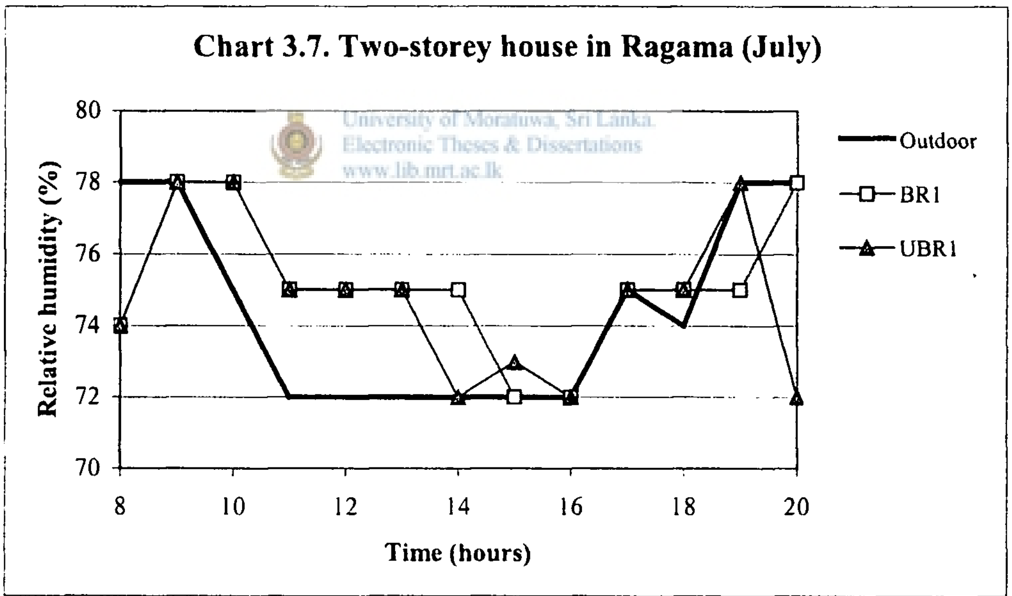
1. A sheltered volume could be more comfortable than an equivalent unsheltered volume due to the reduced undesirable effects of the roof.
2. Light brown colour is darker than off-white, and therefore has a higher absorptance. This may be disadvantageous, especially in the case of a wall totally exposed to the sun due to absence of tree cover.
3. Windows – especially tall windows as found in Living rooms – could contribute to an increase in indoor temperature if left unshaded.

Case 2b: Ragama in July

A thermal survey was conducted in BR1 and UBR1 on a warm day in July, when the sun path lies northward. Charts 3.6 and 3.7 present the variation of dry bulb temperature and relative humidity, respectively. Table 3.4 highlights the maximum temperature and the time it was recorded for each space.

Bedroom BR1 was located downstairs, and UBR1 was located above it. They were of comparable dimensions; however, UBR1 had two windows on two perpendicular walls. The front window was not completely constructed at the time of survey. It consisted of small openings due to bricks being laid at a space. The lower half of the opening was covered with a sheet of polythene. The roof of the house was of calicut tiles, and there was no ceiling.





	Maximum temperature (C)	Time of occurrence (hours)
Outdoor	31.5	12,13,15
BR1	31.5	16
UBR1	32.0	15

Table 3.4 Maximum temperature and time of occurrence for each space

On this day, the outdoor temperature reached a miximum of 31.5°C. Maximum temperature of BR1 and UBR1 were 31.5 and 32.0°C respectively, indicating the higher value of UBR1 may be due to the undesirable effect of the roof. However, there could be another reason as well. The unshaded window of UBR1 facing north-east of UBR1 could have contributed to direct solar gains. BR1 had no such window. On the other hand, its effect can be considered as "neutralised" by the presence of two perpendicular openings, promoting cross ventilation enhanced by the adjoining paddy field.

The observation that can be made out of the thermal survey is that a sheltered volume could be maintained at a lower indoor temperature than an equivalent unsheltered volume due to reduced effects of the thermally undesirable roof.

3.4.3 Case 3: Two-storey house in Ratmalana

Case 3 is a two-storey house located in Ratmalana. Part of the floor plan is given in Figure 3.4.

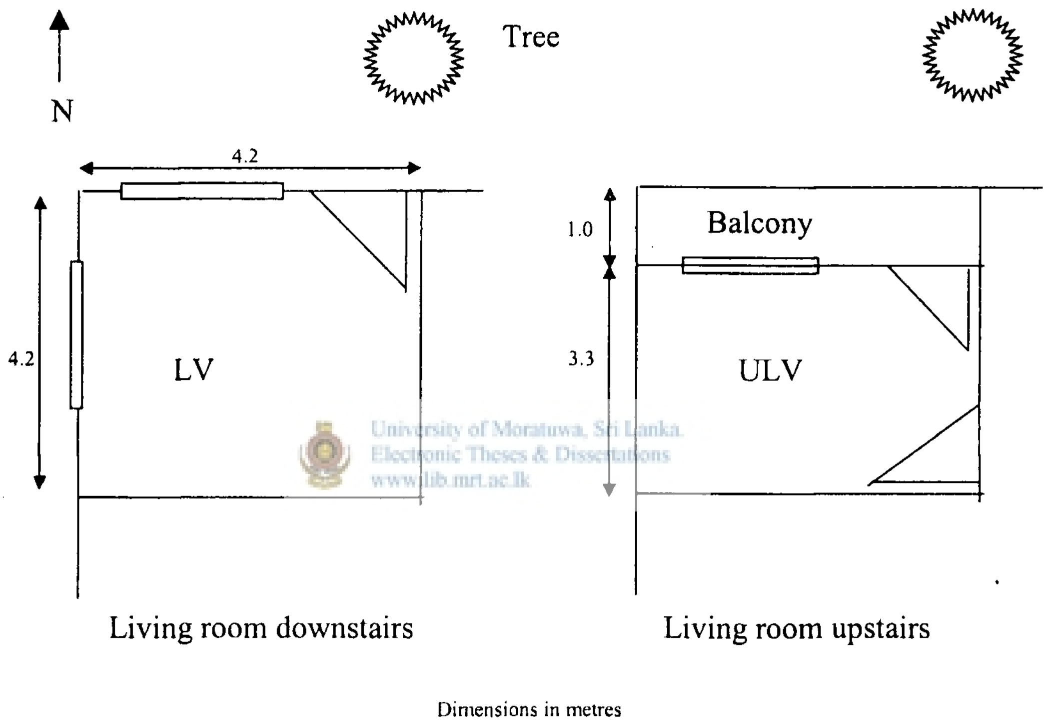


Figure 3.4. Living rooms of house in Ratmalana

The orientation of the house is given in Figure 3.4. The roof covering was of cement fibre sheets; the ceiling was a flat cement fibre ceiling. The wall material was brickwork. The colour of the exterior surface of the house was off-white. The windows had no shading devices. The garden had a large tree in front of Living room and some shrubbery. The ground was predominantly covered with grass.

A thermal survey was conducted in July in two Living rooms downstairs and upstairs (LV and ULV). The two Living rooms were located at one corner. Living room downstairs (i.e. LV) is larger in plan than the Living room upstairs (i.e. ULV). Moreover, LV had two windows – one facing north and the other facing west. ULV had only one window, and it faced north.

Charts 3.8 and 3.9 present the variation of dry bulb temperature and relative humidity respectively. Table 3.5 highlights the maximum temperature and the time it was recorded for each space.

Chart 3.8. Two-storey house in Ratmalana (July)

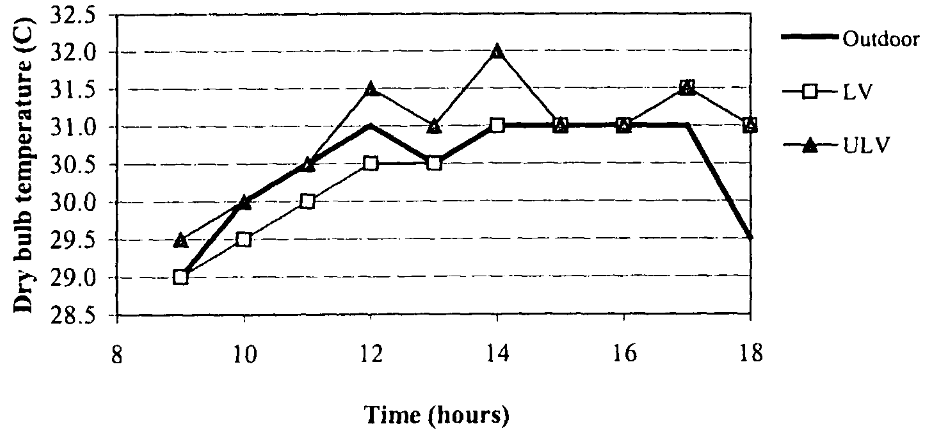
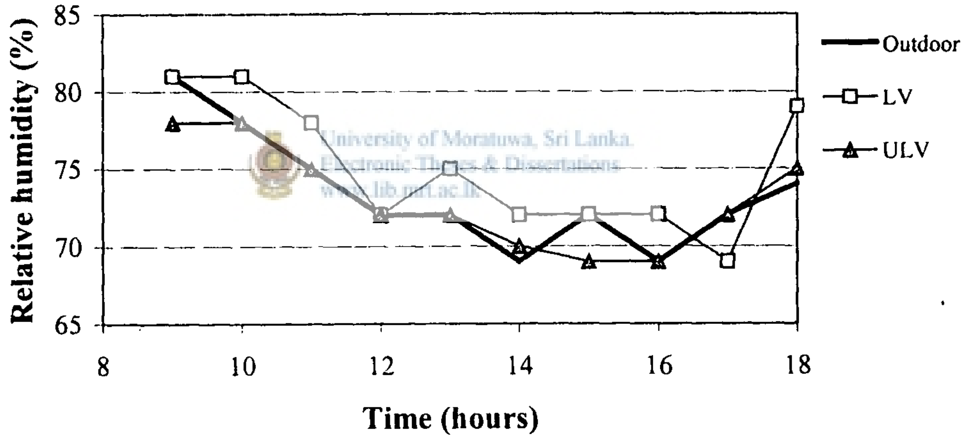


Chart 3.9. Two-storey house in Ratmalana (July)



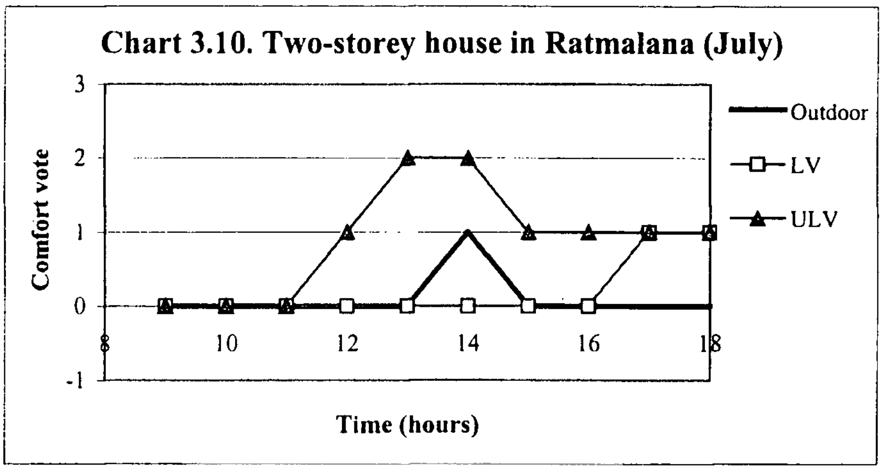
	Maximum temperature (C)	Time of occurrence (hours)
Outdoor	31.0	12,14,15,16,17
Living (LV)	31.5	17
Upstairs Living (ULV)	32.0	14

Table 3.5 Maximum temperature and time of occurrence for each space

Maximum indoor temperature of LV and ULV were 31.5 and 32°C respectively; the outdoor temperature reached a maximum of 31°C. The higher value of ULV could be attributed to the undesirable effect of the roof. The flat cement fibre ceiling may have contributed to mitigate this to some extent.

Chart 3.8 shows that the indoor temperature of LV remained within 31°C until 16.00 hours, and then shows an increase of 0.5°C. This could be due to the west-facing unshaded window.

Since the indoor temperature of both volumes substantially exceeds 30°C, it would be difficult to achieve indoor thermal comfort, even with forced ventilation. This is clearly shown in Chart 3.10, which shows the variation of the comfort vote as felt by the author. Towards the evening, the sheltered volume (i.e. LV) was "slightly warm", and the unsheltered volume (i.e. ULV) was "warm". The outdoor environment on the other hand remained "comfortable" throughout the daytime in general probably due to the physiological effects of cooling resulting from the prevailing natural ventilation.



The following observations can be made from the surveys:

1. A sheltered volume could be more comfortable than an equivalent unsheltered one
2. A window facing west could increase the indoor temperature towards the evening
3. Because of the unshaded windows, the indoor conditions of a sheltered volume could be too adverse to achieve thermal comfort, even with forced ventilation.

3.4.4 Case 4: Two-storey house in Wijerama

Case 4 is a two-storey house located in Wijerama. The floor plan is given in Figure 3.5a and 3.5b.

The orientation of the house is given in Figure 3.5a. The roof covering was of cement fibre sheets, and there was no ceiling. The wall material was of blockwork. The colour of the exterior surface of the house was off-white. The windows had no shading devices. The garden had several trees. The ground was predominantly covered with grass or shrubbery.

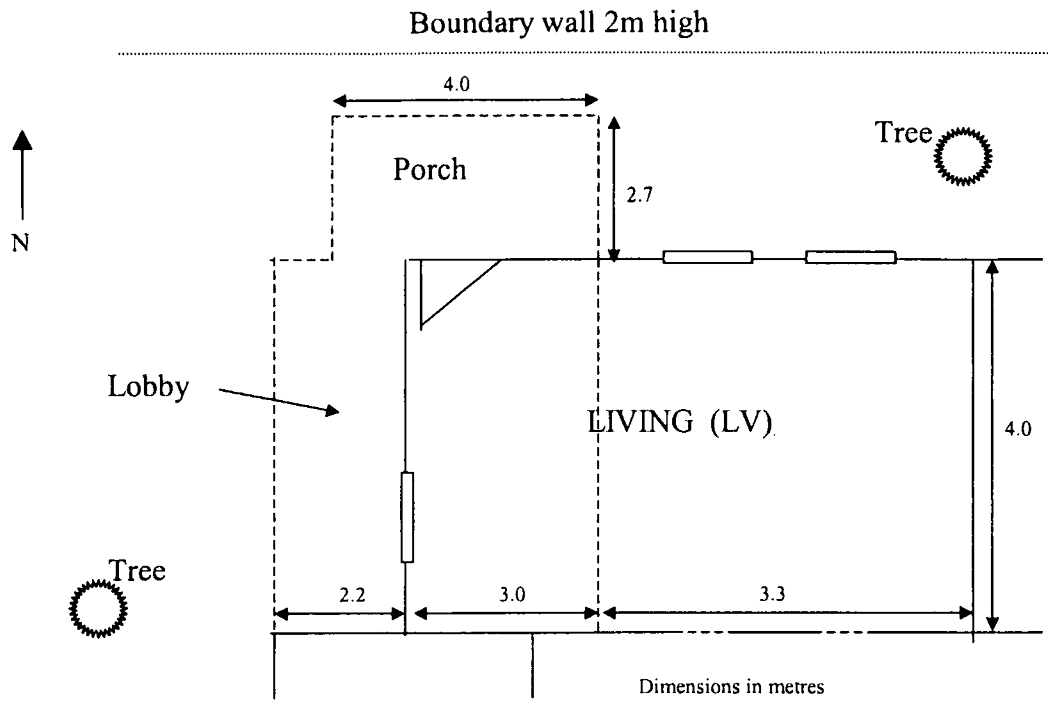


Figure 3.5a. Ground floor plan of house in Wijerama

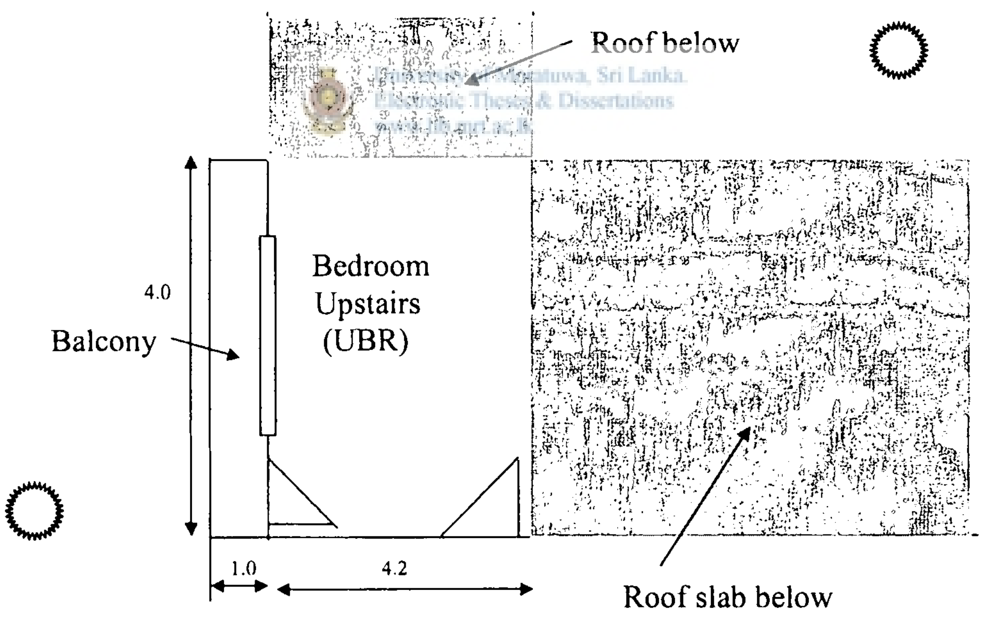
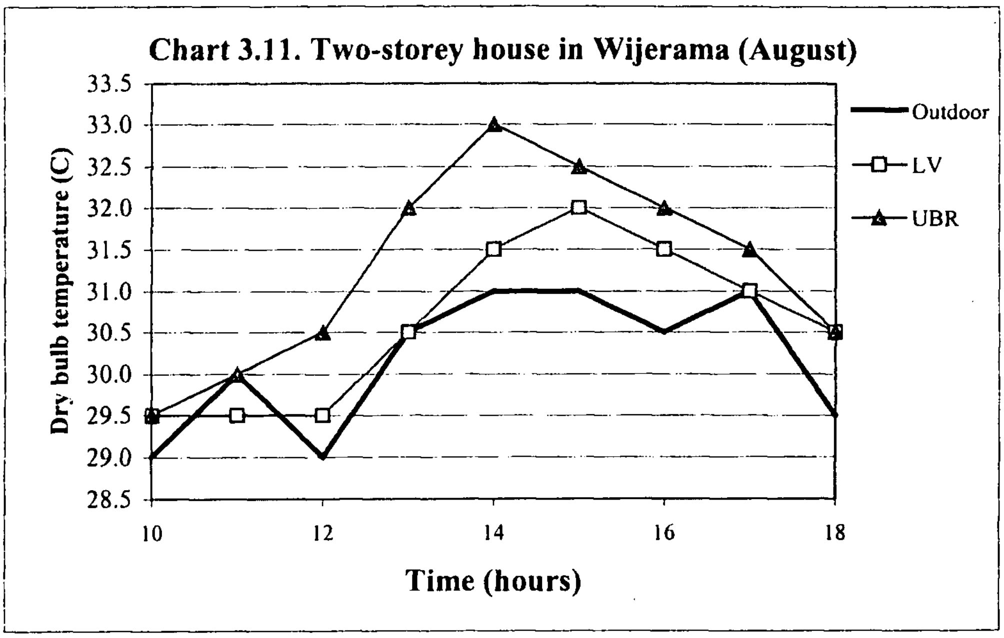
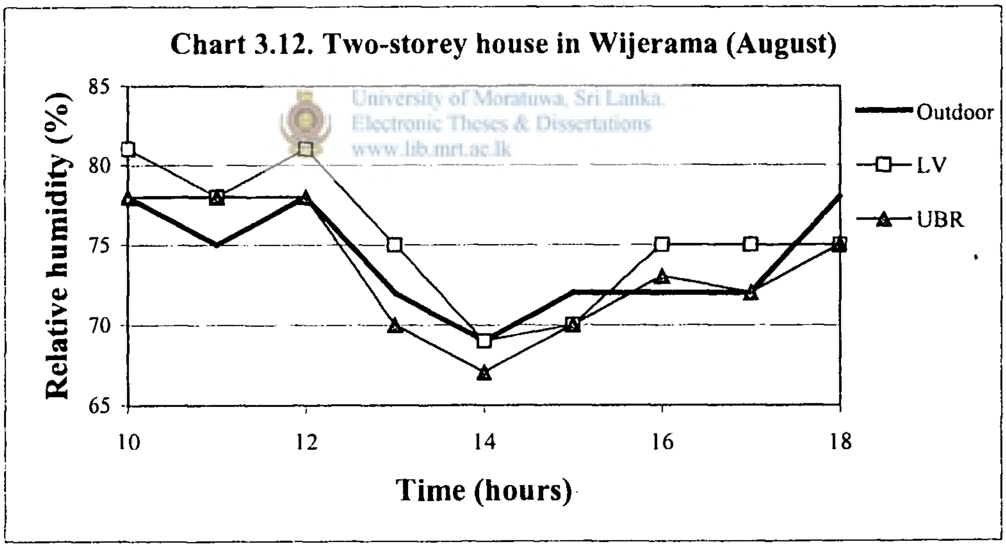


Figure 3.5b. Upper floor plan of house in Wijerama

A thermal survey was carried out in August in Living room downstairs (LV) and bedroom upstairs (UBR). Charts 3.11 and 3.12 present the variation of dry bulb temperature and relative humidity, respectively. Table 3.6 highlights the maximum temperature and the time it was recorded for each space.

Upper floor bedroom UBR had three external walls which were of blockwork. It had a window only on the west-facing wall. The window was shaded by the balcony roof. The roof was of cement fibre sheets, and there was no ceiling. Living room downstairs (i.e. LV) was partly sheltered by the UBR above; the rest of the Living room had a concrete slab as the roof (Figures 3.5a and 3.5b).





	Maximum temperature (C)	Time of occurrence (hours)
Outdoor	31.0	14,15,17
Living LV	32.0	15
Upstairs bedroom UBR	33.0	14

Table 3.6 Maximum temperature and time of occurrence for each space

The maximum outdoor temperature was only 31°C, but the indoor temperature of partly sheltered LV and unsheltered UBR rose to 32 and 33°C respectively. Although the windows of LV were unshaded, they were protected from the morning sun by a tree.

Therefore, the high value of the maximum indoor temperature of LV could be due to the heat gains from the roof slab exposed to the sun. The very high maximum temperature of 33^0C is likely to be a result of the roof. It could be considered that absence of a ceiling had worsened the situation. Heat gains by conduction through the block wall exposed to the sun could also be cited as a contributory factor.

The following observations could be made from the results of the survey:

1. A roof slab exposed to the sun could significantly contribute heat gains to indoors
2. Absence of a ceiling for a cement fibre roof would make the conditions so undesirable that thermal comfort may not be achievable even with forced ventilation.

3.4.5 Case 5: Two-storey house in Colpetty

Case 5 is a two-storey house located in Colpetty. The floor plans are given in Figures 3.6a and 3.6b.

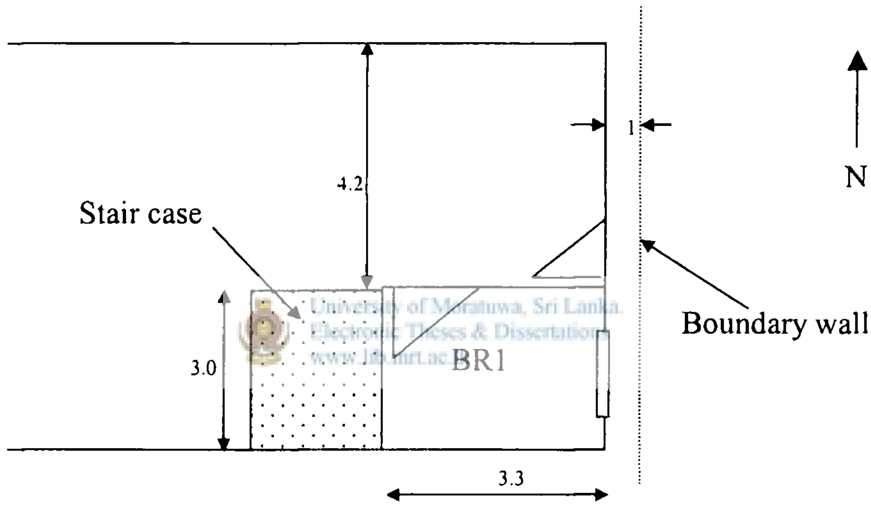


Figure 3.6a. Ground floor plan of house in Colpetty

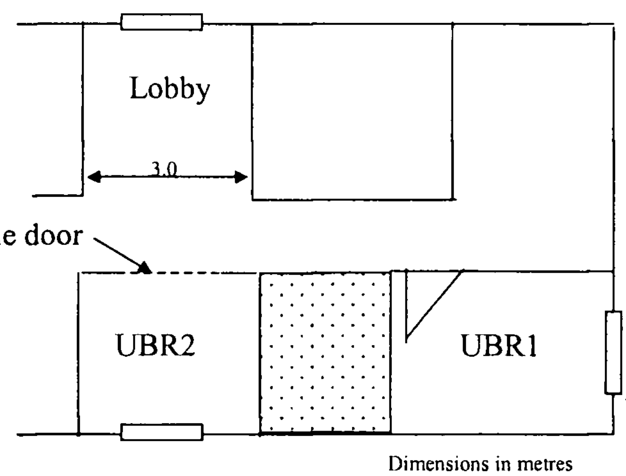
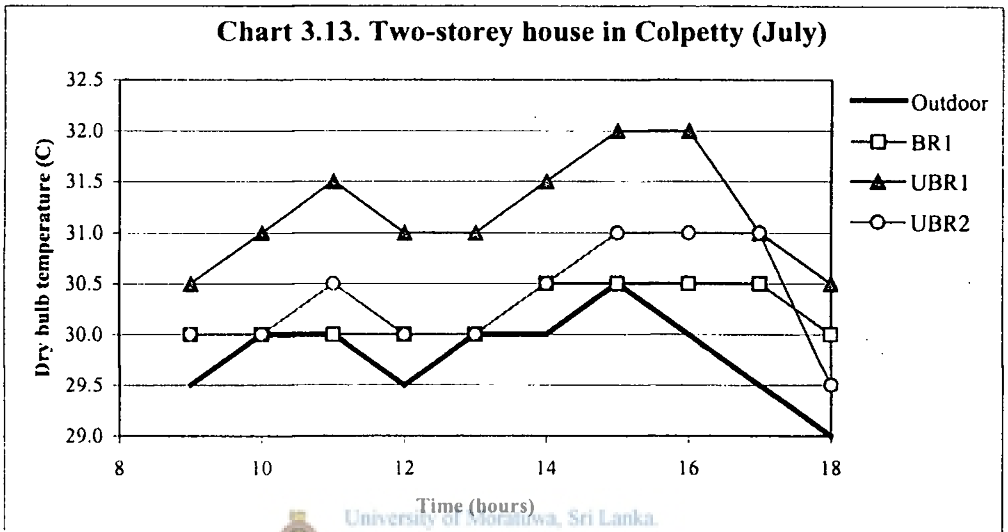
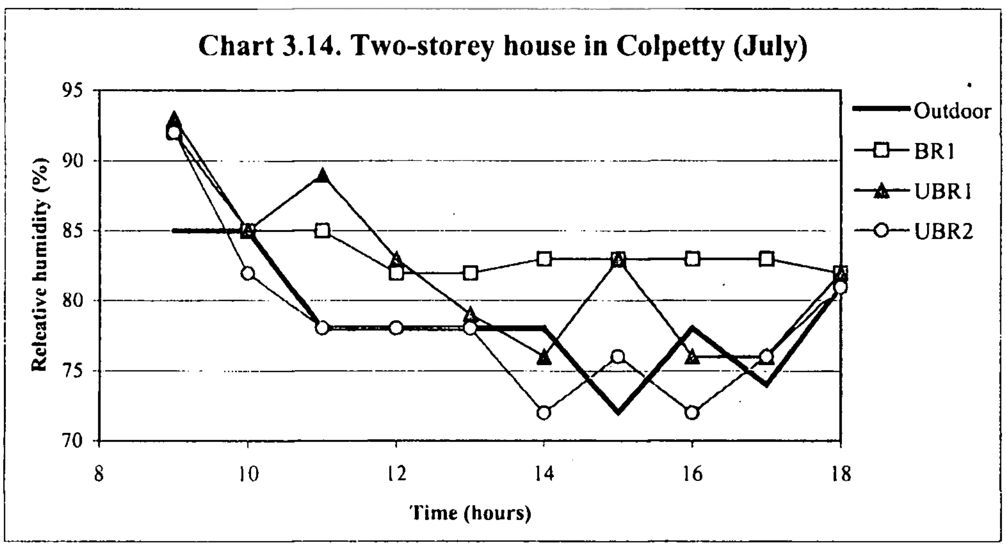


Figure 3.6b. Upper floor plan of house in Colpetty

The front of the house faced east. The roof covering was of clay tiles; the ceiling was a flat cement fibre ceiling. The wall material was brickwork. The colour of the exterior surface of the house was off-white. The windows had shading devices. There was no garden, except for a strip along the south-facing wall.

The thermal survey was conducted on a warm day in July, when the sun path lies northwards. The survey involved the only bedroom downstairs (BR1), the bedroom above it (UBR1), and another bedroom upstairs (UBR2). Charts 3.13 and 3.14 present the variation of dry bulb temperature and relative humidity, respectively. Table 3.7 highlights the maximum temperature and time it occurred in each space.





The maximum temperature recorded in BR1 was the same as the outdoor maximum, i.e. 30.5°C. However, the 1.5-metre high boundary wall was just one metre away from the front wall of the house. Therefore, the window of BR1 looked like "blocked" by the boundary wall. As a result, the room was gloomy during the daytime, and was also stuffy due to little air movement present. Therefore, although its maximum temperature rose to 30.5°C, which was not very high in comparison to other volumes, its indoor environment was not comfortable.

	Maximum temperature (C)	Time of occurrence (hours)
Outdoor	30.5	15
Bedroom BR1	30.5	14,15,16,17
Upstairs Bedroom BR1	32.0	15,16
Upstairs Bedroom BR2	31.0	15,16,17

Table 3.7 Maximum temperature and time of occurrence for each space

UBR1, which was located above BR1 had an east-facing window similar to that of BR1. The roof and the flat ceiling of BR1 were of calicut tiles and cement fibre sheets, respectively. Indoor temperature of BR1 rose to 32°C, which is 1.5°C above the outdoor maximum. This could be due to three reasons: the undesirable effect of the roof, presence of an east-facing window exposed to the morning sun, and unsatisfactory level of air movement due to single-sided ventilation (i.e. only one window).

UBR2 was another bedroom located upstairs. However, its maximum temperature rose to only 31°C although it was also unsheltered like UBR1 (i.e. the undesirable effect of the roof is similar in both cases). However, there were several factors, which could contribute to the superior performance of UBR2. Firstly, it had a south-facing window. Therefore, its exposure to the sun was not as severe as in the case of an east-facing window as found in UBR1. Besides the survey was conducted in July, when the sun path lies northward. Secondly, in UBR2, on the internal wall running along east-west, there was full height, foldable glazed door, which was wider than a normal door. This arrangement promoted air movement across UBR2, with the aid of the lobby window.

The following observations can be made from the thermal survey:

1. When a tall boundary wall runs close to a window of a room, the room could tend to be uncomfortable due to poor ventilation conditions. It would also be gloomy during the day time.
2. A sheltered volume tends to be cooler than an equivalent unsheltered one.
3. Even without shading, a south-facing window is more desirable than an equivalent east-facing window.
4. In an unsheltered volume, the indoor temperature tends to be higher than the outdoor value. This can be reduced by promoting natural ventilation across the room.

3.4.6 Case 6: Three-storey hostel in Moratuwa

Case 6 is a three-storey hostel building of Moratuwa University. Its floor plan is given in Figure 3.7.

As shown in Figure 3.7, the openings of the rooms surveyed faced south. The roof covering was cement fibre sheets; the ceiling of the top floor was of flat cement fibre type. The wall material was brickwork. The windows had no shading devices and the ground was predominantly bare.

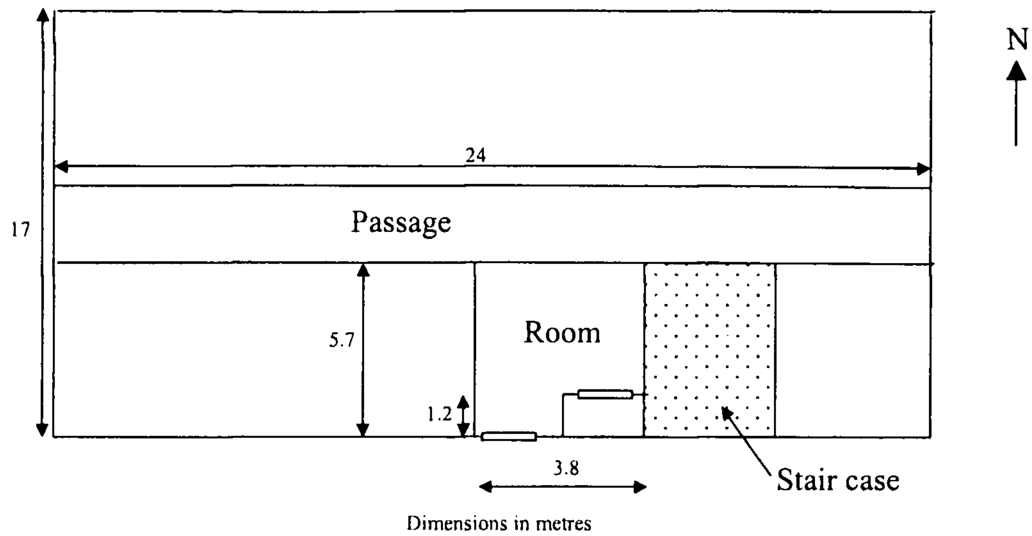
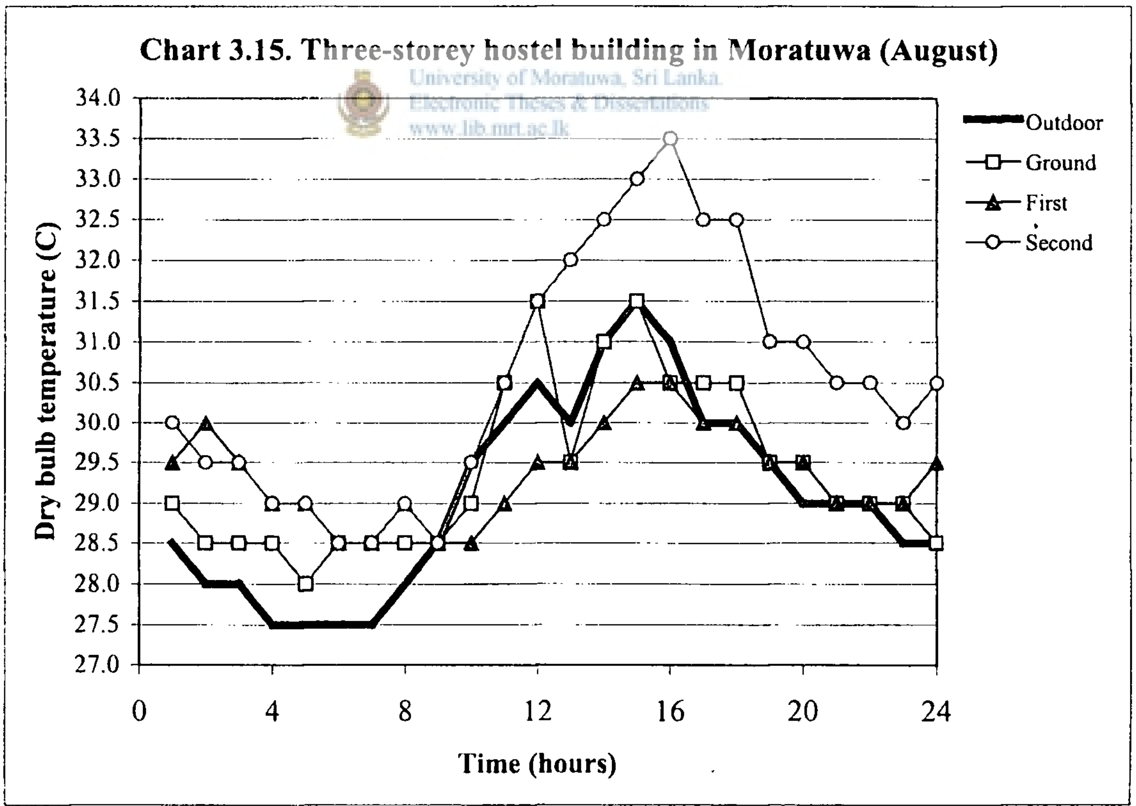
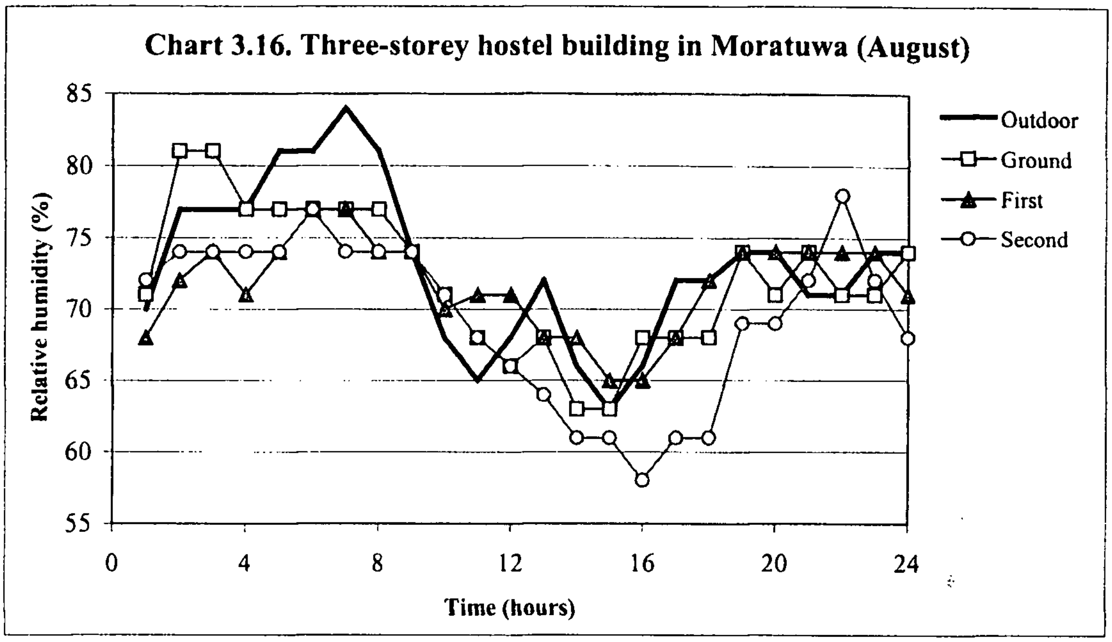


Figure 3.7 Ground floor plan of hostel

In August, a thermal survey was conducted in three rooms for 24 hours continuously. The windows were kept open from 7.00 hours to 20.00 hours only. Fans were in use at night. Charts 3.15 and 3.16 present the variation of dry bulb temperature and relative humidity, respectively. Table 3.8 highlights the maximum and minimum temperatures along with the time of occurrence and the range, for each space.





	Maximum temperature (C) (Time of occurrence)	Minimum temperature (C) (Time of occurrence)	Range (C)
Outdoor	31.5 (15 hours)	27.5 (4-7)	4.0
Ground floor	31.5 (12,15)	28.0 (5)	3.5
First floor	30.5 (15,16)	28.5 (6.7.9.10)	2.0
Second floor	33.5 (16)	28.5 (6,7,9)	5.0

Table 3.8 Maximum and minimum temperatures along with time of occurrence and the range for each space

On this particular day, the outdoor temperature reached a maximum of 31.5°C. The highest maximum indoor temperature, i.e. 33.5°C, was recorded at the second floor level. It was 2°C above the outdoor maximum. The maximum temperature of the ground floor was the same as that of the outdoors. However, the maximum temperature of the first floor was only 30.5°C, i.e. 1°C lower than the outdoor value. Therefore, it appears that, in a three-storey building, the most desirable floor with respect to thermal comfort is the first floor level; the most undesirable, the second floor.

The most undesirable thermal performance of the second floor could be attributed to the effect of the cement fibre sheet roof. If there was no ceiling, the conditions could have been worse.

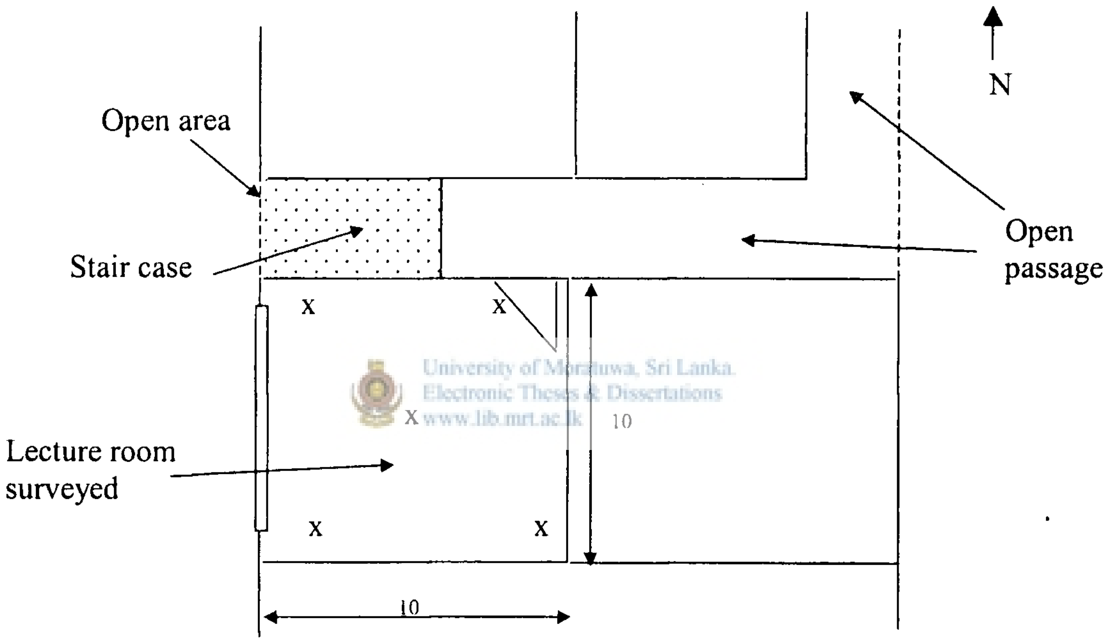
The ground floor and the first floor are both sheltered volumes, i.e. they are not subject to the undesirable effects of the roof. However, the maximum temperature of the first floor is lower than that of the ground floor by 1°C. This could be attributed to the ground reflected radiation. Since the ground was bare, direct solar radiation incident on the ground could have reflected into the room at the ground floor. If there was a vegetative surface as ground cover, the temperature difference could have been less.

The following observations could be made from these surveys:

1. A sheltered volume would be cooler than an equivalent unsheltered volume.
2. In a three-storey building, the first floor is likely to be cooler than the ground floor, especially if the ground in front of the windows is not vegetated.

3.4.7 Case 7: Lecture room in Moratuwa

Case 7 is a lecture room located at the top floor of the three-storey building of the Department of Civil Engineering, University of Moratuwa. The lecture room had a row of windows facing west. There were six ceiling fans. The floor plan is given in Figure 3.8.



Locations where temperature measurements were taken are marked "x"

Dimensions in metres

Figure 3.8 Floor plan of lecture room at Moratuwa University

A thermal and comfort survey was conducted in this lecture room, using 84 students attending a lecture. From 10.00 to 11.40 hours, readings were taken every 20 minutes at four corners and the middle of the room. Simultaneously, the students were asked to select the response that best described the prevailing indoor environment. The choices given in the survey form provided to them: *Cold, Cool, Slightly cool, Comfortable, Slightly warm, Warm,* and *Hot.* Moreover, all six ceiling fans were in operation throughout the survey. However, with each reading, the fan speed was changed. Throughout the survey, the windows remained open.

In the analysis, the responses *Slightly cool, Comfortable,* and *Slightly warm* were grouped together as COMFORTABLE. The rest of the responses were grouped as UNCOMFORTABLE (i.e. both hot and cold discomfort). When the fan speed was 1 or

2, the air movement was assumed to be unperceivable. Above that, it was assumed to be perceivable.

The five temperature readings obtained for at a given time were averaged to obtain a single temperature to represent the entire room. The average results of the survey are given in Table 3.9.

Time (hours)	Outdoor Temperature (C)	Average Temperature (C)	Average Relative Humidity (%)	Air movement (Fan speed)	Comfort (%)	Discomfort (%)
10.00	29.5	30.1	69	Perceivable (full)	96.7	2.4
10.20	29.5	30.0	70	Perceivable (speed 4)	96.7	2.4
10.40	30.0	29.5	72	Perceivable (speed 3)	95.2	4.8
11.00	29.5	30.5	68	Unperceivable (speed 2)	88.0	12.0
11.20	30.0	30.8	68	Unperceivable (speed 1)	82.9	17.1
11.40	30.5	30.6	68	Perceivable (full)	86.3	13.7

Table 3.9 Results of the thermal and comfort survey carried out at a lecture room of Moratuwa University

The neutrality temperature for the low altitudes of Sri Lanka is 26°C (Jayasinghe & Attalage, 1999a). Therefore, it could be approximately considered that Sri Lankans are thermally comfortable at temperatures between 24 to 28°C. However, according to these results, they could feel comfortable at temperatures as high as 30°C, especially when some air movement is present. This finding agrees with that of an earlier study conducted by Jayasinghe & Attalage (1999a). Two reasons can be cited for this:

1. Acclimatization of Sri Lankans to warm humid climatic conditions for generations, as highlighted by Givoni (1998)
2. Physiological effect of cooling due to the air movement.

The observation that could be made from the survey is that, by facilitating cross ventilation, indoor thermal comfort could be achieved even around 30°C.

3.5 Summary

The observations of the thermal and comfort surveys can be summarized as follows:

Comfort requirements

By facilitating cross ventilation, indoor thermal comfort could be achieved for Sri Lankans even around 30°C.

Roof

- In a single-storey house with a cement fibre sheet roof, it could be difficult to achieve indoor thermal comfort due to the thermally undesirable effects of the roof. A ceiling may mitigate the effect, but not sufficiently.
- A roof slab exposed to the sun could significantly make the indoor temperature rise.

Sheltered effect

- In a two-storey building, volumes at the ground floor (i.e. sheltered volumes) could be cooler than equivalent volumes at the top floor (i.e. unsheltered volumes) due to the effects of the roof on the latter.
- In a three-storey building, the second floor tends to be warmer than the floors below because of the effect of the roof. If the ground surface in front of the windows is bare, the ground floor tends to be warmer than the first floor due to the ground reflected solar radiation.

Windows

- Unshaded windows could contribute to increase the indoor temperature. This could apply even to a sheltered volume, thus eliminating the beneficial performance of a sheltered volume.
- In July, probably due to the northward location of the sun path, an unshaded south-facing window could be more desirable than an unshaded east facing window.
- In a room with a window facing west, indoor temperature may rise in the evening due to the exposure to the afternoon sun.
- To shade east or west-facing windows, trees could be planted in front of the window at a distance.

Ventilation

- The relatively high temperature of an unsheltered volume could be lowered by facilitating cross ventilation.
- When a tall boundary wall is located near the window of a sheltered volume, it could make the volume uncomfortable (more precisely "stuffy") even though it is sheltered. Moreover, it would be gloomy during the daytime.

Surface colour

Due to higher absorptance of the dark colors, a room with a dark colour exterior wall surface tends to be warmer than an equivalent light colour room.

Chapter 4

QUESTIONNAIRE SURVEY

4.1 General

A pilot questionnaire survey was conducted among 179 adults residing in Colombo, Gampaha, Kalutara, Galle or Matara district, in order to assess the prevailing situation in houses, the response of the occupants of houses to various passive strategies, and their concern for the environment. The survey provided the information necessary to propose a passive solution for the energy conservation in the domestic sector in the low altitudes of Sri Lanka.

4.2 Need for a questionnaire survey

Firstly, to propose a passive solution to the domestic sector of the low altitudes of Sri Lanka, the prevailing situation should be identified at least to a certain extent if not completely. Unfortunately, such information is not readily available.

Secondly, the passive concepts and techniques identified from the literature survey and thermal/ comfort surveys may already be in use, though not in an effective manner. This should also be identified as it would be easier to incorporate such already accepted concepts and techniques in houses.

Thirdly, the reaction of the people to various passive concepts and techniques identified from the literature and thermal/comfort surveys should be established. A strong rejection of a particular concept or technique would indicate difficulty in gaining public acceptance for it. On the other hand, the concepts and techniques that enjoy wide acceptance should be actively promoted.

Finally, a passive solution is necessarily an environment-friendly one. If people have only scant feeling for the environment, they are unlikely to appreciate this solution. On the other hand, if they have realized the gravity of the problem of environmental degradation and are willing to contribute to its mitigation, they are likely to accept a passive solution. Therefore, the degree of their concern for the environment should be identified.

Thus, a questionnaire survey was a necessity.

4.3 Form of questionnaire survey

The form of the questionnaire survey consist of four sections:

1. General information on occupants and their houses
2. Prevailing situation at their houses
3. Preferences of occupants
4. Occupants' concern for the environment

The section on *general information* covered participants of the questionnaire survey and their houses. This included gender, district, age group, occupation, type of house, and number of occupants.

The section on *prevailing situation* inquired into the existence of thermal or visual discomfort inside houses, the extent to which active means are currently used for their inhibition, various types of the elements of the building envelope, the extent to which gardening is done, and the existence of flash floods following heavy showers.

The section on *preferences of occupants* identified the type of neighbourhood and house they prefer to live in, the special features they like to have in their houses, and the number of bedrooms and bathrooms they require.

The section on *occupants' concern for environment* identified not only their concern for the environment but also their willingness to contribute towards the alleviation of the problem of environmental degradation.

4.4 General information on questionnaire survey

The focus of this study is urban and suburban regions of the low altitudes of Sri Lanka, where the predominant climatic condition is warm humid. Therefore, this pilot questionnaire survey was conducted among middle class adults residing in Colombo, Gampaha, Kalutare, Galle or Matara district. Due to constraints in time and resources, the number of subjects was limited to179. The following charts illustrate the distribution of the sample of subjects.

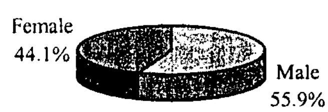


Chart 4.1 Gender

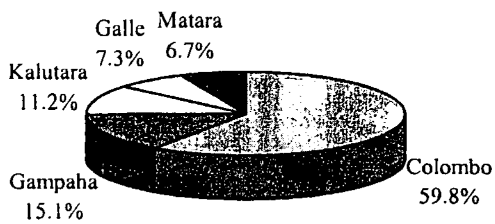


Chart 4.2 District

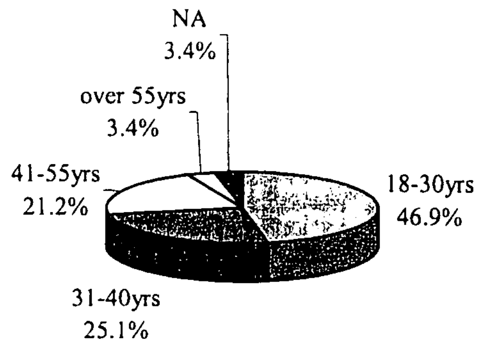


Chart 4.3 Age group

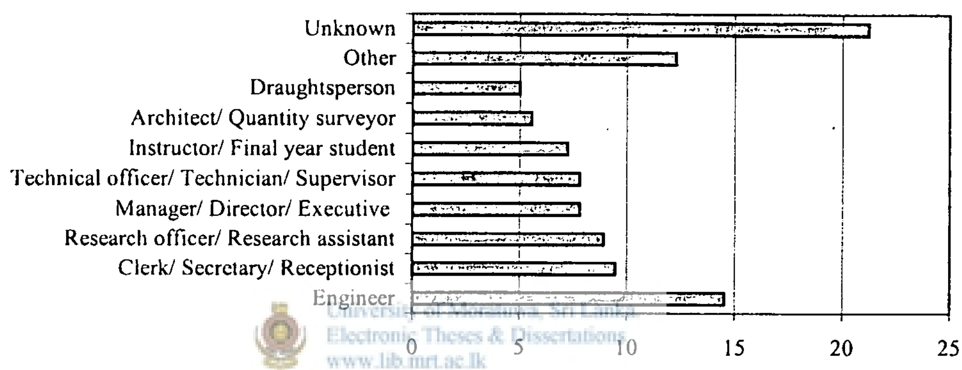


Chart 4.4 Occupation (%)

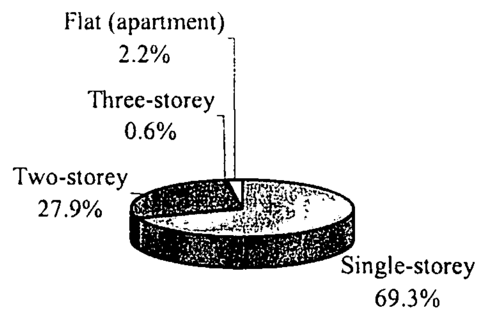


Chart 4.5 House type

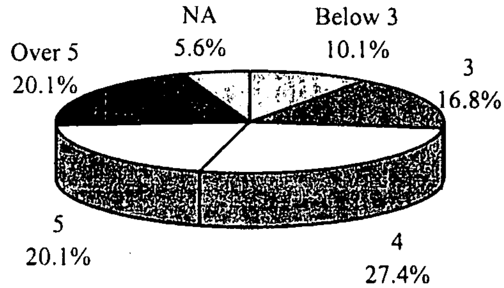


Chart 4.6 Number of occupants

4.5 Discussion of results of questionnaire survey

Results of the questionnaire survey are discussed under the following subtopics:

1 Prevailing situation at houses
2 Preferences of occupants
3 Occupants' concern for environment

4.5.1 Prevailing situation at houses

This section investigated whether thermal or visual discomfort occurs in houses, and if so, what are the measures taken for their alleviation. It also identified the elements of the building envelope that are important with respect to thermal or visual comfort, and the habits of the occupants that would affect indoor thermal comfort. Finally, it investigated the aspects of gardening and flash floods.

4.5.1.1.Occurrence of indoor thermal or visual discomfort

The questionnaire survey revealed that thermal discomfort and, to a lesser extent, visual discomfort occur inside a significant proportion of the houses surveyed. Worse still, the remedies that are adopted are fans and lighting, which are active based and energy intensive.

Of those surveyed, 54.7% revealed that at least one room of their house was too warm to be comfortable even when all its windows were open. Out of them, 86.7% switch on a fan, 19.4% go to another room which is comfortable and, as the percentages show, some take either of the above measures. Or those surveyed, 45.3% said three or more fans are usually used in their house, indicating the actual number of fans available in the house could be even higher.

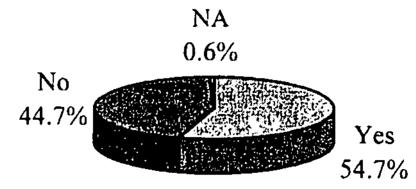


Chart 4.7 Thermal discomfort in houses

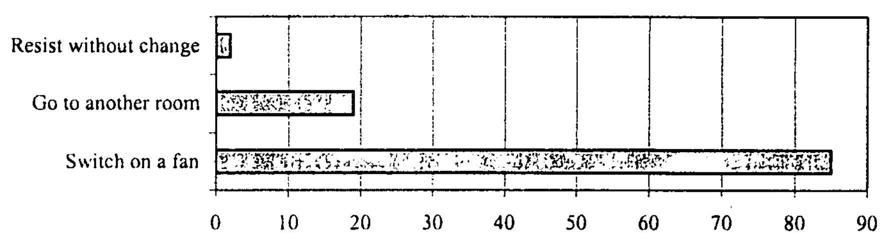


Chart 4.8 Measures taken to achieve thermal comfort (%)

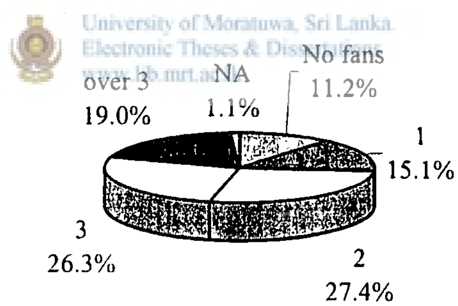


Chart 4.9 Number of fans usually used

Of those surveyed, 30.7% admitted that at least one room is gloomy during the daytime even when all its windows were open. Of them, 90.9% switch on the light if they have any work to do there.

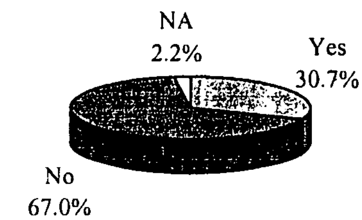


Chart 4.10 Visual discomfort in houses

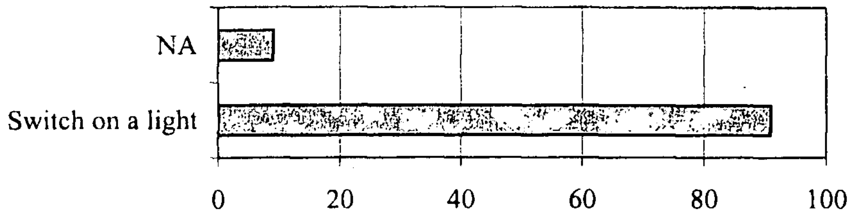


Chart 4.11 Measures taken to achieve visual comfort (%)

Of those surveyed, 20.1% admitted that the roof of their house contained a skylight as a means to enhance indoor visual comfort. However, due to two reasons, this is undesirable. Firstly, it is diffuse sunlight, not direct sunlight, that promotes indoor visual comfort; therefore, it serves little to its intended service. Secondly, a skylight not only provides access to direct sunlight, but does so throughout the daytime round the year because of its upward orientation. Therefore, its contribution to indoor thermal discomfort is significant.

4.5.1.2 Elements of building important with respect to thermal comfort

According to the results, the roof type of houses of 55.9% of those surveyed is cement fibre sheets, 38.0% calicut tiles and 2.8% both. Therefore, the majority of the houses have a cement fibre roof, which can be considered the less desirable of the two – thermally. One out of four of those surveyed said that their house is ceilingless. And 47.5% have a cement fibre ceiling, 18.4% a timber ceiling, and 7.3% both types.

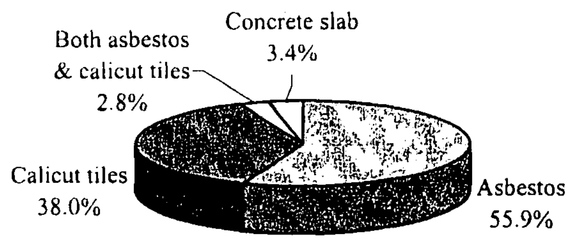


Chart 4.12 Roof type

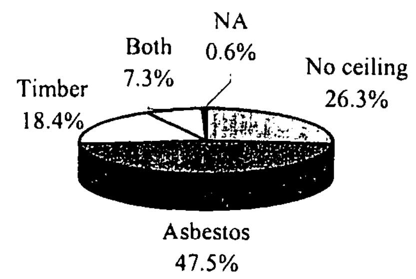


Chart 4.13 Ceiling type

The colour of the exterior surfaces (e.g. external walls) significantly affects indoor thermal comfort (Givoni, 1976), and light colours are desirable (Bansal et al., 1992). In this respect, the existing situation is satisfactory; 69.3% claim that their house has light colour external surfaces.

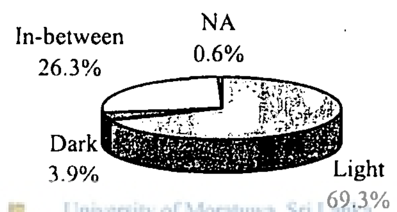


Chart 4.14 Colour of outdoor surface

The colour of the wall surfaces facing indoors has some significance on indoor visual comfort. Light colour surfaces of a room would make diffuse light scatter inside the room, enhancing visual comfort. With respect to walls, the prevailing situation is satisfactory because 72.1% have light colours. However, with respect to floors, the situation is not desirable since dark colours are preferred for floors due to cleaning concerns.

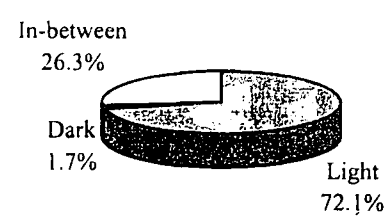


Chart 4.15 Colour of indoor surface

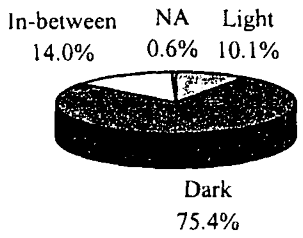


Chart 4.16 Colour of floor surface

Thermally, the window is the weakest element of the building envelope, and therefore needs protection from direct solar radiation. Of those surveyed, 75.4% believed that the curtains they used were serving this purpose. However, curtains are ineffective in this respect although they can solve the problem of glare. If strategically located, trees can protect windows from the sun; 24.6% claimed having trees serving this purpose. The overhang is the most effective measure; however, only 8.4% claimed having overhangs as protection for windows. Although similar to the overhang in appearance, the eave of the roof cannot serve this purpose as it is located at a higher elevation. Tinted glass, employed by 10.6%, not only reduces external gains but also demotes visual comfort.

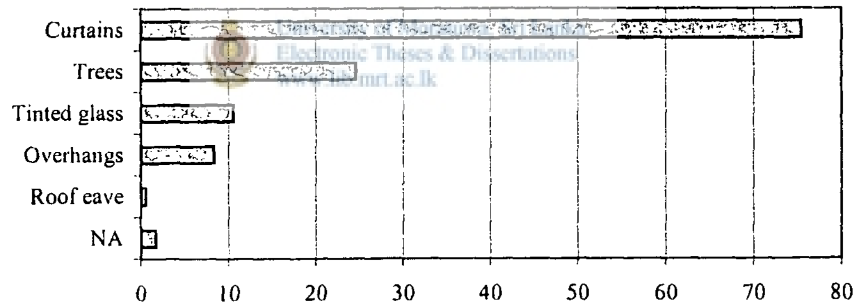


Chart 4.17 Protection for windows (%)

4.5.1.3 Habits of occupants important with respect to indoor thermal comfort

A sheltered volume (e.g. a room in the ground floor of a two-storey house) is more desirable thermally than an equivalent unsheltered volume both during daytime as well as at night. Of those surveyed living in multi-storey houses, 50.9% sleep upstairs at night.

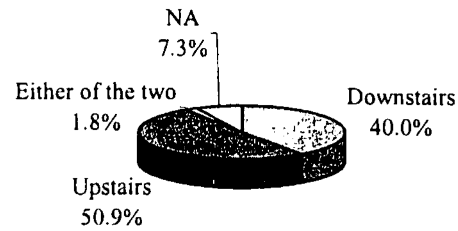


Chart 4.18 Floor level used for sleeping (multi-storey houses only)

Night ventilation is an effective way of achieving indoor thermal comfort not only at night but also during the daytime (Geros et al., 1990). However, even when the indoors are hot at night, only 21.8% of those surveyed keep windows open throughout the night while 19.0% keep them open until late night. Over half those surveyed (i.e. 57.5%) do not keep windows open at night due to various reasons – sometimes more than one. Safety (85.4%) tops the list, followed by mosquito menace (44.7%) and privacy concerns (15.5%).

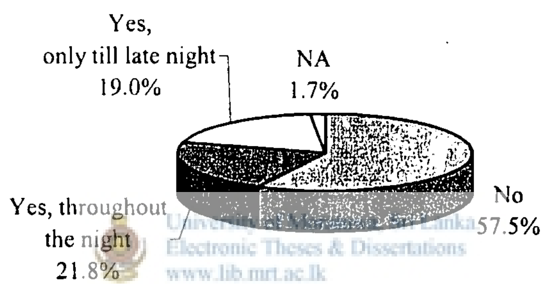


Chart 4.19 Keep windows open at night?

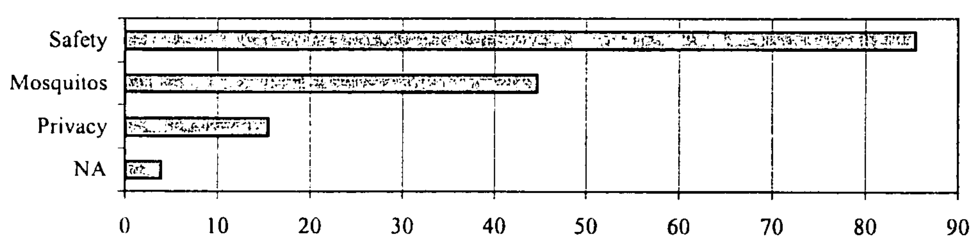


Chart 4.20 Reasons for not keeping windows open at night (%)

4.5.1.4 Gardening

Of those surveyed, 91.1% own at least a small garden. Out of them, 63.8% grow vegetable or fruit, which is an encouraging finding. There are various reasons for cultivation.

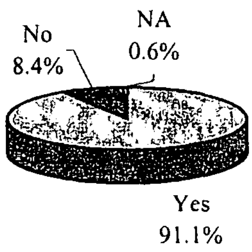


Chart 4.21 Availability of a garden

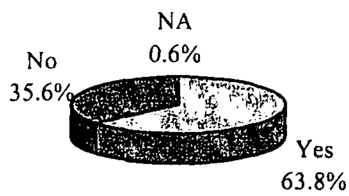


Chart 4.22 If vegetable/ fruit grown in the garden

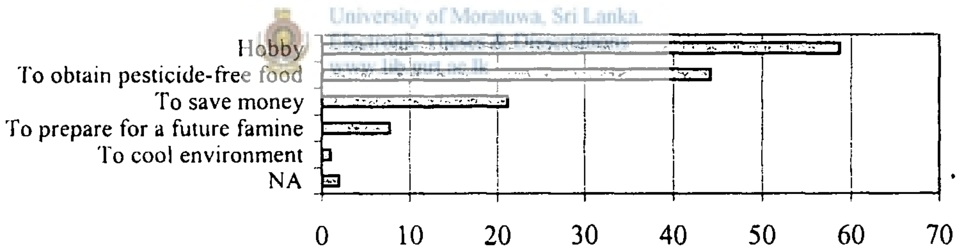


Chart 4.23 Reasons for "cultivation" in the garden (%)

Of those who cultivators, 54.8% use organic waste as a fertilizer. Due to various reasons, 45.2% do not use it. The main reasons for not using organic fertilizer are lack of time and lack of garden space.

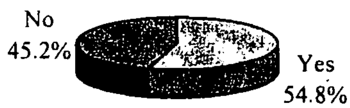


Chart 4.24 Use organic waste as compost?

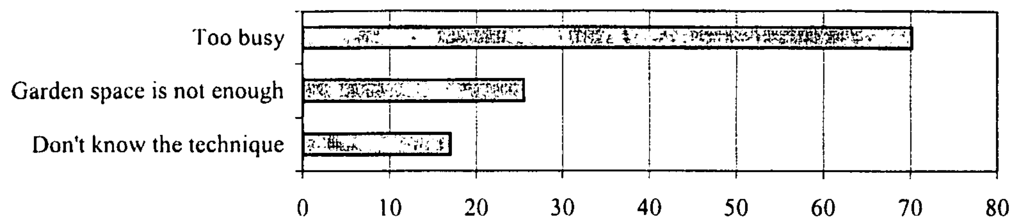


Chart 4.25 Reasons for not using organic waste for "cultivation"(%)

4.5.1.5 Flash floods

One out of five surveyed revealed that their house or street gets flooded following a heavy rain. This reflects the extent to which flash floods have affected the urban and suburban communities.

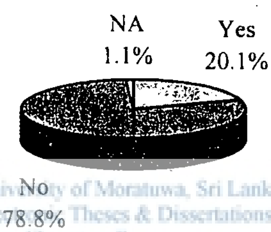


Chart 4.26 House/ street subject to flash floods?

4.5.2 Preferences of occupants

Various combinations of options are available for a passive solution. Therefore, the response of the occupants to various types should be established before generating a final solution. A solution incorporating positive responses would guarantee its acceptance by the majority of the house owners. The aspects investigated include the preferred neighbourhood, type of house, number of bedrooms and bathrooms, and special features such as courtyards.

4.5.2.1 Preferred neighbourhood

The majority (68.7%) prefer an urban area full of trees. The corresponding figure for an urban region is only 3.9%. This highlights the unmistakable role of vegetation in the future residential developments.

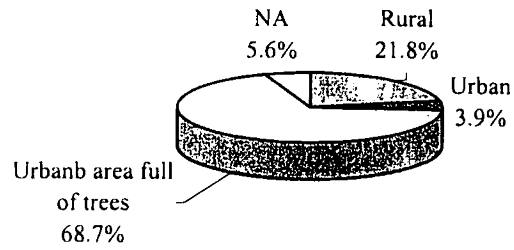


Chart 4.27 Preferred type of neighborhood

4.5.2.2 Preferred house type

Although 69.3% of those surveyed live in single-storey houses, only 38.0% prefer the single-storey type. Only 27.9% live in two-storey houses, but 51.4% prefer the two-storey type. This clearly indicates that the preference has shifted towards the multi-storey type.

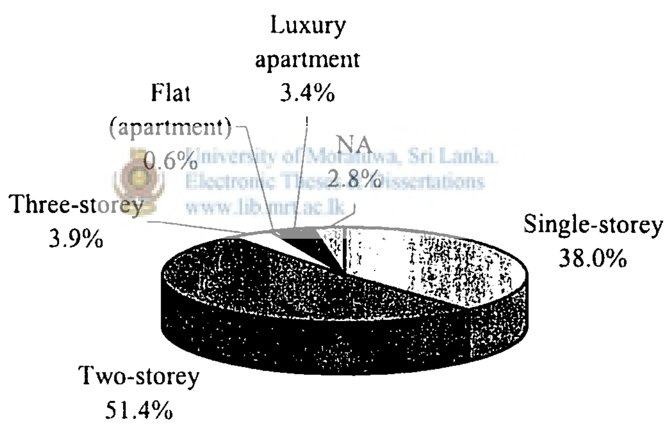


Chart 4.28 Preferred type of house

4.5.2.3 Special features preferred

Although 56.4% of those surveyed prefer to have a visitors bedroom, only 46.4% require a visitors bathroom, probably due to the high cost of bathroom fittings. Moreover, 36.9% prefer a separate storeroom in addition to kitchen while 21.8% would settle for a larger kitchen instead of a separate storeroom. Preferences for a courtyard and a study room are 59.8% and 54.2%, respectively. The former is a good sign since the courtyard is a useful passive element.

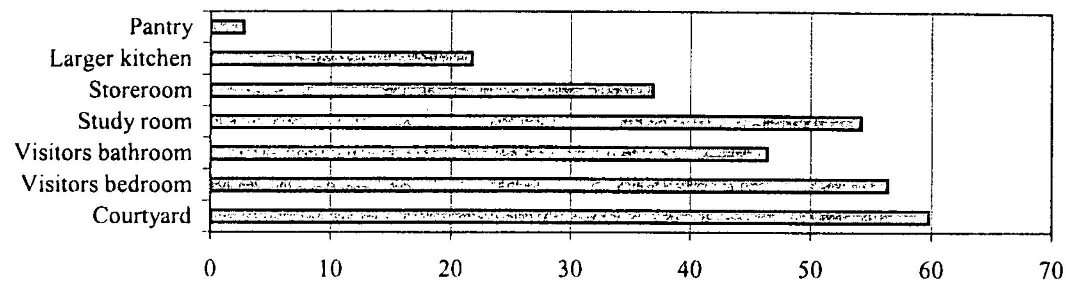


Chart 4.29 Special features preferred (%)

4.5.2.4 Number of bedrooms and bathrooms

The majority of those surveyed, 58.1%, prefer three bedrooms (excluding visitors bedroom). The corresponding figure for the bathrooms, preferred by 64.8%, is two (again excluding visitors bathroom).

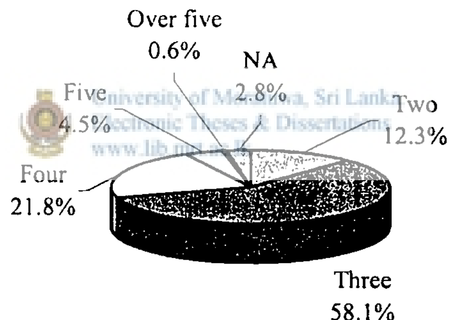


Chart 4.30 Number of bedrooms preferred (excluding visitors bedroom)

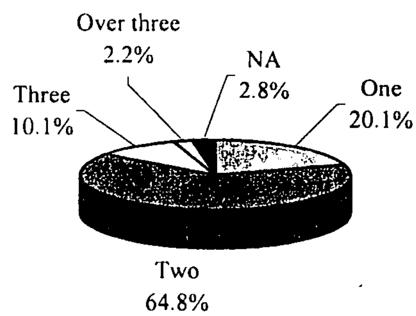


Chart 4.31 Number of bath/toilets preferred (excluding visitors bathroom)

4.5.3 Occupants' concern for the environment

The majority of the subjects (68.2%) consider environmental pollution as "a serious problem threatening the future", which is certainly a positive development. Besides, if garden space is available, nine out of ten are prepared to grow trees.

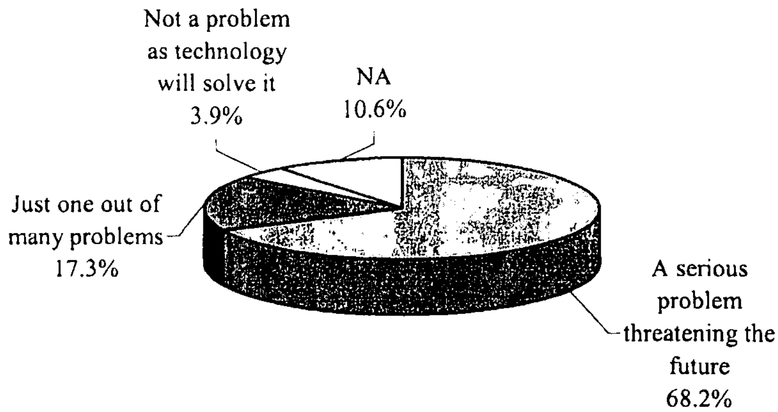


Chart 4.32 View on environmental pollution

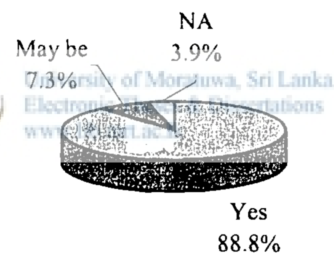


Chart 4.33 Willingness to grow trees if garden space is available

4.6 Summary

A pilot questionnaire survey conducted among 179 adults residing in Colombo, Gampaha, Kalutara, Galle and Matara districts yielded the following information:

1. A significant proportion of those surveyed have been faced with problems such as indoor thermal discomfort and gloomy indoors during daytime. The common solution they adopt to mitigate these problems are active based, and therefore requires electricity.

2. At least 55% of the houses are experiencing thermal discomfort and 31% visual discomfort (during daytime). The remedies adopted by 90% of the occupants are active based, i.e. fans and artificial lighting, respectively.

3. Most houses (around 56%) have a cement fibre sheet roof, which is thermally less desirable, followed by calicut tile roof (38%). Around 25% of the houses are

ceilingless; 48% have a cement fibre sheet ceiling, and 18% a timber ceiling. Therefore, cement fibre sheet is the popular material for roof covering as well as ceiling.

4. Around 69% of the houses have light colour exterior surfaces, which is thermally desirable. Besides 72% have light colour interior wall surfaces, which is desirable with respect to visual comfort. However, 75% have dark colour floor surfaces.

5. The majority (75%) believe that the curtains would protect their windows although in reality they cannot. The effective options are not employed by a significant percentage: trees (25%) and overhangs (8%). Tinted glass is used by 11%, but it contributes to gloomy indoors.

6. Night ventilation is not widely employed as most occupants are reluctant to keep windows open at night due to various reasons: safety (85%), mosquito menace (45%), and privacy (16%).

7. Nine out of ten families have gardens. Two out of three of them grow vegetable or fruit, mainly as hobby (59%) and to obtain pesticide-free food (44%). Half the "cultivators" use organic waste as compost. The main reasons for not using organic fertilizer are lack of time (70%) and lack of garden space (26%).

8. One out of five people reveal either their house or street is affected by flash floods following heavy rain.

9. The majority (69%) prefer to live in an urban area full of trees. Of houses, the preference to the two-storey type is 51% while that to the single-storey type is 38% although, at present, the majority (69%) live in single-storey houses.

10. Three out of five prefer a house with a courtyard. Although 56% prefer to have a visitors bedroom, only 46% require a visitors bathroom. A separate storeroom in addition to kitchen is preferred by 37% while 22% prefer a larger kitchen instead a separate storeroom. Study room is required by 54%.

11. Most people (58%) prefer three bedrooms (excluding visitors bedroom) for their house. The corresponding figure for the bathrooms, preferred by 65%, is two (excluding visitors bathroom).

12. The majority (68%) views environmental pollution as a "serious problem threatening the future." Fortunately, nine out ten are prepared to grow trees if garden space is available.

Chapter 5

PASSIVE CONCEPTS AND TECHNIQUES DESIRABLE TO LOW ALTITUDES OF SRI LANKA

5.1 General

It is important to identify the passive concepts and techniques desirable to the tropical, warm humid climatic conditions prevailing in the low altitudes of Sri Lanka. Therefore, desirable passive features were identified from the literature survey as well as from the results of the thermal and comfort surveys carried out in several existing buildings. Then computer simulations were carried out to investigate the most sensitive building elements of the building envelope with respect to thermal performance – i.e. the roof and the openings. The findings of this chapter are used to develop a set of guidelines for passive residential developments for low altitudes of Sri Lanka.

5.2 Objective and Methodology

The objective of this chapter is to identify the passive concepts and techniques that can be adopted in the development of environment-friendly residential developments in the low altitudes of Sri Lanka. To achieve this, the following methodology was employed:

1. Passive concepts and techniques relevant to the tropical, warm humid climatic conditions experienced in the low altitudes of Sri Lanka, were identified from the literature survey as well as from the results of the thermal and comfort surveys conducted in several existing buildings

2. Effects of the roof and openings on the indoor thermal comfort were identified through computer simulations using the DEROB-LTH software

5.3 Qualitative analysis of passive concepts and techniques desirable for low altitudes of Sri Lanka

Sri Lanka is a tropical country. Its low altitudes (i.e. below 300m in altitude) experience warm humid climatic conditions. In this region, distinct seasonal changes do not occur and the general requirement throughout the year is cooling. For achievement of desirable indoor thermal comfort conditions, the designers should aim to minimize the heat gains and facilitate ventilation (Jayasinghe & Attalage, 1999b). An overview of the passive strategies that could be adopted is summarized below.

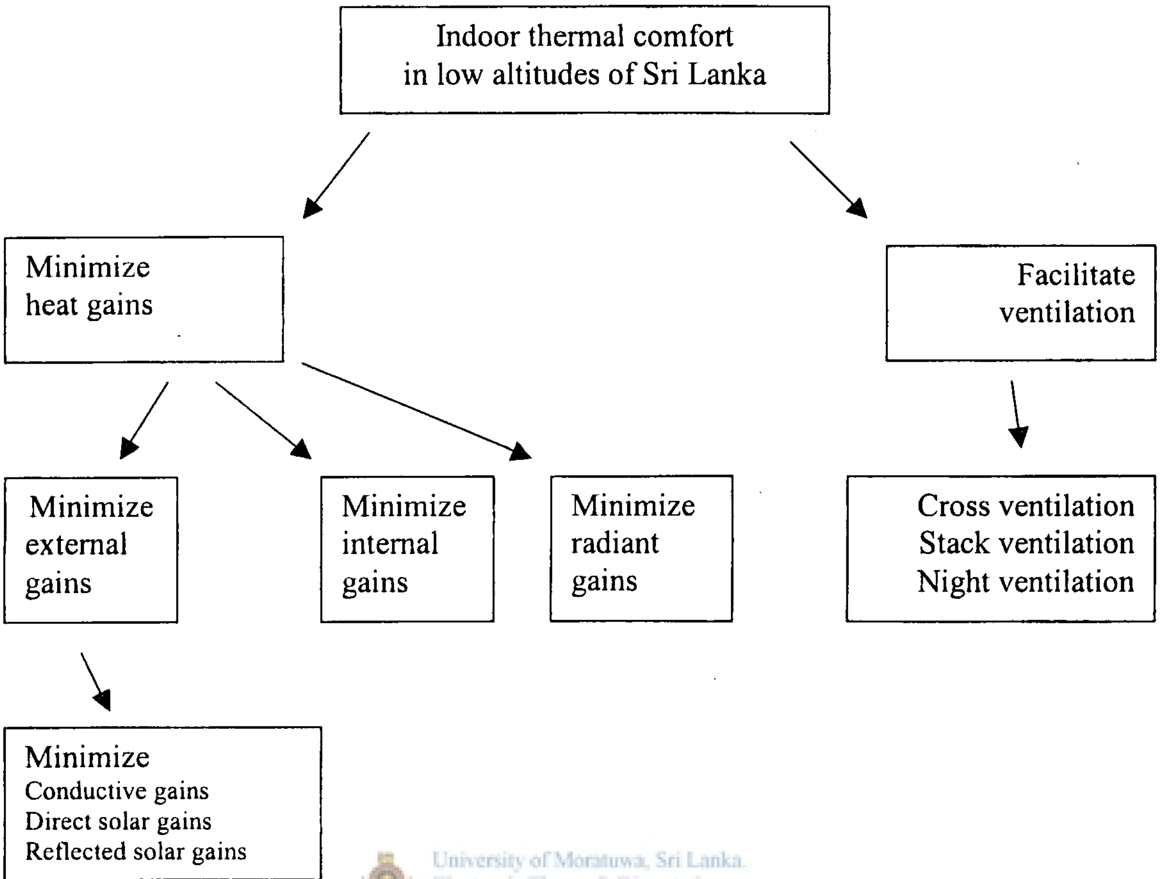


Figure 5.1 An overview of passive strategies desirable to warm humid climatic conditions

5.3.1 Minimization of heat gains

Heat gains can be mainly of three types:

1. External gains that enter the building across the building envelope
2. Internal gains generated indoors due to the use of electrical appliances
3. Radiant gains by human body due to its exposure to hot building elements

Minimization of these gains would help to maintain the indoor thermal comfort at desirable levels. Therefore, means by which they can be minimized are considered in detail.

5.3.1.1 Minimization of external gains

External gains can be of three types: Conductive gains, direct solar gains and reflected solar gains.

Minimization of conductive gains

Heat enters a building through the building envelope by way of conduction if the outdoor temperature is greater than that of indoors. Conductive gains can be inhibited by reducing the difference between the outdoor and indoor temperatures, i.e. by reducing the outdoor temperature. For this vegetation can be effectively employed because of its ability to convert large amounts of solar radiation into latent heat. This process, called evapotranspiration, does not raise the air temperature (Takakura et al., 2000).

Another important aspect of a vegetative surface is that it would not be as hot as an equivalent artificial surface of the same surface colour subjected to similar conditions. For example, according to Shashua-Bar & Hoffman (2000), the difference between the radiative temperature of a vegetative and artificial surface could sometimes be as high as 40°C. Presence of a hot surface will warm the air layer next to it, eventually resulting in an increase in air temperature. Therefore, as a ground covering, grass and shrubbery should be preferred to artificial paving materials such as cement tiles.

To maximize the vegetative cover round the house, there should be garden space. Due to escalating land prices in urban and suburban regions, allowing a substantial space for a garden will be extremely expensive unless multi-storey approach is adopted.

However, as shown by Takakura et al. (2000), the exterior surface of the building itself can be used to maximize the greenery cover. Ivy may be a possible candidate.

The building envelope of a house consists of the roof, walls and openings. Their thermal performance can be compared using the overall thermal conductance, called the U value, and the time lag. The time lag represents the delay a material can cause against heat transfer. The values of a set of materials found in a typical house is given below in Table 5.1.

Element	Material	U value (W/m^2K)	Time lag (hours)
Roof	Corrugated cement fibre sheets	4.9	0.0
Wall	Brickwork (230mm thick)	2.26	6.1
	Dense blockwork (200mm thick)	3.10	5.4
Window	Wood framed, 6mm single glazing	5.0	0.0

Table 5.1 Thermal properties of main elements of the building envelope of a house (Szokolay, 1991)

As shown in Table 5.1, the roof and the openings of a house can be quite weak against heat inflow, and therefore allow almost instantaneous heat transmittance. If the openings are properly shaded by shading devices (as explained in the next section), the opening would not cause any undesirable effect. The roof, however, due to its upward orientation is unshadable.

The sun path lies above the equator in March and September. It is at a north-most location in June and at a south-most location in December. Therefore, when a building located in Sri Lanka is considered, for two months of the year, the sun "travels" above it. For five months, during the daytime, its north-facing walls would be exposed to the direct sun while the south-facing walls would be shaded. For another five months, its south-facing walls would be exposed while its north-facing walls would be shaded. Therefore, north-facing walls and south-facing walls would not receive direct solar radiation during the daytime for five months at different times of the year. Moreover, every day, during the daytime, west-facing walls would be shaded in the morning and east-facing walls would be shaded in the evening. The roof, however, due to its upward orientation, would be exposed to direct solar radiation throughout the daytime round the year. It is also unlikely to be shaded by nearby structures such as trees and other buildings although walls can be subject to such shading.

Therefore, the roof is a thermally undesirable element with respect to materials as well as orientation. Its low thermal mass paves the way for almost instantaneous heat gains while its orientation minimizes the likelihood of shading. Therefore, it is desirable to minimize the roof area by resorting to multi-storey approach.

In a two-storey house, the volumes in the ground floor are sheltered from the sun because of the volumes of the upper floor; therefore, they are termed "sheltered" volumes. The volumes in the upper floor on the other hand are "unsheltered", since they are subject to the undesirable effects of the roof. As a result, a volume in the upper floor (i.e. an unsheltered volume) would be warmer than an equivalent volume in the ground floor (i.e. an equivalent sheltered volume).

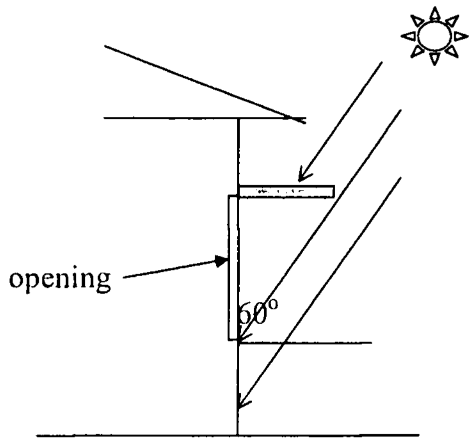
A two-storey house offers only one floor of sheltered volumes while a three-storey house offers two floors (i.e. ground floor and first floor) of such desirable volumes. Therefore, with respect to indoor thermal comfort, three-storey house is the best; two-storey is better than single-storey.

Minimization of direct solar gains

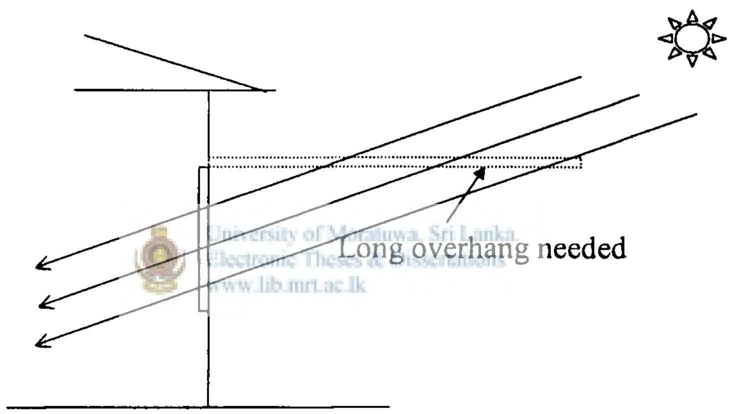
Direct solar radiation enters a building through its openings. This can be prevented by the use of shading devices – overhangs (i.e. horizontal projections) or fins (i.e. vertical projections).

When a building located in Sri Lanka is considered, its north or south-facing openings, depending on the month of the year, would be exposed to the sun from around 10.00 to 16.00 hours. In this case solar altitude is high. Therefore, a window located on a north or south-facing wall can be easily shaded by providing an overhang. Jayasinghe & Attalage (1999b) have shown that an overhang making a horizontal angle of 60° (Figure 2.7) would be adequate for the protection of a north or south-facing opening throughout the year.

When the same building as above is considered, the openings on its east-facing walls would be exposed to the sun in the morning (i.e. from sunrise until around 11.00 hours) and the openings on its west-facing walls would be exposed in the evening (i.e. from around 15.00 hours until sunset). Shading of openings on east or west-facing walls would be very difficult because the solar altitude would be low. The overhang required would be so long that it is considered as impractical. Therefore, east or west-facing openings are said to have "unshadable" orientations.



North/south-facing opening shaded by overhang



East/west-facing opening is difficult to be shaded

Figure 5.2 Shading of openings using overhangs

Therefore, it is important that, whenever possible, openings facing north or south should be provided to a house. These can be effectively shaded with shading devices. For aesthetical reasons, the front façade of a house is likely to consist of a larger area of glazing. Therefore, a house should face north or south so that the glazing of the front façade can be shaded.

If openings facing east or west are unavoidable, they should be short and protected with an overhang with a long projection. For such openings, vertical fins are also effective. Of the two openings east-facing one is less undesirable as it is exposed to the sun in the morning. A west-facing opening would be exposed in the evening when the outdoor temperature is also at its maximum.

Eaves of the roof can also act as overhangs. This is presented in Nayak et al. (1999) as follows:

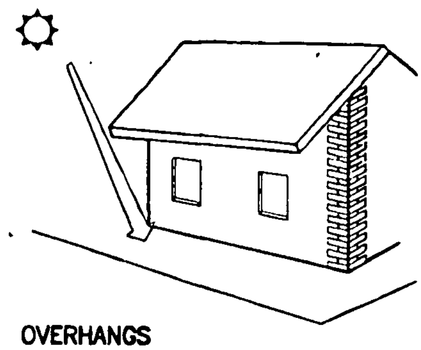


Figure 5.3 Eaves of the roof acting as overhangs (Nayak et al., 1999)

To select a desirable orientation for openings, there should be a choice. This may not be available in a single-storey house. For example, there may be a room which has only one external wall, and it faces west. In a multi-storey house of equivalent floor area, it is more likely to possess more than one external wall so that, for location of an opening, more desirable orientation can be selected. This aspect is shown in more detail in Section 6.7.1.

To shade openings, nearby structures such as buildings and trees can be employed. In fact, a tree or shrubbery strategically planted in front of an east or west-facing opening could be use for shading. This is very useful since overhangs would be ineffective. However, to plant trees, especially for strategic location of trees, garden space would be required. Here, too, multi-storey houses appear to be more desirable.

Minimize reflective solar gains

Although an opening is protected by an overhang from direct solar radiation, solar radiation reflected from the ground can find its way into the house as reflected solar radiation across the protected opening.

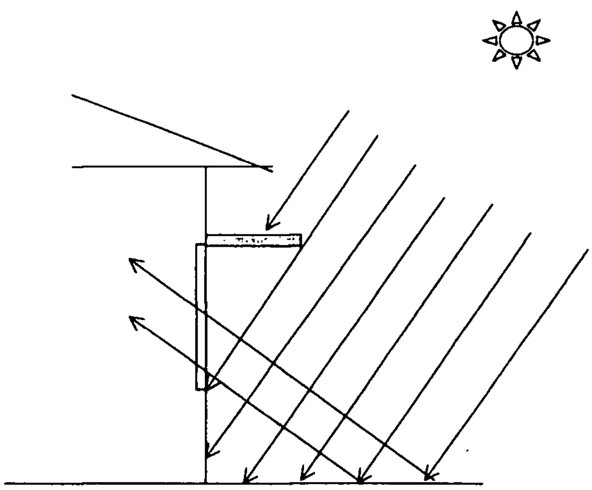


Figure 5.4 Ground reflected radiation entering across a shaded opening

Unlike direct solar radiation, control of ground reflected radiation is difficult. To mitigate the adverse effects of ground reflected radiation, a low reflectivity surface can be provided in front of openings. Watson & Labs (1983) recommend that a vegetative surface should be provided instead of artificial surfaces such as cement tiles. According to Mohan (1989), a concrete surface reflects around 25 to 35% of solar radiation incident on it while the corresponding figure for grass is only 10%. Watson & Labs (1983) state that shrubbery would be even better due to its irregular surface.

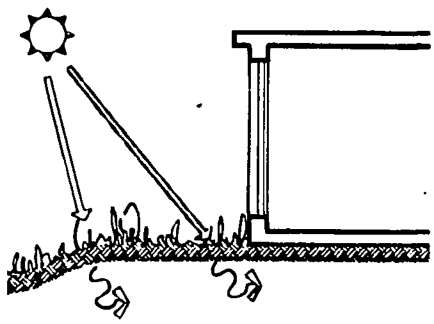


Figure 5.5 Grass minimizing reflected radiation (Nayak et al., 1999)

5.3.1.2 Minimization of internal gains

Due to electrical equipment used indoors, some other type of energy may be converted to heat, contributing to a rise in the indoor temperature. Cooking in the kitchen is an example. However, since it is essential, there is little that could be done for its control.

Another source of internal gains is artificial lighting. It is required at night. However, by prudent use of daylight, use of artificial lighting during the daytime can be minimized, if not avoided. According to Neeman (1977), what contributes to indoor visual comfort is diffuse radiation, not direct radiation. Therefore, use of overhangs does not deteriorate indoor lighting levels. However, openings should be provided for diffuse radiation to enter a room. It would be better if two openings could be provided on two external walls of the same room. Such a choice is more likely to be available in a multi-storey house.

Because of increasing price of urban and suburban land prices, people tend to locate their houses towards one end of the garden by adopting a blind wall, in order to save some usable garden space. This is the likely case in a single-storey house constructed in a small plot of land. The blind wall will further reduce the external wall area available for openings, contributing to gloomy indoors. Therefore, especially in small plots, multi-storey houses should be preferred.

5.3.1.3 Minimization of radiant gains

When a human body is exposed to a hot surface even at a distance, the former would gain heat by way of radiation. This is why a person in a room with a cement fibre ceiling would feel uncomfortable even though he is under shade; the hot ceiling radiates heat to the human body. Therefore, it should be ensured that building elements do not heat up substantially.

Because of its upward orientation and low thermal mass, the roof heats up easily and then radiates heat to the indoors. To a certain degree, a ceiling would improve the conditions as it would act as a shield between the hot roof and the occupants, but it would also be eventually heated up by the roof by way of radiation. Therefore, in this respect too, multi-storey approach would bring desirable indoor conditions.

The situation in an unsheltered volume could be enhanced by use of some insulation layer above the ceiling, so that the radiant heat transfer to the ceiling is mitigated.

5.3.2 Facilitation of ventilation

In a warm humid climate, facilitation of natural ventilation is important due to several reasons. Ventilation promotes:

1. Conductive-convective heat loss from the human body
2. Evaporation of the skin moisture from the human body, resulting in a physiological effect of cooling
3. Structural cooling, paving the way for a cooler structure at the beginning of the next day

In a Sri Lankan context, ventilation is even more important as Jayasinghe & Attalage (1999a) have shown that Sri Lankans generally feel thermally comfortable even at indoor temperatures as high as 30^{0}C when a sufficient air movement upto 1m/s is available.

Ventilation is of three types: Cross ventilation, stack ventilation and night ventilation. How to initiate various types is discussed below in detail.

5.3.2.1 <u>Cross ventilation</u>

Cross ventilation is due to prevailing air movement outdoors (i.e. breeze or wind). For improved results, the inlet should face the general wind direction. However, especially due to local effects, determination of general wind direction for a particular site is difficult. Therefore, it is desirable to locate openings on more than one external wall so that the possibility of catching the prevailing breeze is relatively high. One opening may act as the inlet and the other as the outlet. Some other time, the roles may reverse, depending on the direction of the breeze outdoors.

Moreover, provision of the inlet and outlet in the same volume is recommended by Waston & Labs (1983) for improved cross ventilation. It would be even better if the two openings are located on two external walls perpendicular to each other.

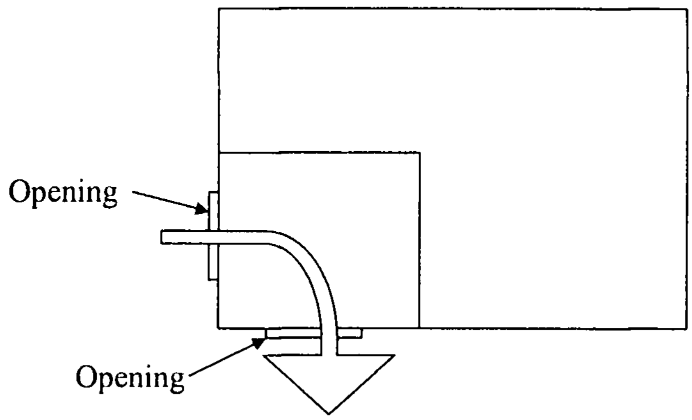


Figure 5.6 Two openings for one room for enhanced cross ventilation

In a single-storey house, most of the rooms would have only one external wall per room. In an equivalent multi-storey house, however, there can be more than one external wall for each room and therefore openings can be located to promote cross ventilation. Due to reduced disturbances to the wind flow, wind speed is higher away from the ground. Therefore, at upper floor levels, cross ventilation is improved. This is another advantage of the multi-storey house. Mohan (1989) reports that single-storey houses located close to each other, as is the case in the urban residential neighborhoods, suffer because the breeze tends to blow over them. A multi-storey house on the other hand can act as a barrier to wind, thereby increasing the air pressure on the surface and forcing the air through the openings on the wall.

The effective location of openings is graphically presented in Nayak et al. (1999):

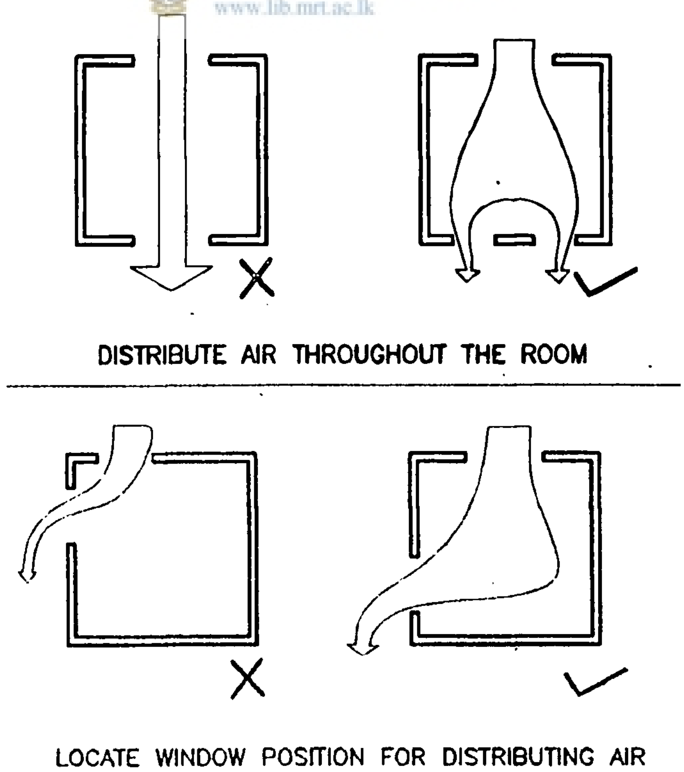


Figure 5.7 Desirable location of openings for cross ventilation (Nayak et al., 1999)

To channel air flow into the building, a baffle wall can be employed.

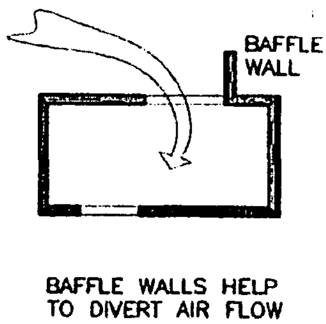


Figure 5.8 Use of baffle wall f or improved cross ventilation (Nayak et al., 1999)

For cross ventilation, openings are desirable. However, openings facing east or west are undesirable in terms of direct solar gains. Therefore, openings cannot be located in a haphazard manner for the sake of promoting cross ventilation. A solution to this problem is the courtyard, which can be considered as a semi-outdoor environment.

The courtyard can be arranged to face west because this orientation is highly undesirable for an opening. Louvers, or small openings, on the courtyard wall would allow air movement across it but would diffuse the direct solar radiation incident on it. The plan view of a courtyard facing west is given in Figure 5.9.

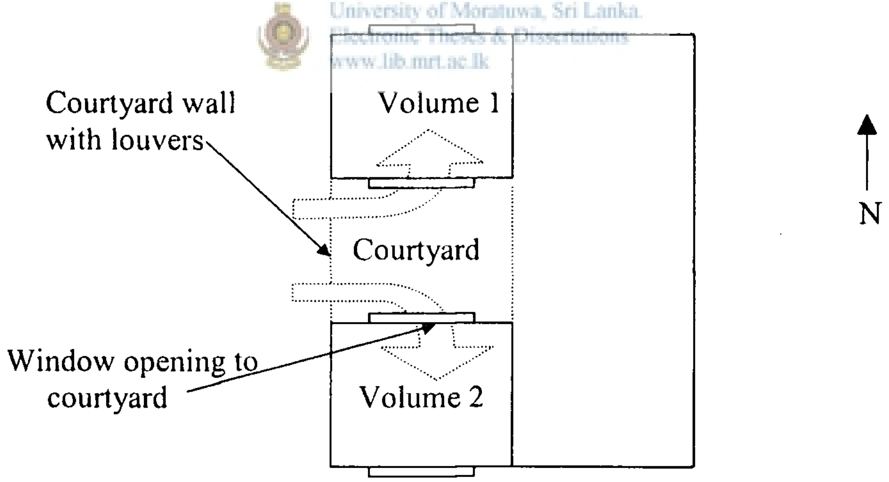


Figure 5.9 Courtyard to promote cross ventilation

The two volumes located adjacent to the courtyard can be provided with large windows opening to the semi-outdoor environment of the courtyard. These windows need no shading devices if the courtyard is provided with pergola beams so that the courtyard space receives diffuse radiation instead of direct solar radiation. For this, the pergolas should be along east-west as shown in Figure 5.10.

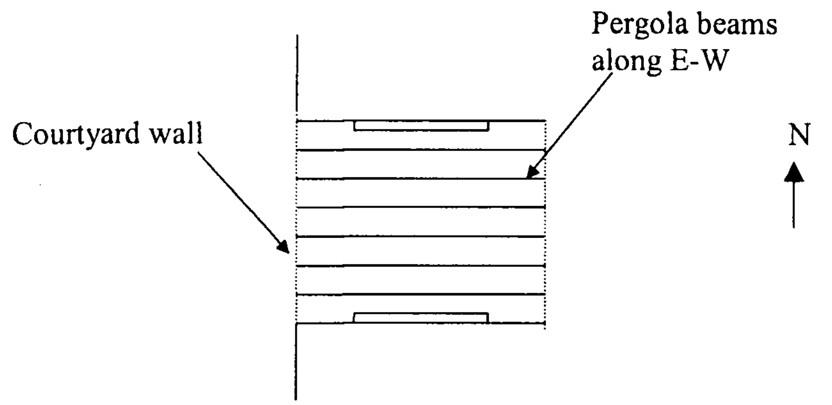


Figure 5.10 Orientation of pergola beams to protect windows opening to courtyard

In a single-storey house, the courtyard can serve volumes like Living and Dining. However, it cannot serve a bedroom because a bedroom window cannot open into a courtyard which has a window belonging to Living or Dining as well. Such privacy concerns can be eliminated by adopting a multi-storey approach. In a multi-storey house, the same courtyard can be used at different floor levels. For example, at the upper floor levels, the courtyard can serve bedrooms. Therefore, a multi-storey approach can be used to maximize the use of the courtyard as a promoter of cross ventilation as well.

5.3.2.2 Stack ventilation

In a room, warm air rises because it is lighter than cool air. If an outlet is available near the ceiling level, warm air would exit. Then, due to the decrease in the air pressure indoors, cool outdoor air would enter the room across the windows. This is called stack ventilation.

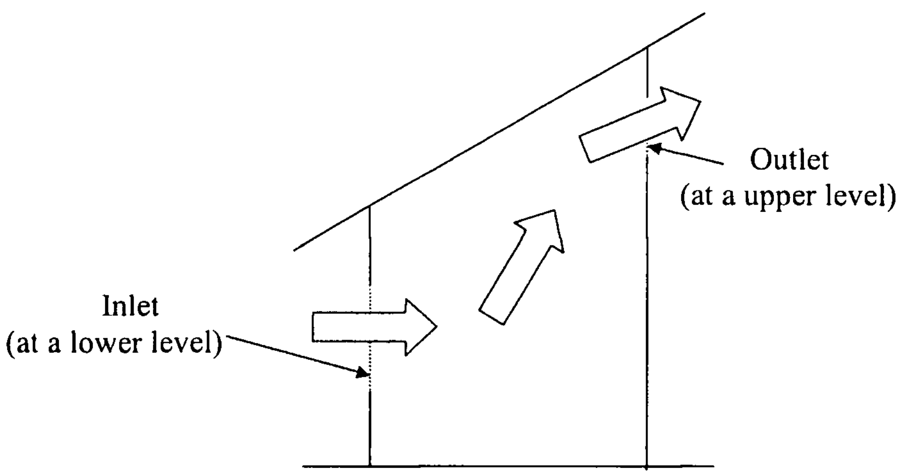


Figure 5.11 Mechanism of stack ventilation

Since air movement is not required for stack ventilation, it can be very useful on days with little or no air movement outdoors. However, since it depends on density difference of air, there should be a sufficient height difference between the inlet and the outlet. The height difference that can be provided in a single-storey house may not be sufficient. On the other hand, in a multi-storey house, this height difference can be provided, taking the stair case as the passage for the air movement as shown in Figure 5.12.

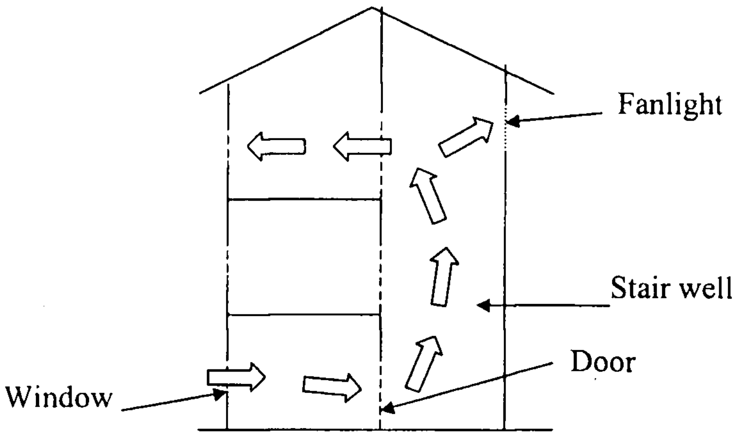


Figure 5.12 Stack ventilation in a multi-storey house

5.3.2.3 Night ventilation

Outdoor temperature starts dropping sharply around 19.00 hours while the indoor temperature remains comparatively unchanged due to thermal mass of the building. Cool outdoor air can be used to flush out warm air trapped inside the house. This can be done by simply opening the windows at night, and is called night ventilation. Its use as a cooling strategy is highlighted by Jayasinghe & Attalage (1999b) and Geros et al. (1999).

Night ventilation not only introduces cool air into the house, but also cools the building elements that have gained heat during the daytime. The latter benefit, also known as structural cooling, is beneficial with respect to indoor thermal comfort since the building would start at a lower temperature the next day. Therefore, a portion of the solar radiation incident on the building would be consumed to heat the building elements. As a result, the undesirable effects of the radiant gains could be reduced by cooling the building through night ventilation.

Night ventilation could be described as cross ventilation at night. Therefore, a multi-storey approach would promote night ventilation as well. Moreover, especially in single-storey houses, people do not like to keep windows open at night due to concerns of safety and privacy. If, however, the bedrooms are located at an upper floor level, this reluctance could be mitigated. This is possible in a multi-storey house. Another problem is the mosquito menace. This could be mitigated by using a thin wire mesh to protect the windows at night. During the daytime, this could be rolled up or drawn aside like a curtain.

5.4 Identification of desirable passive elements from thermal and comfort surveys

From the results of the thermal and comfort surveys, the following features of the building envelope have been identified as thermally desirable or undesirable.

5.4.1 Roof

In a single-storey house with a cement fibre sheet roof, it could difficult to achieve indoor thermal comfort due to the thermally undesirable effects of the roof even with a ceiling as could be found in Veyangoda house in Section 3.4.1. It is better however to have a ceiling since, in the ceilingless house in Wijerama (Section 3.4.4), the cement fibre roof created highly undesirable indoor temperatures upstairs. This points toward multi-storey construction for improvement. The survey results themselves have shown that a multi-storey house is more desirable than an equivalent single-storey house because of the sheltered volumes the former provides.

In a two-storey building, volumes at the ground floor (i.e. sheltered volumes) could be cooler than equivalent volumes at the top floor (i.e. unsheltered volumes) due to the effects of the roof on the latter. This could be observed in the houses at Ragama (Section 3.4.2) and Ratmalana (Section 3.4.3).

In a three-storey building, as seen in the three-storey hosted building in Moratuwa (Section 3.4.6), the second floor tends to be warmer than the floors below because of the effect of the roof. Besides, if the ground surface in front of the windows is bare, the ground floor tends to be warmer than the first floor due to the ground reflected solar radiation.

As seen in the Wijerama house (Section 3.4.4), a roof slab exposed to the sun could significantly make the indoor temperature rise. Therefore, balconies without a roof or terraces should be avoided. Otherwise, the temperature of the volume below the roof slab would go up substantially.

5.4.2 Openings

Unshaded windows could contribute to increase the indoor temperature due to the ingress of direct solar radiation. This could apply even to a sheltered volume, thus eliminating the beneficial performance of a sheltered volume. Therefore, openings should be shaded by shading devices.

As already mentioned, although openings facing north or south are shadable, those facing east or west are unshadable because of the low solar altitudes encountered. Therefore, shading of openings facing east or west could be a problem. However, as seen from the results of a thermal survey, trees planted in front of the window at a distance could be used for this purpose.

In a room with a window facing west, indoor temperature may rise in the evening due to the exposure to the afternoon sun. Therefore, windows facing west should be avoided unless shading can be provided using trees. Such windows are highly undesirable, especially for living rooms since the window size is likely to be comparatively large for aesthetic reasons.

According to the results of comfort survey carried out in a lecture room of Moratuwa University (Section 3.4.7), Sri Lankans could feel thermally comfortable at temperatures as high as 30°C if some air movement is present. Therefore, facilitation of ventilation is important. In fact, as seen in Colpetty house (Section 3.4.5), the relatively high temperature of an unsheltered volume could be lowered by facilitating cross ventilation. For this purpose, openings are needed as inlets and outlets for the air flow. Since a multi-storey house could provide more external wall area than a single-storey house of equivalent floor area, facilitation of ventilation is easier in the former.

When a tall boundary wall is located near the window of a sheltered volume, as is the case in Colpetty house (Section 3.4.5), this could make the volume uncomfortable (more precisely "stuffy") even though it is sheltered. Moreover, it would be gloomy during the daytime, and may require artificial lighting during daytime. Therefore, rather than planning the house to one end of the plot, multi-storey construction should be adopted to save garden space – especially in small plots of land.

5.4.3 Walls

Due to higher absorptance of the dark colors, a room with a dark colour exterior surface tends to be warmer than an equivalent light colour room. This could be one factor that caused high temperatures in the volumes of the Ragama house (Section 3.4.2) because it had a light brown colour surface. Therefore, light colours should be preferred to external wall surfaces.

5.5 Computer analysis of effects of critical passive elements on indoor thermal comfort

Sri Lanka is a tropical country, located between latitudes 5°55'N and 9°51'N. Consequently, the roof of a building would be exposed to the sun more often than the walls because of the high solar altitude angles during mid day. Hence, with respect to orientation, the roof is an undesirable building element. The roof is undesirable as regards to materials as well as it fails to substantially delay the heat inflow because of its relatively low thermal mass. This is highlighted in Table 5.1. Therefore, in the building envelope, the roof deserves the highest attention in studies conducted with the view of achieving thermally comfortable indoors conditions with passive means.

The other critical element of the building envelope is the openings. They are required for provision of ventilation. However, since the glazing is weak against heat transfer (Table 5.1), an unshaded opening could contribute to direct solar gains into the building. Therefore, openings, too, should be investigated further.

Having identified the most critical elements of the building envelope as the roof and the openings, their effect on the indoor thermal comfort was investigated through computer simulations. For this purpose, the Dynamic Energy Response Of Buildings (DEROB-LTH) program was used.

DEROB-LTH was originally developed at the Numerical Simulation Laboratory, School of Architecture, University of Texas. Later, it was further enhanced at the Department of Building Science, Lund Institute of Technology (LTH), Sweden. It is a versatile simulation tool that facilitates the creation of models of actual buildings with a relatively high level of accuracy. It handles energy transmission across the building envelope by taking account of thermal properties of building materials. In addition to the thermal loads from direct and diffused solar radiation, it considers solar radiation reflected from the ground and shading devices. It takes account of infiltration and forced ventilation. It can also take account of static pressure driven air exchanges between volumes, that take place across openings at different levels (advection connection). It can also calculate the air-conditioning loads and required plant capacities (DEROB-LTH, 1999). Validation of the software is given in Appendix D.

The following aspects of the roof and the openings were considered in detail:

1. Effect of orientation of roof

2. Effect of roof materials
    - Roof covering materials
    - Roof insulation materials
    - Roof surface colour

3. Effect of orientation of openings

5.5.1 Effect of roof orientation

5.5.1.1 The details of simulation

The model house selected for simulations is given in Figure 5.13. It consists of four volumes, namely NW, NE, SW and SE. The openings provided were properly oriented (i.e. facing north or south) and shaded with overhangs. The width and height of an opening were 1.2 and 1.5m, respectively.

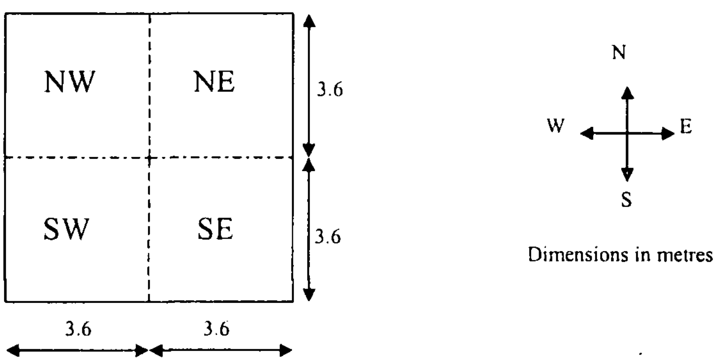
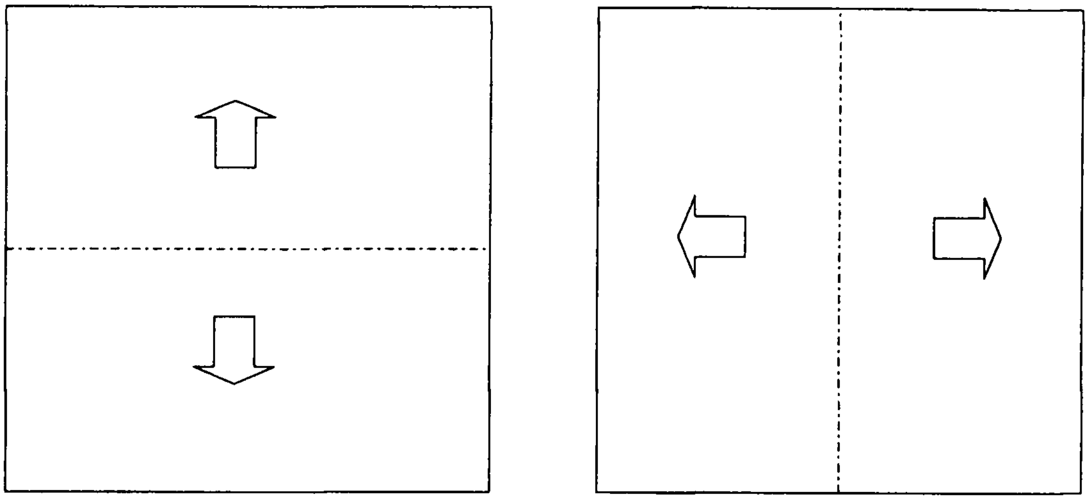


Figure 5.13 Floor plan of model house

Two roof orientations were selected for the simulations, namely R1 and R2 (Figure 5.14). Roof R1 had its ridge along east-west while R2 had its ridge along north-south. Front and side elevations of model house are given in Figure 5.15.



East-west ridge roof (R1)

North-south ridge roof (R2)

Figure 5.14 Roof orientations used for simulations

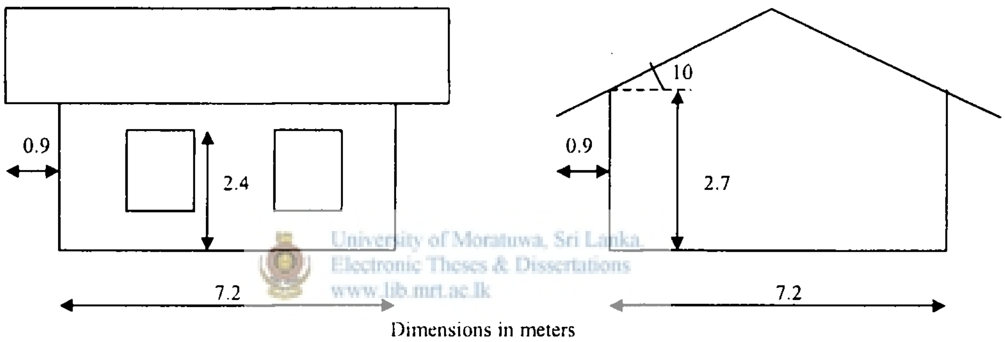
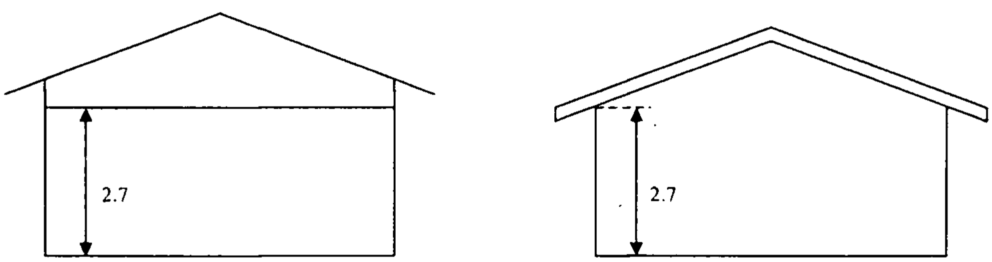


Figure 5.15 Front and side elevation of model house with east-west ridge roof

These roofs were combined with two ceiling types that are commonly used in houses in Sri Lanka. They were flat and sloping cement fibre ceiling (Figure 5.16). For all volumes in all case, the number of air changes was maintained as 1ach/hour, representing the conditions of closed windows. However, the space between the roof and the flat ceiling was considered as sealed. The three dimensional view of the model is given in Figure 5.17. Simulations were carried out for March, June and December, using climatic data applicable to Colombo (Table 2.3).



Flat ceiling

Sloping ceiling

Dimensions in metres

Figure 5.16 Ceiling types used for simulations

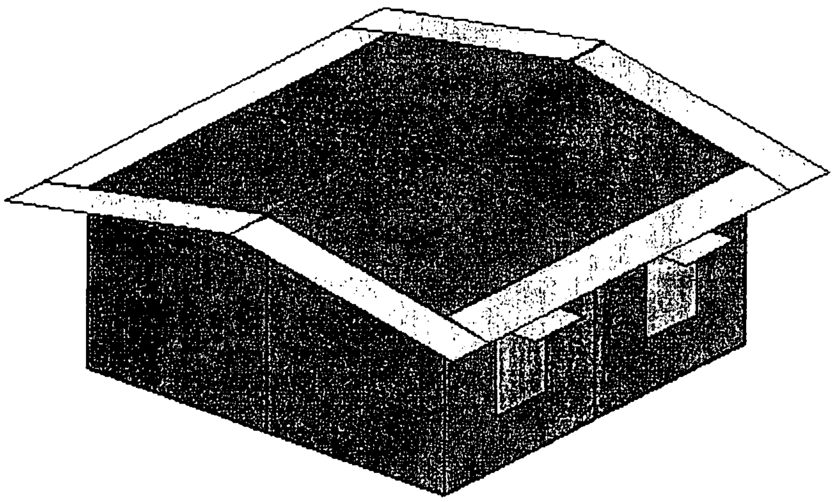


Figure 5.17 Three dimensional view of the model with cement fibre roof

5.5.1.2 Data used for simulation

Since the attention is on the thermal performance of the roof, the materials used for walls and the floors were kept the same for all simulations. The values of absorptance and emittance used for the simulations are given in Table 5.2. They were obtained from Nayak et al. (1999).

	Surface colour	Absorptance (%)	Emittance (%)
Walls	Off-white	35	90
Floors	Red, green, brown etc.	70	90
Cement firbe sheets of roof and ceiling	Off-white painted surface	35	90
	Light grey of new surface	60	95
	Blackish grey of aged surface	75	95
Eaves	Blackish grey	75	95
Shading devices (overhangs)	Off-white	35	90

Table 5.2 Absorptance and emittance of building elements

The important properties of the building materials used for the simulations are given in Table 5.3 and the constituent materials and the overall properties are given in Table 5.4. They were obtained from BRE (1984), Evans (1980) and Nayak et al.(1999).

Material type	Conductivity (W/mK)	Specific heat (Wh/kgK)	Density (kg/m^3)
Earth	1.4	0.22	1300
Plain concrete	1.7	0.25	2300
Hand moulded bricks	0.82	0.24	1850
Cement plaster	0.72	0.24	1800
Cement fibre sheets	0.22	0.25	1600
Air space	0.024	0.28	1.201

Table 5.3 Properties of the materials used for the simulations

	Constituent materials from front to back as defined for DEROB-LTH	Dynamic attenuation	Time lag (Hours)
Concrete floor	500mm earth, 50mm plain concrete, 20mm cement plaster	0.258	10.430
External or internal wall	15 mm cement plaster, 210mm thick brick wall, 15mm cement plaster	0.569	6.134
Cement fibre roof with cement fibre sloping ceiling	8mm thick cement fibre sheets, 250 mm air gap, 6mm thick cement fibre sheets	0.999	0.217
Cement fibre roof	8 mm thick cement fibre sheets	1.000	0.047
Cement fibre flat ceiling	6mm thick cement fibre sheets	1.000	0.027

Table 5.4 Constituent material properties and thicknesses for the walls, floors and roofs

5.5.1.3 <u>Discussion of results</u>

The results are presented as the maximum temperature that occurred during the course of the day. Generally, indoor temperature also reaches a maximum around 14.00 hours, i.e. when the outdoor temperature reaches its maximum. The time of occurrence of the maximum temperature is given in Appendix C1.

For simulations, two roof orientations were considered. Roof R1 had its ridge along east-west direction and roof R2 along north-south direction. The cement fibre sheet roof with a 10° was considered with two types of cement fibre sheet ceilings, i.e. flat and sloping ceilings. Openings were properly oriented (i.e. facing north or south) and shaded with overhangs. To determine the effects throughout the year, simulations were performed for June, December and March, which represented the northmost, southmost and overhead location of the sun.

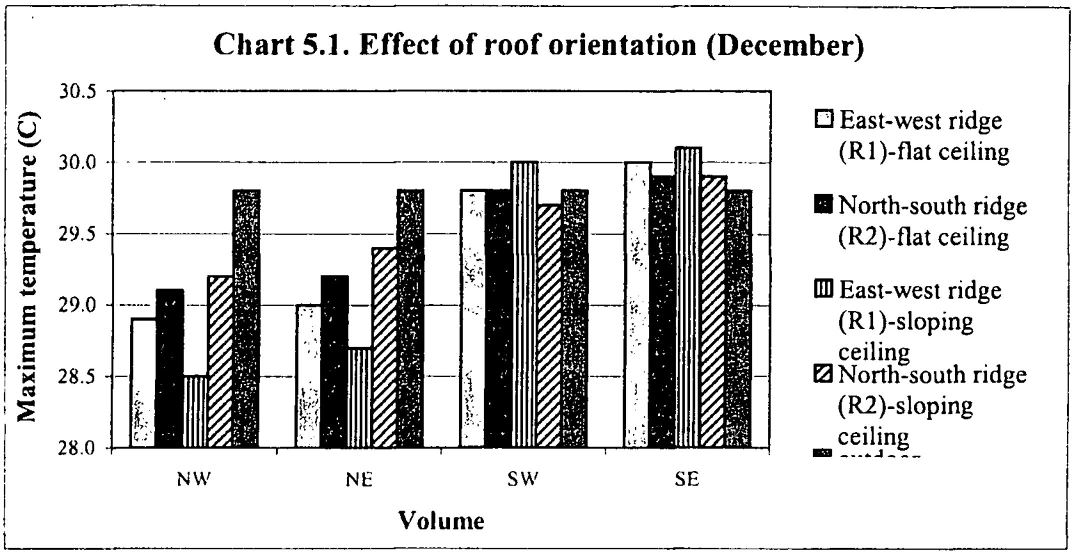


Chart 5.1 presents the results for December, comparing the effect of roof orientation for both flat and sloping ceilings. Since the sun is at a south-most location, the northern volumes (i.e. NW and NE) show a lower maximum temperature than the corresponding southern volumes (i.e. SW and SE).

For both ceiling types, the difference in the maximum indoor temperature due to the effect of the roof orientation lies within 0.3°C except for the two isolated cases of north facing volumes with sloping ceiling. Although the east-west ridge case performs marginally better, a distinct difference cannot be found between the two roof orientations.

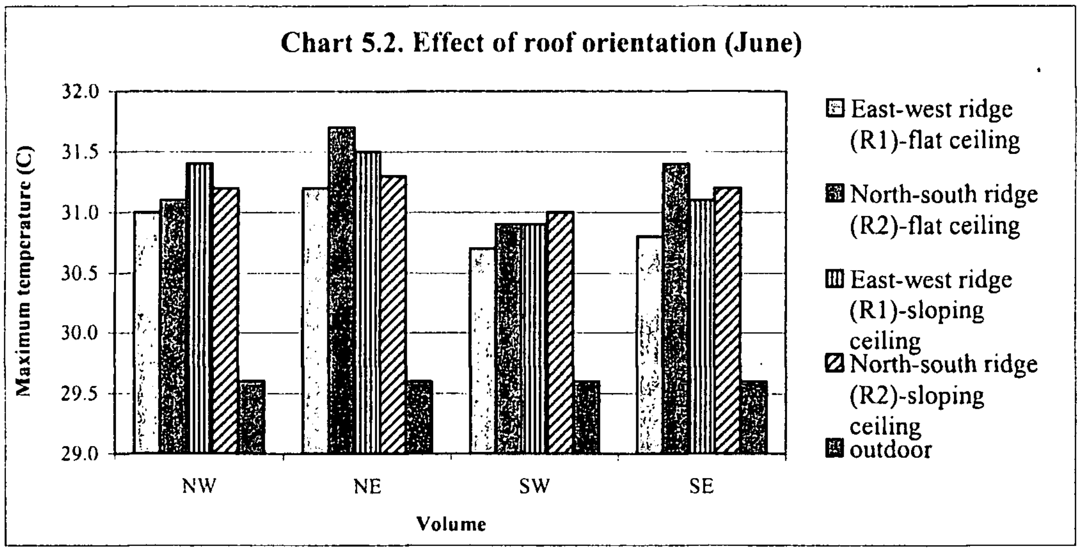
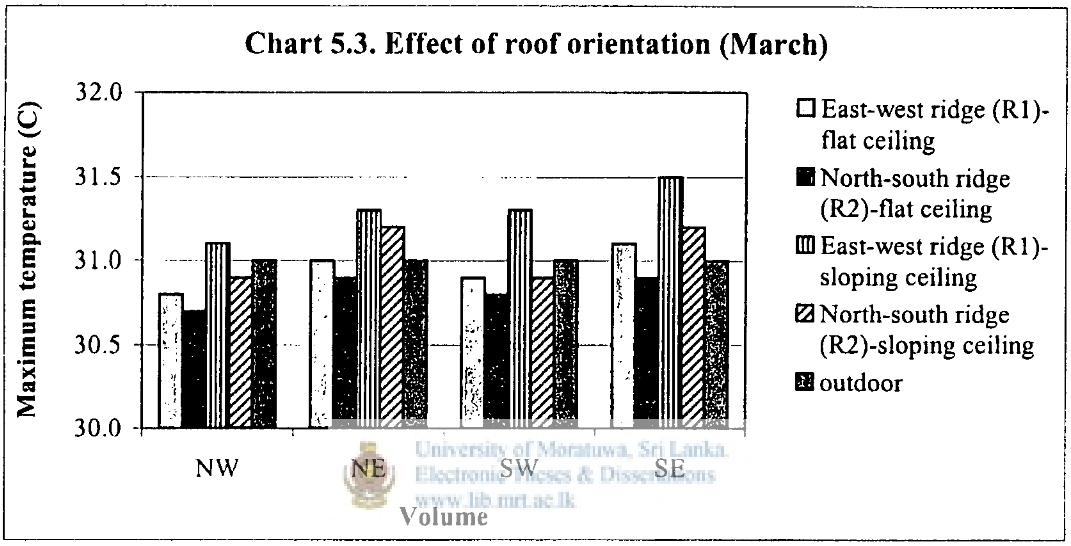


Chart 5.2 presents the results for June. Even though the sun is at a northmost location, the maximum temperatures of the north facing volumes are not appreciably higher than those of southern volumes although the corresponding difference in December is quite significant. This may be due to the fact that, although the outdoor temperature of December drops to 22.4°C around 6.00 hours, the minimum temperature in June is only 25.2°C. Although the maximum outdoor temperature is

only 29.6°C, the maximum indoor temperature of most volumes varies between 31 and 31.5°C.

For both ceiling types, the east-west ridge roof performs better but marginally. The difference of the maximum outdoor temperature due to the effect of the roof orientation lies within 0.6°C. Therefore, in June as well, the performance of the both roof orientations is approximately the same.

Chart 5.3 compares the effect of roof orientation in March, when the sun is located above the equator. As can be expected, the performance of all volumes looks the same. The maximum indoor temperature of all volumes lies about the maximum outdoor temperature of 31°C.



For both ceiling types, the performance of the north-south ridge roof is marginally better. However, the difference in the maximum temperature due to roof orientation is less than 0.5°C. Therefore, in March too, both roof orientations perform in similar fashion.

A distinct difference in the performance of the two roof orientations (i.e. east-west ridge roof R1 and north-south ridge roof R2) cannot be found throughout the year when the cement ceiling is of cement fibre sheets.

5.5.2 Effect of roof covering and insulation materials, and roof surface colour

5.5.2.1 The details of simulation

The floor plan of the model house selected for simulations is the same as that given in Figure 5.13. It consists of four volumes, namely NW, NE, SW and SE. It is compatible to the Building Regulations in Sri Lanka (Building Regulations, 1985). The openings provided were properly oriented (i.e. facing north or south) and shaded with overhangs. The width and height of an opening were 1.2 and 1.5m, respectively.

The ridge of the roof of the model was in east-west direction. Roof covering materials selected were cement fibre sheets and calicut tiles, with roof angles 10° and

30^{0}, respectively. In addition to these, half calicut tiles on asbestos was considered, with a roof angle of 10^{0}. These roof covering materials were considered along with two commonly adopted ceiling materials in Sri Lanka, namely cement fibre sheets and timber. The roof insulation materials used for simulations were aluminium foil and polystyrene. To determine the effect of roof surface colour, the cement fibre sheet roof was employed. The blackish grey colour of old sheets (absorptance 80%) of the base case was changed to two lighter colours, namely light grey of new cement fibre sheets (absorptance 60%) and off-white colour (absorptance 40%).

Front and side elevations of model house are the same as given in Figure 5.14. For all volumes in all cases, the number of airchanges was maintained as 1 ach/hour, representing the conditions of closed windows. The space between the roof and the flat ceiling was considered as sealed for the asbestos roof, but an airchange of 1 ach/hour was used for the calicut tiles. Simulations were carried out for March, using the climatic data applicable to Colombo (Table 2.3).

5.5.2.2 Data used for simulation

Since the attention is on the thermal performance of the roof, the materials used for walls and the floors were kept the same for all simulations. The values of absorptance and emittance used for the simulations are given in Table 5.5. They were obtained from Nayak et al. (1999).

	Surface colour	Absorptance (%)	Emittance (%)
Walls	Off-white	35	90
Floors	Red, green, brown etc.	70	90
Cement fibre sheets of roof and ceiling	Off-white painted surface	40	90
	Light grey of new surface	60	95
	Blackish grey of old surface	80	95
Eaves of cement fibre sheet roof	Blackish grey	80	95
Calicut tiles	Brown	70	90
Eaves of calicut tile roof	Brown	70	90
Shading devices (overhangs)	Off-white	35	90
Aluminium foil	Silver	20	10
Polystyrene	Off-white	35	90

Table 5.5 Absorptance and emittance of building elements

The important properties of the building materials used for the simulations are given in Table 5.6 and the constituent materials and the overall properties are given in Table 5.7. They are obtained from BRE (1984), Evans (1980) and Nayak et al. (1999).

Material type	Conductivity (W/mK)	Specific heat (Wh/kgK)	Density (kg/m^3)
Earth	1.4	0.22	1300
Plain concrete	1.7	0.25	2300
Hand moulded bricks	0.82	0.24	1850
Cement plaster	0.72	0.24	1800
Cement fibre sheets	0.22	0.25	1600
Calicut tiles	0.8	0.24	1900
Timber	0.072	0.46	800
Aluminium foil	160	0.25	2700
Polystyrene	0.036	0.47	70

Table 5.6 Properties of the materials used for the simulations

	Constituent materials from front to back as defined for DEROB-LTH	Dynamic attenuation	Time lag (Hours)
Concrete floor	500mm earth, 50mm plain concrete, 20mm cement plaster	0.258	10.43
External or internal wall	15 mm cement plaster, 210mm thick brick wall, 15mm cement plaster	0.569	6.13
Cement fibre sheets	8 mm thick cement fibre sheets	1.000	0.05
Calicut tile roof	15mm calicut tiles	1.000	0.06
Half tile roof	8mm calicut tiles, 8mm calicut tiles 8mm cement fibre sheets	1.000	0.09
Cement fibre sheet flat ceiling	6mm thick cement fibre sheets	1.000	0.03
Timber flat ceiling	4mm thick timber	1.000	0.03
Aluminium foil	1mm aluminium foil	1.000	0.00
Aluminium foil with polystyrene	15mm polystyrene, 1mm aluminium foil	1.000	0.09

Table 5.7 Constituent materials and thicknesses for the walls, floors and roofs

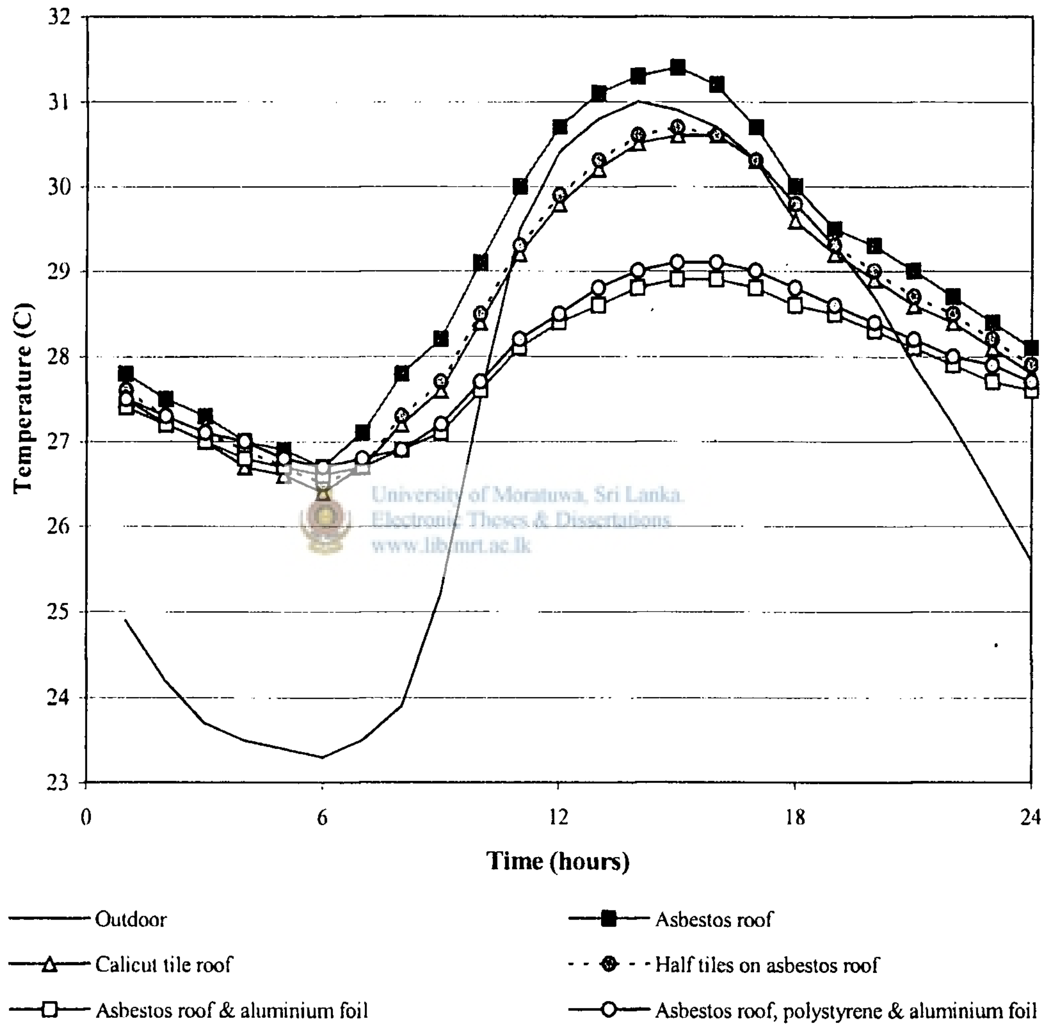
5.5.2.3 Discussion of results

Effect of roof covering material

The results of the computer simulations are presented as the maximum temperature that occurred during the course of the day. Generally, indoor temperature reaches a maximum value around 14.00 hours, i.e. when the outdoor temperature reaches its maximum. The time of occurrence of the maximum temperature is given in Appendix C2. Since the walls are of light colour and the properly oriented openings are shaded with shading devices, the resulting indoor temperatures could be considered as predominantly due to the effects of the roof. For clarity and easy reference, the word "asbestos" is used instead of "cement fibre sheet" in charts.

To obtain a general idea of the roof covering and insulation materials on the indoor thermal comfort of a typical volume, Chart 5.4 can be used. It shows the variation of the indoor temperature of SE volume for March for the case of cement fibre sheet ceiling.

Chart 5.4 Variation of indoor temperature of SE volume in March (All cases with asbestos ceiling)

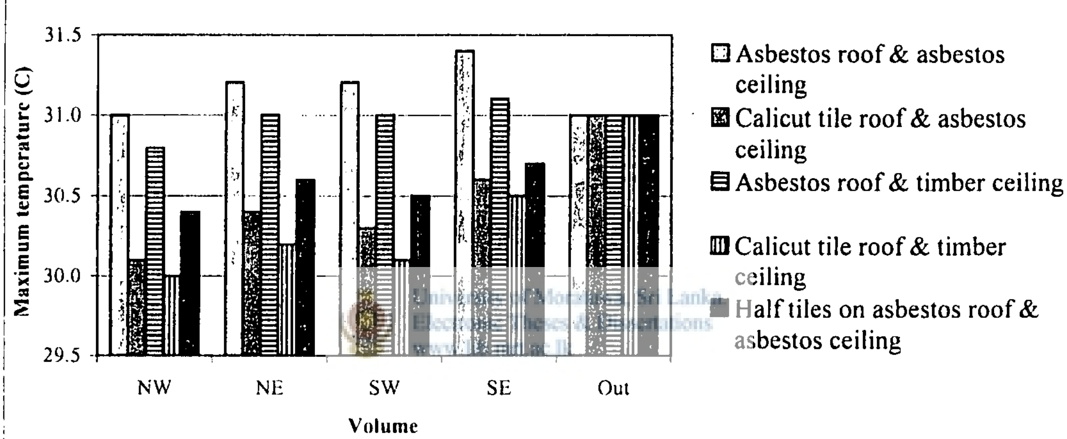


As shown in Chart 5.4, cement fibre sheet roof is the worst, causing a maximum indoor temperature of around 31.5°C. The performance of the calicut tile roof and the half tile roof is similar, registering a maximum indoor temperature of 30.5°C. Therefore, these types can be considered better than the cement fibre sheet roof, but may not be good enough to achieve thermal comfort with sufficient ventilation. The insulation materials, on the other hand, can maintain the indoor temperature of this volume within 29°C, thus minimizing or even eliminating the need for forced ventilation for achieving thermal comfort indoors. The effect of the roof covering

materials, roof insulation materials and roof surface colour is further considered in more detail.
Two commonly used roof covering materials (i.e. cement fibre sheets and calicut tiles) were considered. In addition to these, another roof type of half calicut tiles laid on the cement fibre sheet roof were considered. These roof covering materials were considered along with two commonly adopted ceiling materials, namely cement fibre sheets and timber.

Chart 5.5 presents the condensed results for March for all volumes. For both ceiling types, the maximum indoor temperature of the cement fibre sheet roof is higher than that of the calicut tile roof by almost 1°C. By laying half calicut tiles on the cement fibre sheet roof, the maximum temperature can be lowered by around 0.7°C with respect to the cement fibre sheet roof. Still, the half tiles on cement fibre sheets would result in warmer indoors than the calicut tile roof.

Chart 5.5 Effect of roof covering material on maximum indoor temperature (East-west ridge roof with flat ceiling in March)



The effect of the ceiling material could also be compared. By using a timber ceiling instead of a cement fibre sheet ceiling along with as cement fibre sheet roof, the maximum indoor temperature could be marginally lowered, i.e. by around 0.2°C. With the calicut tile roof as well, the timber ceiling performs better than the cement fibre sheet ceiling, but the effect is even less significant. Therefore, the effect of ceiling material seems insignificant on the indoor thermal comfort.

	Cement fibre sheet roof (C)				Calicut tile roof (C)			
	NW	NE	SW	SE	NW	NE	SW	SE
Cement fibre sheet ceiling	28.7	28.7	28.7	28.7	28.3	28.3	28.3	28.4
Timber ceiling	28.6	28.6	28.7	28.7	28.3	28.3	28.3	28.4
Cement fibre sheet ceiling with half tile roof	28.5	28.5	28.5	28.5	—			

Table 5.8 Indoor temperature at 22.00 hours for different volumes

To determine the night time performance, indoor temperature at 22.00 hours (i.e. when people go to bed) is compared. As shown in Table 5.8, the calicut tile roof performs better than the cement fibre sheet roof. The performance of the half tile roof is in between the above two. There is no significant effect of the ceiling material.

Effect of roof insulation material

Since, it is difficult to achieve indoor thermal comfort using commonly adopted roof covering materials, roof insulation materials were also investigated. Two arrangements of roof insulation materials were considered for the simulations. The first one consisted of an aluminium foil laid over a flat cement fibre sheet ceiling. The second one consisted of an additional layer of polystyrene above this aluminium foil.

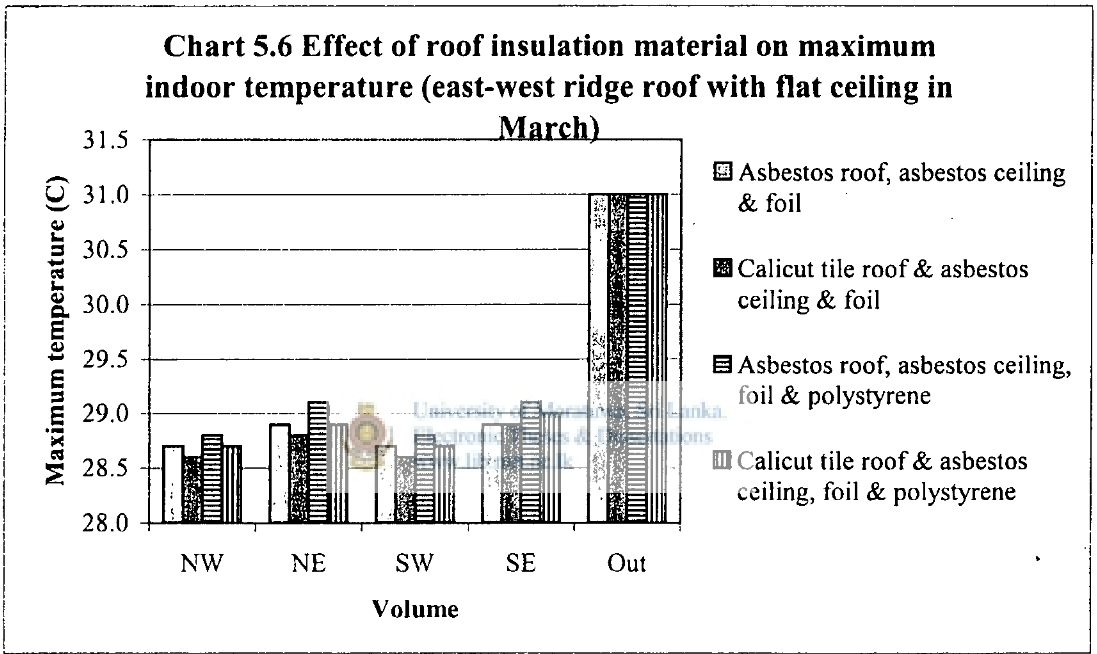


Chart 5.6 presents the condensed results for March for insulation materials. When both the roof and the ceiling are of cement fibre sheets, use of an additional layer of aluminium foil reduces the maximum indoor temperature by around 2.5°C when compared with Chart 5.5. In the calicut roof with cement fibre sheet ceiling, the corresponding reduction is about 1.5°C. It is significant though not as pronounced as in the former case. Use of an additional layer of polystyrene above the aluminium foil does not cause an appreciable improvement in the previous case (i.e. aluminium foil alone).

For the cement fibre sheet ceiling, in either arrangement of roof insulation, the maximum indoor temperature of both cement fibre sheet and calicut roofs lies in general between 28.5 and 29°C in March when the outdoor temperature rises to 31°C. Therefore, the indoors may seldom require forced ventilation for achievement of thermal comfort. Although the timber ceiling was not considered here, its performance should be even better.

Table 5.9 presents the indoor temperatures at 22.00 hours, showing that an additional layer of polystyrene could result in marginally warmer conditions, probably due to the obstruction to cooling.

	Cement fibre sheet roof (C)				Calicut tile roof (C)			
	NW	NE	SW	SE	NW	NE	SW	SE
Cement fibre sheet ceiling & foil	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9
Cement fibre sheet ceiling, foil & polystyrene	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0

Table 5.9. Indoor temperature at 22.00 hours for different volumes

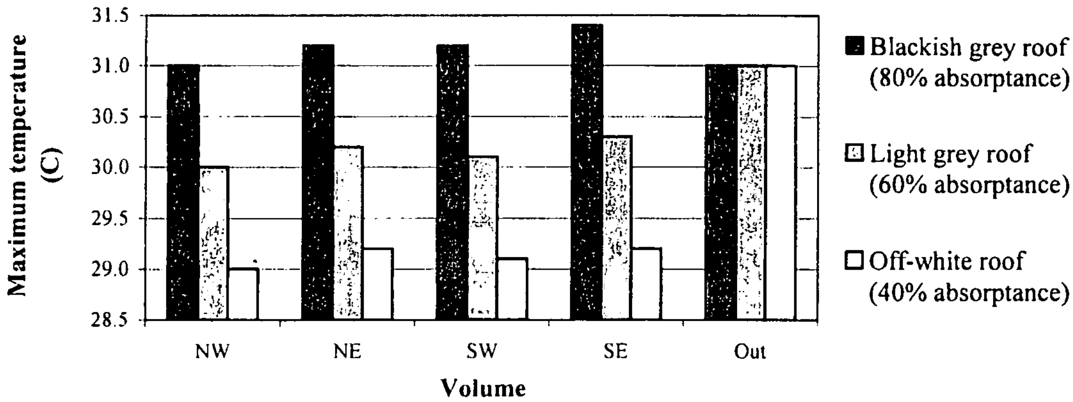
Effect of roof surface colour

Although roof insulation materials can achieve thermally desirable conditions, they are expensive. Therefore, an alternative means of achieving thermal comfort was investigated, by varying the colour of the exterior surface of the asbestos roof.

To investigate the effect of the surface colour the roof, the most undesirable roof type was selected, i.e. cement fibre sheet roof with cement fibre sheet ceiling. The results presented in Chart 5.5 correspond to an absorptance of 80% for the exterior colour of the roof surface, representing the blackish grey colour of the old cement fibre sheets.

Chart 5.7 presents the results for March. The case of old cement fibre sheets with 80% absorptance corresponding to the blackish grey colour is considered as the base case. When the absorptance of the external roof surface is 60% (corresponding to the light grey colour of the new cement fibre sheets), the maximum indoor temperature drops by 1°C, i.e. to a level marginally above 30°C. However, since new sheets become quickly discoloured due to the tropical weather conditions, light grey colour should be maintained by application of a roof paint.

Chart 5.7 Effect of exterior surface colour on maximum indoor temperature (East-west ridge roof with asbestos ceiling)



When the absorptance is 40% (corresponding to off-white colour), the maximum indoor temperature drops by another 1°C. Now the maximum indoor temperature is marginally above 29°C, i.e. slightly above the maximum temperature registered when roof insulation materials were used. Therefore, the most undesirable roof case could be enhanced to the level of the most desirable case by the mere application of a roof paint of off-white colour.

This can be considered as a solution suitable to existing houses, where laying of roof insulation material would be relatively difficult. Besides, roof paints may be more economical than roof insulation material, and therefore this is an important finding. However, high reflectance of an off-white colour roof may cause problems to adjacent houses, especially if two houses in question are of different heights. For example, the solar radiation reflected from a light colour roof of a single storey house may heat the neighbouring two-storey house. Roof paints and colour tiles have already gained popularity in Sri Lanka. This study shows that, to reap the passive benefits, they should be of light colour such as off-white.

Air temperature does not take into account the thermally undesirable effect of any hot body present. For example, in a room with a hot cement fibre sheet roof, air temperature may be at a reasonably acceptable level although a person in that room may feel very uncomfortable. This is due to the heat transfer by radiation from the hot roof to the human body, and a normal thermometer reading does not reflect this component. On the other hand, the parameter called Operative Temperature takes this radiation component into account; therefore, in this instance, the operative temperature would be higher than the air temperature. Thus the operative temperature is a better indicator of a prevailing thermal environment, especially when a hot body is present.

Chart 5.8 shows the variation of operative and indoor temperature of the SE volume in March. When compared, the operative temperature is higher than the indoor temperature for all three roof surface colours. However, the difference is greater in the dark colour cases because the ceiling is heated more than in the off-white case. This also shows the importance of avoiding heated bodies exposed to indoors.

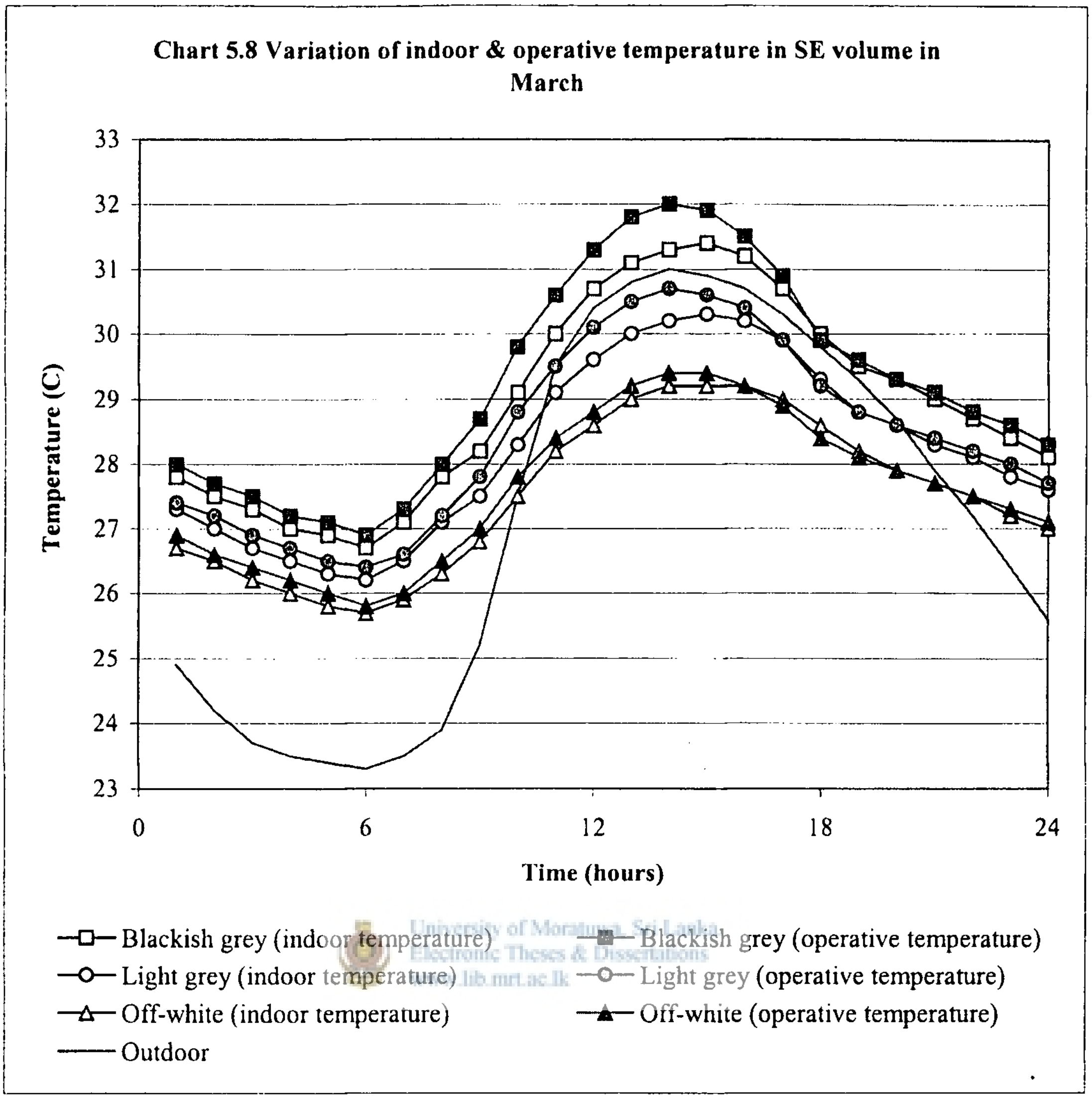


Table 5.10 presents the indoor temperatures at 22.00 hours, showing that application of off-white roof paint on the cement fibre sheet roof surface could lower the indoor temperature by 1.2°C from the normal cement fibre sheet roof case. Therefore, a light colour cement fibre sheet roof surface could enhance the thermal comfort indoors not only during daytime, but also at night.

Colour of cement fibre sheet roof	Absorptance (%)	NW	NE	SW	SE
Blackish grey	80	28.7	28.7	28.7	28.7
Light grey	60	28.1	28.1	28.1	28.1
Off-white	40	27.4	27.4	27.5	27.5

Table 5.10 Indoor temperature at 22.00 hours for different volumes

It should be emphasized that, for the simulations, heat gains from people and appliances were not considered, and the model consisted of properly oriented shaded openings and light colour walls. If internal gains were considered and the above-mentioned passive features were absent, the indoor temperatures given in the results would be somewhat higher.

5.5.3 Effect of orientation of openings

5.5.3.1 The details of simulation

This is the same as Section 5.5.1.1.

5.5.3.2 Data used for simulation

This is the same as Section 5.5.1.2

5.5.3.3 Discussion of results

Because the effect of the roof orientation was insignificant on the maximum indoor temperature, the effects of the orientation of openings was investigated. The east-west ridge roof was considered along with the most undesirable month (i.e. June). Openings with undesirable orientations (i.e. east or west facing) were added step by step to the house with shaded, properly oriented openings (i.e. north or south facing). The effects were considered for the two types of ceilings separately.

Chart 5.9 Effect of orientation of openings
(East-west ridge roof with flat ceiling in June)

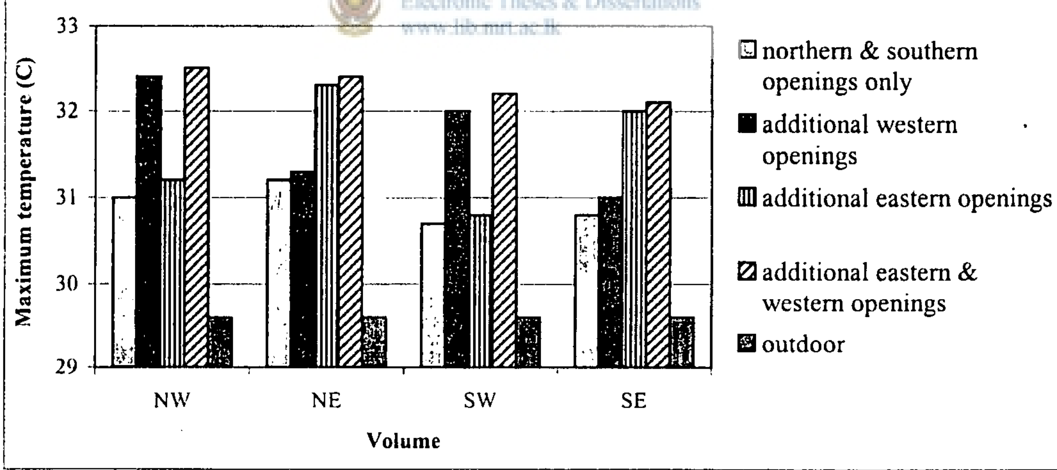
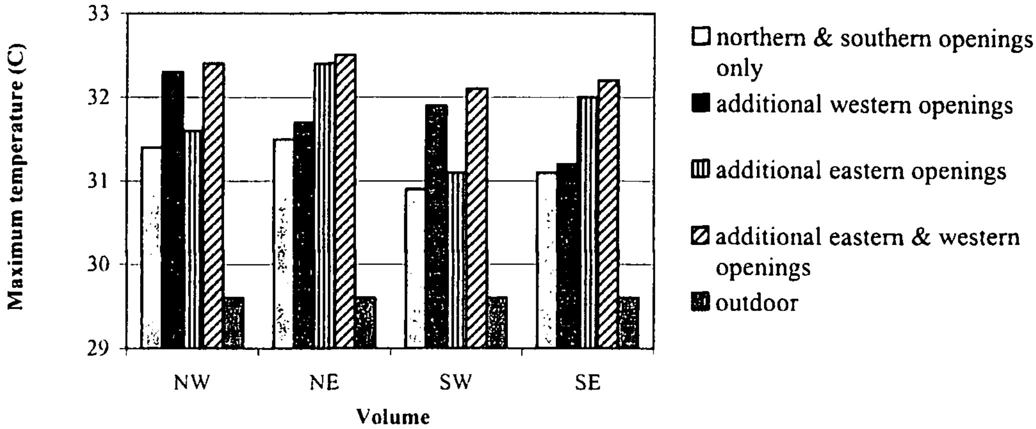


Chart 5.9 considers the flat ceiling case for June. Provision of additional west facing openings causes a rise of maximum indoor temperature of the western volumes by as much as 1.4°C. However, its effect on the volumes facing east is negligible. Introduction of additional east facing openings causes a rise of 1°C in the maximum temperature of eastern volumes, but the effect on the western volumes in insignificant. Provision of additional west facing openings as well as east facing openings results in the most undesirable conditions.

Chart 5.10 considers the sloping ceiling case for June. The results shown are similar to the flat ceiling case given in Chart 5.9.

Chart 5.10 Effect of orientation of openings
(East-west ridge roof with sloping ceiling in June)



Whether the ceiling type is flat or sloping, provision of openings with an undesirable orientation (i.e. east or west facing) could result in maximum indoor temperatures as high as 32.5°C. These temperatures are so high that forced ventilation alone is very unlikely to achieve thermally comfortable conditions.

Although the roof orientation has no significant effect on the maximum indoor temperature, the effect of the orientation of openings is quite pronounced. Therefore, it should be ensured that the openings provided face north or south, but not east or west.

5.6 Summary

The findings of the qualitative analysis through the literature survey, thermal and comfort surveys and computer analysis could be separately summarized as the following:

Findings from the literature survey

From the qualitative analysis carried out through the literature survey, the following features have been identified as desirable or undesirable from a thermal point of view:

- A desirable microclimate should be created round the house by planting trees. Some of these trees could be located in such a way that they provide shading to openings. Garden space for trees could be saved by resorting to multi-storey construction. Another way to maximize the vegetative cover is to grow ivy on the exterior surface of the house.

- The ground, especially in front of openings, should be covered with grass, or more preferably, shrubbery. Paved areas around the house should be avoided whenever possible to avoid ground reflected solar gains.

- To minimize the area of the thermally undesirable roof, multi-storey approach should be pursued. In a multi-storey house, spaces that would be seldom used or used for a relatively short period of time should be located in the top floor.

- When exposed to a hot element, the human body gains heat by radiation. One such element that becomes hot is the roof. Minimization of the roof area by way of multi-storey construction could be an effective solution. Alternatively, the roof could be separated from the occupants by providing a ceiling. However, the ceiling may become hot by radiant heat exchange with the roof, and then may start radiating heat to the occupants. The radiant heat transfer to the ceiling could be reduced by providing a reflective foil such as aluminium.

- Whenever possible, openings facing north or south should be provided since they are shadable orientations. The openings should be shaded with an overhang, making a horizontal angle of 60^{o}. In a multi-storey house, there is more choice for selection of the orientation of openings than in a single-storey house of an equivalent floor area. Due to aesthetic concerns, the front façade is likely to have a relatively large area of glazing. Therefore, the front façade should face a shadable orientation. If an opening facing east or west is unavoidable, it should be short, and be protected from the sun by a very long overhang or a tree. Where there is a choice between east or west facing opening, the east facing one should be preferred.

- To facilitate cross ventilation, it is desirable to have both inlet and outlet in the same volume. Then the possibility of the openings' catching the prevailing breeze would be high. However, such a choice of external walls may not be available in a single-storey house. If possible, the inlet and outlet provided for a volume should be on two perpendicular external walls.

- By introducing a courtyard with pergolas, large openings could be provided for cross ventilation without exposing them to direct solar radiation. The use of the courtyard could be maximized by adopting a multi-storey approach. In a multi-storey house, the same courtyard could be used to serve various volumes requiring different levels of privacy.

- In a multi-storey house, for stack ventilation, an adequate height difference between the inlet and the outlet could be provided. The height of a single-storey house may not be enough for this purpose.

- For night ventilation, windows should be kept open at night. However, occupants of a single-storey house may be reluctant to do so on the grounds of privacy or safety. In a multi-storey house, this reluctant could be mitigated by locating bedrooms at upper floor levels.

- Blind walls are undesirable because they could make the indoors gloomy, requiring artificial lighting during the daytime. This in turn could contribute to warm indoors.

Findings from the thermal and comfort surveys

From the thermal and comfort surveys carried out, the following features have been identified as desirable or undesirable from a thermal point of view:

- In a single-storey house with a cement fibre sheet roof, it could be difficult to achieve indoor thermal comfort due to the thermally undesirable effects of the roof even with a ceiling. It is better however to have a ceiling as the cement fibre roof could create highly undesirable indoor temperatures. An effective alternative is to minimize the roof area by multi-storey construction. The survey results have shown that sheltered volumes are cooler than equivalent unsheltered ones.

- In a two-storey building, volumes at the ground floor (i.e. sheltered volumes) could be cooler than equivalent volumes at the top floor (i.e. unsheltered volumes) due to the effects of the roof on the latter. In a three-storey building, the second floor tends to be warmer than the floors below because of the effect of the roof. Besides, if the ground surface in front of the windows is bare, the ground floor tends to be warmer than the first floor due to the ground reflected solar radiation.

- A roof slab exposed to the sun is undesirable as it could significantly make the indoor temperature rise. Therefore, balconies without a roof or terraces should be avoided. Otherwise the temperature of the volume below the roof slab would go up substantially.

- Unshaded windows could contribute to increase the indoor temperature due to the ingress of direct solar radiation. This could apply even to a sheltered volume, thus eliminating the beneficial performance of a sheltered volume. Therefore, openings should be shaded by shading devices.

- Although openings facing north or south are shadable, those facing east or west are unshadable because of the low solar altitudes encountered. Therefore, shading of openings facing east or west could be a problem. However, trees planted in front of the relevant window at a distance could be used for this purpose.

- In a room with a window facing west, indoor temperature may rise in the evening due to the exposure to the afternoon sun. Therefore, windows facing west should be avoided unless shading can be provided using trees. Such windows are highly undesirable, especially for living or dining rooms since the window size is likely to be comparatively large for aesthetic reasons.

- Sri Lankans could feel thermally comfortable at temperatures as high as 30^{o}C if some air movement is present. Therefore, facilitation of ventilation is important. In fact, the relatively high temperature of an unsheltered volume could be lowered by promoting cross ventilation. For this purpose, openings are needed as inlets and outlets for the air flow. Since a multi-storey house could provide more external wall area than a single-storey house of equivalent floor area, facilitation of ventilation is easier in the former.

- Presence of a tall boundary wall near the window of a sheltered volume could make the volume uncomfortable (more precisely "stuffy") even though it is sheltered. Moreover, it would be gloomy during the daytime, and may require artificial lighting during daytime. Therefore, rather than planning the house to one end of the plot, multi-storey construction should be adopted to save garden space – especially in small plots of land as found in urban and suburban regions.

- Due to higher absorptance of the dark colors, a room with a dark colour exterior surface tends to be warmer than an equivalent light colour room. Therefore, light colours should be preferred to external wall surfaces.

Findings from the computer analysis

From the computer simulations carried out, the following features have been identified as desirable or undesirable from a thermal point of view:

- When the ceiling is of flat and sloping type, the effect of roof orientation is of no appreciable significance throughout the year.

- The roof cover material has a significant effect on the maximum indoor temperature, and therefore on indoor thermal comfort. With flat cement fibre ceiling, all three roof covering materials – i.e. cement fibre sheets, clay tiles and half clay tiles on cement fibre sheets – sometimes raise the indoor temperature above the outdoor maximum in March. Therefore, achievement of thermally desirable conditions with forced ventilation could be difficult. Of the three, cement fibre sheet is the worst while clay tile is the best, although the difference in the resulting maximum indoor temperature is within the range of 1°C.

- By using of roof insulation materials such as aluminium foil or aluminium foil along with polystyrene, the indoor temperature of cement fibre sheet and calicut tile roof cases could be maintained within 29°C. The difference between the two arrangements (i.e. aluminium foil alone and aluminium foil along with polystyrene) is marginal.

- By application of light colours on the external surface of the cement fibre sheet roof, the maximum indoor temperature could be substantially lowered. When the external roof surface is of blackish grey colour (corresponding to old cement fibre sheets), the maximum indoor temperature lies between 31 and 31.5°C. When the colour is light grey, the maximum indoor temperature could be reduced to a level marginally above 30°C. When the colour is off-white, the maximum indoor temperature further drops to 29°C, which is as good as the case of expensive insulation materials. Such indoor temperatures would result in thermally comfortable indoors so that forced ventilation would be seldom required or would not be required at all. At night too, off-white colour cement fibre sheet roof could achieve desirable indoor temperatures around 27.5°C (i.e. lower than the normal cement fibre sheet roof case by over 1°C).

- Although the performance of the calicut tile roof is better than that of the cement fibre sheet roof, both types would result in indoors so warm that forced ventilation may fail to inhibit the resulting thermal discomfort. Use of roof insulation materials such as aluminium or polystyrene could achieve a more desirable thermal environment, minimizing or even eliminating the need for forced ventilation. However, this is not a practical solution always, especially in existing houses. An alternative is the application of light colour roof paint on the exterior surface of the cement fibre sheet roof. This could achieve indoor thermal conditions as desirable as those achieved with roof insulation. Therefore, for low altitudes of Sri Lanka, light colour roof paints that are durable should be developed for achievement of thermally comfortable indoors.

- Provision of additional openings with undesirable orientations (i.e. facing east or west) can degrade the indoor thermal conditions further. Therefore, whenever possible, openings should be provided facing north or south only.

- Even with properly oriented openings protected with overhangs, the maximum indoor temperature in March and June rose in general to 31°C or more for both ceiling types and both roof orientations, making achievement of thermally comfortable indoors by means of fans difficult. Therefore, at the planning stage, multi-storey construction should be preferred so that the floor area covered by unsheltered volumes can be reduced. For example, in a three-storey house, two floors (i.e. ground and first floors) will be sheltered and only the top floor will be unsheltered. Therefore, volumes that are used less often (e.g. visitors bedroom), volumes that will be used for a short period of time (e.g. balcony used for relaxation late in the evening) and spare rooms could be located at the top floor.

Chapter 6

DEVELOPMENT OF GUIDELINES FOR PASSIVE HOUSING SCHEMES IN THE LOW ALTITUDES OF SRI LANKA

6.1 General

To make passive concepts popular among the prospective house builders and, in particular, developers of housing schemes and townships, it is necessary to have a set of guidelines that could be easily adopted for planning and design purposes. Therefore, in this study, a set of guidelines was developed. It consists of land subdivision guidelines for a residential neighbourhood (i.e. a housing scheme) and a set of passive house plans of various sizes compatible with the guidelines.

Firstly, from the literature survey, the passive concepts and techniques desirable to warm humid climatic conditions were identified. Then, from the results of the questionnaire survey, the existing conditions of houses and the preferences of the people were identified. Several thermal and comfort surveys were conducted at several existing houses to gain some first hand observation on the prevailing situation. They were also used to validate certain aspects of thermal performance of buildings found in the literature survey. Finally, by simulating a model house using DEROB-LTH computer program, the effect of the most sensitive elements of the building envelope on indoor thermal comfort (i.e. roof and openings) were investigated. Using all these results, a set of guidelines was developed for a passive housing scheme.

If this set of guidelines is adopted in developing a housing scheme, it is expected to achieve indoor thermal comfort of its houses in an environment-friendly and energy-efficient manner. In addition, a set of recommendations is provided for the improvement of indoor thermal comfort of new houses and existing houses.

6.2 Desirable passive features identified from the literature survey, thermal and comfort surveys and computer simulations

The following could be listed as the desirable passive features identified from the literature survey, thermal and comfort surveys, and computer simulations:

- A multi-storey house performs better than an equivalent single-storey house with respect to thermal comfort.
- Plant trees around the house to create a thermally desirable microclimate.
- Grow grass, or more preferably shrubbery, to cover the bare ground – especially in front of the openings. Avoid pavements of cement tiles.
- Face the house to north or south.
- Whenever possible, provide openings on north or south-facing walls, and shade them with overhangs making a horizontal angle 60°.
- If an east or west-facing opening is unavoidable, make it short. Shade it with an overhang of a long projection. If possible, plant a tree to protect it from the sun.

- Avoid east-facing, or especially west-facing walls, for spaces like Living Room, which tend to attract large openings due to aesthetical reasons.
- If two external walls are available for a single volume, locate openings on both of them.
- If possible, introduce a courtyard to the house so that the walls of the volumes next to it could have windows opening to the semi-outdoor space of the courtyard.
- In a multi-storey house, locate the volumes that will be used less often (e.g. visitors bedroom or spare bedroom) or used for a relatively short period of time (e.g. balcony) at the top floor.
- If possible, provide a ceiling. Also provide openings to ventilate the attic space. As further improvement, use a reflective foil above the ceiling.
- Prefer calicut tiles for the roof. If cement fibre sheets are used, ensure that its surface is maintained at a reasonably light colour by applying a roof paint after some time.
- If the preference is coloured tiles, select a light colour.
- Always provide a roof for a balcony.
- Avoid tall boundary walls near openings as found in most urban houses located in small plots of land.
- Paint external wall surfaces with a light colour.
- If possible, grow ivy on external wall surfaces.

As already shown, most passive features could be relatively easily adopted for a multi-storey house. However, in a single-storey house, achievement of desirable levels of indoor thermal comfort could be difficult. Therefore, the following features could be recommmeded as essential for single-storey houses. In multi-storey houses these features could be considered optional; however, their use would improve the thermal conditions of a multi-storey house further. They could be listed as:

- Light colours for exterior wall surfaces and the roof surface.
- Light colours for walls indoors.
- Clay tiles instead of cement fibre sheets for the roof.
- Ceiling with a reflective foil above it
- Ventilated attic space
- Facing house to north or south
- Bricks or hollow cement blocks for external walls
- Courtyard

6.3 Requirements and preferences of the people identified from the questionnaire survey

From the results of the questionnaire survey, the following were identified as the trends in the requirements and preferences of the people.

6.3.1 Type of neighbourhood

As shown in Chart 4.27, nearly 70% of the people surveyed prefer to live in an urban neighbourhood full of trees. Since urban and suburban regions are facing a land scarcity problem, it is desirable to minimize the lot coverage to save garden space. As shown in Chart 4.33, nine out of ten are willing to grow trees if garden space is available. Therefore, a multi-storey approach was emphasized in the development of the guidelines, not only because of its superior passive performance but also to save the expensive urban and suburban land.

6.3.2 Type of house

As shown in Table 6.1, preference is divided for single-storey and two-storey houses. However, the shift from single-storey to multi-storey is clearly visible. Although 69% live in single-storey houses, only 38% prefer to live in a single-storey house. The corresponding figures for the two-storey house are 28% (current) and 51% (preferred) respectively. The three-storey house, which is relatively new concept, also shows an increase in preference.

	Type of House now living in (%)	Type of house preferred to live in (%)
Single-storey	69.3	38.0
Two-storey	27.9	51.4
Three-storey	0.6	3.9

Table 6.1 Current and preferred type of house

6.3.3 Size of the house

According to Chart 4.30, the majority (58.1%) of those surveyed prefer three bedrooms per house, followed by four bedrooms (21.8%), excluding the visitors bedroom. According to Chart 4.31, the majority (64.8%) prefer two bathrooms/ toilets, followed by one (20.1%), excluding that of visitors. The preferences are given in Table 6.2.

Preferred number of spaces		Preference (%)
Bedrooms (excluding visitors)	Three	58.1
	Four	21.8
Bathrooms/ toilets (excluding visitors)	One	20.1
	Two	64.8

Table 6.2 Preferred number of bedrooms and bathrooms/toilets

As can be seen from Chart 4.29, which gives the special features preferred by the subjects of the questionnaire survey, over 55% prefer a separate visitors bedroom while over 45% prefer a separate bathroom/ toilet for visitors. Moreover, over 55% prefer a separate study room. Therefore, addition of a visitors bedroom and a study room would give the range of total number of rooms preferred as from 3 to 6. Similarly, the total number of bathrooms/ toilets could range between 1 to 3.

Over 35% require a separate storeroom while over 20% prefer a larger kitchen instead of a storeroom. Only 3% prefer a separate pantry.

6.3.4 Courtyard

As shown in Chart 4.29, around 60% prefer a courtyard in the house. Therefore, courtyard house plans should also be developed.

6.4 Development of passive house plans

The set of passive house plans developed consists of single, two or three-storey houses of various sizes of floor area. Except the single-storey house plans, all the others are compatible to the proposed passive housing scheme with land subdivision guidelines. Single-storey house plans are too large to be included in the compact plot of land proposed.

The strategy adopted in the development of the passive house plans is as follows:

- For all houses the following utility spaces are provided: Living room, Dining room (Living and Dining together in some cases), and Kitchen.

- Total number of rooms (including Study room and Visitors bedroom where applicable) is from 3 to 6.

- Total number of bathrooms/ toilets including visitors bathroom/toilet where applicable is from 1 to 3

- Some houses are courtyard houses

- The houses are categorized into three sizes: small, medium and large on the basis of the total number of rooms (i.e. bedrooms, visitors bedroom, study room, and balcony as a separate space with common access which is termed Common Balcony hereafter). In houses where a common balcony is not provided, a projecting balcony was provided with access from Master bedroom

- The small scale house consists of three rooms. No courtyard or common balcony space was provided for this type of house

- The medium scale house consists of four bedrooms. The two-storey type may or may not have a courtyard and/or common balcony. The three-storey type is provided with a common balcony but not a courtyard

- Large scale houses may or may not be provided with a courtyard and/or common balcony.

In addition, the following aspects were considered in developing the house plans:

- Front of house faces north or south so that openings of the Living room visible to the street face a shadable direction (i.e. north or south). For aesthetical concerns, people prefer large windows facing the street. Window of the Living room facing the street is 1.8m tall. Windows facing north or south are 1.2m in height while those facing east or west are only 0.6m due to the difficulty in shading. Whenever possible, at least two external walls are provided for each volume for provision of windows. Windows facing east or especially west were avoided whenever possible.

- Two types of semi-outdoor spaces were provided: porch and, for some houses, a courtyard. A porch is provided in front of the Living room. The roof of the porch provides shade for the tall window and the door of the Living room. Sometimes the projecting balcony of the Master bedroom created a porch downstairs. Courtyard was selected to face the most undesirable orientation for the openings, i.e. west.

- Kitchen is given easy access to Dining. However, from Living room, the interior of the kitchen cannot be seen. Whenever possible, Kitchen is provided with an east-facing window to get morning sunlight in. Space under the stair case could be used as a store.

- In a multi-storey house, whenever possible, a bedroom was provided at the ground floor level for the sick, elderly and handicapped. Master bedroom was given prominence. It is usually allocated the largest area. In a multi-storey house, it is located at a sheltered level whenever possible. In a courtyard house, it is given a window opening to the courtyard space. When a common balcony is not provided for a house, a small projecting balcony is provided for the Master bedroom. This projection is used for shading of the tall Living room window below. Visitors bedroom was given the least prominence. Usually the smallest in floor area, it was located at an unsheltered floor level in a multi-storey house. However, in a two-storey house, it was located at the ground floor as the top floor is intended for exclusive use of the family.

- In multi-storey houses, for convenience in construction and to minimize the need for beams, walls of the upper floors were planned on walls of the floor below. Kitchen and bathroom/ toilet were located next to each other for convenience in plumbing work. However, their doors were located at a distance. In multi-storey houses, Bathrooms/ toilets are located one above the other for ease in plumbing work. Roof is kept simple for minimized construction cost.

- When the front and kitchen doors are closed, the entire house would be closed. A passage is provided with a width of 0.9m.

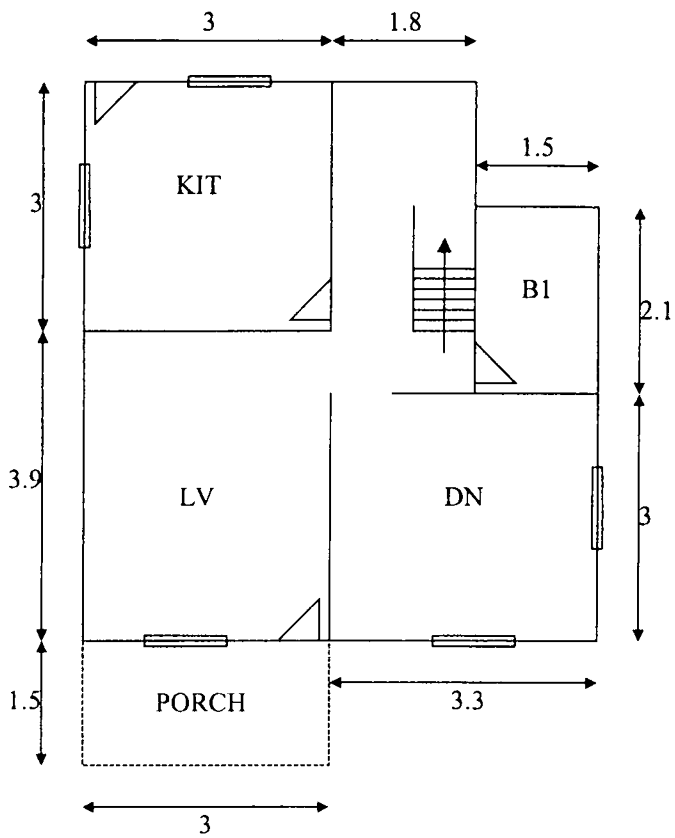
A brief summary of the house plans is given in Table 6.3.

House No	House type (storey)	No of rooms (All bedrooms, study but without common balcony)	No of bath/toilets	Total floor area (m^2) (without courtyard)	Courtyard	Common balcony
Small						
S3	Two	3	2	90.54	No	No
Medium						
M1	Two	4	2	91.80	No	No
M2	Two	4	2	93.60	No	Yes
M6	Two	4	2	102.78	No	No
M5	Two	4	2	104.04	Yes	No
M3	Three	4	2	130.68	No	Yes
Large						
L2	Two	5	2	115.74	Yes	No
L3	Two	5	2	136.08	No	Yes
L6	Three	5	3	142.65	No	Yes
L5	Three	5	3	145.17	No	Yes
L7	Three	6	3	128.70	No	No
L8	Three	6	3	158.31	Yes	Yes

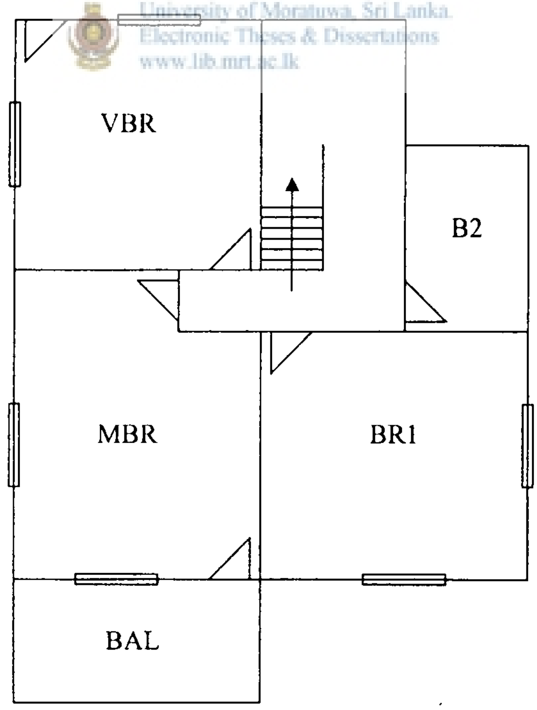
Table 6.3 A summary of passive house plans developed

6.4.1 Small category house plans

Only one house plan was developed for this category. It is a two-storey house, containing three bedrooms and two baths/toilets. The balcony serving Master bedroom upstairs creates a porch downstairs, shading the tall windows of Living room.



Ground Floor

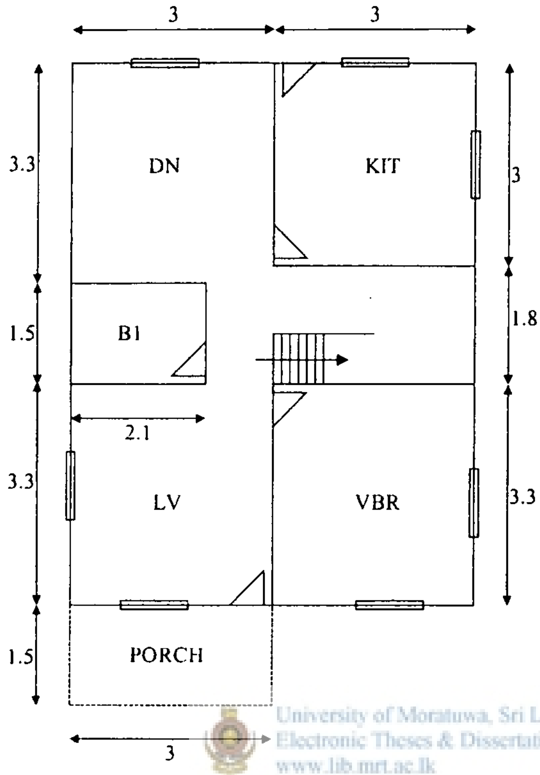


First Floor

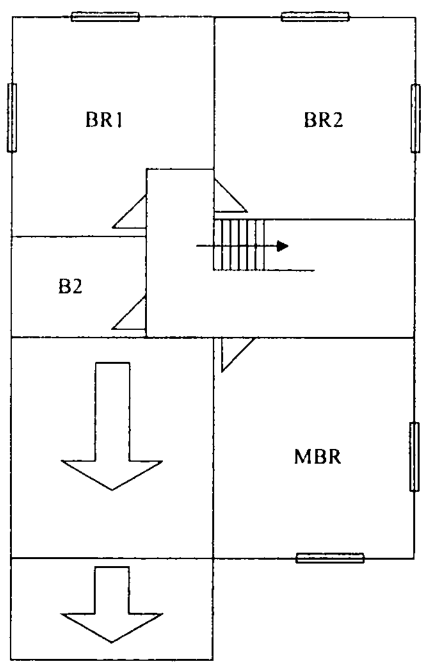
Figure 6.1 Floor plans of House S3

6.4.2 Medium category house plans

Five medium scale house plans were developed. Each house contains four rooms and three baths/toilets. One is a three-storey house; the others are two-storey. Some of the houses have a courtyard or a common balcony.

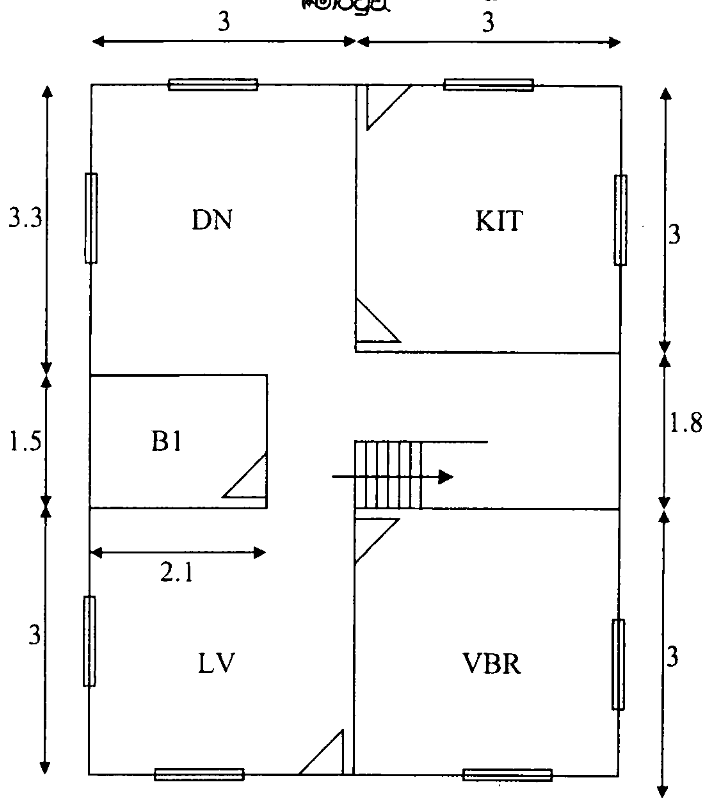


Ground Floor

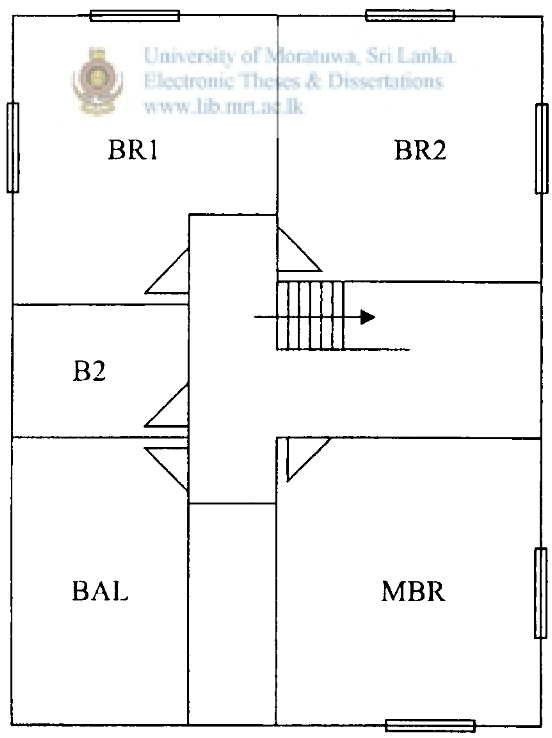


First Floor

Figure 6.2 Floor plans of House M1

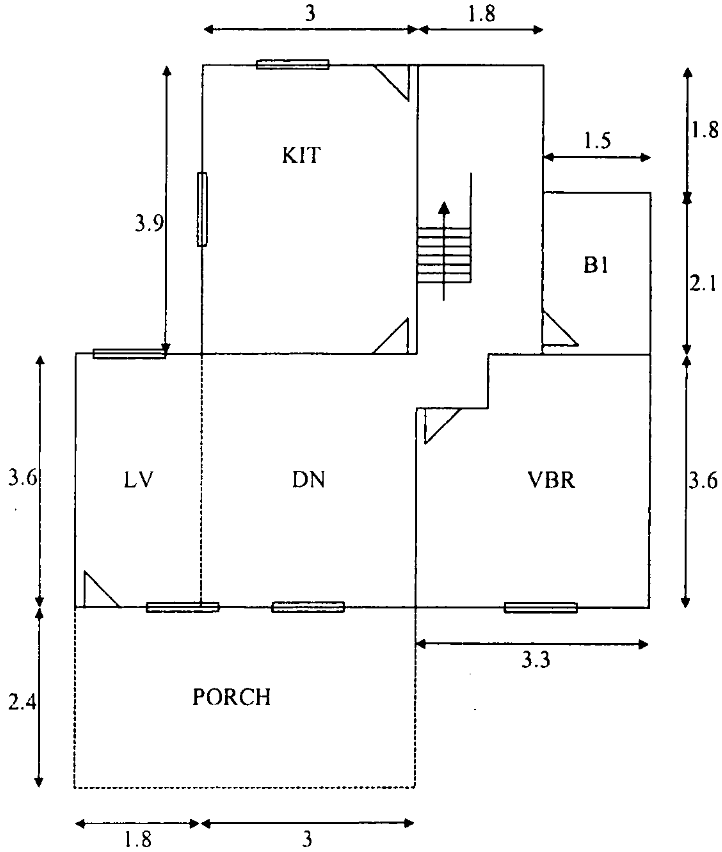


Ground Floor

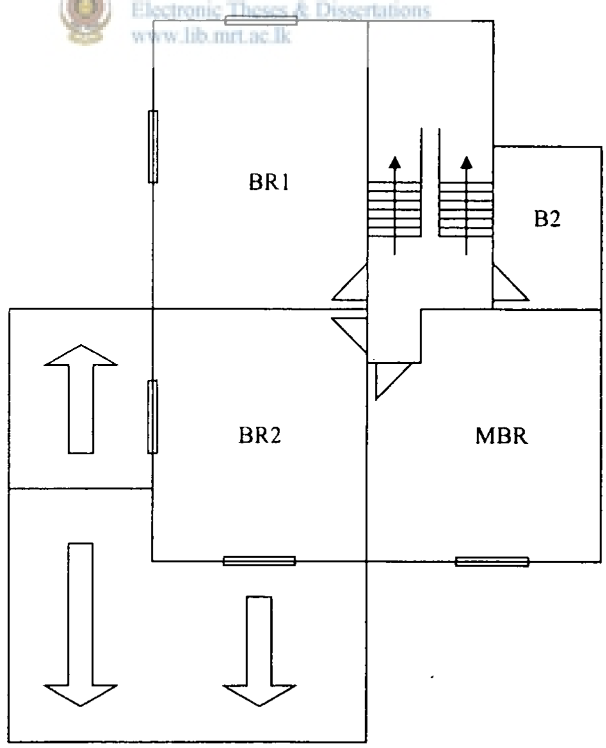


First Floor

Figure 6.3 Floor plans of House M2

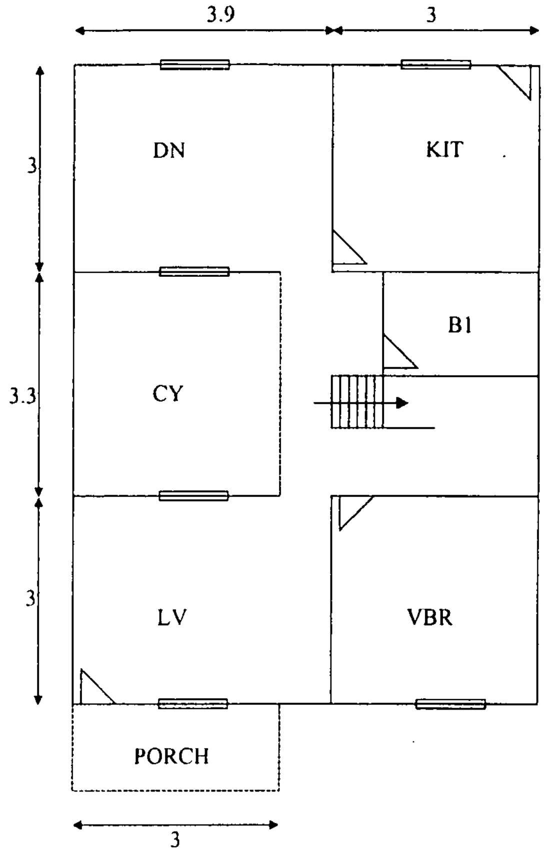


Ground Floor

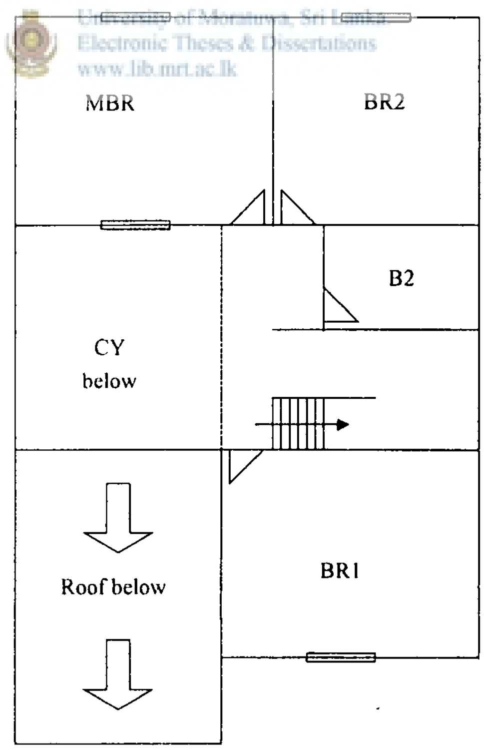


First Floor

Figure 6.4 Floor plans of House M6



Ground Floor



First Floor

Figure 6.5 Floor plans of House M5

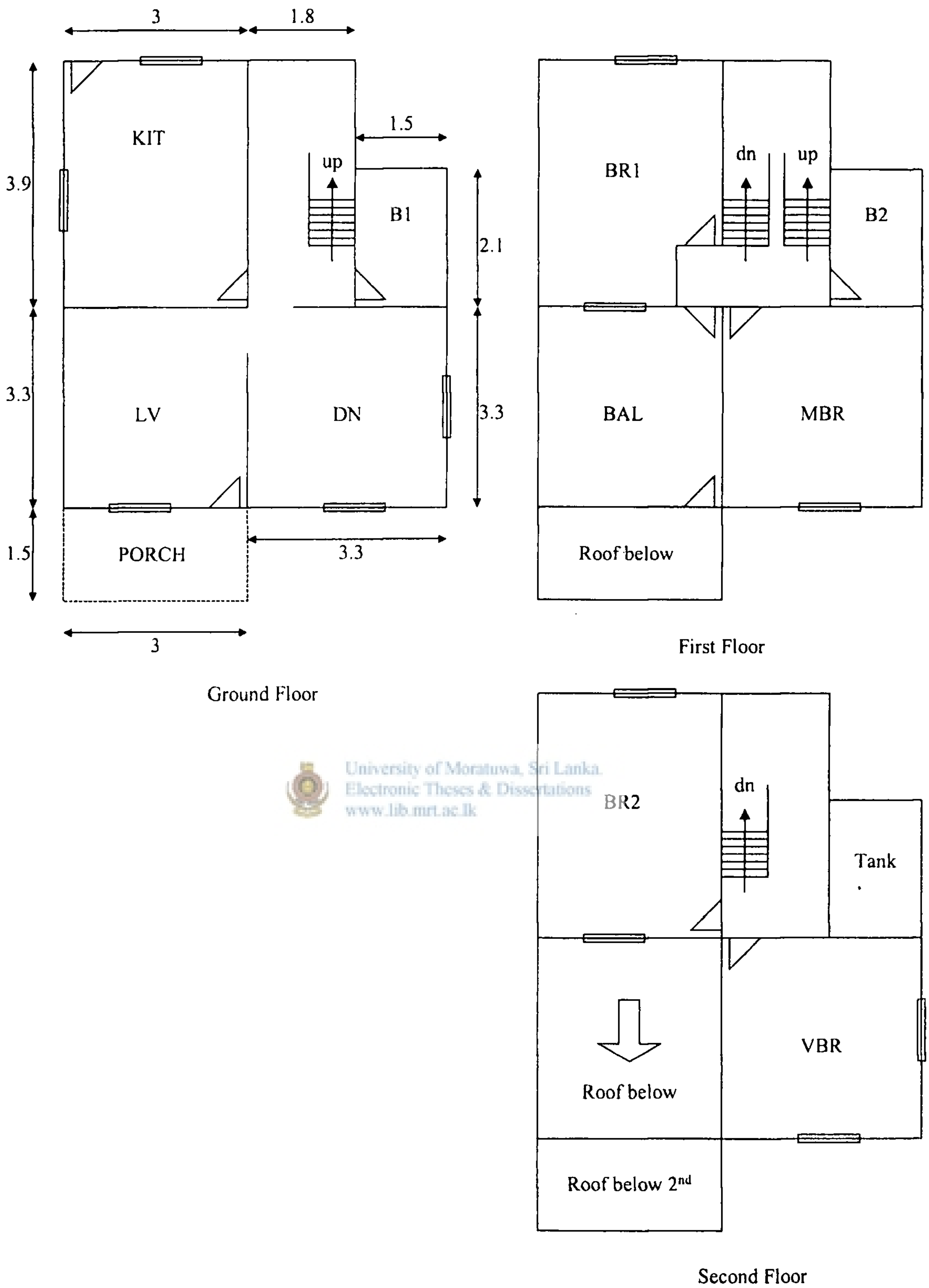
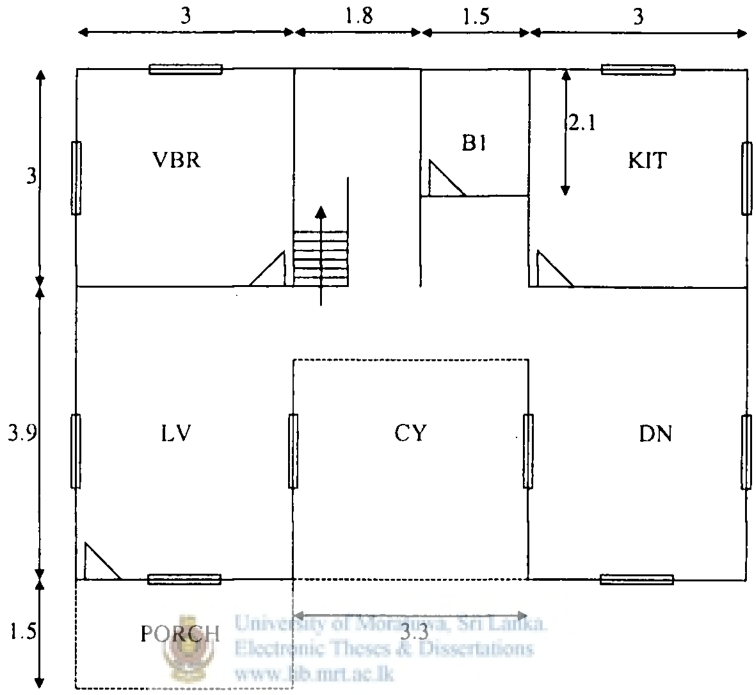


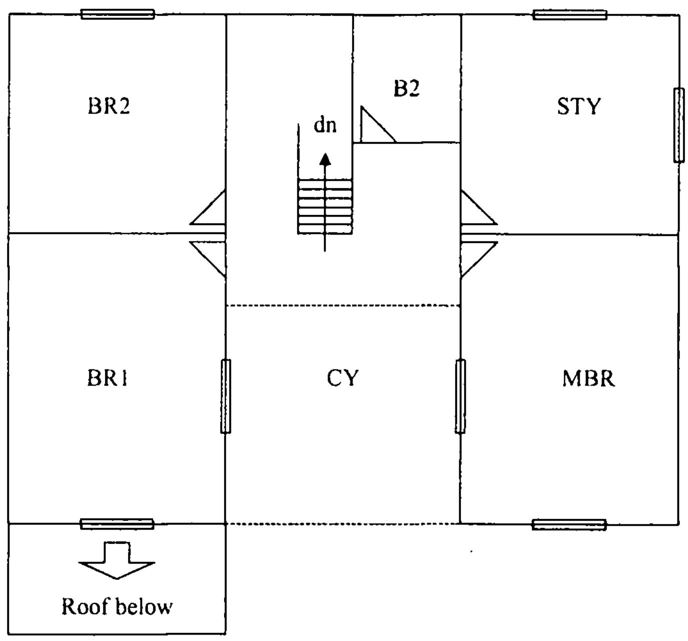
Figure 6.6 Floor plans of House M3

6.4.3 Large category houses

Six large scale house plans were developed. Of them, two are two-storey houses, each consisting of five rooms and two baths/toilets. The other four houses are three-storey. Two of them have five rooms each, and the other two have six rooms each. Each of these three-storey houses is provided with three baths/toilets. Except house L7, each of these large scale houses is provided with a courtyard and/or a common balcony.



Ground Floor



First Floor

Figure 6.7 Floor plans of House L2

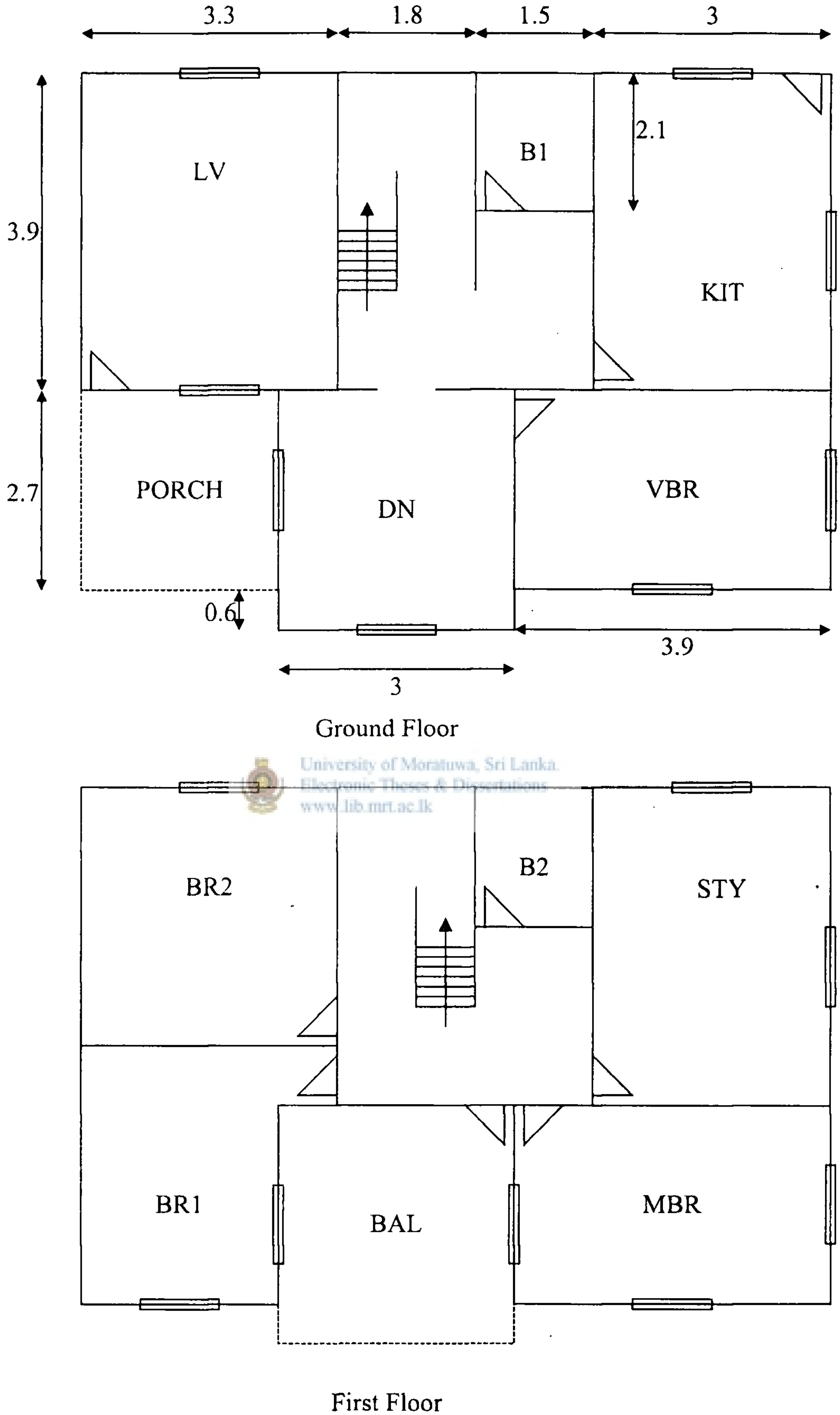


Figure 6.8 Floor plans of House L3

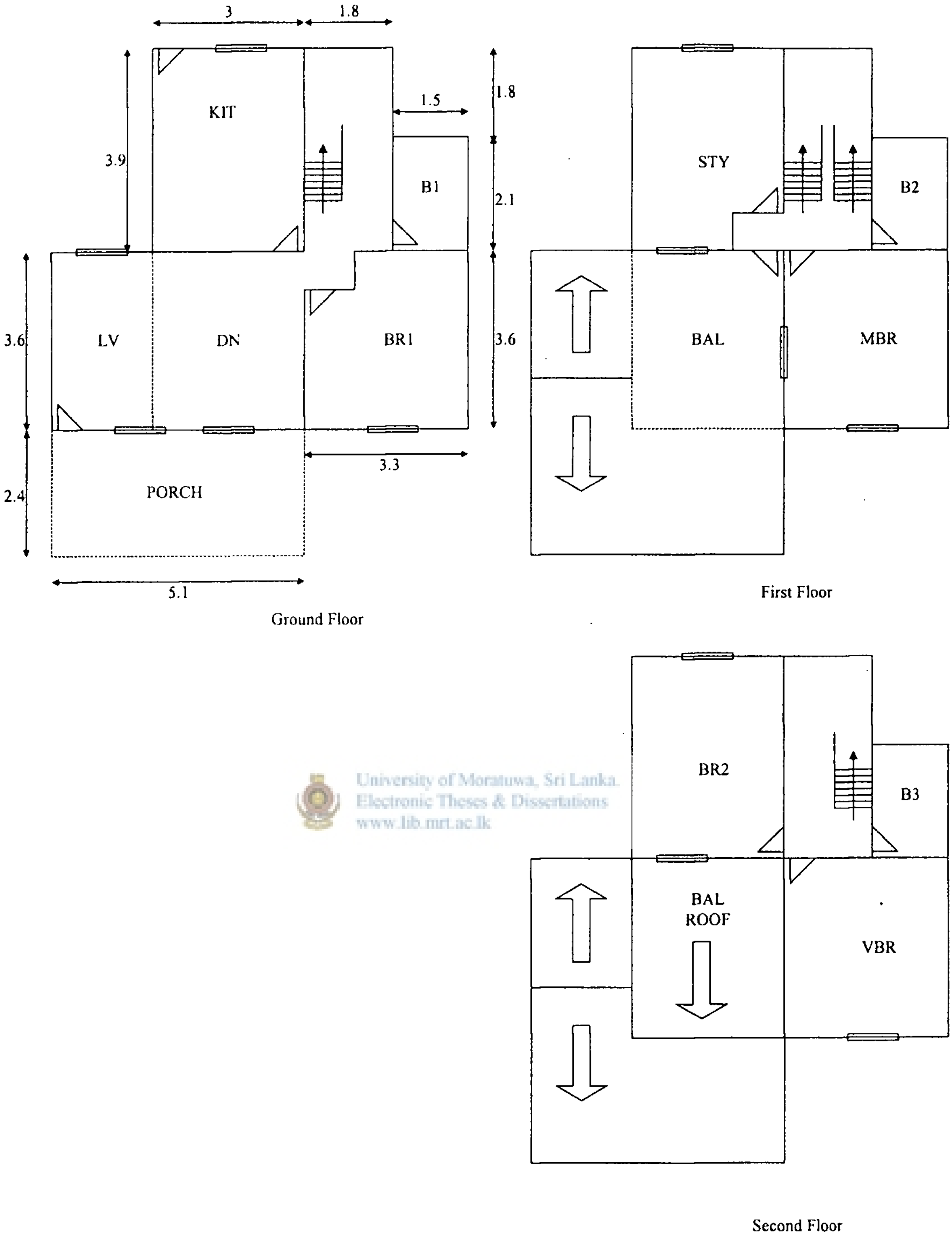


Figure 6.9 Floor plans of House L6

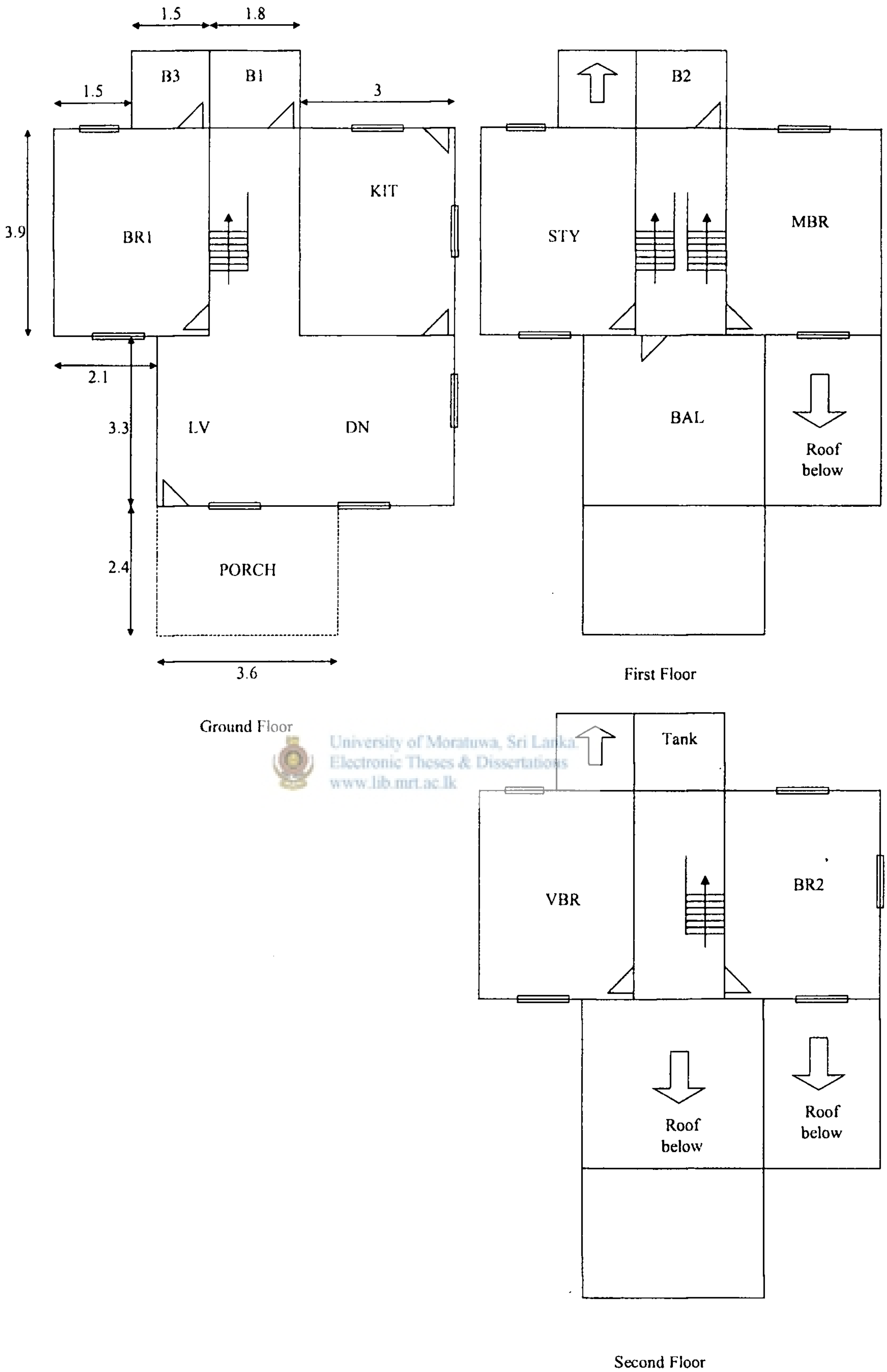


Figure 6.10 Floor plans of House L5

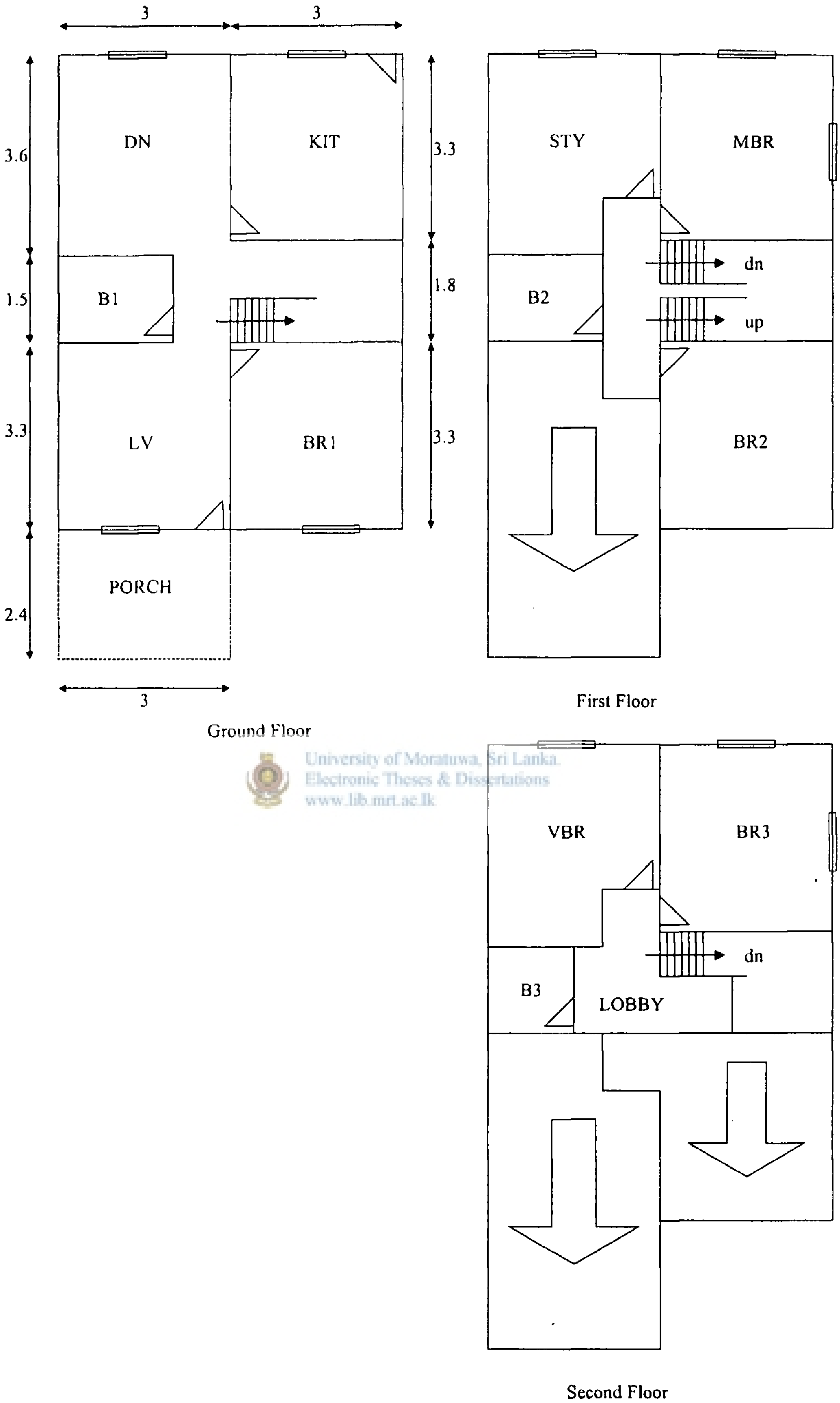


Figure 6.11 Floor plans of House L7

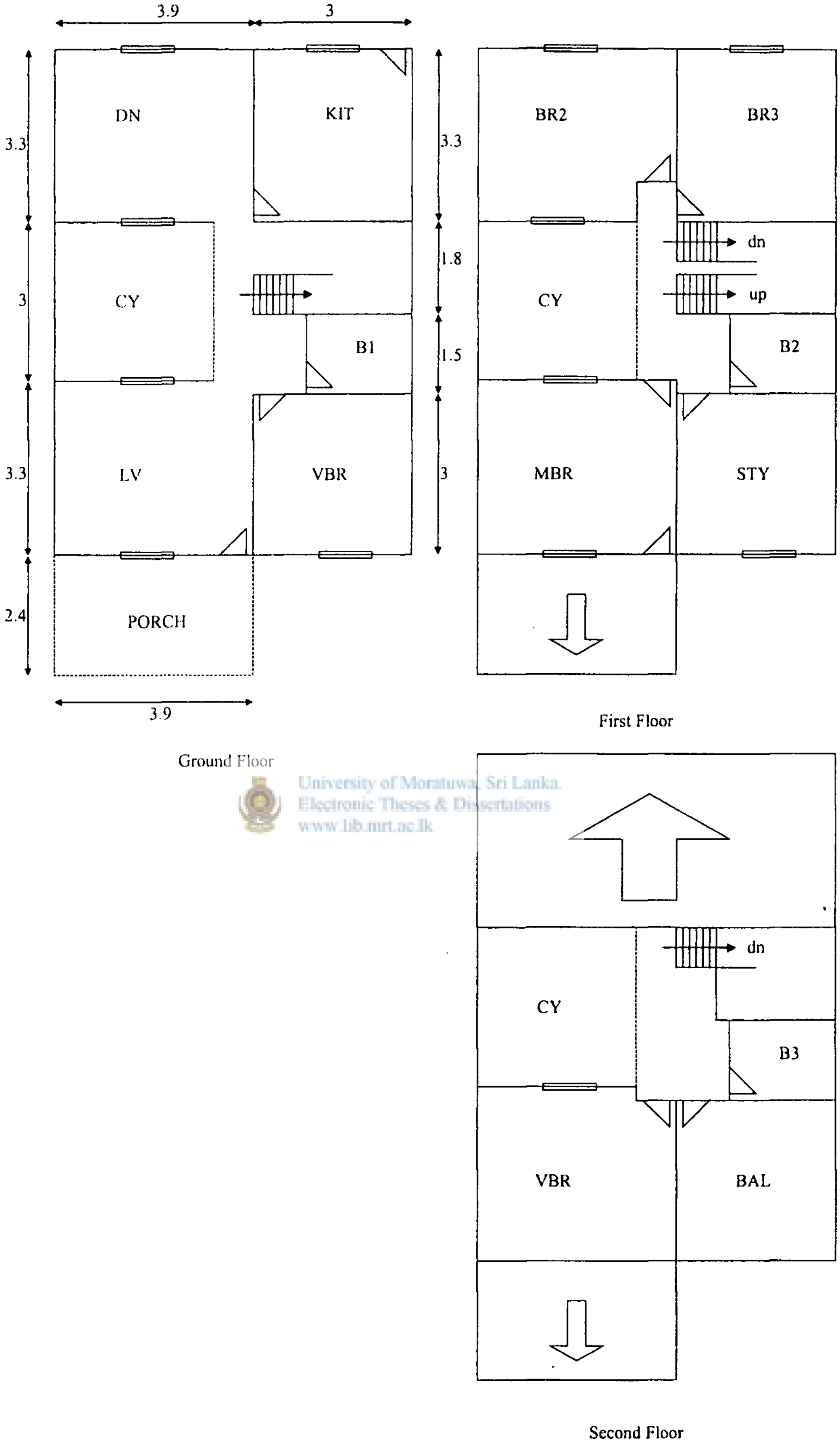


Figure 6.12 Floor plans of House L8

6.5 Analysis of the thermal performance of a typical passive house through computer simulations

To carry out computer simulations, a simple typical house plan (L4) was selected. The floor plan of this house is given in Figure 6.13. This house, however, was not given in the set of developed plans as it has no bedroom in the ground floor. House plan L5 could be described as an improved version of this. The computer program DEROB-LTH was used to investigate the degree of effect of various passive features on indoor thermal comfort of this house.

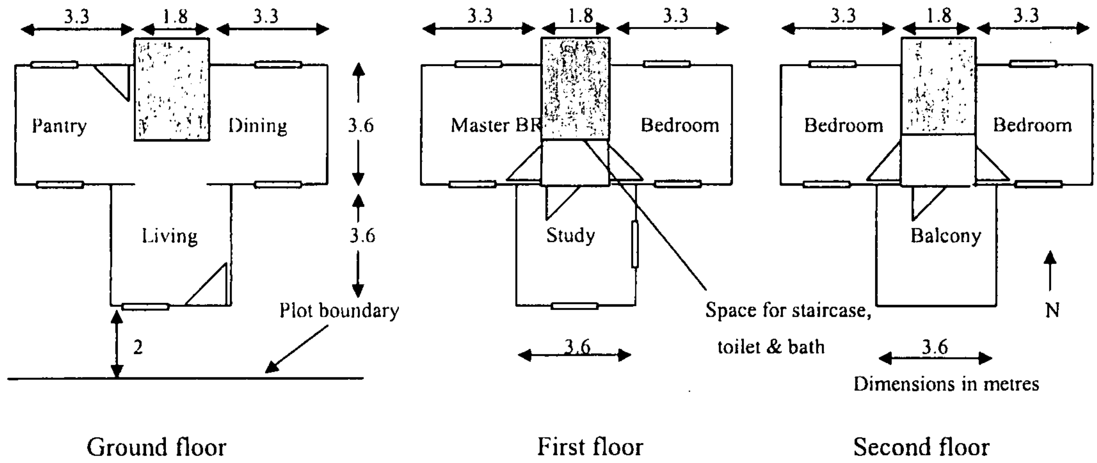


Figure 6.13 Ground floor, first floor and second floor plans of the modeled house

6.5.1 The simulation details

The simulations were carried out for the 21st day of the month of March. With respect to thermal comfort, March can be considered as the most undesirable month for Colombo; the sun is directly above the equator; the number of sunshine hours is the maximum and the rainfall is relatively low. Climatic data given in Table 2.3, applicable to Colombo, was used for the simulations.

Out of this floor plan given in Figure 6.13, two houses were created: House No 1 and House No 2.

House No 1 is a detached house developed for Sri Lanka with desirable passive features. The house faces south. Its windows face north or south, which are shadable orientations. The shading devices for windows have a 0.8m projection from the external walls. Its common balcony is provided with a roof. Additional shading is also available due to trees planted in the front of the house and also due to detached houses located in the nearby plots. The only undesirable feature for thermal performance is the window facing east provided for the study room at the first floor level. However, this is quite useful with respect to enhancing the daylight penetrating into the house in the morning. No roof insulation was considered for this case. Because of the desirable passive features, this is hereafter termed the "passive house".

House No 2 is the same house with the same orientation. However, it has a number of undesirable features that could be found when no attention is paid for the use of passive features. Those are the lack of shading devices for windows, additional windows facing west for Master bedroom and Study room at the first floor, and Bedroom at the top floor. The balcony is not provided with a roof. Therefore, this house is hereafter termed the "unpassive" house.

To represent the adverse conditions of closed windows, a ventilation rate of 1 air change per hour was used for all simulations. The variables considered in order to determine the effects of colour of walls, floors and roof on thermal performance of these two houses are given in Table 6.4.

Building element	Surface colour	Notation	Absorptance for shortwave radiation
Wall/floor	Off-white	WA	35% (Walls)
			50% (Floor)
	Green, blue, red etc.	WB	70% (Walls)
			70% (Floor)
Roof	Light grey (new cement fibre sheets)	RA	50%
	Blackish grey (old cement fibre sheets)	RB	85%

Table 6.4 Variables used for simulation of surface colour

For the month of March, a set of three cases was considered for each house, representing the following practical situations:

1. The series of WARA cases represents light colour walls and floors, and a light colour roof surface. Therefore, it is the most desirable series. It represents the case when the roofing sheets are new.

2. The series of WARB cases represents light colour walls and floors, and a dark colour roof surface. Under tropical climatic conditions, cement fibre sheets turn to blackish grey with time. This series represent such a roof along with light colour walls and floors.

3. The series of WBRB cases represents dark colour walls and floors, and a dark colour roof surface. Therefore, it is the most undesirable series. This situation occurs when the walls and floors are of colours like green, blue and red, and the roof is not new.

The different cases used for the simulations are given in Table 6.5.

Month	House	Wall & floor surface colour (W)	Roof surface colour (R)	Case
March (M)	No. 1	Light (A)	Light (A)	M1WARA
		Light (A)	Dark (B)	M1WARB
		Dark (B)	Dark (B)	M1WBRB
	No. 2	Light (A)	Light (A)	M2WARA
		Light (A)	Dark (B)	M2WARB
		Dark (B)	Dark (B)	M2WBRB

Table 6.5 Different cases used for computer simulations.

6.5.1.1 The simulation method

Although these houses have three-storeys, only two storeys were simulated as shown in Figure 6.14. The ground floor was eliminated since its conditions are likely to be similar to those of the first floor. The existence of this similarity was simulated by defining an adiabatic floor. Of the five volumes of the first and second floors, only three were simulated: Master bedroom (MBR), Study room (STY) and the second floor Bedroom with a western wall (BR). The balcony, being not enclosed, can be simulated by using a shading screen in DEROB-LTH. The model of the house used for simulation is shown in Figure 6.14.

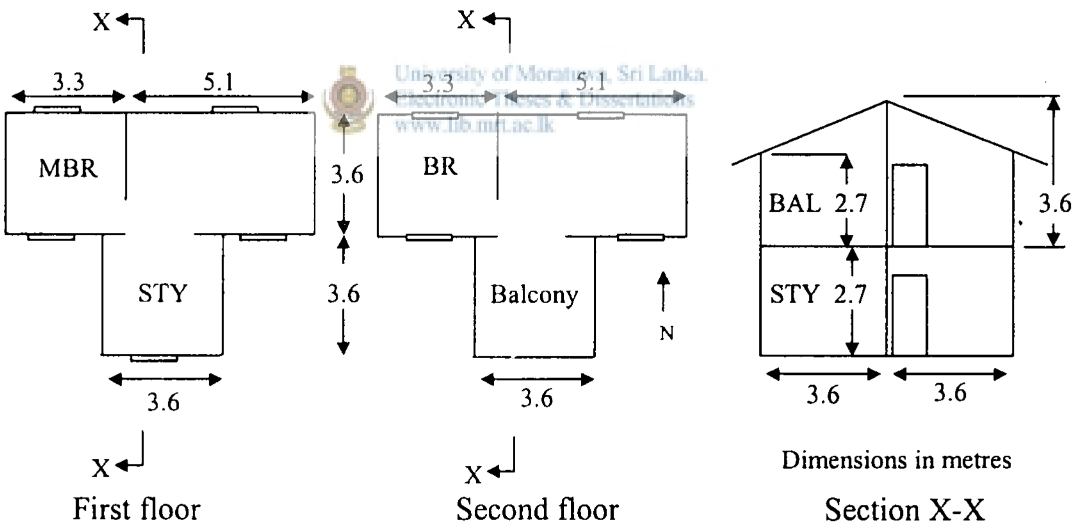


Figure 6.14 First floor and second floor plans, and Section X-X of the model used for simulations for the house given in Figure 6.13

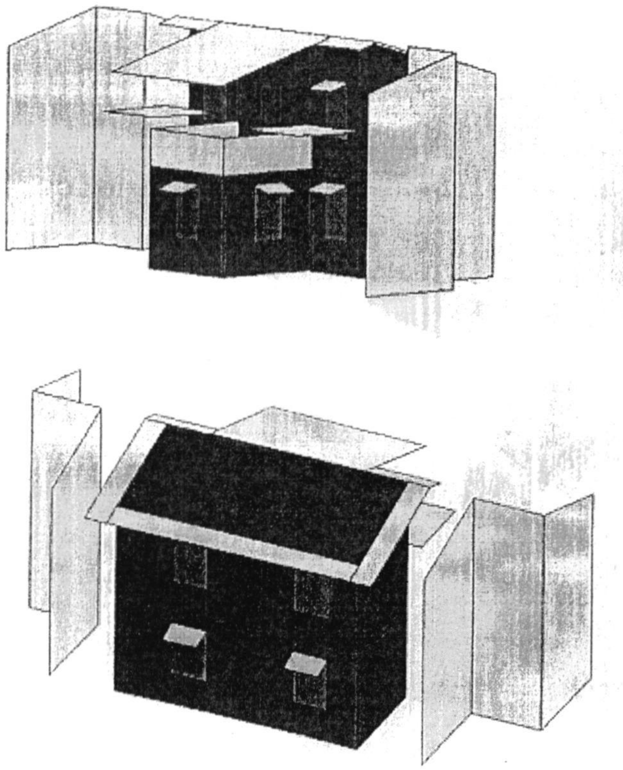


Figure 6.15 Three-dimensional view of the modeled passive house (i.e. House 1)

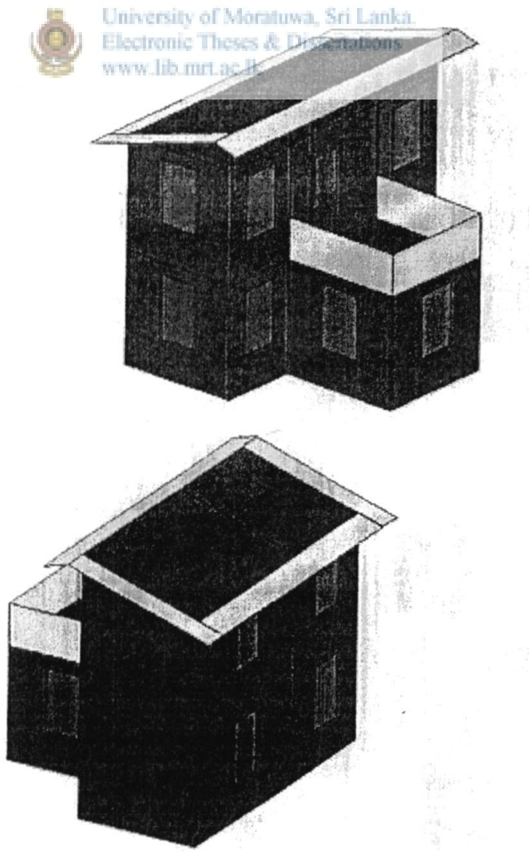


Figure 6.16 Three-dimensional view of the modeled "unpassive" house (i.e. House 2)

6.5.1.2 The composition of building elements

The constituent materials and thicknesses of walls, floors and roofs used for the simulation are given in Table 6.6. The details of the materials are given in Table 6.7. The contents of both tables are based on BRE (1984) and Evans (1980).

	Constituent materials from front to back as defined for DEROB-LTH	Dynamic attenuation	Time lag (hrs)
Adiabatic floor	1000mm mineral wool, 60mm reinforced concrete, 20mm cement plaster	0.02	0.79
Reinforced concrete floor	20 mm cement plaster, 115 mm reinforced concrete, 15mm cement plaster	0.91	2.27
External or internal wall	15 mm cement plaster, 210 mm thick wall, 15 mm cement plaster	0.59	6.05
Cement fibre roof with cement fibre ceiling	8 mm thick cement fibre sheets, 200 mm air gap, 6 mm thick cement fibre sheets	0.99	0.216

Table 6.6 Constituent materials and thicknesses for the walls, floors and roofs

Material type	Conductivity (W/mK)	Specific heat (Wh/kgK)	Density (kg/m^3)
Reinforced concrete	2.0	0.25	2400
Hand moulded bricks	0.75	0.24	1800
Cement plaster	1.4	0.28	2000
Timber	0.15	0.76	800
Cement fibre sheets	0.22	0.25	1600
Air space	0.24	0.28	1.201

Table 6.7 Properties of the materials used for the simulations

6.5.1.3 The internal loads

Since the main aim is to distinguish the effects of passive features, the internal loads were not considered for the simulations. The internal loads in a house would be mainly due to two or three people occupying different volumes at a given time. In addition, there could be a contribution from the bulbs used for lighting. The effect of these could be quite low when natural ventilation is available.

6.5.2 Analysis of simulation results

The cases given in Table 6.5 were simulated for the volumes given in Figure 6.14. The results relevant for discussion are presented in the form of charts for clarity.

The effect of the adopting or ignoring the following passive features on the thermal performance of various volumes is investigated:

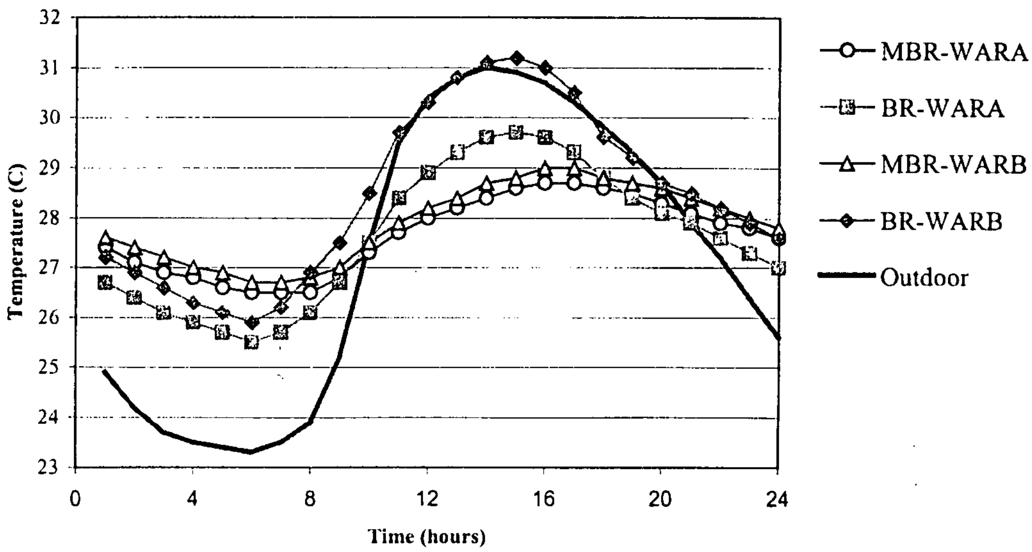
1. Sheltering of a volume by another above it (i.e. by way of multi-storey construction).
2. Use of light colours for roof, wall and floor surfaces.
3. Provision of openings with desirable orientation (i.e. north or south facing)
4. Provision of shading devices for openings
5. Provision of roof for balcony
6. Provision of shading for walls from adjacent buildings

For comparison of the thermal performance of different volumes, the indoor temperature around 14.00 hours can be employed as a good indicator because the outdoor temperature becomes a maximum around this time. For comparison of the performance of a typical sheltered and unsheltered volume, Master bedroom (MBR) at first floor level and Bedroom (BR) at second floor level are selected as their dimensions and the arrangement of openings are similar. The only difference is that the bedroom (BR) has a roof while the master bedroom (MBR) is sheltered from the bedroom above.

6.5.2.1 Effect of the roof surface colour in a passive house

Chart 6.1 presents the results of House 1 (i.e. passive house) for March, comparing the effect of roof surface colour on sheltered and unsheltered volumes. The roof is a highly undesirable element as it is exposed to the sun throughout the daytime around the year because of its upward orientation. This is clearly evident in Chart 6.1. When the roof of the passive house (i.e. House 1) is of light colour, the temperature of the sheltered MBR remains below 29°C whereas that of the unsheltered BR reaches almost 30°C.

Chart 6.1 Effect of roof colour on sheltered and unsheltered volumes of a passive house (Master bedroom MBR & Bedroom BR of House 1 in March)



However, to maintain an asbestos roof in a light colour condition, it should be painted with a light colour periodically. Otherwise, due to tropical climatic conditions, the light grey sheets turn to blackish grey. If the roof is left unpainted, the indoor temperature of BR exceeds 31°C around 14.00 hours. However, the corresponding increase in the MBR is marginal because the undesirable effect of the roof cannot strongly influence a sheltered volume. However, it is interesting to note that, except for BR with a dark colour roof, the indoor temperature remains below 30°C during March; i.e. 1°C below the maximum outdoor temperature. The reason is the adoption of passive concepts such as proper orientation and shading for openings, and the use of light colours for surfaces.

6.5.2.2 Effect of surface colour of roof, walls and floor in a passive house

Chart 6.2 presents the results of House 1 for March, comparing the effect of the surface colour of the roof, walls and the floor on a sheltered volume (i.e. MBR). When all the surfaces are of light colour, the indoor temperature of MBR can be maintained just above 28.5°C although the outdoor temperature reaches a maximum of 31°C around 14.00 hours. When the roof is changed into a dark colour, the indoor temperature rises slightly, by less than 0.5°C, but remains within 29°C. When walls and floors are also changed to dark colour, the indoor temperature shows another slight increase, again less than 0.5°C. This observation, i.e. desirable thermal performance by light colours, is in agreement with the findings by Givoni (1976).

Chart 6.2 Effect of surface colour on a sheltered volume of a passive house (Master bedroom MBR of House 1 in March)

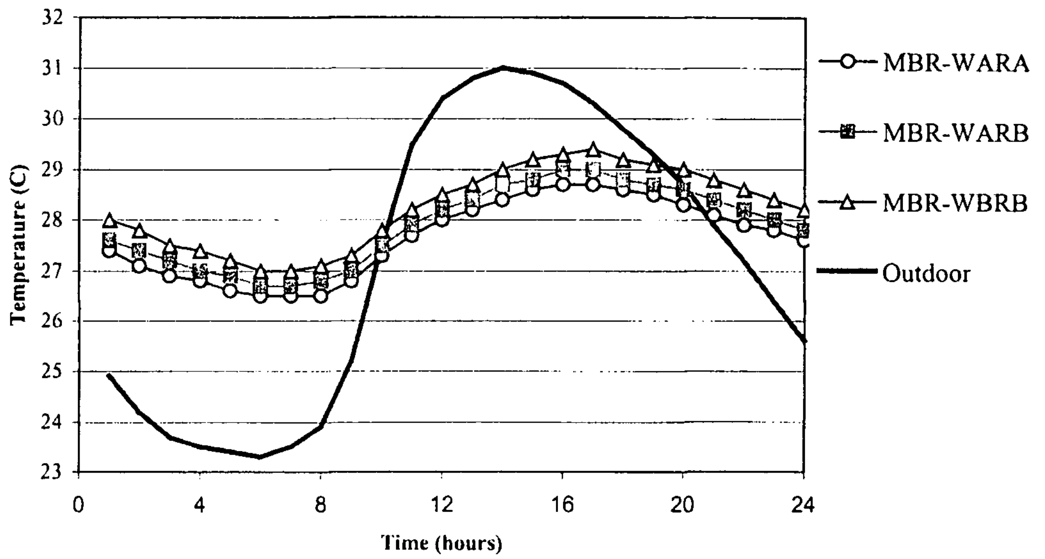
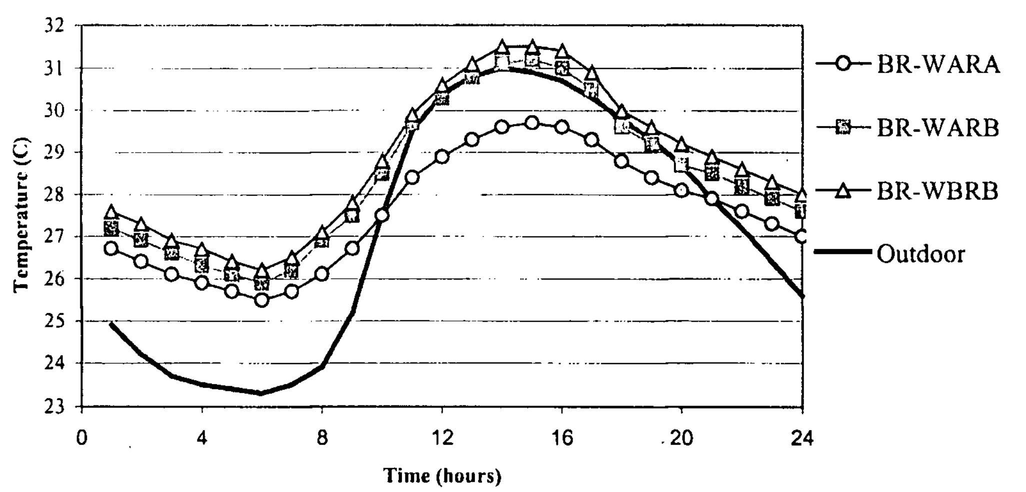


Chart 6.3 presents the results of House 1 for March, comparing the effect of the surface colour of the roof, walls and the floor on an unsheltered volume (i.e. BR). When all the surfaces are of light colour, the indoor temperature of BR can be maintained within 30°C, i.e. 1°C less than the maximum outdoor temperature. However, change of roof colour from light to dark results in an increase of indoor temperature by almost 2°C, displaying the sensitivity of an unsheltered volume to the changes in the roof colour. Change of wall and floor colour to dark causes a further increase of 0.5°C, reaching 31.5°C, which is undesirable in terms of thermal comfort.

Chart 6.3. Effect of surface colour on an unsheltered volume of a passive house (Bedroom BR of House 1 in March)



This amply demonstrates that, for a sheltered volume, the undesirable effect of the surface colour is of little significance if the volume is provided with shaded openings with proper orientation. However, for an unsheltered volume, the surface colour is of significant importance even when passive techniques such as orientation and shading are adopted. As Chart 6.3 shows, even when the surfaces are of light colour, the indoor temperature of an unsheltered volume can reach 30°C in March whereas the corresponding figure for a sheltered volume as shown in Chart 2 is only 29°C. Therefore, even in a passive house, sheltered volumes are more desirable than unsheltered ones.

6.5.2.3 Effect of surface colour of roof, walls and floor in an "unpassive" house

House 1 is a passive house, comprising shaded openings with proper orientation and a balcony with a roof. House 2 is obtained through undesirable modifications on House 1, such as provision of additional openings on west-facing walls, removal of shading devices provided for openings, removal of the balcony roof and removal of the shading effects from adjacent structures.

Chart 6.4 presents the results of House 2 (i.e. "unpassive" house) for March, comparing the effect of the surface colour on a sheltered volume (i.e. MBR). Even with light colour surfaces, the indoor temperature almost reaches 32°C around 16.00 hours. The delay in the occurrence of the maximum could be attributed to its west-facing opening. Use of dark colours further raises the indoor maximum temperature by 1°C, resulting in a highly undesirable temperature of 33°C around 16.00 hours, i.e. 2°C above the maximum outdoor temperature of 31°C in March.

Chart 6.4 Effect of surface colour on a sheltered volume of an "unpassive" house (Master Bedroom MBR of House 2 in March)

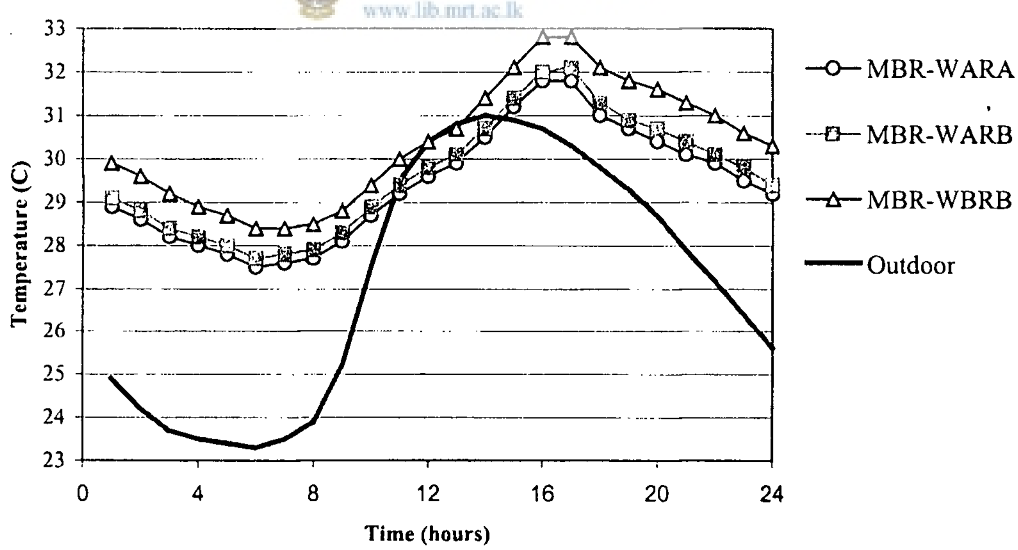
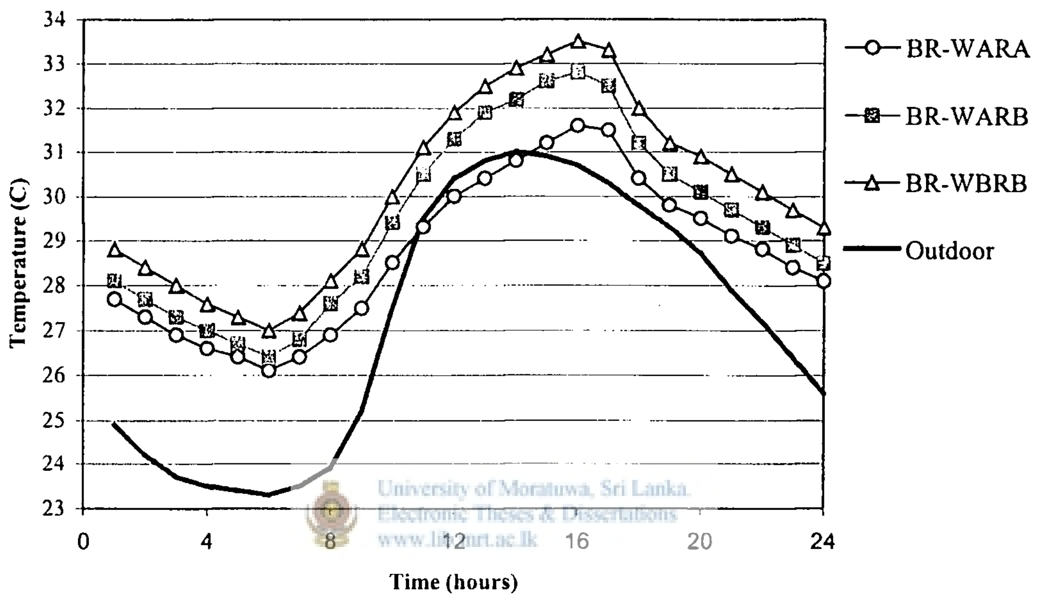


Chart 6.5 presents the results of House 2 for March, comparing the effect of the surface colour on an unsheltered volume (i.e. BR). For light surface colours, the indoor temperature of an unsheltered volume reaches 31.5°C, i.e. the same as for a sheltered volume. However, as can be expected, change of roof colour to blackish grey causes a rise of 1.5°C in the maximum indoor temperature. Darkening walls and floors as well causes another increase of over 0.5°C. Consequently, an unsheltered volume of House 2 in March experiences a maximum indoor temperature of almost

33.5°C. Inhibition of the resulting thermal discomfort may be impossible even with forced ventilation.

Therefore, provision of shaded openings with proper orientation is an important passive aspect that should not be overlooked. Such ignorance in the initial stages cannot be rectified by way of using light colours for roof, walls and floors at a latter stage.

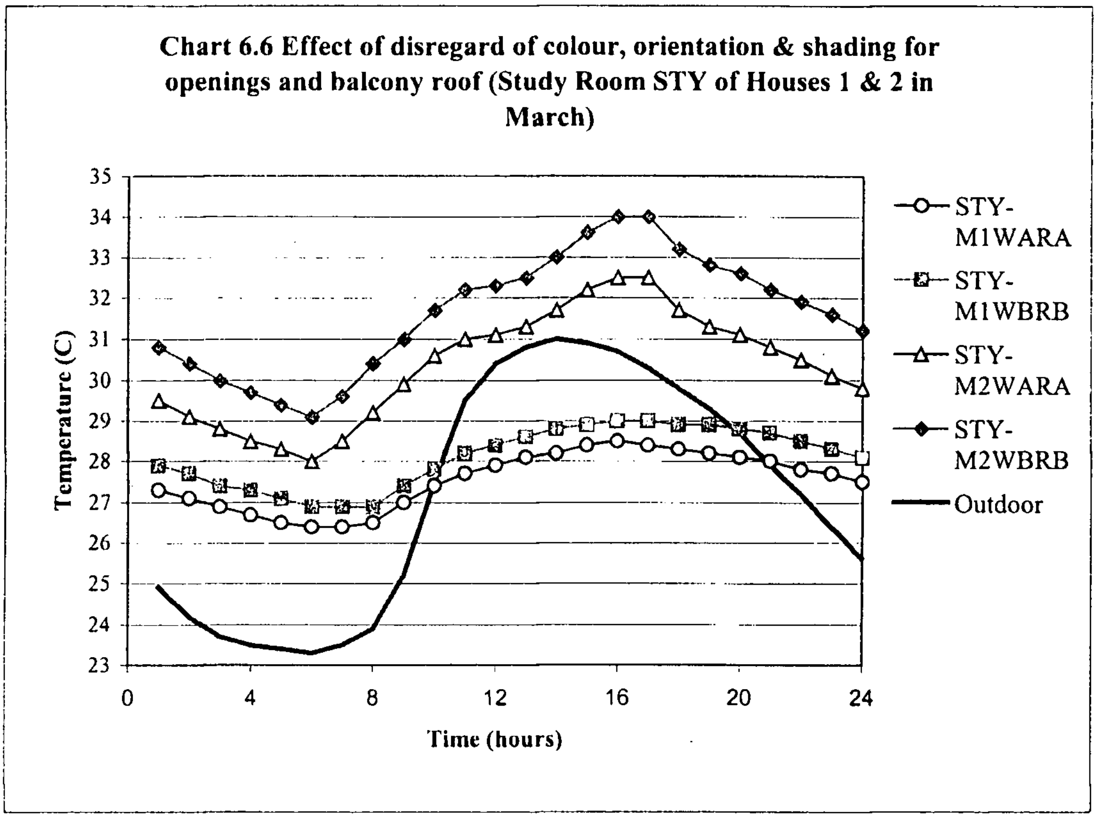
Chart 6.5 Effect of surface colour on an unsheltered volume of an "unpassive" house (Bedroom BR of House 2 in March)



6.5.2.4 Effects of Balcony Roof on the Volume Below (i.e. Study Room)

In House 1 the balcony is provided with a roof. The Study room (STY) below the balcony has two openings: one south-facing and the other east-facing. The latter though not the best is not so undesirable as an equivalent west-facing opening. As shown in Chart 6.6, when the surfaces are of light colour, the indoor temperature of the study room of House 1 rises in March to 28.5°C. Dark colour surfaces further increase the indoor temperature by 0.5°C.

On the other hand, House 2 (i.e. "unpassive" house) contains several undesirable features such as lack of shading devices for openings, west-facing openings and a balcony without a roof. All these cause an increase in the maximum indoor temperature by 4°C over the corresponding case of the passive house. The resulting indoor temperature of 32.5°C is highly undesirable, and achievement of reasonable levels of thermal comfort is very difficult even by using forced ventilation. Resorting to dark colour surfaces will further aggravate the thermal situation in the study room as the indoor temperature reaches 34°C when the maximum outdoor temperature is only 31°C.



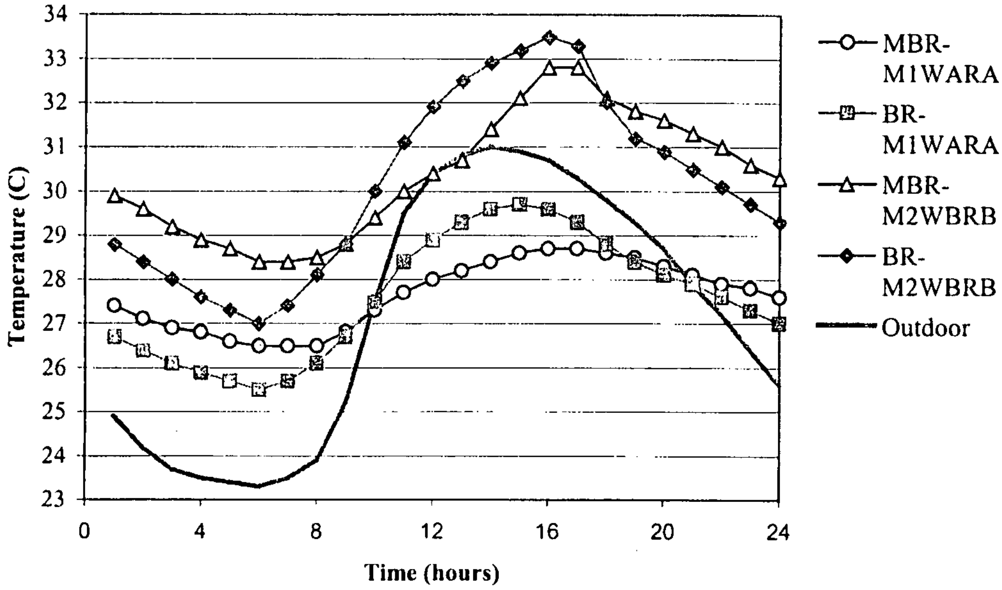
Therefore, by providing the balcony with a roof, the volume below can be maintained within 29°C provided its surfaces are of light colour and the openings are properly oriented and shaded. Neglect of all those aspects may cause the indoor temperature to rise to as much as 34°C, which is highly undesirable.

6.5.2.5 Total effect of disregard of passive features

Chart 6.7 compares the best and the worst scenarios in March. House 1 is a properly designed passive house with shaded openings with proper orientation. Its passive performance can be further enhanced by adopting light colour surfaces for roof, walls and floors. In this most desirable scenario, a sheltered volume like MBR can be maintained within 29°C and an unsheltered volume like BR within 30°C in March when the maximum outdoor temperature reaches 31°C.

House 2 is designed without any regard to proper orientation and shading for openings and its balcony is roofless. Its thermal performance can further be degraded by applying dark colours to its surfaces. In this most undesirable scenario, the indoor temperature of a sheltered volume reaches 33°C while that of an unsheltered volume reaches 33.5°C. These temperatures are so high that it is unlikely that even forced ventilation can achieve thermally comfortable conditions.

Chart 6.7 Total effect of disregard of colour, orientation & shading for openings on sheltered and unsheltered volumes (Master Bedroom MBR & Bedroom BR of Houses 1 & 2 in March)

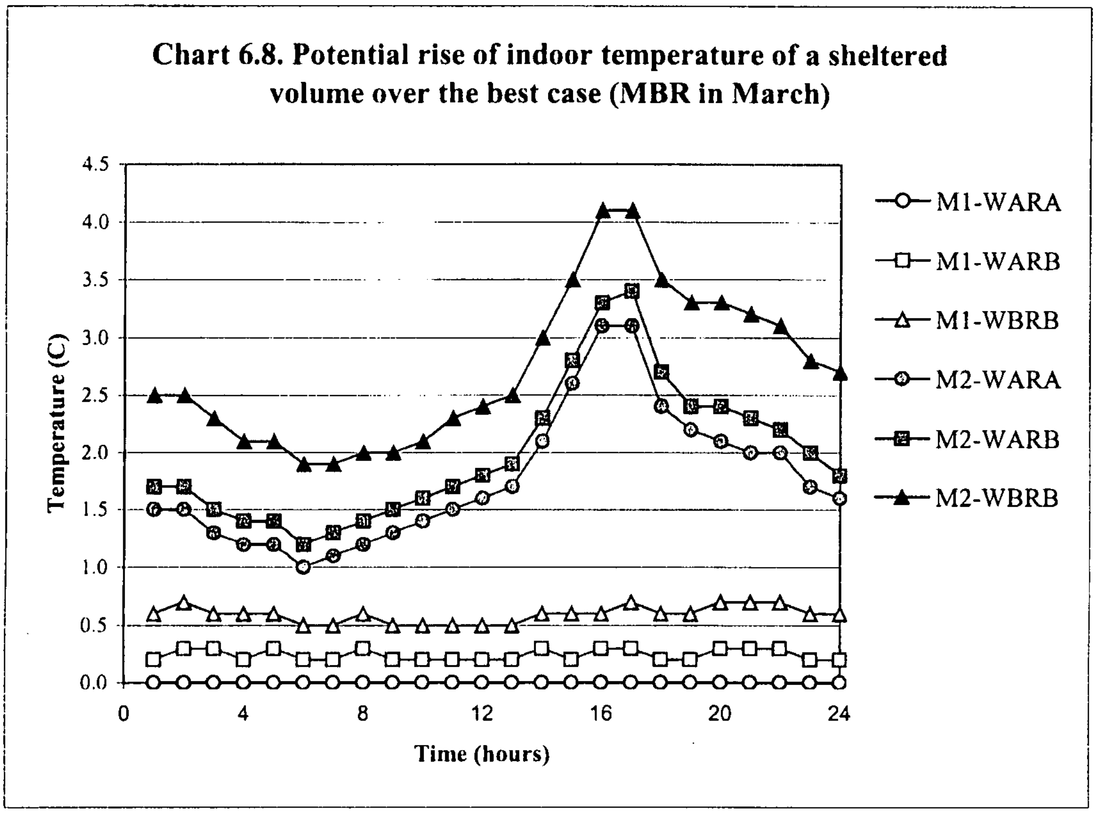


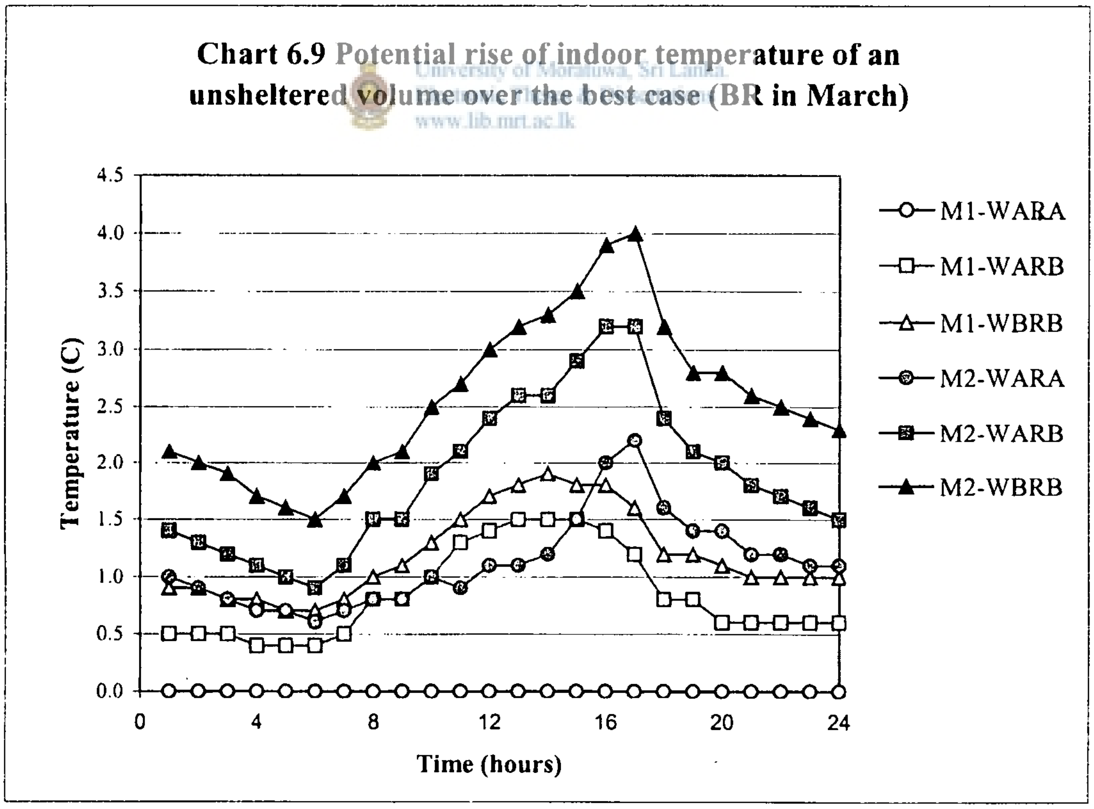
6.5.2.6 Quantification of effect of disregard of passive features

To quantify the effects of disregard of colour of walls, floors and roof, orientation and shading of openings, the results for March are presented as a potential rise of indoor temperature above a base case for sheltered and unsheltered volumes separately. As the base case, the most desirable set of conditions was selected, i.e. light colour walls and floors (WA) and light colour roof (RA).

Chart 6.8 compares the potential rise in the indoor temperature of a sheltered volume (MBR) above the base case of M1WARA. In House 1, which consists of properly oriented shaded openings, the potential rise is slightly over 0.5°C even when all surfaces are of dark colour. In House 2, which contains west facing openings in addition to its properly oriented unshaded openings, the potential rise exceeds 3°C even when all surfaces are of light colour. When the surfaces are of dark colour, it rises by another 1°C.

Chart 6.9 compares the potential rise in the indoor temperature of an unsheltered volume (BR) above the base case of M1WARA. In House 1 with properly oriented shaded openings, the potential rise reaches 1.5°C when the roof is changed to dark colour while the walls and floors remains light in colour. Change of the colour of the walls and the floor into dark as well makes a further increase of 0.5°C. Therefore, it is clear that, in an unsheltered volume, maintaining the roof surface in light colour is of paramount importance. In House 2, which can be described as "unpassive" due to neglect of orientation and shading for openings, a rise of 4°C above the base case is detected when all surfaces are of dark colour.





Therefore, it is clear that, by adopting passive techniques from the early stages of planning, there exists a significant possibility to achieve thermally comfortable conditions in houses throughout the day round the year. Disregard of orientation and shading for openings cannot be rectified by painting surfaces with light colours although it somewhat improves the passive performance. Neglect of passive concepts, especially during the early stages of planning, can result in indoor conditions so hot that even forced ventilation may not be effective in inhibition of the resulting thermal discomfort.

6.6 An integrated approach to the development of a passive housing scheme

There are several important factors that matter in the successful implementation of passive features to houses. They are listed here:

1. Passive concepts and techniques should be introduced at an early stage of planning and design because of their high sensitivity to orientation.

2. Adoption of passive concepts and techniques by a large number of houses if not all houses in a particular neighbourhood is highly effective because of the resulting thermally desirable enhancement in the microclimate.

These factors point towards one thing. That is, there is a need for a set of guidelines, beginning from land subdivision guidelines and ending with the finishing work of the house. This would not only facilitate the introduction of passive features to houses but also create the much desired microclimate so that the occupants of the houses could achieve indoor thermal comfort by little or no use of electricity. Thus this could be described as a sustainable solution to the interrelated problem of energy crisis and environmental degradation the country is now facing.

6.6.1 Features thermally desirable from a point of view of town planning

From the literature survey, three points have been identified as crucial in the development of land subdivision guidelines for a passive housing scheme. They are:

1. Provision of a desirable orientation for the houses
2. Use of vegetation
3. Provision of measures to mitigate excessive surface runoff

They are now considered in detail.

6.6.1.1 Provision of a desirable orientation for the houses

Due to aesthetic reasons, people tend to select a comparatively large area of glazing for the front façade of the house, which would be visible to the road. Therefore, the front of the house should face a shadable orientation, i.e. north or south. This arrangement could be achieved by planning the access roads along east-west direction.

In this arrangement, there is another advantage. Since the plot width would be smaller than the depth in order to reduce the area spent for road, the east or west facing walls of the house would be shaded from the morning and evening sunlight.

This is highly beneficial since the solar altitude is comparatively small during these times of the day, making overhangs virtually ineffective as shades.

6.6.1.2 Use of vegetation

Vegetation is an important passive means since it could be helpful in several ways. They can be listed as:

- To shade houses from direct solar radiation
- To shade non-vegetative ground surfaces, especially roads and paved slabs of sidewalks
- To create a desirable microclimate in the neighbourhood

A line of trees along the sides of the roads can serve several benefits. Firstly, the canopies would shade the front of the houses, reducing the heat gains into the houses.

Secondly, the canopies would shade the road surface and the cement slabs of the sidewalks. If left exposed to the sun, both these surfaces would easily heat up and start radiating heat all bodies exposed to them – including the houses and pedestrians. Besides, the air next to these surfaces would also be heated up, raising the outdoor air temperature. Therefore, it is important to maintain the surface temperature of such artificial surfaces as low as possible.

Thirdly, the leaves of these trees will use the solar radiation incident on them for evapotranspiration. Thus solar radiation that would otherwise have contributed to the increase of air temperature would now be consumed in another way.

The desirable effects of the use of vegetation could be magnified by providing substantially large areas of greenery such as parks instead of isolated trees or lines of trees. Past research (Emmanual (1993), Honju & Takakura (1990), and Landsberg (1981)) has shown that it would be more desirable to have several small areas of vegetation instead of a large park of equivalent area. A possible solution is to combine the back-gardens of two adjacent rows of houses, so that the combined entity would be one small "park". Since this could be done for all rows of houses in the neighbourhood, a system consisting of several small "parks" at a distance to each other could be provided, which is highly desirable in a thermal point of view for the creation of a desirable microclimate.

6.6.1.3 Provision of measures to mitigate excessive surface runoff

In a warm humid climate, rainfall is relatively high and frequent. This leads to various problems associated with surface runoff. They can be listed as:

- Soil erosion
- Siltation of drainage network
- Flash floods

When there are trees in the area, tree canopies act as an obstruction to rain drops, thus reducing the loosening of soil of exposed ground, leading to siltation of the drainage network. This problem could be mitigated by growing grass rather than keeping the ground surface bare.

In most built up areas, the ground surface is paved with impermeable slabs, leading to fast runoff following heavy showers since water is unable to seep into the ground. Silted drainage network, unable to cope with the large amount of runoff, would make the situation far worse. The result would be flash floods. In the questionnaire survey, 20% of those surveyed revealed that their house or street would be subject to flash floods following a heavy rain (Section 4.4.1.5).

There are three alternatives: letting ground remain bare, growing grass and shrubbery, and use of permeable slabs as ground cover. For the growth of vegetation, ground water recharge is important, and it could be promoted by minimizing the impermeable surface area. Another strategy is to retain rain water in pits with unlined bases. This will considerably enhance the ground water recharge as well as reduce the possibility of flash floods.

6.6.2 Development of land subdivision guidelines for a passive housing scheme in the low altitudes of Sri Lanka

The proposed solution addresses the problems of an urban or suburban region, where the land price is on the rise due to unavailability of suitable land for construction of houses. Therefore, in developing the house plans, effort was taken to minimize the plan area of the house as much as possible – firstly to minimize the extent of the plot in which it would be located and secondly to maximize the garden space to plant trees. Therefore, multi-storey type (two- or three-storey) was selected for the proposal. The fact that the thermal performance of a multi-storey house is superior to that of an equivalent single-storey house further reinforced the choice.

One of the most important requirements to achieve indoor thermal comfort is that the house should face a shadable orientation, i.e. north or south. This could be promoted by planning roads along east-west. According to the building regulations in Sri Lanka, the width of the access roads is likely to be a minimum of 6.0m when the number of blocks served are substantial. The building regulations require sufficient space from the centre of the road to the building line, which is about 4.5m to 6.0 for access roads. It is also necessary to respect a lighting angle of 62^{o} at the rear of the house, imposed by the Building Regulations (1985). Thus, the blocks should have the narrow side facing the access road and the longer side perpendicular to it. Since the creation of a microclimate is important, specially to shade the roads to minimise the ground reflected radiation, a reservation strip of 1.5m in width on either side of the access road for planting small shady trees can be particularly useful.

To locate any of the developed house plans conforming to the Building Regulations in force, a plot of seven perches, measuring 11m x 16m was found to be adequate. In Sri Lanka, the minimum block size for constructing houses is 6 perches when the pipe borne water service is available and 10 perches when this service is not available (Building Regulations, 1985). Therefore, the seven-perch plot is acceptable in this respect. The plan view of a typical proposed plot is given in Figure 6.17.

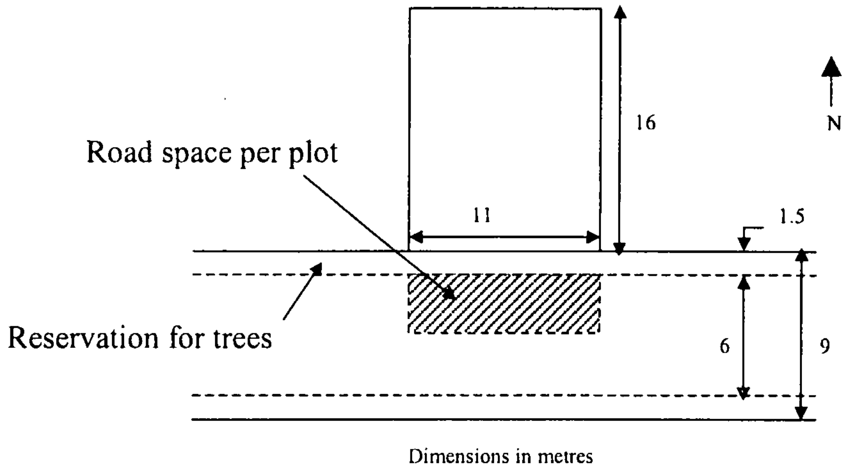


Figure 6.17 Profile of the proposed plot

Roads are required to provide access to plots. Therefore, to save land space for the allocation of plots, it is desirable to minimize the road area. Besides, road surface – whether it is paved or gravel – would be heated up more than a grass or other vegetative surface, and thereby contributing to the increase of outdoor temperature significantly. In this respect, too, locating the shorter side along the road is desirable as one plot would then consume only 33m^2 (11x3) of road space. The corresponding figure for the other arrangement is larger, i.e. 48 m^2 (16x3).

Each access road serving 20 plots is arranged in a staggered manner due to two reasons. Firstly, it would disturb the direction of the prevailing wind, enhancing the potential for cross ventilation of the houses. Secondly, the speeding of vehicles could be controlled by avoiding a long single stretch of road. The arrangement of the road network is given in Figure 6.18.

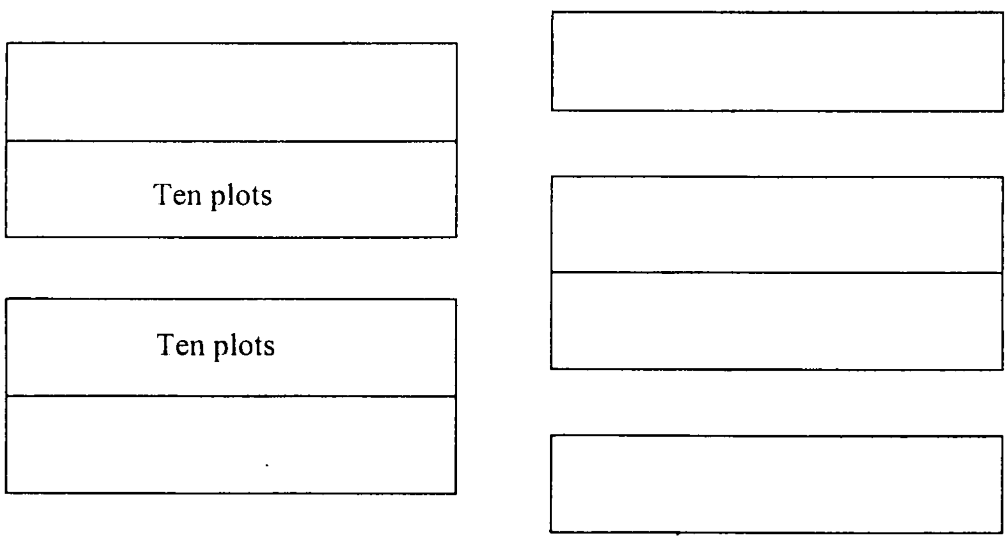


Figure 6.18 Staggered road arrangement

Frequent use of areas of vegetation is a traditional recommendation in town planning (De Waal, 1993). It is stated by Landsberg (1981) that many small areas of vegetation is more effective than one equivalent large park. This is supported by

Hunjo & Takakkura (1990) and Emmanual (1993). In the block arrangement proposed by this study, two adjacent rows of back gardens can de considered as a "park" measuring 9m by 110m (i.e. around 0.1 ha). These parks, located at 32m-intervals, could help to create a desirable microclimate resulting in a cooler outdoor environment. This land subdivision proposal will also allow trees along the roads, converting roads into linear parks. Thus a desirable microclimate could be promoted in the neighbourhood. The location of the "parks", i.e. vegetated plots of land, is given in Figure 6.19.

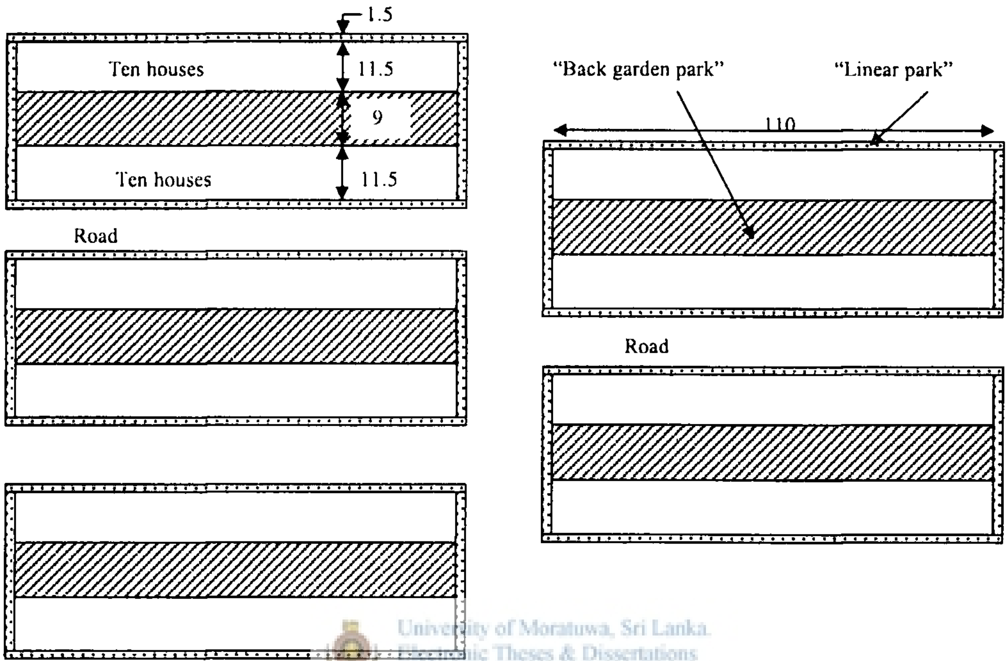


Figure 6.19 Location of vegetated portions of the neighbourhood

Since a space of 1.5 m is kept on either side of the road, it is possible to construct covered underground water detention and infiltration pits at a suitable interval along access roads, thus eliminating the need for a drainage network and also improving the groundwater recharge, thus supporting the growth of trees. These unlined pits can be provided with a suitable concrete cover. For example, if water detention pits are located at 15 m intervals, to collect all the water falling in a rainfall intensity of 25 mm/hour lasting one hour (or 50 mm/hour rain lasting half an hour), a pit would need only 1.5 m^3 of volume. This can be easily achieved with an unlined pit of 1.0 m length x 1.0 m width x 1.5 m depth.

It should be noted that these are not expected to completely eliminate the surface runoffs, but to substantially reduce them. Increased surface runoff from the developed land is one of the main reasons for flash floods in many low lying areas. This concept has already been successfully implemented at Karanawanwatta industrial estate at Dankotuwa as described by Wijesekera (1999). A longitudinal cross section taken along the road across a detention pit is given in Figure 6.20.

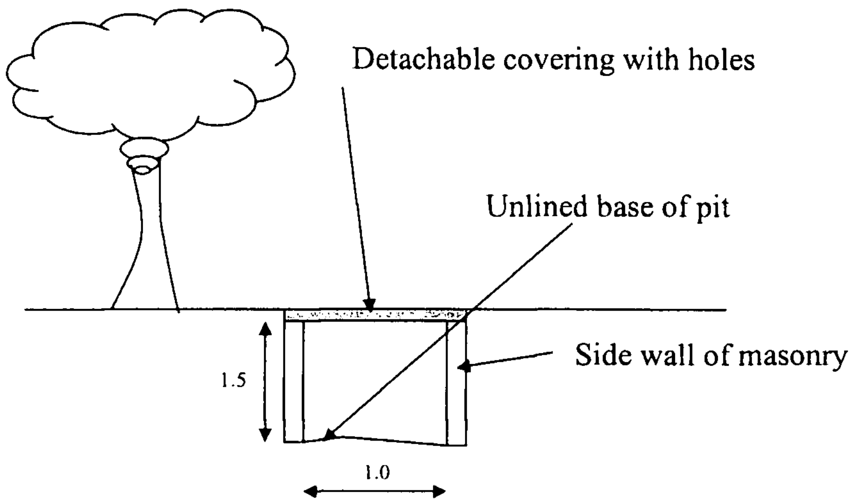


Figure 6.20 Underground water detention and infiltration pit

In this arrangement, each block will consume about 10 perch (250 m^2) area with roads. If 10% of land is reserved for common facilities as required for large housing projects, around 3600 houses can be located in an area of 1km^2. Therefore, with an average occupancy rate of 4 persons per house, a population of over 14,000 can be accommodated in an area of 1km^2 comfortably with minimum impact on the environment.

6.7 Benefits of an integrated passive solution

The proposed integrated passive solution consists of a scheme of multi-storey passive houses located in a neighbourhood planned with a set of land subdivision guidelines to achieve a desirable microclimate. Besides promotion of indoor thermal comfort of the houses by natural means, this proposal brings about a string of additional benefits. All benefits can be grouped as:

1. Superior performance of multi-storey houses over equivalent single-storey houses
2. Improved functionality of multi-storey houses
3. Environmental benefits
4. Cost aspects

6.7.1 Superior performance of multi-storey houses over equivalent single-storey houses

In order to compare the advantages of three storey houses with those of single and two storey ones, a case study was conducted for the houses given in Figures 6.21, 6.22 and 6.23.

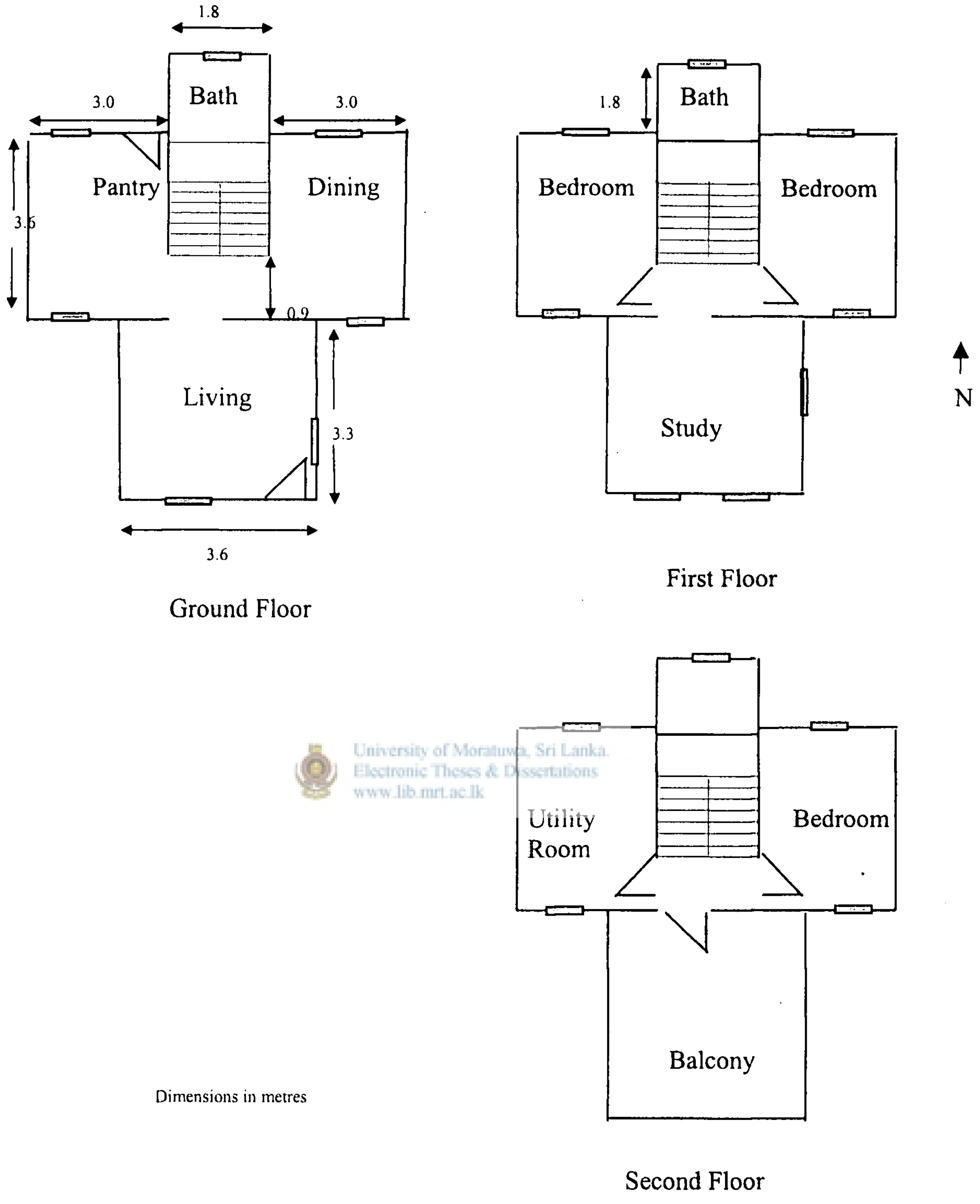


Figure 6.21 Three storey house of floor area $130m^2$

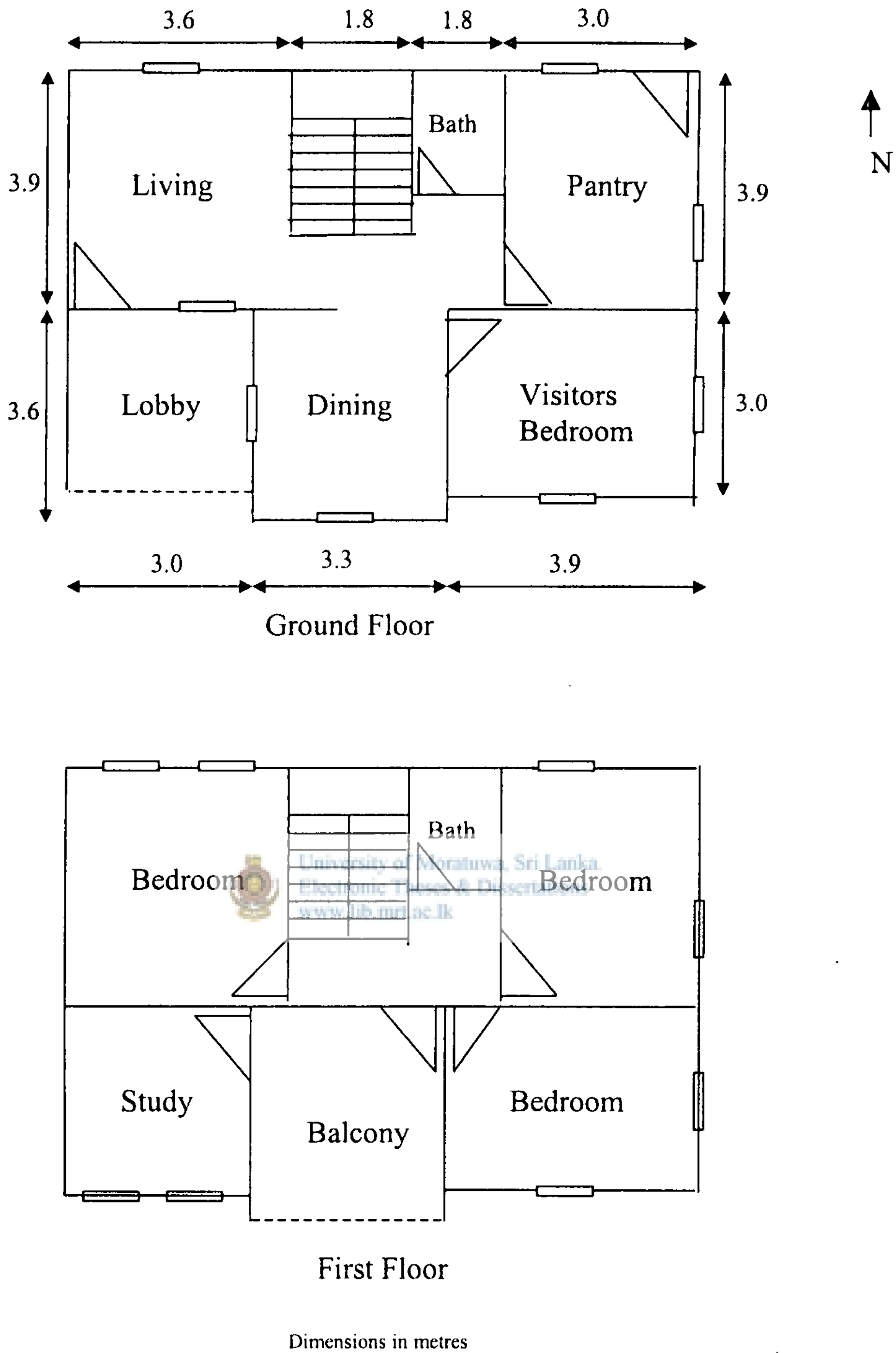


Figure 6.22 Two-storey house of floor area $140m^2$

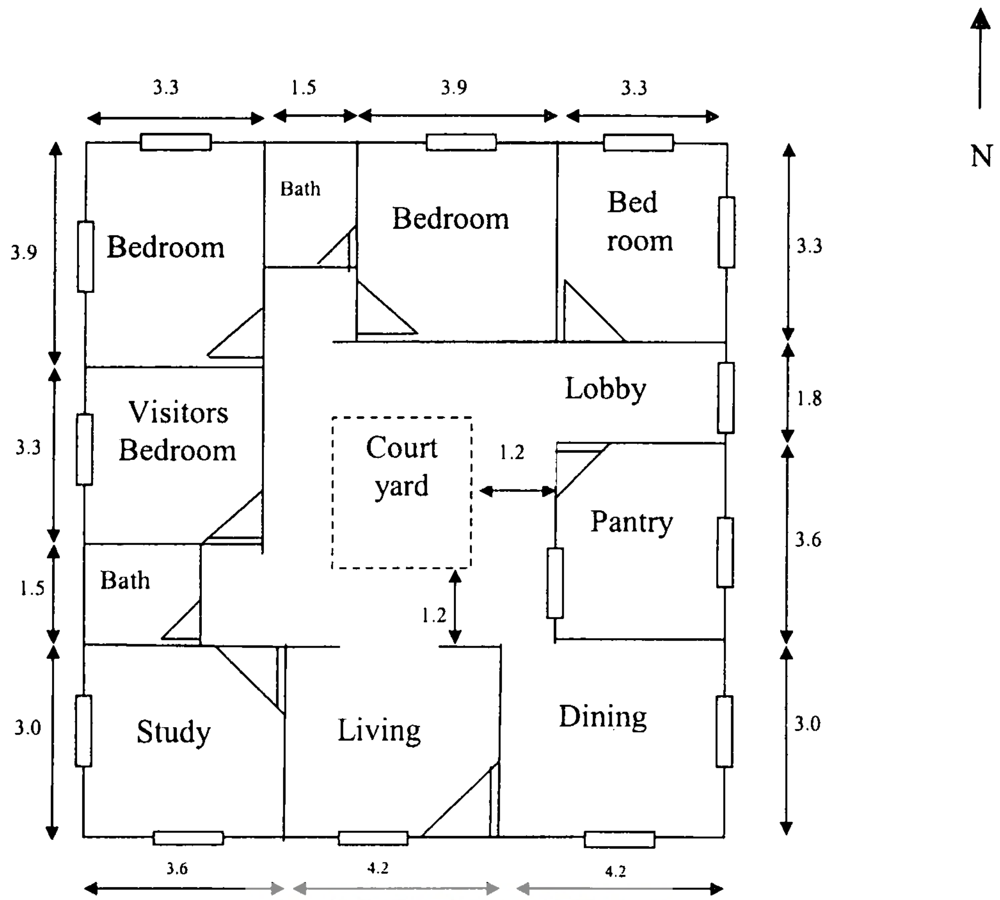


Figure 6.23 Single storey house of floor area 130m^2

The plot extent selected for the comparison purposes is 11.5 perches (17m x 17m) because the single storey house requires a minimum plot of this extent. The two and three storey houses can be easily constructed on 7-perch plots, measuring 13mx13.5m and 11mx16m, respectively. In the comparison, the parameters for the three storey house is considered as 100% to calculate the corresponding percentages for the other two houses. A comparison for these houses based on centre line dimensions can be presented as given in Table 6.8.

The usable area to total area in both three and two-storey houses are comparable. Single-storey houses may need more area for circulation, thus resulting in a lower ratio for usable to total area.

As shown in Table 6.8, in the single storey house in Figure 6.23, the roof area with respect to the total floor area as well as the plot area can be around 2.5 times that in the three storey house in Figure 6.21. Besides, the garden space can be doubled by preferring the three storey house to the single storey house. Therefore it is clear that the three storey houses facilitate reduction of heat gains, creation of a desirable microclimate, and reduction of the possibility of flash floods.

	3-storey	2-storey	Sinlge-storey
Total usable floor(m^2)	100.44	116.64	101.34
Total floor(m^2)	126.36	144.72	131.40
Usable/Total floor	0.795	0.806	0.771
Plot extent(m^2)	175 (7 perches)	175 (7 perches)	289 (11.5 perches)
Plot extent for comparison(m^2)	289 (11.5 perches)	289	289
Plan area of groundfloor (with courtyard) (m^2)	43.20	72.36	140.40
Plan area of roof (with 1 m eaves) (m^2)	72.24	111.76	190.80
Roof/Total floor	0.572 **(100%)**	0.772 **(135%)**	1.452 **(254%)**
Roof/Plot area	0.250 **(100%)**	0.387 **(155%)**	0.660 **(264%)**
Exposed area/plot area	0.750 **(100%)**	0.613 **(82%)**	0.340 **(45%)**
Gross external wall area for windows(m^2)	200.88	156.33	119.88
Gross ext wall area for windows/Served floor	2.268 **(100%)**	1.492 **(66%)**	1.183 **(52%)**

Table 6.8 A comparison of alternative types of houses

Table 6.8 also shows that the area of external walls where windows can be provided is reduced by 50% when the preference shifts from three storey to single storey even when the single storey house contains a courtyard. In the single storey house, the benefits of the courtyard are limited due to privacy concerns. For its bedrooms, windows cannot be provided on the external walls facing the courtyard as the living room is open to the courtyard, which is in turn open for visitors . On the other hand, if a courtyard is provided for a three-storey house, the same courtyard can be used at three different levels in a three storey house without any privacy problems. Therefore, it is clear that a three storey house provides a larger choice of external walls so that shadable orientations can be selected for its windows.

6.7.2 Improved functionality of multi-storey houses

In a single storey house, all activity spaces are located at ground floor level, resulting in problems associated with privacy. A three storey house as shown in Figure 6.21 provides three different levels for space allocation. The ground floor can be occupied by the family members and visitors during the daytime comfortably. The first floor can be occupied by the family members. The second floor bedrooms can be allocated for infrequent use such as visitors bedrooms. The balcony can be used for sleeping in hot nights or for drying of clothes during daytime.

In three storey houses, activity spaces can be arranged around the staircase as shown in Figure 6.21, minimising the circulation space. The space beneath the staircase at ground floor can be used as a storage area. The water tank can be located at the roof level above the staircase or bathrooms.

6.7.3 Environmental benefits

Of those surveyed, 20.1% revealed that, following a heavy rain, their street or house gets flooded. Such flash floods occur in urban and suburban areas mainly due to two reasons; inadequate exposed surface area for infiltration of storm water and inadequate capacity of the drainage system which now has to handle a much larger amount of storm water. For example, for a rainfall intensity of 25 mm/hour lasting for one hour, the total volume of runoff due to roof is about 190.80 x 0.025 =4.770 m^3 for the single storey house (Figure 6.23); 2.794 m^3 for the two storey house (Figure 6.22) and, 1.806 m^3 for the three storey house (Figure 6.21). Thus, the runoff from the roof of a three storey house will be only about 40% of the runoff from a single storey house of similar total area.

Another main advantage of lower lot coverage of three storey house is that there will be sufficient vacant space on the land for the construction of a detention pond (Wijesekera, 1999) than in other two types. The effect of constructing a such pond on the foundations of a three storey house also could be minimized by locating it away from the house. These ponds will be helpful to increase the ground water recharge, which in turn will sustain the growth of trees. Trees will reduce the speed of runoff thus reducing soil erosion and siltation of drains.

6.7.4 Cost aspects

Despite these advantages, the general public is reluctant to consider three storey houses as a possible alternative due to the misconception that three storey houses can cost much more than single or two storey houses. It is shown by Jayasinghe & Jayawardena (2001) that loadbearing brickwork can be safely used in three storey house construction while achieving substantial cost savings with respect to reinforced concrete framed structures.

In order to compare the likely costs of single, two and three storey houses, a comparison is made for different types of gross surface areas of the houses given in Figures 6.21, 6.22 and 6.23. The results are given in Table 6.9.

It can be seen that three storey house needs only two thirds of non vertical surface area of that of the single-storey house. A reason, for example, is that the first floor slab serves both as the floor of the first-storey and the roof of the ground-storey. Thus, efficient use of structural materials such as loadbearing brickwork would be able to keep the cost per unit area for two and three storey houses approximately the same.

		3-storey	2-storey	1-storey
Vertical surfaces(m^2)	Total	327.24	326.43	268.92
	Total surface/ Total floor	**2.590 (100%)**	**2.256 (87%)**	**2.047 (79%)**
Non-vertical surfaces(m^2)	Earth fill area	43.20	72.36	131.40
	RC slab area (incl. Stair slab)	85.14	73.08	0
	Roof (plan area)	72.24	111.76	190.80
	Total	200.58	257.20	322.20
	Total surface/ Total floor	**1.587 (100%)**	**1.777 (120%)**	**2.452 (155%)**

Table 6.9 Comparison of gross surface areas of alternative types of houses

In order to compare the actual costs of the three types of houses, a detailed cost study was carried out by Subashi et al. (2000), assuming that the houses were provided with basic finishes such as asbestos roofs, asbestos ceilings and cement rendered floors etc. The cost of bathrooms and fittings was not considered. All three houses have loadbearing brickwork and rubble foundations. The rates used were those specified for the local authority contracts by the Western Provincial Organization for the year 1999, which includes a mark-up of about 15%. These results are given in Table 6.10. It can be seen that the construction cost per unit area is in the same region.

	Three storey	**Two storey**	**Single storey**
Total cost (Rs)	1002,164/=	949,915/=	904,392/=
Total floor area (m^2)	139.86	144.72	132.66
Cost per unit area (Rs/m^2)	7165.50	6563.80	6817.40

Table 6.10 A comparison of cost of construction for single, two and three storey houses of comparable floor area

Moreover, non-dependence of passive houses on active techniques for comfort will bring savings in the long run in particular. Those are the savings in capital, maintenance and repair cost of various mechanical plant. It will also have desirable environmental benefits such as lesser use of energy.

6.8 Summary

Identifying the desirable passive features from the literature survey, the thermal and comfort surveys, and the computer analysis, and taking into account the requirements and preferences of the people, a set of concepts and guidelines was developed from this study. They could listed as:

1. Access roads along east-west direction to minimize solar gains.
2. Staggered road arrangement to improve road safety.
3. Minimised plot width to maximize the number of blocks in a given area.
4. Promotion of vegetation and gardening by allowing sufficient space for the creation of a desirable microclimate.
5. Three-storey single-unit housing to minimize the plot coverage, to minimize the roof area and to maximize the number of external walls for the provision of openings.
6. Brickwork for both loadbearing and partitioning walls to reduce the construction cost.
7. Light colours for exterior and interior surfaces to inhibit conductive gains and to enhance visual comfort indoors.
8. Sheltered spaces for frequent occupation to inhibit the use of active means.
9. Maximization of the number of external walls per functional space to promote ventilation.
10. Large openings on shadable and small ones on unshadable orientations to minimize solar gains.
11. Sharing of the same courtyard at different storey levels to maximize desirable effects.

Incorporating the above concepts and guidelines, a land subdivision proposal (Figure 6.24) for a housing scheme and a set of sketch passive house plans were developed. These sketch plans are compatible with the land subdivision proposal. Architects can use these sketch plans to develop house plans to suit the needs and tastes of the clients.

With a properly planned access road network and proper orientation, it will be possible to have about 3600 houses in an area of 1.0 km^2 (even with an allowance of 10% for common facilities), thus allowing a population density of over 14,000 persons/km^2. That is, an area of only 70 km^2 (8.5km x 8.5km) is required to settlė one million people comfortably with a minimum impact on the environment. In other words, for the total population of 18 million Sri Lankans, only about 1300 km^2 is required, which is less than 2% of the total land mass of Sri Lanka (65000 km^2). This is a particular advantage in an urban or suburban context as the land is scarce and the environment is under threat.

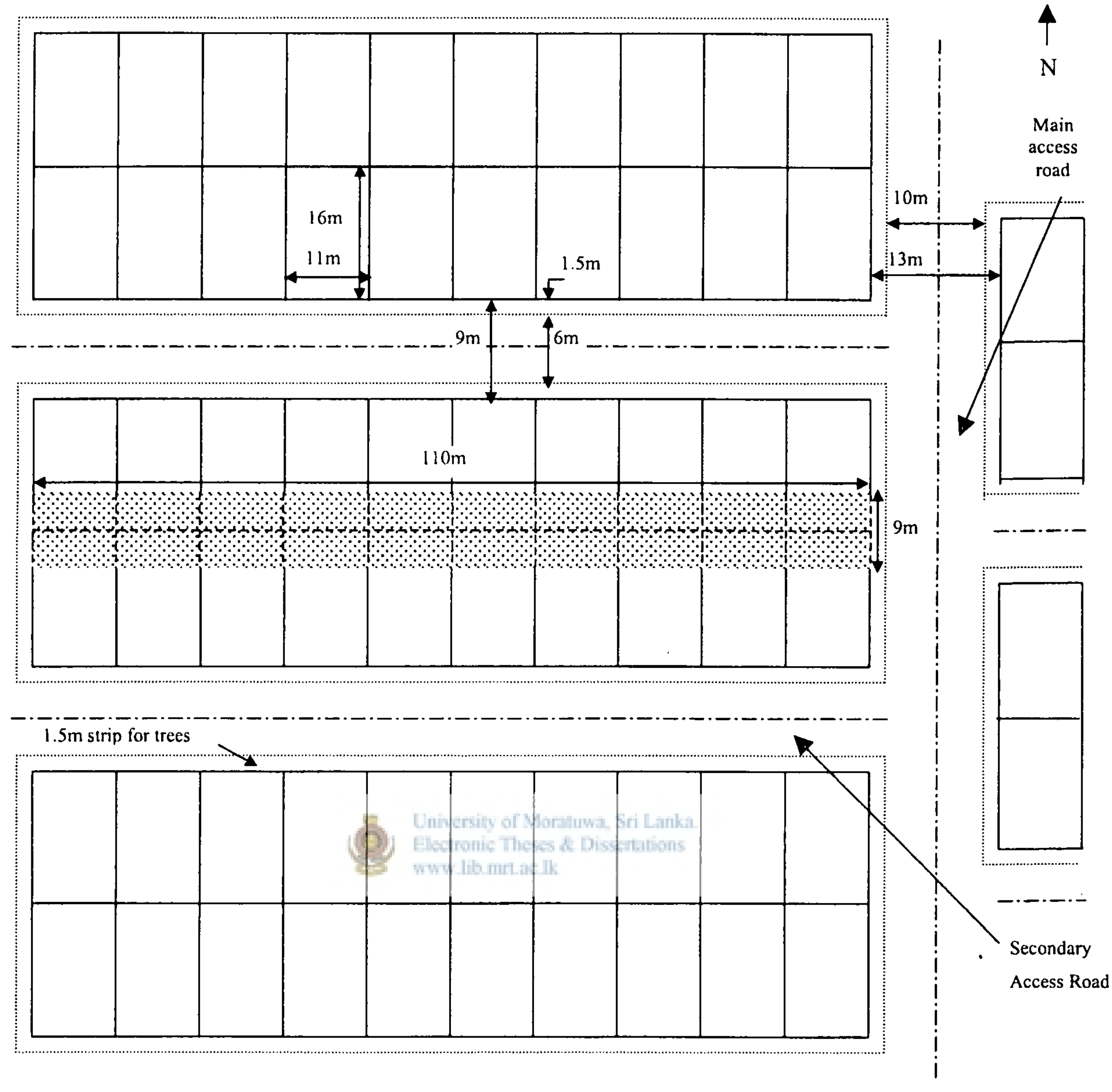
It is also shown that such concepts allow the creation of a much desirable microclimate with increased vegetation. The low plot coverage of three storey houses will also allow the construction of detention ponds to minimise the runoffs from the roofs. This will minimise the changes to the drainage patterns and will inhibit flash floods.

In addition, the following set of recommendations could be provided for the improvement of indoor thermal comfort of existing houses:

1. Grow trees in the garden, especially in front of east or west-facing windows.
2. Grow grass and shrubbery in the garden, especially in front of windows
3. Paint both interior and exterior surfaces of the house with a colour lighter than the existing colour

4. Paint roof surface with a light colour, especially if the roof covering is of cement fibre sheets
5. Fix a ceiling
6. Provide overhangs for north or south-facing windows
7. Use external blinds to shade east facing windows in the morning and west-facing windows in the afternoon and evening
8. Keep windows open unlit late into the night, preferably throughout the night

To reap the benefits of passive concepts, understanding and appreciation of their importance is vital. The general public should also be prepared to work for the creation and maintenance of a much desirable microclimate in the whole neighbourhood since that can bring more benefits than creating such an environment around a small number of houses. Thus a united effort is required to solve the inter-related crisis of environmental degradation and energy crisis.



"Park" comprising back gardens

Figure 6.24 Proposed land subdivision plan

Chapter 7

FINDINGS, RECOMMENDATIONS AND FUTURE WORK

The main objective of the study is to conserve electricity in the domestic sector of Sri Lanka, by developing a set of guidelines for the achievement of indoor thermal comfort at houses in the low altitudes of Sri Lanka through passive means, which are energy-efficient and environment-friendly.

A literature survey was conducted to determine the passive concepts and techniques desirable to warm humid climatic conditions. To identify the thermally undesirable features of the building envelope and the indoor temperatures that occur in reality, a series of thermal and comfort surveys was conducted at several existing buildings, mostly houses. A pilot questionnaire survey was conducted to identify the current situation with respect to thermal comfort and preferences of the people which would be crucial in developing a solution. Then, a series of computer simulations was carried out using the software DEROB-LTH to determine the effect of various features of the building envelope on indoor thermal comfort. Using the findings of the surveys and computer simulations, a set of thermally desirable and undesirable features was prepared. Incorporating the desirable features and eliminating the undesirable ones, a set of passive house plans was developed. To locate them in a housing scheme, a set of land subdivision guidelines was also developed.

The output of the study could be presented as Findings and Recommendations. Further, suggestions for future work can be given, highlighting the ways by which a study of similar nature could be developed.

7.1 Findings of the study

The study revealed, through the questionnaire survey and the thermal and comfort surveys, that thermal discomfort occurs in existing houses and other buildings – in some cases, at alarming levels. The computer simulations further reinforced this finding. The questionnaire survey also revealed that, to a lesser degree, visual discomfort, too, occurs in these houses during the daytime. The occupants of most houses, according to the results of the questionnaire survey, resort to fans and artificial lighting to inhibit the thermal and visual discomfort, respectively. These are active means that consume electricity.

The literature survey and the computer simulations showed that the indoor temperature of the houses in the low altitudes of Sri Lanka could be lowered by resorting to passive concepts and techniques applicable to warm humid climates, such as desirable microclimate, proper orientation and shading for openings, multi-storey construction, ventilation, courtyard and light colours for surfaces. The questionnaire survey further revealed that the majority of those who surveyed prefer to grow trees if garden space is available. This is the most crucial requirement for the creation of the thermally desirable microclimate in the neighbourhood.

7.2 Recommendations

Recommendations can be given as three sets of passive guidelines for the following:

1. A housing scheme
2. A house being planned
3. An existing house

7.2.1 Passive guidelines for planning a housing scheme

The following can be listed as the major features of the guidelines developed for a passive housing scheme, which include land subdivision guidelines as well as a set of passive house plans:

- Access roads along east-west direction
- Staggered road arrangement
- Lines of trees along the sides of the roads
- Storm water detention pits at intervals on the sidewalks
- A seven-perch plot, measuring 11m by 16m
- A set of passive house plans compatible to the above plot
- Vegetated back garden measuring at least 4.5m by 11m for each house

An overview of the land subdivision proposal is given in Figure 6.24. This proposal can accommodate about 3600 houses in an area of 1.0 km^2 (even with an allowance of 10% for common facilities). At four persons per household, it would be a population density of over 14,000 persons/km^2. That is, an area of only 70 km^2 (8.5km x 8.5km) is required to settle one million people comfortably with a minimum impact on the environment. In other words, for the total population of 18 million Sri Lankans, only about 1300 km^2 is required, which is less than 2% of the total land mass of Sri Lanka (65000 km^2). This is a particular advantage in an urban or suburban context as the land is scarce and the environment is under threat.

7.2.2 Passive guidelines for planning a house

The following is the set of guidelines for a house that is being planned:

- Select multi-storey type (i.e. two or, more preferably, three)
- If the house is selected as multi-storey, locate spaces used less often (e.g., Visitors Bedroom) or spaces used for a relatively short period (e.g., Balcony) at the top floor
- Face the front of the house to north or south
- Provide at least two external walls, preferably perpendicular to each other, for provision of openings
- Face openings to north or south, and shade them with an overhang making a horizontal angle of 60^o
- If openings facing east or west are unavoidable, ensure that they are short and shaded with an external blind
- Avoid tall boundary walls next to openings

- Plan a courtyard serving to Living and Dining, and locate large windows opening to the courtyard. In a multi-storey house, windows of the upstairs bedrooms can open into the courtyard
- Paint both interior and exterior surfaces with a light colour preferably off-white
- Avoid skylights
- Avoid roof terraces. Provide a roof for balcony
- Avoid tinted glazing, especially for openings of Living and Dining
- For the roof, prefer clay tiles to cement fibre sheets unless cement fibre sheets will be maintained in a light surface colour by painting from time to time
- Fix a ceiling and, if possible, have openings to ventilate the attic space
- If possible, fix a reflective foil
- Grow trees in the garden, especially in front of openings facing east or west
- Grow grass, or preferably shrubbery, especially in front of openings
- Grow ivy on external wall surfaces
- Keep windows open late into night, preferably throughout night

Since the passive performance of a single-storey house is relatively poor, the following are strongly recommended if the house type is single-storey:

- Facing house to north or south
- Light colours for exterior wall surfaces and the roof surface.
- Light colours for walls indoors.
- Clay tiles instead of cement fibre sheets for the roof.
- Ceiling with a reflective foil above it
- Ventilated attic space
- Courtyard

7.2.3 Passive guidelines for an existing house

For an existing house, the following steps would enhance the indoor thermal comfort:

- Grow trees in the garden, especially in front of east or west-facing windows.
- Grow grass and shrubbery in the garden, especially in front of windows
- Paint both interior and exterior surfaces of the house with a colour lighter than the existing colour
- Paint roof surface with a light colour, especially if the roof covering is of cement fibre sheets
- Fix a ceiling
- Provide overhangs for north or south-facing windows
- Use external blinds to shade east facing windows in the morning and west-facing windows in the afternoon and evening
- Keep windows open unlit late into the night, preferably throughout the night

7.3 Future work

Due to constraints of time and manpower, and non-availability of equipment, this study could not cover certain aspects adequately. Especially taking those into consideration, the following could be recommended for future work:

- A nationwide questionnaire survey with the patronage of a governmental institution should be conducted to identify the current situation in houses and the preferences of the inhabitants

- The effect of the building materials should be covered more deeply although this study covered only the roofing materials, that also not in depth. Wall materials, glazing types and ceiling types could be cited as potential areas

- A massive series of thermal surveys should be conducted in houses to identify the real indoor temperatures they are subjected to. This also may need the backing of a governmental institution. Preferably, thermal surveys should be conducted simultaneously so that the subjects represent a wider cross-section with respect to age, instead of university students

- A more detailed computer analysis could be performed using DEROB-LTH although this study did not use it extensively

7.4 Concluding remarks

By restorting to passive concepts and techniques, the occupants can reduce their electricity bill while achieving comfortable indoor environment. The benefits of passive houses at the national level, though not as significant as those at the user level, could be magnified if a significant slice of the population adopts them. . The energy saved by the use of passive means could be channelled to the industrial sector, paving the way for economic growth.

By resorting to passive techniques, the number of fans as well as the duration for which they are used in houses could be minimised, or fans may be eliminated altogether. Such development would make air conditioning, which is more energy intensive than fans and more undesirable to the environment, even a remote option in the domestic sector.

A reduction in the rate of electricity demand would save foreign exchange that would otherwise be needed for importing petroleum for thermal power plants and new power generation plants. Also beneficial to the nation is the mitigated need for the development of new power plants because it would minimise possible adverse effects on the environment. The environment is already threatened by the diminishing forest cover and the adverse climatic changes due to the massive artificial reservoirs catering to the hydropower plants.

The importance of the passive concepts and techniques should be more visible to all in the light of the ongoing and lengthening daily power cut.

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Appendix A1 Form of thermal surveys

Thermal survey

Date :

Location :

Time	Volume :					Time	Volume				
	DBT	WBT	RH%	Fan	Wndw		DBT	WBT	RH%	Fan	Wndw
0						0					
1						1					
2						2					
3						3					
4						4					
5						5					
6						6					
7						7					
8						8					
9						9					
10						10					
11						11					
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22						22					
23						23					
24						24					

Appendix A2 Form of comfort survey

Comfort Survey

Date :

Name : ....

Age :

below 21	
21-30	
31-40	
41-50	
over 50	

Location :

Male	
Female	

	Volume :									Volume :									Volume :							
	Fan	Windows	Comfort vote							Fan	Windows	Comfort vote							Fan	Windows	Comfort vote					
	(Y/N)	(Y/N)	-3	-2	-1	0	1	2	3	(Y/N)	(Y/N)	-3	-2	-1	0	1	2	3	(Y/N)	(Y/N)	-3	-2	-1	0	1	2
Time			cool zone				warm zone					cool zone				warm zone					cool zone				warm zo	
5																										
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Appendix A3

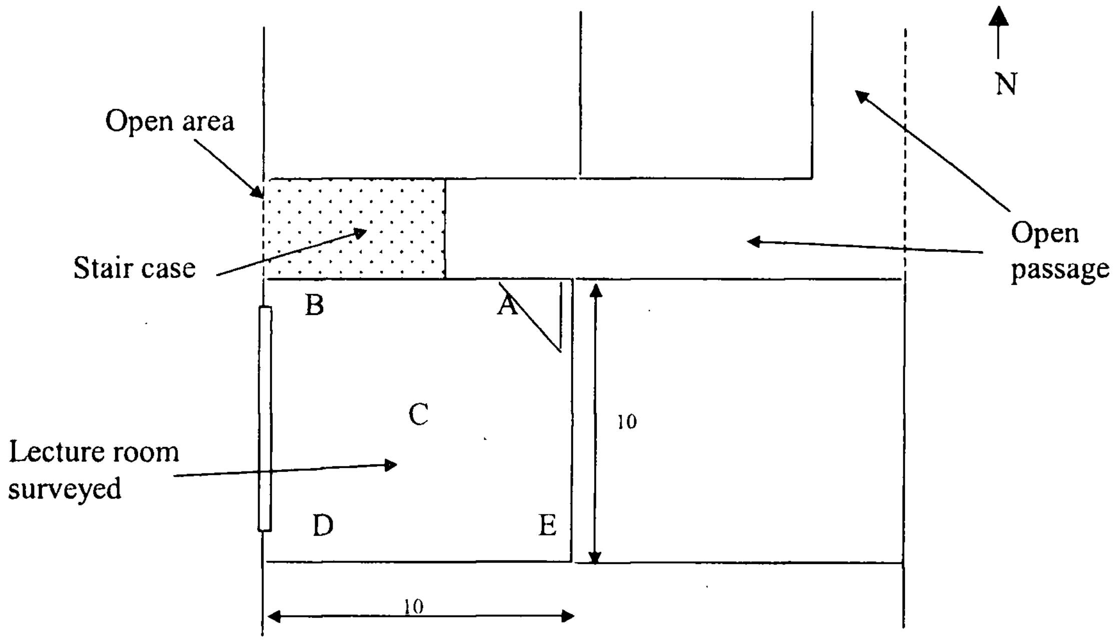
Additional information on houses used for thermal and comfort surveys

Location of House	Owner's name	Address
Veyangoda	Mr S Liyanarachchi	48/24A, Veralugollawatte, Vattaddara, Veyangoda
Ragama	Mr JS Kumara	35, Paradise Place, Ragama
Ratmalana	Mr I Mohotti de Silva	19, 4th Lane, Ratmalana
Colpetty	Mr Bandula Abeysirigunawardena	10, 27th Lane, Off Inner Flower Road, Colombo 3

Table A3 Owner's name and address of the houses used for thermal and comfort surveys

Appendix A4

Original readings of the thermal and comfort survey conducted at a lecture room at Moratuwa University



Locations where temperature measurements were taken are marked "x"

Dimensions in metres

Figure A4 Floor plan of lecture room at Moratuwa University

Time (hrs)	Fan speed	A		B		C		D		E		Outdoor	
		DBT (°C)	WBT (°C)	DBT (°C)	WBT (°C)	DBT (°C)	WBT (°C)	DBT (°C)	WBT (°C)	DBT (°C)	WBT (°C)	DBT (°C)	WBT (°C)
10.00	Full	30.0	25.5	30.0	25.5	30.0	25.5	30.0	26.0	30.5	26.0	29.5	25.5
10.20	Four	30.0	25.5	30.0	25.5	30.0	25.5	30.0	26.0	30.0	26.0	29.5	25.5
10.40	Three	29.5	25.5	30.0	26.0	30.0	26.0	30.0	26.0	30.0	26.0	30.0	25.5
11.00	Two	30.0	25.5	30.0	25.5	30.5	26.0	31.0	26.5	31.0	26.0	29.5	25.0
11.20	One	30.5	26.0	30.5	26.0	31.0	26.0	31.0	26.5	31.0	26.5	30.0	25.5
11.40	Full	30.5	25.5	30.5	26.0	30.5	26.0	30.5	26.0	31.0	26.5	30.5	25.5

Table A4 Readings of DBT and WBT of the thermal and comfort survey conducted at a lecture room at Moratuwa University

Notes:

1. DBT stands for Dry Bulb Temperature, i.e. reading of the dry bulb thermometer of the hygrometer
2. WBT stands for Wet Bulb Temperature, i.e. reading of the wet bulb thermometer of the hygrometer.
3. Using these two readings along with the conversion chart provided with the hygrometer, the relative humidity was determined

Appendix B
Form of questionnaire survey

Questionnaire Survey

Project : Passive Techniques for Energy Efficiency of Buildings in Sri Lanka
Researchers : Dr MTR Jayasinghe, Dr RA Attalage & AI Jayawardena
Funding : Senate Research Committee, University of Moratuwa

INSTRUCTIONS
1. Only those who were born before January 01, 1982 should take part.
2. DISTRICT you live in should be Colombo, Gampaha, Kalutara, Galle, or Matara
3. UNDERLINE your choice or FILL IN the blanks as expected

Name : ....
Address : ....
Age : .... Sex : Male / Female
Occupation & Place of Work : ....
Type of House : flat / single-storey / two-storey / three-storey
Number of Occupants : ....
Date of Participation in the Questionnaire Survey : ....

THE HOUSE NOW YOU LIVE IN ...

A1. Roof type of your house?
Clay tiles / Asbestos / ....

A2. Ceiling type? No ceiling / Asbestos / Timber / ....

A3. Any room in your house which is sometimes too warm to be comfortable even when all its windows are open? Yes / No

A4. If Yes, what do you do then ?
Switch on the fan / Go to a comfortable room /..

A5. Usually, how many fans are used in your house? No fans / One / Two / Three / More than three

A6. For the windows of your house, what provides protection from sunlight ?
Overhangs / Tinted glass / Trees / Curtains / External blinds / ....

A7. Colour of the outside surfaces of your house?
Light colour / Dark colour / In between Colour is ....

B1. Inside the house, what is the colour of the walls?
Light colour / Dark colour / In between Colour is ....

B2. Colour of the floor?
Light colour / Dark colour / In between Colour is ....

B3. Any skylight in the roof to take daylight in? Yes / No

B4. Any room that is gloomy during the daytime even when all its windows are open? Yes/No

B5. If Yes, what do you do if you have work to do there ?
Switch on the light / ....

B6. In your electricity bills for the last 3 months, number of units used and amount ?
Units:...... Rs............/ Units:......, Rs.........../ Units:......, Rs.........

C1. Usually, where do you sleep at night ? Downstairs / Upstairs / ....

C2. When the night is hot, do you keep the windows open ?
No / Yes, throughout the night / Yes, only till late night

C3. If No, why? Security / Privacy / Mosquitos / ....

D1. Do you have a garden ? No / Front garden only / Back garden only / Both

D2. Your family grow vegetables or fruit there ? Yes / No

D3. If Yes, why ? Hobby / To save money / To obtain pesticide-free food
/ To prepare for a famine in the future / ....

D4. You use organic waste as compost manure ? Yes / No

D5. If No, why ?
Garden space not enough / No time / Don't know the technique /..........

D6. Following a heavy rain, your street or house gets flooded ? Yes / No

THE HOUSE YOU LIKE TO HAVE...

NOTE: Please avoid over-imagination; you should be able to afford what you like to have

E1. Neighbourhood you like to live in ? Rural / Urban / Urban area full of trees

E2. Type of house you prefer ? Flat / Luxury apartment / Single-storey / 2-storey / 3-storey house

E3. Special features needed :
Visitors bedroom / Visitors bathroom / Court yard (indoor garden) / Study room
/ Storeroom / Larger kitchen instead of a storeroom / ....

E4. Number of bedrooms (without visitors) needed ? ....

E5. Number of bathrooms (without visitors) needed ? ....

ENVIRONMENT AND YOU

F1. Your view on Environmental Pollution ?
A serious problem threatening the future / Just one out of many problems /
Not a problem because modern technology will always find a solution

F2. Are you prepared to do something about this problem ? Yes / No

F3. If garden space is available, will you grow trees ? Yes / No / May be

NOTE : Please submit the completed questionnaire to :...................................

Appendix C1

Maximum temperature and time of occurrence in computer simulations for effect of roof simulations

Month	Minimum outdoor temperature	Maximum outdoor temperature
December	22.4 (6)	29.8 (14)
June	25.2 (5,6)	29.6 (14,15)
March	23.3 (6)	31.0 (14)

Table C1.1 Maximum and minimum outdoor temperatures (time of occurrence given in brackets)

Month	East-west ridge roof (R1)				North-south ridge roof (R2)			
	NW	NE	SW	SE	NW	NE	SW	SE
December	28.9	29.0	29.8	30.0	29.1	29.2	29.8	29.9
	14,15	14,15	15,16	15,16	15	15	15,16	15,16
June	31.0	31.2	30.7	30.8	31.1	31.7	30.9	31.4
	14,15	15	15	14,15	15	15	15	15
March	30.8	31.0	30.9	31.1	30.7	30.9	30.8	30.9
	15	15	15	14,15	15	14,15	15	14,15

Table C1.2 Maximum indoor temperature (time of occurrence given below) for flat ceiling

Month	East-west ridge roof (R1)				North-south ridge roof (R2)			
	NW	NE	SW	SE	NW	NE	SW	SE
December	28.5	28.7	30.0	30.1	29.2	29.4	29.7	29.9
	14	15	15	14,15	15	14,15	15,16	14,15
June	31.4	31.5	30.9	31.1	31.2	31.3	31.0	31.2
	14,15	14,15	14,15	14,15	15	14,15	15	14
March	31.1	31.3	31.3	31.5	30.9	31.2	30.9	31.2
	15	14,15	14,15	14,15	15	14,15	15	14,15

Table C1.3 Maximum indoor temperature (time of occurrence given below) for sloping ceiling

Appendix C2

<u>Maximum temperature and time of occurrence in computer simulations for effect of roof materials and roof surface colour</u>

Month	Asbestos roof				Clay tiles roof			
	NW	NE	SW	SE	NW	NE	SW	SE
Asbestos ceiling	31.0 14,15	31.2 14,15	31.2 15	31.4 15	30.1 15,16	30.4 15	30.3 15	30.6 15,16
Timber ceiling	30.8 15	31.0 14,15	31.0 15	31.1 14,15	30.0 15	30.2 15,16	30.1 15,16	30.5 15
Asbestos ceiling & Al foil	28.7 15,16	28.9 15,16	28.7 16	28.9 15,16	28.6 16	28.8 15,16,17	28.6 16,17	28.9 15,16,17
Asbestos ceiling, Al foil & polystyrene	28.8 15,16,17	29.1 16	28.8 15,16,17	29.1 15,16	28.7 16,17	28.9 15,16,17	28.7 16,17	29.0 15,16,17
Asbestos ceiling & half tiles	30.4 15	30.6 15	30.5 15	30.7 15	—	—	—	—

Table C2.1 Maximum indoor temperature (time of occurrence given below) for different roof types

Colour of exterior surface of asbestof roof (absorptance)	Asbestos ceiling			
	NW	NE	SW	SE
Blackish grey (80%)	31.0 14,15	31.2 14,15	31.2 15	31.4 15
Light grey (60%)	30.0 15	30.2 15	30.1 15	30.3 15
Off-white (40%)	29.0 15	29.2 15	29.1 15	29.2 14,15,16

Table C2.2 Maximum indoor temperature (time of occurrence given below) for different surface colours of asbestos roof

Appendix C3

Maximum temperature and time of occurrence in computer simulations for effect of orientation of openings

Orientation of openings	Flat ceiling				Sloping ceiling			
	NW	NE	SW	SE	NW	NE	SW	SE
N & S-facing openings only	31.0 14,15	31.2 15	30.7 15	30.8 14,15	31.4 14,15	31.5 14,15	30.9 14,15	31.1 14,15
Additional west facing openings	32.4 16	31.3 14,15	32.0 16	31.0 14,15	32.3 16	31.7 14,15	31.9 16	31.2 14,15
Additional east facing openings	31.2 14,15	32.3 14	30.8 14,15	32.0 14,15	31.6 14,15	32.4 14,15	31.1 14,15	32.0 14,15
Additional west & east facing openings	32.5 16,17	32.4 14,15	32.2 16	32.1 14,15	32.4 16	32.5 14,15	32.1 16	32.2 14

Table C3 Maximum indoor temperature (time of occurrence given below) for east-west ridge roof R1 in June

Appendix D
Validation of the software DEROB-LTH

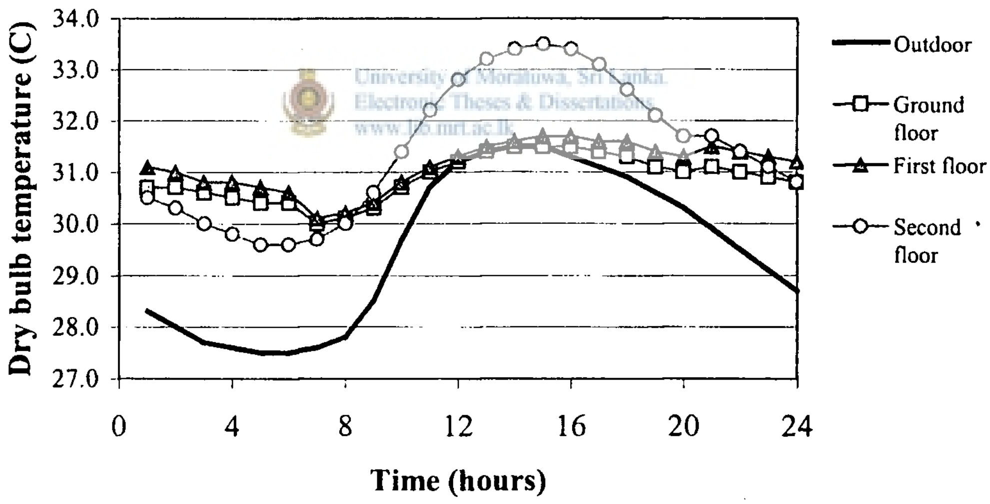
Although the validation of the software is an important component of the study, there were several practical problems making a proper validation difficult. They can be listed as the following:

1. One of the important inputs required by the software is the number of sunshine hours. This could not be measured in the thermal surveys as the equipment needed (i.e., the sunshine recorder) was not available.

2. The software takes into account the effect of ventilation by way of the number of airchanges, which is not very satisfactory.

However, using the average value for the sunshine hours, an attempt was made to validate the software. For this, the three-storey hostel building was used. The variation of the air temperature simulated by the software is given below in graphical form (Chart D.1). For comparison, the variation of the air temperature obtained form the actual measurements is given in Chart D.2.

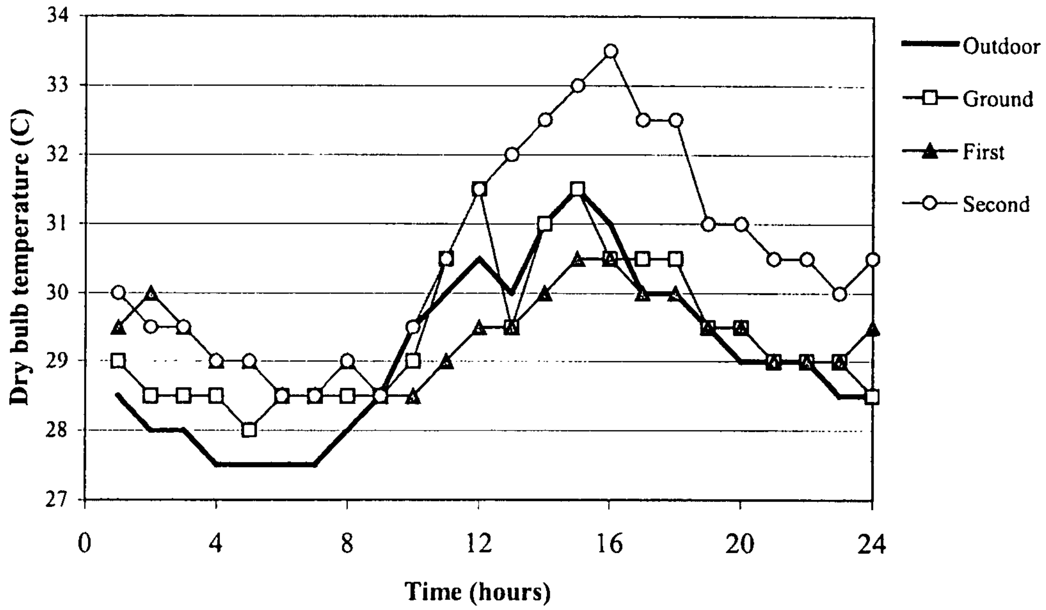
Chart D.1. Simulated results of three-storey hostel building in Moratuwa (August)



	Maximum temperature (C) (Time of occurrence)	Minimum temperature (C) (Time of occurrence)
Outdoor	31.5 (15 hours)	27.5 (5-6)
Ground floor	31.5 (14, 15, 16)	30.0 (7)
First floor	31.7 (15,16)	30.1 (7)
Second floor	33.5 (16)	29.7 (7)

Table D.1 Maximum and minimum temperatures for the simulated model, along with time of occurrence for each space

Chart D.2. Results of the thermal survey at three-storey hostel building in Moratuwa (August)



	Maximum temperature (C) (Time of occurrence)	Minimum temperature (C) (Time of occurrence)
Outdoor	31.5 (15 hours)	27.5 (4-7)
Ground floor	31.5 (12,15)	28.0 (5)
First floor	30.5 (15,16)	28.5 (6.7.9.10)
Second floor	33.5 (16)	28.5 (6,7,9)

Table D.2 Maximum and minimum temperatures along with time of occurrence for each space

Comparison of Charts 5.11 and 5.12 shows the following:

1. The software has simulated to a reasonable level the variation of the indoor temperature of the ground floor level and second floor level, highlighting the thermally undesirable effect of the roof.

2. However, it has not satisfactorily shown the difference between performance of the ground floor level and the first floor level.

Since the software is capable of simulating the thermally undesirable effect of the roof to a reasonable level, its use could be justified to a certain extent. However, the fact that the interest of this study is the prediction of the trends and not the prediction of exact conditions further reinforces the justification.

The simulated temperatures are given below.

Hour	Outdoor	Ground floor	First floor	Second floor
1	28.3	30.7	31.1	30.5
2	28	30.7	31	30.3
3	27.7	30.6	30.8	30
4	27.6	30.5	30.8	29.8
5	27.5	30.4	30.7	29.6
6	27.5	30.4	30.6	29.6
7	27.6	30	30.1	29.7
8	27.8	30.1	30.2	30
9	28.5	30.3	30.4	30.6
10	29.7	30.7	30.8	31.4
11	30.7	31	31.1	32.2
12	31.2	31.2	31.3	32.8
13	31.4	31.4	31.5	33.2
14	31.5	31.5	31.6	33.4
15	31.5	31.5	31.7	33.5
16	31.3	31.5	31.7	33.4
17	31.1	31.4	31.6	33.1
18	30.9	31.3	31.6	32.6
19	30.6	31.1	31.4	32.1
20	30.3	31	31.3	31.7
21	29.9	31.1	31.5	31.7
22	29.5	31	31.4	31.4
23	29.1	30.9	31.3	31.1
24	28.7	30.8	31.2	30.8