THERMAL DESIGN OF ROOF – A CASE STUDY OF PWD NEW QUARTERS DESIGN, MALAYSIA

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ABSTRACT

The housing industry in Malaysia is faced with one of the challenges of sustainable development in the built environment; that is providing quality modern houses with respect to thermal and energy performances. This research was carried out to address this challenge and several related issues, which are energy efficiency documentation and guidelines for residential buildings in Malaysia, climatic design of modern houses to address the problem of thermal comfort and concerns on energy efficiency, and recommended climatic design features to be adopted.

The aim of this research is to identify the thermal design of roof assemblage for optimum whole-building thermal and energy performances for low-rise detached residential buildings in Malaysia. The objectives are to quantify the optimum roof thermal parameters for best thermal performance, to apply the combined optimum roof thermal parameters and evaluate whole-building thermal and energy performances, and lastly to analyse the roof thermal design options pertaining to the thermal impact and cooling energy needs. The outcome is to contribute to recommendations for thermal design of the roofs for low-rise detached residential buildings in Malaysia.

The investigations were performed via numerical simulation on computer using **Tas** as a thermal design tool. The Public Works Department New Quarters Design (PWD-NQD) double-storey bungalow was used as the building model. The performance evaluations were based on dynamic whole-building analyses for each roof model. The material and construction of the envelope were based on conventional practice. The roof thermal parameters are the external surface colour of roof covering, air space layer beneath roof covering, supplementary thermal insulation beneath conventional radiant barrier, ventilation of roof space, option for horizontal ceiling, and thermal insulation over horizontal ceiling.

The respective computed optimum roof thermal parameters are light surface colour of roof covering, 50 mm of air space, 40 mm of supplementary thermal insulation, 10 air change per hour (ach) for roof space ventilation rate, and 20 mm of thermal insulation for horizontal ceiling. Selective combination of the optimum roof thermal parameters produced seven design options, each with models of four colours to consider the colour preference. The findings are compiled into charts for comparative performance evaluations of the roof thermal design options. All the design options reveal more significant thermal impact in the roof space than the selected occupied living spaces. The modest temperature modification found in the selected occupied living spaces results in a nominal thermal comfort improvement. The ultimate solution to augment the thermal comfort needs was provided by active cooling. While the thermal improvement is minimal, the impact on the energy for cooling needs indicated by the sensible cooling load is quite notable with a savings between 2.8 % to 12.6 %. This could be equivalent to an energy savings of up 2.1 % by the residential sector that translates to a national savings of 0.4 %.

In conclusion, the findings of this study reveal some potential in climatically responsive roof design alternatives. Despite the nominal thermal modifications from the investigated roof thermal design options, the implication on energy for cooling needs is noteworthy in view of the emerging demands for active cooling to ameliorate the thermal comfort condition.

ABSTRAK

Industri perumahan di Malaysia menghadapi salah satu daripada cabaran pembangunan mapan dalam alam terbina; iaitu untuk menyediakan rumah moden yang berkualiti dari segi prestasi terma dan tenaga. Kajian ini dibuat untuk menghadapi cabaran ini dan beberapa isu yang berkaitan, iaitu dokumen dan garispanduan kecekapan tenaga untuk bangunan kediaman di Malaysia, rekabentuk rumah moden yang berasaskan iklim untuk menghadapi masalah keselesaan terma dan kecekapan tenaga, dan adaptasi ciri-ciri rekabentuk berasaskan iklim.

Tujuan kajian ini ialah untuk mengenalpasti rekabentuk terma pemasangan bumbung untuk prestasi terma dan tenaga yang optima untuk keseluruhan bangunan bagi bangunan kediaman rendah berasingan di Malaysia. Objektif kajian adalah untuk mengkuantifikasi parameter terma bumbung yang optima untuk prestasi terma yang terbaik, untuk mengaplikasikan gabungan parameter terma optima bumbung dan menilai prestasi terma serta tenaga untuk keseluruhan bangunan, dan akhir sekali untuk menganalisis pilihan-pilihan rekabentuk terma bumbung yang berkaitan dengan impak terma dan keperluan tenaga untuk penyejukan. Hasil kajian ialah untuk menyumbang kepada cadangan rekabentuk terma bumbung untuk bangunan kediaman rendah berasingan di Malaysia.

Kajian telah dilakukan melalui simulasi komputer dengan menggunakan **Tas** sebagai satu peralatan rekabentuk terma. Kuarters banglo dua tingkat rekabentuk baru Jabatan Kerja Raya telah digunakan sebagai model bangunan. Penilaian adalah berdasarkan analisis dinamik keseluruhan bangunan untuk setiap model bumbung. Bahan dan pembinaan sampul bangunan adalah berdasarkan praktis semasa. Parameter terma bumbung adalah terdiri dari warna luar kepingan bumbung, lapisan udara di bawah kepingan bumbung, insulasi terma tambahan di bawah lapisan penghalang

radiasi, pengudaraan ruang bumbung, pilihan untuk pengunaan siling mendatar, dan insulasi terma di atas siling mendatar.

Parameter terma bumbung optima yang dikira adalah warna kepingan bumbung tidak gelap, 50 mm lapisan udara, 40 mm insulasi terma tambahan, 10 tukaran udara per jam (ach) untuk kadar pengudaraan ruang bumbung, dan 20 mm insulasi siling mendatar. Pemilihan gabungan parameter terma bumbung yang optima telah menghasilkan tujuh rekabentuk alternatif, setiap satu dengan empat pilihan warna untuk mengambilkira kegemaran warna. Semua hasil kiraan disusun dalam bentuk carta untuk penilaian perbandingan prestasi bagi rekabentuk terma bumbung. Setiap rekabentuk menunjukkan impak terma yang lebih ketara di ruang bumbung berbanding dengan ruang kediaman yang dipilih. Perubahan suhu kecil yang didapati di dalam ruang kediaman yang dipilih tersebut membawa kepada pembaikan keselesaan terma yang nominal. Penyejukan aktif digunakan sebagai penyelesaian muktamat untuk memenuhi keperluan keselesaan terma. Oleh itu, walaupun penambahbaikan terma adalah kecil, impaknya agak ketara ke atas keperluan tenaga untuk penyejukan aktif dengan penjimatan diantara 2.8 % ke 12.6 %. Ini boleh memberikan penjimatan tenaga sehingga 2.1 % dari sektor perumahan yang dapat ditukarkan kepada 0.4 % daripada kegunaan tenaga negara.

Sebagai kesimpulan, hasil kajian ini telah menunjukkan beberapa rekabentuk alternatif terma bumbung yang berpotensi untuk memberikan respon kepada iklim persekitaran. Walaupun rekabentuk alternatif bumbung dalam kajian ini membawa kepada penambahbaikan terma yang nominal, implikasi terhadap tenaga untuk penyejukan adalah wajar dipandang dari sudut peningkatan kehendak penggunaan alat penghawa dingin untuk memperbaiki keadaan keselesaan terma.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

Symbol	Unit	Meaning
A	m^2	area
c	$J\ kg^{-1}\ {}^{o}C^{-1}$	specific heat capacity
C	$Wm^{-2}K^{-1}$	thermal conductance
C1	-	roof colour
C2	-	roof colour
C3	-	roof colour
C4	-	roof colour
d	m	thickness
E	-	effective emissivity
h	$Wm^{-2}K^{-1}$	surface coefficient
k	$Wm^{-1}K^{-1}$	thermal conductivity
Q	J	quantity of heat
r	$m\ K\ W^{-1}$	thermal resistivity
R	$m^2\ K\ W^{-1}$	thermal resistance
R_i	$m^2\ K\ W^{-1}$	air film resistance of external surface
R_o	$m^2\ K\ W^{-1}$	air film resistance of external surface
t	s	time
T_1	^{o}C	external temperature
T_2	^{o}C	internal temperature
T_{diff}	^{o}C	temperature difference
$T_{i\ max}$	^{o}C	indoor peak temperature
T_{max}	^{o}C	maximum temperature
T_{mean}	^{o}C	mean / average temperature
T_{min}	^{o}C	minimum temperature
$T_{o\ max}$	^{o}C	outdoor peak temperature
T_{tc}	^{o}C	thermal comfort temperature
U	$Wm^{-2}K^{-1}$.	thermal transmittance
V	m^3	volume
H	$J\ {}^{o}C^{-1}$	heat capacity
α	-	solar absorptivity
β	$Wm^{-2}K^{4}$	Stefan-Boltzmann constant
ε	-	emissivity
ϕ	hour	time-lag

λ	-	solar reflectivity
μ	-	decrement factor
ρ	$kg\ m^{-3}$	density
τ	-	solar transmittivity

LIST OF ABBREVIATIONS

Abbreviation	Unit	Meaning
2D	-	two dimensional
3D	-	three dimensional
8^{th} MP	-	Eight Malaysian Plan
ach	per hour	air change rate
ACMV	-	Air Conditioning and Mechanical Ventilation
AS	-	air space
ASHRAE	-	American Society of Heating, Refrigerating, and Air Conditioning Engineers
BASE	-	base case model
BSI	-	British Standard Institution
CET	-	Corrected Effective Temperature
CFD	-	computational fluid dynamic
CIBSE	-	Chartered Institution of Building Services Engineer
CIn	-	ceiling insulation
CL	-	cooling load
CLI	-	cooling load index
CO_2	-	carbon dioxide
COLOUR	-	roof design option
COMBO	-	roof design option
COMBOCIn	-	roof design option
COMBOnc	-	roof design option
COMBORV	-	roof design option
COMBORVCIn	-	roof design option
COMBORVnc	-	roof design option
COP	-	coefficient of performance
CZ	-	comfort zone
DANIDA	-	Danish Agency for Development Assistance
DBT	°C	dry bulb temperature
ECI	-	Equatorial Comfort Index
EE	-	energy efficiency

EMS	-	Energy Management System
EP	-	energy performance
ET	-	Effective Temperature
GRB	-	Government Residential Building
HRB	-	horizontal radiant barrier
HVAC	-	Heating Ventilating and Air Conditioning system
IC	-	internal condition
IEA	-	International Energy Agency
J		Joule
K	-	Kelvin
kg	-	kilogram
LEO	-	Low Energy Office
m	-	metre
MHLG	-	Ministry of Housing and Local Government
mm	-	millimetre
MYC	-	Model Year Climate
nc	-	no-ceiling
NFVA	-	net free vent area
NQD	-	New Quarters Design
°C	-	degree Celsius
OTTV	-	Overall Thermal Transfer Value
PC	-	personal computer
PMV	-	Predicted Mean Vote
POE	-	Post Occupancy Evaluation
PPD	-	Predicted Percentage of Dissatisfied
PWD	-	Public Works Department
PWD-NQD	-	Public Works Department New Quarters Design
RB	-	radiant barrier
RG	-	Report Generator (**Tas** module)
RH	%	relative humidity
RIn	-	supplementary roof insulation
RTTV	-	Roof Thermal Transfer Value
RV	-	roof ventilation
s	-	second

SET	-	Standard Effective Temparature
SSG	-	surface solar gain
TC	-	thermal comfort
TCH	-	Thermal Comfort House
TMY	-	Typical Mean Year
TP	-	thermal performance
TRB	-	truss radiant barrier
TRY	-	Test Reference Year
U.K	-	United Kingdom
U.S.A	-	United States of America
UPM	-	University Putra Malaysia
W	-	watt
WBT	ºC	wet bulb temperature
WYEC	-	Weather Year Energy Calculation

CHAPTER 1: INTRODUCTION

1.1 Research background

One of the primary purposes of a building is to protect the occupants from the unfavourable external climatic elements. Besides providing the basic needs for shelter, the building industry is going through many conceptual as well as physical reformations in tandem with the human civilisation. This is clearly demonstrated by the interest of many professionals and academics in a sustainable built environment that has led to numerous studies on building designs (Santamouris, 2001; Baker and Steemer, 2000; Hyde, 2000; Givoni, 1998; Anink et al., 1996; Edwards, 1996; Thomas et al., 1996) and sophisticated building performance evaluations (Augenbroe, 2002; Hensen, 2002; Clarke, 2001; Cole, 1998) as well as energy resources (Australia, 2004a; FSEC, 2003; U.S.A, 2003). The primary concern is for harmonization of climate, building, man, and energy.

The alarm about global warming has galvanised the international community towards formulating global agreements to address the emerging related issues on humankind and environment (United-Nations, 2002, 1997, 1992). In the aspiration for Vision 2020, the Government of Malaysia has included sustainable development as one of the development thrusts in the ***Eight Malaysia Plan*** (Malaysia, 2001a). One of the strategies includes the provision for quality housing to enhance the quality of life, and the Malaysia Public Works Department (PWD) is taking the challenge by initiating a New Quarters Design (NQD) programme that embraces the principles of sustainability (Jaffar, 2004). The programme is at the forefront towards establishing the relevant standards and code of practices for residential buildings in Malaysia. Towards that end, building performance evaluation is one of the fundamental undertakings to be accomplished.

The national reviews regarding sustainable development focusing on climatic designs and energy efficiency (EE) have revealed the lack of supporting documentation and guidelines for residential buildings. While some general recommendations on climatic design strategies adopted from similar climates are available, a systematic and comprehensive study on the impact of the local climate is prudent and highly imperative to establish the national benchmarks. This need is substantiated by the findings of several studies on the climatic suitability of traditional houses (Zain-Ahmed, 2000; Harith, 1997; Abdul Rahman, 1994) and modern houses (Davis et al., 2000; Harith, 1997; Abdul Rahman, 1994; Hanafi, 1991) in Malaysia. Traditional houses were reported to demonstrate adaptations to the climate through the architectural design, and materials and construction of the envelope while the contemporary modern houses were criticised of being not climatically responsive.

For buildings in equatorial regions with warm humid climate such as Malaysia, the roof has been said to be a major source of heat gain (Olgyay, 1992; Koenigsberger et al., 1980; Markus and Morris, 1980; Givoni, 1976). Roof studies in other climates have shown significant impact on the thermal performance (Parker et al., 2003; Al-Sanea, 2002; Emmanual, 2002) and the cooling loads (Parker et al., 2003; Nini, 2002; Parker et al., 2001). Similar studies on houses in Malaysia have shown a nominal roof impact on the whole-building thermal performance in natural ventilation (Davis and Nordin, 2002a; Zakaria and Woods, 2002a, 2002b; Hanafi, 1991). However, except for Davis and Nordin (2002a) the data were not analysed for the cooling energy demand.

Despite the climatic design of traditional houses, previous findings have concluded that in both traditional and contemporary modern houses, a whole-day indoor thermal comfort could not be attained merely by natural means due to climatic factors as well as constructional constraints (Zain-Ahmed, 2000; Abdul Rahman, 1994; Hanafi, 1991); hence active cooling is necessary to augment the comfort needs. Therefore, in view of the global concerns on the various humanity and environmental issues in relation to energy, it is imperative to investigate the impact of building design on thermal and energy performance of houses in Malaysia. Consequently, this research is carried out in response to the discussed issues on residential buildings with reference to the contemporary modern houses focusing on the roof design.

1.2 Research issues and statement

The research issues discussed in the preceding section are summarised as follows:

- EE documentation and guidelines for residential building
- Failure of modern houses to provide quality housing with respect to thermal and energy performances
- Climatic design strategies to be adopted.

The stated research issues relate to the performance of the building based on a whole-building analysis. The thermal and energy performances are determined by the heat exchanges of the building. These exchanges are influenced by the building response to the local climate. Control of the heat exchanges can be achieved via proper thermal design of the building envelope. For buildings in lower latitude regions, vis-a-vis the Equator, the roof has been said to be the major source of heat gain. This heat gain would be more significant in low-rise residential buildings. Thus, appropriate thermal design of the roof would be able to moderate the thermal impact from the local climatic conditions. This research explores the thermal design of the roof for a Public Works Department New Quarters Design (PWD-NQD) double-storey bungalow by evaluating the dynamic whole-building thermal and energy performances.

1.3 Aim, objective and outcome of research

The research aim, objectives, and outcome were resolved following the stated research issues and statement.

a) **Aim**: The aim is to identify the thermal design of roof assemblage for optimum whole-building thermal and energy performance for low-rise detached residential buildings in Malaysia.

b) **Objectives**: To achieve this aim, the objectives of this research are:

i) To quantify the optimum roof thermal parameters for best thermal performance

ii) To apply the combined optimum roof thermal parameters and evaluate whole-building thermal and energy performances

iii) To analyse the roof thermal design options pertaining to the thermal impact and cooling energy needs.

c) **Outcome**: The outcome of the study is to contribute to recommendations for thermal design of the roofs for low-rise detached residential buildings in Malaysia.

1.4 Significance of research

This research investigates the strategies for the roof thermal design for warm humid climate that have been recommended by researchers in the country and from abroad. It is a systematic study to identify and quantify the suggested climatic design elements and analyses the detail impact of various design alternative approaches for the roofs of low-rise detached residential buildings in Malaysia. It produces a series of definitive analysis on the impact in terms of thermal performance and energy consumption requirement incorporating realistic loads and heat transfer in a real building. Every roof thermal parameter identified in the previous international and national studies were methodically analysed to converge to several realistic design alternatives within the bounds of the conventional contemporary practices and the available construction technology in Malaysia. The research findings could assist designers for a comparative analysis and serve as a basis for other design tools to be transpired from further research.

1.5 Research Methodology

This study has proposed to achieve the aim of the research by exploring and evaluating the suitable thermal design of the roofs for low-rise detached residential buildings in Malaysia. Subsequently, several roof design options were identified and quantified by dynamic whole-building thermal and energy analyses. To achieve these, a number of roof parameters and variables were considered and selected permutations were executed.

For those endeavours, the most realistic and economical research method was numerical simulation via computer modelling. Suitable computer thermal design software was selected as the experimental tool. The investigations were performed within the defined scope of research, the analyses were confined within the capacity of the generated output data, and the research outcome was formulated within the limitation of research. The research process is illustrated in Figure 1.1.

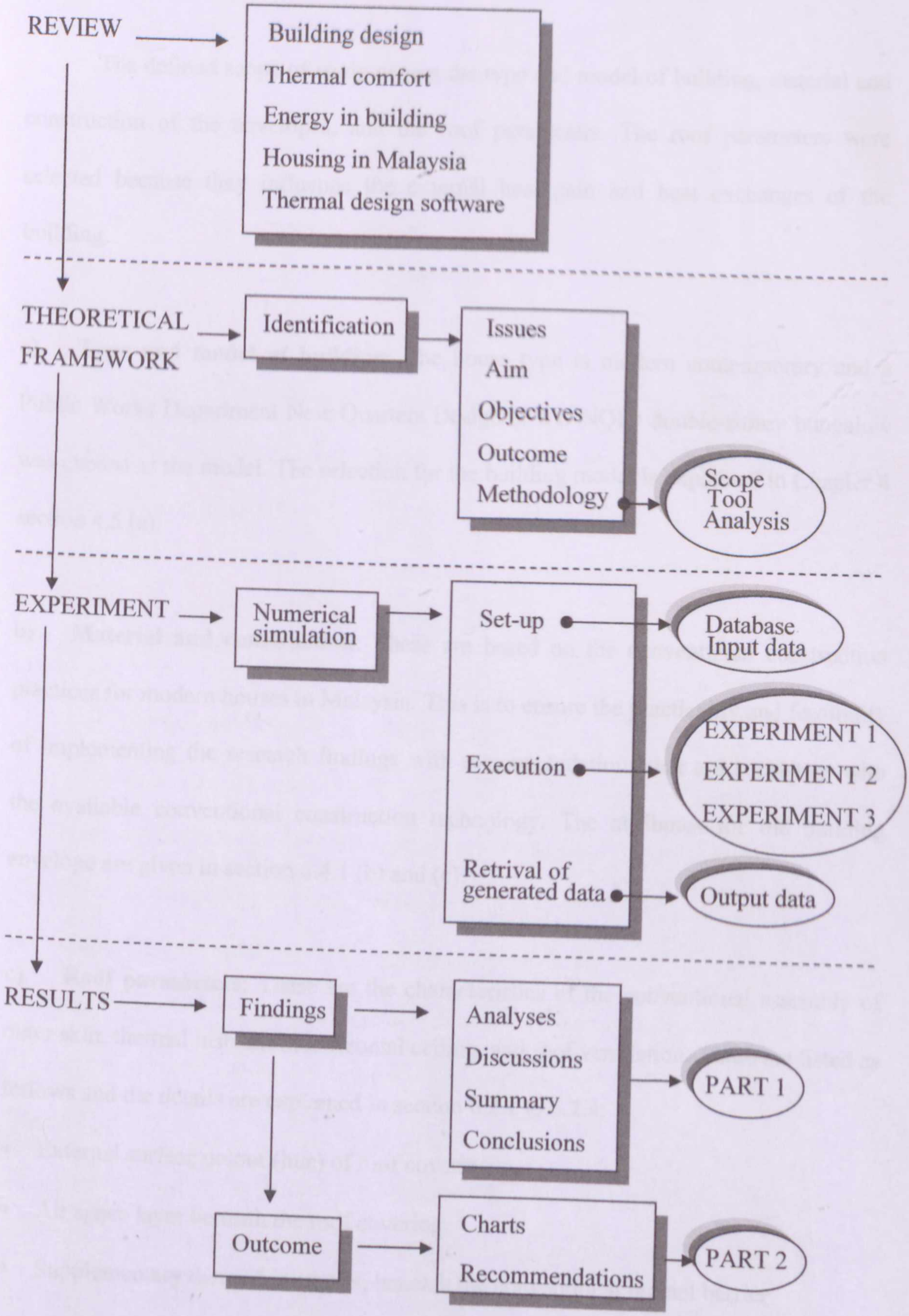

Figure 1.1: Research process chart

1.5.1 Scope of research

The defined scope of study covers the type and model of building, material and construction of the envelopes, and the roof parameters. The roof parameters were selected because they influence the external heat gain and heat exchanges of the building.

a) **Type and model of building**: The house type is modern contemporary and a Public Works Department New Quarters Design (PWD-NQD) double-storey bungalow was chosen as the model. The selection for the building model is explained in Chapter 4 section 4.5 (a).

b) **Material and construction**: These are based on the conventional construction practices for modern houses in Malaysia. This is to ensure the practicality and feasibility of implementing the research findings with recommendations that are consistent with the available conventional construction technology. The attributes for the building envelope are given in section 6.4.1 (b) and (c).

c) **Roof parameters**: These are the characteristics of the conventional assembly of outer skin, thermal insulation, horizontal ceiling, and roof ventilation. These are listed as follows and the details are explained in section 6.2.1 to 6.2.4:

- External surface colour (hue) of roof covering
- Air space layer beneath the roof covering
- Supplementary thermal insulation beneath the conventional radiant barrier
- Ventilation of roof space
- Option for horizontal ceiling
- Thermal insulation over the horizontal ceiling

1.5.2 Investigation tool

Tas was selected as the most appropriate thermal design software (refer to Chapter 5 for the selection). It was used to perform dynamic whole-building simulations and the analyses were based on the generated output data.

1.5.3 Analysis

Appraisal for performance evaluations were based on the analyses of thermal performance in terms of the thermal comfort hours, and energy performance in terms of cooling load consumption.

1.6 Thesis organisation

The thesis comprises of eight chapters as follows:

Chapter 1 presents an overview of the research that covers a brief introduction to the research background, issues and statement, aim, objectives, outcome, significance of research, and the research methodology employed in the study.

Chapter 2 reviews the international studies of building design for warm-humid climates. It covers the climatic design strategies and thermal designs of the roof. A brief introduction to some basic thermophysical properties of material and construction is included.

Chapter 3 reviews the national studies on climatic design of residential buildings in Malaysia. It covers the thermal performances of traditional and modern houses. An overview of the climate, thermal comfort studies, and energy in building are included.

Chapter 4 outlines the research methodology that includes discussions on the research issues and statement, aim, objectives, outcomes, scope, approach, and analyses.

Chapter 5 discusses the evaluation for the selection of the computer-modelling simulation tool and includes an overview of **Tas** that was chosen as the thermal design software. The evolution and applications of the building simulation technology in building performance assessments in research and real practices are highlighted.

Chapter 6 explains and elaborates the process for the numerical simulation by means of computer modelling. It includes the experimental design, setting up of the relevant input data for the software, and finally the execution of the simulation.

Chapter 7 presents the analyses and discussion of results. These are illustrated in tables and graphs. The findings are summarised to produce charts to assist with the comparative analyses for the performance evaluations.

Chapter 8 concludes the thesis by relating the major findings to the research objectives and suggest a design recommendation. The significant contribution to knowledge is highlighted. It also discusses the probable implications on the national energy usage and the conventional design concepts. Subsequently, recommendations for further work in this research area are made.

In this thesis, residential building refers to domestic dwelling in form of houses and the terms are used interchangingly. Optimum is defined as the condition for the best thermal performance that would be constructionally viable and would not deviate from the contemporary conventional construction practices in Malaysia. EE refers to the necessary usage of active cooling to supplement the thermal comfort needs in response to the thermal impact of the envelope designs.

CHAPTER 2: GENERAL OVERVIEW OF BUILDING DESIGN IN WARM HUMID CLIMATE

2.1 Introduction

This chapter presents a summary of an international review on the concepts and applications of climatic and thermal design of buildings in warm humid climate, for houses in general and roofs in particular. The recommended characteristics and strategies as suggested in many references based on the architectural concepts and general principles of heat transfer are discussed. This includes studies on thermal design of roofs that discuss the influence of thermophysical properties on thermal and energy performances of roof spaces as well as the whole building.

2.2 Climatic building design

The concerns and the necessity of the harmonization involving climate, building, man and energy have been extensively discussed, and articulately expressed and documented in numerous references from countless thermal studies of buildings (Krishan et al., 2001a; Santamouris, 2001; Baker and Steemer, 2000; Hyde, 2000; Givoni, 1998; Santamouris and Asimakopolous, 1996; Givoni, 1994; Olgyay, 1992; Szokolay, 1991; Simha, 1985; Hawkes and Owers, 1981; Markus and Morris, 1980; Koenigsberger et al., 1980; Saini, 1980; Evans, 1979; Givoni, 1976; Straaten, 1967; Rogers, 1964). Consequently, a range of recommendations and guidelines for climatic design strategies has been proposed. In this section, the discussions, suggestions, and recommendations on building designs and the appropriate design strategies are subsequently reiterated, examined, summarised, and discussed together with the findings from other related studies.

One of the primary purposes of a building is to protect the occupants from the unfavourable outdoor conditions such as heat, cold, wind, and rain. Apart from providing shelter, to make the building habitable and functional, it should provide the needed and required indoor environment. Thus, the building should be designed and constructed to provide the desirable indoor climate by acting as a barrier or modifier between the exterior and interior climates. This means to take advantage of the favourable climatic elements and control or modify the unfavourable ones. The indoor climate is the condition consisting of all the physical properties in a room that influence the sensation of comfort of a person (Fanger, 1972). The main concern is the thermal impact of climate on building that subsequently affects the physiological, psychological, and physical functions of the human body for health, well being, and comfort.

For tropical climate where heat and humidity are the dominant problems, wind is beneficial while the intense solar radiation could be detrimental. Climatic control by the building can be accomplished through climatic design with the application of thermal design of buildings and these are further discussed in detail throughout the chapter. The control of the built environment could be achieved by passive and/or active mechanical means. However, passive means have their limitations where active mechanical means would be the final alternative to augment the comfort requirements. Therefore, various forms and sources of energy would be used to operate and maintain these buildings for its functional use to attain the necessary level of comfort.

There are growing global interests and concerns on the energy resources and related environmental matters, and the consequential impact of human activities on the environment for our future generations (United-Nations, 2002; 1997; 1992). The worldwide awareness and the initiatives taken by the international community with the commitments and support by the many world leaders and governments have heightened the public awareness on the issues in various related sectors.

With regards to built environment, the primary concern is for sustainability in the developments of building industry and building energy consumption. These have positioned many professionals in the building industry; builders, engineers, architects and scientists alike, into the limelight, and have added vigour to inspire further research in the areas of *climatic design* (Capeluto et al., 2003; Prianto and Depecker, 2003; Oktay, 2002; Al-Homoud, 1997; Hyde and Docherty, 1997; Kindangen, 1997; Coch and Serra, 1996; Krishan et al., 1996; Chancellor, 1994; Ali et al., 1993; De Wall, 1993), *passive design* (Oral et al., 2004; Tang, 2002; Marsh et al., 2001; Ansley, 1999; Khedari et al., 1996; Yezioro and Shaviv, 1996), *bioclimatic design* (Emmanual, 2002; Labaki and Kowaltowski, 1998; Yeang, 1998), *thermal design* (Emmanual, 2002; BRANZ, 2001; Marsh et al., 2001; Gamble, 1999; Al-Homoud, 1997; Friedman and Cammalleri, 1996), *low energy design* (Coley and Schukat, 2002; Ahmad, 1999; Ansley, 1999), *energy efficient design* (Oral et al., 2004; Marsh et al., 2001; Carpenter et al., 1996; Elnahas, 1994), and *green* or *sustainable* or *environmental design* (Huong and Soebarto, 2003; Oktay, 2002; Yeang, 1998) with an endless list of researchers, not forgetting the contributions from renewable energy studies.

The ultimate aim of the studies was to maximise the utilisation of beneficial parameters of external climate and to minimise the impact of the unfavourable ones on the building, which is the principle of *climatic design.* In other words, it was to maximise indoor comfort by minimising the adverse climatic effect with optimum energy consumption using sustainable resources for protection of the environment. All those studies on building design are subsets of each other and interrelated in many aspects; differed perhaps by the approach and terminology in some, whereby the fundamental concept is *climatic design* that is 'design for the climate'.

Bioclimatic designs are designs to respond to the environment by the use of suitable material to achieve comfort with the minimum use of energy by active and/or passive means (Givoni, 1994; Olgyay, 1992). On the contrary, comfort in the *passive designs* is to be obtained by means of appropriate design and structural controls that utilise the natural climatic elements such as sun and wind (Santamouris, 2001; Givoni, 1998; Santamouris and Asimakopolous, 1996; Givoni, 1994). The moderation of the adverse climatic elements through building envelope can be achieved via the application of the principles of *thermal design* (Rogers, 1964). *Thermal design* of building can be defined as *a technical design technique for the construction of the envelopes to act as an efficient thermal barrier between the indoor and the outdoor conditions* (Rogers, 1964). It controls the indoor climate by the thermal characteristics of the material and construction of the envelope, consequently minimising the heating and cooling needs. The application of any mechanical devices to modify the indoor climate would be illogical if the architectural design, the material, and the construction of the envelopes are not appropriate for the climate. Thus, these can be categorised as studies in the area of *low energy design*. It is a study of architectural designs that lead to low energy consumption to achieve the desirable indoor climate via active or passive means. If these designs were to consider the environmental impact and the sustainability of the resources for construction, operation, and maintenance, then they can also be clustered into *green* and *sustainable design* (Thomas et al., 1996; Anink et al., 1996; Vale and Vale, 1991). As much as the physical building is concerned, these features are also among the characteristics for *energy efficient designs* – to be augmented with energy efficient building service systems, and lastly the most crucial element is the 'energy efficient behaviour' of the occupants (Baker and Steemer, 2000).

To conclude, climatic design of buildings can therefore be defined as buildings designed with adaptation to climate by means of appropriate architectural design strategies employing the principles of thermal design using suitable building material. Climatic designs are designs that are thermally efficient for air-conditioned buildings, or thermally comfortable for passively cooled buildings (De Wall, 1993). Thus, a climatically well-designed building should either improve the desirable indoor comfort in natural environment, or reduce the energy required for active control (Turner and Szokolay, 1982).

Various design strategies have been studied and several design characteristics are recommended for the different types of climate. The first approach in the climatic design suitability is passive design by means of thermal controls employing appropriate thermal design techniques. The principal strategy of thermal design is the control of building heat transfer via the thermophysical properties of the material and construction. Therefore, the architectural design and the thermophysical properties of the building material are two main elements of climatic design. The former influences the ventilation and heat transfer in the spaces while the latter determines the heat gains and/or losses into and out of the building. In the thermal design process, the climatic suitability of the building material can be evaluated by the thermal and energy performances of the building.

In summary, it is concluded that climatic design and thermal design are the basis for energy efficiency in building with respect to the requirements for indoor comfort. Accordingly, the design strategies recommended for houses in warm/hot humid climate are described and discussed in terms of the climatic architectural design and thermal design. The architecture climatic design strategies are presented in the following section while the thermal design is presented in section 2.3.

2.2.1 Architectural climatic design strategies

For a tropical climate, solar radiation is one of the most important natural contributors to heat gains in dwellings where heat and humidity stresses are exacerbated by low and variable wind speed, with roof being the greatest receiver during daytime

(Al-Sanea, 2002; Emmanual, 2002; Santosa, 2000; Olgyay, 1992; Koenigsberger et al., 1980; Markus and Morris, 1980; Evans, 1979; Mukhtar, 1978; Givoni, 1976). The direct effect of solar radiation is overheating and an extra load on air conditioning (Szokolay, 1975). Therefore, the control of heat gain is of paramount importance for this climate, and the first control of heat entry is at the surface of the envelope (Olgyay, 1992).

Thermal control for buildings in hot climates can be achieved by means of mechanical control, structural control, and ventilation and air movement (Koenigsberger et al., 1980). Mechanical controls involve the use of mechanical or active systems for cooling needs. On the other hand, structural controls are passive strategies via appropriate thermophysical properties of material, building orientation and configurations, and sun shading devices. Lastly, fenestration is a crucial factor for ventilation and air movement.

The objectives of thermal control in warm humid climate are to prevent heat gain, maximise heat loss and to remove any excess heat by cooling (Koenigsberger et al., 1980). The first two can be achieved via structural control and ventilation using passive means, while the last one requires mechanical control using active sources of energy. With due considerations on energy efficiency, the former strategies must be fully exploited before resorting to the latter. The recommended strategies (Krishan et al., 2001b; Hyde, 2000; Givoni, 1998; Koenigsberger et al., 1980; Markus and Morris, 1980; Olgyay, 1992; Evans, 1979; Givoni, 1976) are summarised below.

a) **Form and planning**: These are to minimise solar gains and assist cross ventilation so as to maximise air movement which can be achieved with the following approaches:

- Shape, configuration and orientation
- Large openings with shading devices

- Elevated above ground

b) **Walls**: The principles of thermal storage do not work for regions with small diurnal variations. Thus, the use of lightweight with low thermal capacity material and minimising the wall area are strategies that can take advantage of the accessible wind. This would downplay the influence of the wall; therefore, the roof would have a more dominant thermal effect.

c) **Roof**: Roof is the greatest receiver of solar radiation in tropical climate where heat is the prevailing problem coupled with heavy rainfall. It must be designed to reject heat, and provide adequate shading and water drainage. The suggested roof characteristics are:

- Pitched
- Large eaves
- Double roof
- Ventilated roof space
- Low thermal capacity with reflective upper surface
- Thermal insulation

d) **Ceiling**: The use of ceiling with the following features is recommended to act as a thermal barrier:

- High reflective upper surface
- Low thermal capacity
- Good resistive insulation.

e) **Thermal insulation**: The application of thermal insulations at several locations are suggested;

- Ceiling level or underneath the upper roof layer
- Aluminium foil beneath roof to reduce radiant heat transfer
- Supplementary insulation above or beneath the ceiling

2.3 Thermal design

The decisions in the thermal design process are considered mainly on three factors; the required indoor climate, the outdoor prevailing weather condition, and lastly the thermophysical properties of material (Chandra, 1980; Straaten, 1967; Rogers, 1964). The underlying principle is heat exchange of building, which is a complex process of heat transfer involving external and internal heat gains and losses comprising of sensible and latent heat, influenced by the thermal properties of the materials and constructions as well as the weather conditions (Koenigsberger et al., 1980). Koenigsberger et al. (1980) described the heat exchange process as in Equation 2.1 and illustrated in Figure 2.1.

$$Q_i + Q_s \pm Q_c \pm Q_v \pm Q_m - Q_e = 0 \qquad \text{Equation 2.1}$$

where;

Q_i = internal heat gain (human bodies, lamps and household appliances)

Q_s = heat gain due to solar radiation through opaque surfaces and glazing

Q_c = heat transfer via conduction (gains and/or losses) by building envelopes

Q_v = heat exchange via ventilation

Q_m = heat introduction (heating) or removal (cooling) by mechanical controls (heater/air-conditioner)

Q_e = heat removal via evaporation

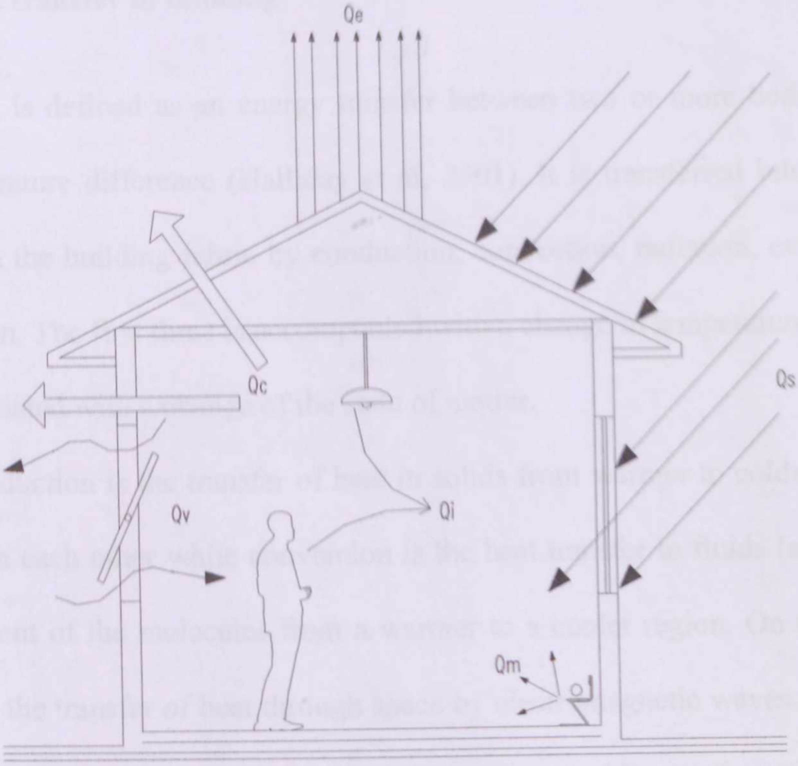

Figure 2.1: Heat exchange of building
(source: Koenigsberger et al, 1980)

A thermal equilibrium is maintained when the net heat exchange is zero. The building is cooling down (losing heat) when the net heat exchange is negative and conversely is heating up (gaining heat) when it is positive. The energy efficiency strategies for warm humid climate are to optimise the structural controls by minimising the heat gains via Q_s (radiation) and Q_c (conduction) while maximising the heat losses via Q_v (ventilation) and Q_e (evaporation) with the aim of minimising Q_m. The application of the thermal design requires knowledge on the concepts of heat transfer and understanding of the thermal effects of building materials. These are briefly explained in subsequent sections together with thermophysical properties and the climatic suitability of materials (Olgyay, 1992; Szokolay, 1987; Simha, 1985; Markus and Morris, 1980; Koenigsberger et al., 1980; Evans, 1979; Givoni, 1976; Szokolay, 1975; Straaten, 1967; Rogers, 1964).

2.3.1 Heat transfer in building

Heat is defined as an energy transfer between two or more bodies as a result from temperature difference (Halliday et al, 2001). It is transferred into and out of a building via the building fabric by conduction, convection, radiation, evaporation, and condensation. The first three is accompanied with a change in temperature while the last two is associated with a change of the state of matter.

Conduction is the transfer of heat in solids from warmer to colder molecules in contact with each other while convention is the heat transfer in fluids (air or water) by the movement of the molecules from a warmer to a cooler region. On the other hand, radiation is the transfer of heat through space by electromagnetic waves. Evaporation is the process of heat gain where liquid changes to gas while condensation is heat lost when gas changes to liquid.

The mode of heat transfer may change during the process of heat exchange. When a building receives solar energy by radiation all of the incident solar energy is absorbed (α), reflected (λ), or transmitted (τ) by the different parts of the envelope depending on the type of material and properties of the receiving surfaces (refer to Figure 2.2). The absorbed energy is later being transmitted into or out of the building, whereby the sum of heat transferred is equal to the total energy received.

$$\alpha + \lambda + \tau = 1 \qquad \text{Equation 2.2}$$

For opaque materials, all energy must either be absorbed or reflected. The proportion depends on the thermophysical properties of the envelope that includes the type of material and construction as well as the surface characteristics. These properties are explained in section 2.3.2. The absorptivity to solar radiation ranges from 15 % for polished aluminium surfaces to 97 % for black matte surfaces (Olgyay, 1992). Transparent material directly transmit most of the solar radiation falling on it and the remaining is reflected and/or absorbed in proportion that depends on the transmission characteristics of the glazing materials. The respective proportion of solar radiation transmitted, absorbed, and reflected ranges from 80 %, 13 %, and 7 % for clear glass to 46 %, 15 %, and 39 % for heat reflecting solar control glass (Evans, 1979).

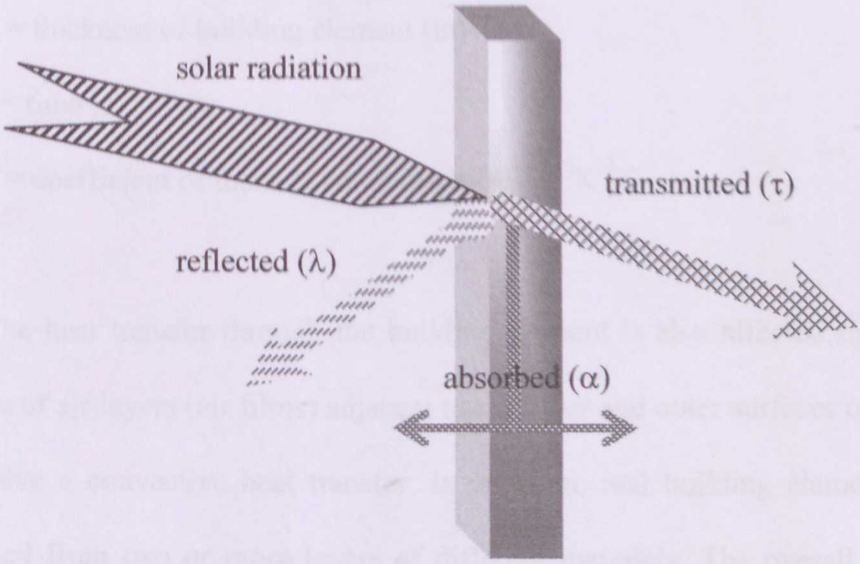

Figure 2. 2: Effect of solar radiation on building envelope
(source: Givoni, 1976)

The calculation of the heat transfer through a building element is complicated because more than one mode of heat transfer could occur at different parts of the envelope sections. The modes and the proportions are determined by the type and properties of the material as well as the external weather variations.

For the simplest case by looking at only Q_c in Equation 2.1, refer to Figure 2.2 for heat absorbed at the surface of a building element via conduction under steady-state condition. This is the heat transfer when the temperature difference between the outdoor and indoor is constant. The rate of heat conducted into the building (P_{cond}) is given by (Halliday et al, 2001, Incropera and DeWitt, 1996):

$$P_{cond} = \frac{Q}{t} = \frac{kA(T_1 - T_2)}{d} \quad \left(\text{W or Js}^{-1}\right) \qquad \text{Equation 2.3}$$

where;

Q = quantity of heat

T_1 = external temperature (°C)

T_2 = internal temperature (°C)

A = area of building element (m^2)

d = thickness of building element (m)

t = time (s)

k = coefficient of thermal conductivity ($Wm^{-1}K^{-1}$)

The heat transfer through the building element is also affected by the thermal resistance of air layers (air films) adjacent to the inner and outer surfaces of the element that involve a convective heat transfer. In addition, real building elements could be constructed from two or more layers of different materials. The overall heat transfer then depends on the property of the construction assembly called the thermal transmittance or the U-value. Therefore, the actual heat transfer calculation is expressed in terms of the U-value that includes the total resistance of the materials as well as the air film resistance of outer and inner surfaces. These properties are explained in section 2.3.2. The heat transfer equation is then given as (Incropera and DeWitt, 1996);

$$Q = UA(T_1 - T_2) \qquad \text{Equation 2.4}$$

where;

U = thermal transmittance ($Wm^{-2}K^{-1}$)

In actual situations, the diurnal variations of the weather conditions produce a non-steady state or transient heat transfer. It is a repetitive 24-hour cycle of increasing and decreasing temperatures described as periodic and is illustrated in Figure 2.3. The pattern of heat transfer shows the thermal effect of building material on the indoor air temperature. The proportion between the indoor peak temperature ($T_{i\ max}$) and the outdoor peak temperature ($T_{o\ max}$) is determined by the decrement factor, μ, and occurs at a later period determined by the time-lag, φ, and is given as (Koenigsberger et al, 1980);

$$\mu = \frac{T_{i\ max}}{T_{o\ max}} \qquad \text{Equation 2.5}$$

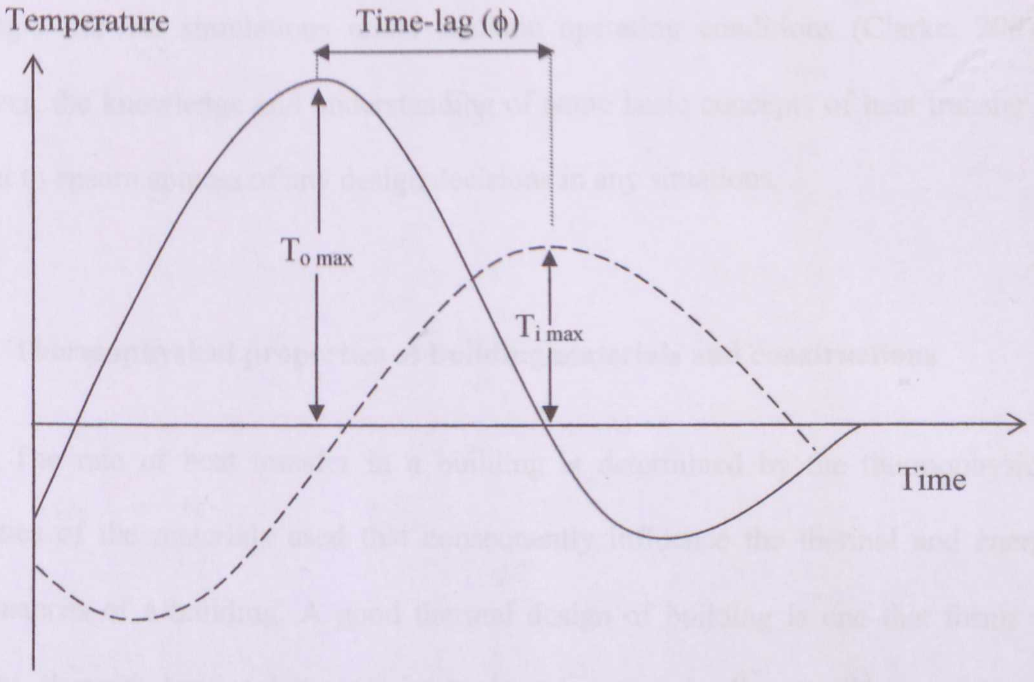

Figure 2.3: Temperature profile due to transient heat transfer
(source: Koenigsberger et al, 1980)

The preceding steady-state and transient state heat transfer equations are an oversimplified mathematical representation for one type of heat transfer through a segment of an envelope. In reality, the heat exchange of building as shown in Figure 2.1 and the detail calculations for Equation 2.1 involves a series of complex transient-state mathematical formulations. These are due to the interactive thermal effect between the building and the external as well as the internal environment, and the interplay effects of multi-layer constructions arising from the different physical and thermophysical properties. The predictions of the thermal and energy performances require a whole-building analysis that involves further computations coupling the thermal and the cooling energy loads. These complex computations require a highly knowledgeable person for the design or performance appraisals, thus are unwieldy for general practical applications (Straaten, 1967).

The advent of advanced and sophisticated computer-modelling softwares to compute the complex mathematical formulations has provided a solution and an impetus for the evaluation of numerous performance appraisals at various stages of a building's life via simulations under realistic operating conditions (Clarke, 2001). However, the knowledge and understanding of some basic concepts of heat transfer is prudent to ensure aptness of any design decisions in any situations.

2.3.2 Thermophysical properties of building materials and constructions

The rate of heat transfer in a building is determined by the thermophysical properties of the materials used that consequently influence the thermal and energy performances of a building. A good thermal design of building is one that forms an efficient thermal barrier between internal and external climates (Rogers, 1964). Therefore in thermal design, building materials that could stop, delay, or dampen the rate of heat transfer would be more desirable. The basic thermophysical properties of materials in relation to the heat transfer and the subsequent thermal effects are briefly discussed along with climatic suitability as follows:

a) Heat transfer

The thermophysical properties in relation to heat transfer in building envelope via conduction, convection, and radiation are identified as follows:

i) *Thermal conductivity (k-value), thermal resistivity (r-value), thermal conductance (C), and thermal resistance (R)* – heat transfer via conduction:

- *k-value and r-value*: k-value is the ability of the material to absorb and transmit heat while r-value is the resistance to heat transfer and is the reciprocal of the k-value.

$$r = \frac{1}{k} \quad \text{(Malaysia, 1989)} \qquad \text{Equation 2.6}$$

  These are the properties of material and are independent of the size and thickness of the material. The unit for k-value is $Wm^{-1}K^{-1}$ and for r-value is mKW^{-1}. The k-value is affected by the moisture content, temperature, and porosity of the material.

- *C and R*: the actual heat transfer across a building element depends on the k-value and the r-value of the material as well as its thickness, d, whereby the rate of heat transfer is inversely proportional to the thickness. The properties with a given thickness are denoted by C or R. C is defined as the ability of a specific thickness of material or construction to transmit heat. The unit for C is $Wm^{-2}K^{-1}$.

$$C = \frac{k}{d} \quad \text{(Malaysia, 1989)} \qquad \text{Equation 2.7}$$

- R is the resistance to heat transfer of a material or construction of a specific thickness. R is the reciprocal of C and the unit is m^2KW^{-1}.

$$R = \frac{1}{C} = \frac{d}{k} \quad \text{(Malaysia, 1989)} \qquad \text{Equation 2.8}$$

ii) *Thermal transmittance (U-value)* – heat transfer via conduction and convection: The air-to-air heat transmission through a building section is determined by the U-value that depends on the material, thickness, construction, and the air film resistances. It is the reciprocal of the total thermal resistance (R_t) and is a property of a construction assembly. The unit for U is $Wm^{-2}K^{-1}$.

$$U = \frac{1}{R_t} \quad \text{(Malaysia, 1989)} \qquad \text{Equation 2.9}$$

where

$$R_t = R_o + R_1 + R_2 + ... + R_n + R_i$$

$$= R_o + \frac{d_1}{k_1} + \frac{d_2}{k_2} + ... + \frac{d_n}{k_n} + R_i$$

and

R_o= air film resistance of external surface ($m^2\ K\ W^{-1}$)

R_i = air film resistance of internal surface ($m^2\ K\ W^{-1}$)

R_1, R_2, ….., R_n = thermal resistance of the respective material.

The reciprocal of the air film resistance is the surface coefficient and is explained in (iv) below.

iii) *Absorptivity (α), reflectivity (λ) and emissivity (ε)* – heat transfer via radiation: The surface characteristics determine the means and the rate of heat transfer from the external surface of a body to one or more other bodies, or to other surfaces such as the surrounding air, or the sky.

- α: it determines how much solar radiation will be absorbed. A surface colour with darker hues absorbs more solar radiation than the lighter ones. The value ranges from 0.3 for white paint to 0.9 for black paint.
- λ: it determines the how much solar radiation will be reflected. It ranges from 0.9 for light coloured with smooth and shinny surfaces to 0.1 for dark, rough, and dull surfaces.
- ε: it is the ability of a surface to emit or re-radiate the absorbed radiant energy and is exhibited by all building materials. The net radiant heat exchange depends on various factors, such as colour, texture, as well as the shape and the configurations with respect to the each other. This radiant heat is referred as low-temperature radiation, or thermal radiation, or long-wave radiation as opposed to short-wave solar radiation from the sun. It ranges from 1.0 for a perfectly black surface to 0.05

for bright aluminium. A black coloured surface has a high α value, thus is hot at daytime. However, the high ε value of the black coloured surface causes it to cool down faster and at night-time could be at a lower temperature than a bright reflective surface. For all parallel surfaces regardless of the orientation, both surfaces simultaneously absorb and emit radiation. The radiation heat exchange between the surfaces depends on the emissivity of both surfaces, whereby the effective emissivity (E) is (Givoni, 1976);

$$E = \frac{\varepsilon_1 \varepsilon_2}{(\varepsilon_1 + \varepsilon_2) - (\varepsilon_1 \varepsilon_2)} \qquad \text{Equation 2.10}$$

- The use of relective foil as a radiant barrier on one of the surfaces would reduce the E of an enclosed air space by about 94 % while the usage of such material on both surfaces would reduce it by 96 % – an additional reduction of only 2 % (Givoni, 1976).

iv) *Surface coefficient* (*h*) – heat transfer via conduction, convection, and radiation: This is due to heat transfer at the surface that comprises of convective and radiative heat exchanges. The rate of heat exchanges is determined by the surface coefficient. The convective surface coefficient (h_c) is dependent on the air velocity near the surface, which is influenced by wind or air movement. The radiative part (h_r) is dependent on the emissivity as well as the temperature of the surfaces. The surface coefficient is the reciprocal of air film resistance and the unit is $Wm^{-2}K^{-1}$.

v) *Thermal conductance of air spaces* – heat transfer via radiation, convection, and conduction: The air spaces inside a material or construction provide resistance to heat transfer. The conductive and convective components are dependent on the thickness of air space (width of cavity), position of the spaces (horizontal, vertical, sloping), and lastly on the direction of heat transfer (horizontal, upwards or downwards). The radiative part is independent on the direction of the heat transfer but is greatly influenced by the effective emissivity of the inner surfaces, E, as given in Equation 2.10. The application of aluminium foil as a radiant barrier reduces the E of the surfaces, thus improving the insulation value of the air space. Covering one surface of the cavity with foil reduces the thermal conductance by two to three times (Straaten, 1967), but the little additional reduction with the use foil on both surfaces entails a cost saving analysis.

vi) *Heat capacity (C):* Heat capacity is defined as the amount of heat (Q) required to increase the temperature of a solid or liquid by one degree in unit of J $°C^{-1}$. It can be expressed as heat capacity per unit mass, that is the specific heat capacity, c, ($Jkg^{-1} °C^{-1}$) or heat capacity per unit volume, that is the volumetric heat capacity, C_V, ($Jm^{-3} °C^{-1}$).

b) Thermal effect

The periodic heat transfer in transient state illustrated in Figure 2.3 shows the indoor temperature due to external heat transfer is determined mainly by the decrement factor (μ) and the time-lag (ϕ). These are the thermal effects of the interplay of thermal conductivity, thermal resistance, heat capacity, and heat transmission, and are not elaborated in this discussion due to the intricacy of the interactions. Nonetheless, the understanding of these interactive effects could be exploited to create the desirable indoor conditions.

It can be summarised that for application purposes the decrement factor and the time-lag are the fundamental thermal effects to be considered in selecting the materials and the constructions for the envelope. These are determined by the thermal insulation properties and thermal capacity that are directly influenced by the thickness of the material, whereby the thickness also affects the U-value.

i) Thermal capacity

Thermal capacity is the ability of the material and construction to store and release heat. It is also known as thermal storage or thermal mass, and is a product of mass and specific heat capacity (Koenigsberger et al, 1980);

thermal capacity = $mc = \rho Vc = \rho\,(Ad)\,c$ $(J\,°C^{-1})$ Equation 2.11

where;

m = mass of building element (kg)

c = specific heat capacity ($Jkg^{-1}\,°C^{-1}$)

ρ = density ($kg\,m^{-3}$)

V = volume (m^{-3})

A = area of building element (m^2)

d = thickness of building element (m)

Due to the small range of specific heat capacity in building materials (from 0.4 for wood to 0.11 for steel) compared to that of density (1 kgm^{-3} for air to 24000 kgm^{-3} for concrete), the thermal capacity is closely related to its mass and thus is determined mainly by the thickness (Markus and Morris, 1980; Givoni, 1976). A lightweight material has a lower thermal capacity than heavyweight material, thus stores less heat. It warms up, quickly releases the heat, and cools down rapidly. The indoor temperature profile follows very closely with the ambient (large μ with short ϕ), which could cause overheating during the hot days but could prevent or reduce the night-time thermal stress (Szokolay, 1990; Forwood, 1983; Haigh, 1980). On the other hand, heavyweight material stores more heat before dissipating it indoors at a later period with a damping effect (Bansal et al., 1992; Forwood, 1983).

The effect of thermal capacity is only significant when thermal conditions are fluctuating due to a large diurnal temperature range, whereby it allows higher control of indoor thermal condition (Koenigsberger et al., 1980; Markus and Morris, 1980; Givoni, 1976; Straaten, 1967). It can act as heat sink in hot arid climates and mitigates winter heat lost in cold and temperate climates (Szokolay, 1990; Simha, 1985; Straaten, 1967), and even in cool season of tropical climate (Malama and Sharples, 1997). The combined effect of U-value and heat storing capacity is important in warm climates when the control is entirely on the envelope structure (Kolokotroni and Young, 1990).

ii) Thermal insulation

Thermal insulation provides resistance to conductive, convective, or radiative heat transfer (ASHRAE, 1981). This can reduce the temperature fluctuations within an enclosure. The insulation materials can be grouped as conductive and reflective while the effects can be considered as resistive, reflective, and capacitive (Straaten, 1967).

The conductive insulating material depends on the low k-value to provide the resistive effect by retarding heat transfer via conduction and convection. The reflective type depends on the surface characteristics, i.e. low α, high λ, and low ε to provide the reflective effect by preventing heat transfer via radiation. The reflective effect is instantaneous while the resistive effect of conductive insulation materials provides quick response to intermittent heating and/or cooling of heavyweight structures. The resistive effect is most effective for heat transfer under steady-state conditions or when the rate of heat transfer is almost constant for long periods, such as in heated or air-conditioned spaces. The impact is not very significant if the diurnal variation is small where the temperature reduction is minimal. The insulation lowers the U-value, therefore similar heat transfer pattern could be obtained between insulated lightweight construction and non-insulated heavyweight construction (Kolokotroni and Young, 1990; Rogers, 1964; Lucas, 1963). Unlike the immediate resistive and the reflective effect, the capacitive effect is a function of time due to the periodic heat transfer characterised by the time-lag factor and provides a temporal control of heat transfer as discussed earlier.

For optimum performance, there should be a balance between the thermal mass and insulation. This could effectively moderate the daytime heat and impede the night-time cooling (Hyde and Docherty, 1997; Forwood, 1983). The benefits of thermal insulation due to the positioning and location in the envelope construction with respect to climatic conditions are paradoxical, thus it is prudent to analyse the cost effectiveness and identify the optimum value (Abdelrahman and Ahmad, 1991; Evans, 1979; Givoni, 1976; Straaten, 1967; Rogers, 1964).

iii) Colour

Besides the impact of the thermal capacity and insulation of the envelope, the colour of the external surface also directly determines the thermal impact of solar radiation based on the absorptivity to short-wave radiation. This directly influences the thermal performance in unconditioned buildings and the cooling load in conditioned buildings (Givoni, 1998).

In summary, the final thermal impact on the indoor climate that determines the thermal and energy performances of a building is primarily influenced by the interaction of all the climatic parameters with the building and a complex interplay of many thermal properties of the envelope in a dynamic heat exchange process (Clarke, 2001; Lord and Wilson, 1980). Thus, there is no single and simple thermal design solution for all applications. Every design is unique in accordance to its locality and functionality. The design decisions require an evaluation of the indoor requirements, basic knowledge of the principles of heat transfer, and the understanding on the interactive thermal effects of the building construction in terms of the thermophysical properties of the materials. Nevertheless, general recommendations and guidelines can be used as a reference because the physical theories in science remain.

2.3.3 Thermal design of roof

The preceding section gives an overview of the heat transfer in building. It is discussed in terms of the modes of heat transfer as well as the pertinent thermophysical properties of the material and construction. Since this thesis is a study on thermal design of roof, it is important to understand the heat transfer through the roof.

Figure 2.4 illustrates the modes of heat exchange in a roof (Wonorahardjo, 2000; Givoni, 1994; Koenigsberger et al, 1980). Various forms of heat transfer occur at the surface of the roof as well as in the roof space and through the ceiling. However, the proportion of each mode of heat transfer is not discussed in detail as the main focus in this study is the final thermal impact on the whole-building performance.

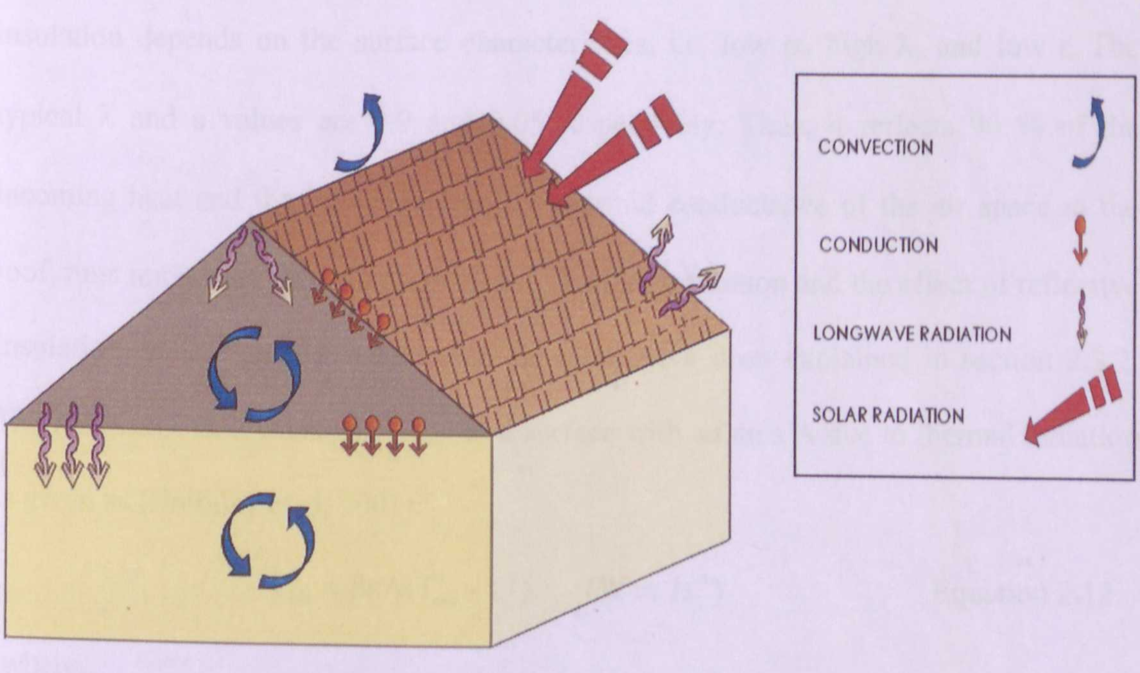

Figure 2. 4: Heat transfer in roof

At the surface of the roof, solar radiation is reflected, absorbed, and transmitted by the roof covering in proportion that depends on the material and construction, and are determined by the surface characteristics. These are as mentioned earlier in this section and are further explained in section 2.3.2. The absorbed heat is later conducted and radiated into the roof space. The first convection occurs near both the external and internal roof surfaces due to a higher roof surface temperature compared to the air just above it.

The heat enters the roof space via conduction and radiation from the roof covering. Here, a second convective heat transfer occurred as the temperature increases due to radiation and conduction. Across the roof space, 60 % to 65 % of heat is transferred by radiation and the remainder is mainly by convection (Straaten, 1967). The conductive heat transfer can be reduced by installing a conductive insulation. Likewise, the radiative heat transfer can be reduced by using a reflective thermal insulation underneath the roof covering. Aluminium foil is a common type of reflective insulation used as a radiant barrier for the roof. The principles of reflective insulation are reflecting the heat and lowering the thermal conductance of air space. The reflective insulation depends on the surface characteristics, i.e. low α, high λ, and low ε. The typical λ and ε values are 0.9 and 0.05 respectively. Thus, it reflects 90 % of the incoming heat and the low ε reduces the thermal conductance of the air space in the roof, thus improving the insulation value. Thermal insulation and the effect of reflective insulation on thermal conductance of air space have been explained in section 2.3.2. The net rate of heat exchange (P_{net}) of a surface with an area A due to thermal radiation is given as (Halliday et al, 2001):

$$P_{net} = \beta\varepsilon A(T_{env}^4 - T^4) \quad (\text{W or Js}^{-1}) \qquad \text{Equation 2.12}$$

where,

β = Stefan-Boltzmann constant = 5.6703×10^{-8} $Wm^{-2}K^4$

ε = emissivity

A = surface area (m^2)

T_{env} = temperature of environment (K)

T = temperature of the surface (K)

The heat from the roof space is absorbed by the ceiling, and later conducted and radiated into the living spaces underneath. The use of conductive or reflective insulation can also reduce the heat transfer from the ceiling. The final stage of convection occurs in the spaces underneath the ceiling due to the heat radiated and conducted from the roof space and also from other parts of the building envelope.

At night, roof is the envelope where most heat is lost via long-wave radiation due to its orientation to the cooler night sky. Therefore, roof is the most critical part of a building's envelope as it is exposed to all the climatic variations. It often has the most complex construction compared to the other parts, thus susceptible to numerous roofing problems. Among the roof problems are moisture that leads to condensation and hygrothermal problems in cold climates (Hens et al., 2003; Holm and Kuenzel, 2002; Derome, 2000) as well as hot humid climates (Rudd et al., 2000; Rudd and Lstiburek, 1997), leakage due to rain in tropical climates, and heat gains and losses in all climates (Parker et al., 2003; Emmanual, 2002; Parker et al., 2001, 2000; Alsaiegh, 1998; Parker and Sherwin, 1998a, 1998b; Alasmar, 1995; Suman and Saxena, 1992). Proper thermal design of roof should curtail these problems within the life span of the building material, as highlighted, and recommended in some of the reviews below. However, it is not within the scope of this thesis to discuss the roofing problems in detail. This section presents and discusses the findings of previous studies on the thermal impacts of various roof designs in warm humid climate. These studies were selected in view of the recommended design strategies as discussed in section 2.2.1, and the influence of the thermophysical properties of building materials and construction on the heat transfer as explained in section 2.3.2.

a) Surface characteristics – α, λ, and ε

Several experiments in test and real buildings have been performed during summer periods in Florida, in the United States of America (U.S.A) to study the thermal impact of various roofing configurations on thermal performance and the cooling energy demands (Parker et al., 2003, 2000; Parker and Sherwin, 1998a, 1998b).

Comparing the data collected for vented dark and light coloured roofing material, Parker et al. (2003) concluded that white metal roof with solar reflectance of 67.6 % (α = 0.32) reduced the average attic maximum temperature (T_{max}) by 12.8 °C, the average attic mean temperature (T_{mean}) by 4.5 °C, and the overall cooling load (CL) by 15 % over black shingles with solar reflectance of 2.7 % (α = 0.97). However, the average attic minimum temperature (T_{min}) for both the white and the black roof were the same due to the same emissivity of both roof colours. The air space layer underneath the shingles was inferred to have provided effective thermal insulation, beneficial during daytime but on the other hand elevated the night-time temperature.

In an earlier study, the average attic T_{max} of white tile roof with higher solar reflectance of 75.4 % was 6 °C lower than that of the white metal roof (Parker and Sherwin, 1998a). In other studies; light coloured shingles reduced the attic T_{mean} by 3.6 °C and the cooling load by 4 % over black shingles, a further 23 % load reduction was achieved with a higher reflectivity white metal roof (Parker et al., 2000), light grey shingles reduced the average attic T_{mean} by up to 3.8 °C over dark grey shingles (Parker and Sherwin, 1998b).

These studies have proven that in hot climate the white roof performed better to reduce attic air temperature and cooling energy demand, and was further improved with higher reflectivity roofing materials. On the other hand, while white roofing systems have demonstrated superior thermal and energy performances over the others, it retained the highest attic relative humidity (RH) due to the lower attic temperature.

Roof ventilation has been disputed to be the solution to the heat and moisture problems (Rudd et al., 2000; Rudd and Lstiburek, 1997).

b) Roof ventilation

Ventilation in the roof could mean venting a single component or the roof assemblies or the attics (BSC, 2003). Figure 2.4 shows that the main modes of heat transfer in roof space are conduction, convection, and radiation

According to (Straaten, 1967), the largest proportion of heat transfer in roof is via radiation. He argued that ventilating the roof space would not appreciably reduce the heat transfer as radiation is not affected by air movement, but has an indirect effect to slightly reduce the roof temperature. It was concluded that the improvement on thermal condition from ventilation of roof space was negligible when a test result in a full-scale brick dwelling with roof space ventilation of 22 ach reduced the maximum inner surface temperature of the ceiling by up to only 3.9 °C.

However, according to Givoni (1976) roof ventilation has a direct affect on convective heat transfer as the surface coefficient increases with the velocity of air near its surface. It reduces the temperature of the roof and ceiling that indirectly affects the radiative heat transfer and has a greater advantage on darker coloured roofs.

U.S.A building codes require the following ventilation for attic or any space in roof that is enclosed by ceilings (Parish, 1997): a minimum attic ventilation requirement is specified as *net free vent area* (NFVA) 1:150 of ventilated spaces, or 1:300 if vapour retarder is used in the attic, or if 50 % of the required ventilating area is located in the upper portion of attic space and the airflow must not be blocked by any insulation. NFVA is the ratio of an unobstructed total area (free from screens, louvers, or other materials through which air can enter or exhaust a non-powered ventilation system) to the horizontal projection of attic floor area (Corning, 2002; Teed and Burton, 2002; Bianchina, 2001).

Attic ventilation can be provided by three types of ventilation systems – active powered fans; passive mechanical wind assisted turbine vents; and passive structural vents such as soffit vents, eave vents, ridge vents, gable vents, wall vents, or of any combination (Teed and Burton, 2002; Waibel, 2002; Corning, 2002; Bianchina, 2001; Satterwhite, 2000). Appropriate sizing of the intake and exhaust vents is essential to meet the ventilation requirement and the rule of thumb is 10 air changes per hour (ach) (Teed and Burton, 2002; Alsaiegh, 1998).

A combination of soffit and ridge vents showed better performance than soffit venting only (Parker and Sherwin, 1998b) or gable-to-gable ventilation (Alasmar, 1995). Roofing vendors have proclaimed the benefits of attic ventilation in cold climate to prevent condensation due to moisture, and ice dams at the roof edges due to temperature gradient. For hot humid and hot dry climate, it is needed to expel hot attic air (Teed and Burton, 2002; Corning, 2002; Satterwhite, 2000) and to reduce cooling load (Teed and Burton, 2002; Satterwhite, 2000), which can also be achieved by using ceiling insulation (Satterwhite, 2000). Straaten (1967) suggested that ceiling insulation would be more economical as the needed high ventilation rates would require an expensive mechanical means.

Several research findings have provided evidence of the influence of roof ventilation on the temperature of the rooftops. Alsaiegh (1998) concluded the temperature variations from the experiments on steady-state heat transfer analysis using a 2-D finite element physical model and a numerical model. Berrub (1998) performed an experiment on a scale-model of channelled roof with continuous eave and ridge opening, and the measured data showed a temperature reduction of up to 4 °C. Parker and Sherwin (1998b) investigated various roof configurations with radiant barrier in test cells and found that the T_{max} in NFVA 1:150 attic was 8 °C lower than the 1:300, and the added ventilation rate reduced the attic heat gain by 10 %. Alasmar (1995) conducted a steady-state experiment on a large-scale insulated attic with radiant barrier in an environmental chamber and concluded that the attic heat gains from the vented attic was 7 % to 16 % lower than the unvented attic.

Some other research findings have questioned the significant benefits of attic ventilation and have suggested other alternatives to deal with the heat and moisture problems in the attic and roof structures. It was asserted that venting the attic in hot humid climate could cause condensation due the cooling systems in the space that would degrade the thermal performance of roof, which would be resolved by unvented attic with sloping internal ceiling (Rudd et al., 2000; Rudd and Lstiburek, 1997). And venting the airspace below the thermal insulation could cause interstitial condensation (Hens et al., 2003). Simulation studies showed sealed sloping internal ceiling enclosed with air and thermal barrier did not imposed any energy penalty (Rudd and Lstiburek, 1997), while empirical studies have shown savings in cooling and heating load compared to the conventional 1:150 vented attic (Rudd et al., 2000).

A recent study (Porter, 2003) concluded that moisture transport into attic and sloping ceiling spaces existed. However, a combination of continuous soffit and ridge vents assisted the removal of moisture, and the roof sheathing moisture content was at an acceptable level regardless of whether the attic was vented or not.

Hens et al. (2003) investigated the hygrothermal performance on compact zinc roof and ventilated metallic roof in cold climate. The findings of the 4-year study concluded comparable performance between the models.

The requirement for venting attics in hot-dry and hot-humid climate was questioned (BSC, 2003) and was argued as being non-scientific (Ueno, 2002).

In summary, it is concluded that the decisions on roof ventilation depends on the climatic conditions and largely on the roof configuration whereby the impact of certain components such as surface characteristics and insulation could offset the others (BSC, 2003).

c) Insulation

Studies on the impact of insulation are divided into two types, which are the conductive insulation and reflective insulation.

i) Conductive insulation

Al-Sanea (2002) performed a study on steady-state heat transfer on a finite–volume numerical model in hot arid region. The findings showed the use of 50 mm molded polystyrene and polyurethane reduced the heat transmission load by about 66 % and 75 % respectively. The performance was further improved when it was located closer to the inside surface of the roof.

Emmanual (2002) studied the bio-climatic effects of roof cover in equatorial tropics. It was concluded the use of ceiling that acted as an insulation layer between the roof space and the spaces below improved the thermal conditions during daytime. But, it elevated the night-time temperature and resulted in a less desirable condition at night. According to Straaten (1967), the use of mineral wool and vermiculite for flat ceiling insulation in warm climates are more beneficial to reduce ceiling temperature than to lower the indoor air temperatures

ii) Reflective insulation

Radiant barriers (RB) could be installed under the rafters as truss RB (TRB) or on the floor attic over the ceiling as horizontal RB (HRB) (Alasmar, 1995; Levins and Hall, 1990).

Alasma (1995) investigated the influence of radiant barrier locations on the steady-state heat transfer. The results showed that its usage under roof deck between rafters (TRB) reduced attic temperature 6 °C to 8 °C compared to no RB, while that mounted over ceiling insulation (HRB) had lesser impact. However, it was concluded that the location of the barrier had little effect on the ceiling heat gain.

Levins and Hall (1990) reported that the advantages of HRB are easier to install for retrofit and uses less material. However, it was at risk of condensation during winter that could lead to structural damage, and dust accumulation that could degrade the thermal performance due to the increased emissivity (Straaten, 1967).

Levin and Hall (1990) conducted tests on dusted HRBs at research houses in Tennessee, U.S.A. and analysed the data as follows: A dirty HRB with $\varepsilon = 0.185$ increased the house cooling load by 8.4 % when compared to a clean HRB with $\varepsilon = 0.05$. However, this was still 7 % lower compared to ceiling with no RB. In terms of heat flux, the clean HRB ($\varepsilon = 0.05$) reduced the net ceiling flux by 58 % while another dirty HRB with $\varepsilon = 0.51$ reduced it by only 19 %. However, the dirty HRB with $\varepsilon = 0.185$ increased the attic heat flux by 28.4 %. This demonstrated that the degraded HRB reduced the internal heat transfer from attic to spaces underneath via ceiling but increased the external heat gain, which was indicated by the attic heat transfer. Nevertheless, it was finally concluded that the use of HRB was not prohibitive despite its degradation due to dust accumulation as it was still effective in reducing the ceiling heat flux and house cooling loads compared with no radiant barrier.

Similarly, Straaten (1967) also concluded that the performance of ceiling lined with degraded HRB was better than the unlined ceiling. Results of experimental tests on a scale model of a typical roof/ceiling combination showed that dust built up on the HRB reduced its thermal resistance by 75 % while the thermal resistance of an unlined ceiling was 85 % lower than that of a bright new foil.

The performance of a TRB was studied on real full-scale buildings during summer periods in Florida, U.S.A.; it reduced the average attic T_{max} in a 1:300 vented attic from 3.8 °C to 4.4 °C (Parker et al., 2001; Parker and Sherwin, 1998a) and 1.1 °C in the interior spaces. This reduction was three times greater than adding extra insulation (Parker et al., 2001).

Waewsak et al. (2003) studied a bioclimatic roof cum solar chimney for hot tropical climate. White concrete tiles on the outside were used to reduce the solar absorption and a translucent sheet to provide low-glare daylight together with a combination of gypsum and aluminium board were used as the ceiling. The roof showed significant reduction of heat gain, provided sufficient daylight without overheating, and induced high ventilation rate to ameliorate the indoor comfort.

2.4 Summary and conclusion

For equatorial climates, roof has been said to be the major source of heat gain and several design strategies have been suggested. Studies on climatic building design in general and thermal design of roof in particular with an understanding on thermal design have provided evidences for provision of better indoor condition with practical energy saving measures. The emergence of advanced sophisticated computer-modelling software to compute the complex mathematical formulation of heat transfer in building is becoming a valuable tool for numerous decision-makings in building designs. The development and applications of computer simulation tools for building performance evaluations are discussed in Chapter 5.

The empirical research findings have verified the roof surface characteristics such as colour and reflectivity; and assemblies of roofing elements such as insulation, radiant barrier, and roof ventilation could lower indoor temperature to alleviate the thermal stress as well as reducing heat gains to minimise the cooling load. In tropical equatorial climate, besides the abundance of sunshine the region is also endowed with copious rain, thus adding the criticality of a proper roof design. More studies on climatic and thermal design of roof in tropical equatorial climate are certainly needed and are discussed along with a review of the climatic suitability of houses in Malaysia in the next chapter.

CHAPTER 3: A REVIEW ON CLIMATIC DESIGN OF RESIDENTIAL BUILDINGS IN MALAYSIA

3.1 Introduction

This chapter presents a national review of climatic design of low-rise residential buildings in Malaysia. The discussions on climatic suitability are evaluated in terms of the building thermal performances concerning thermal comfort and energy for space cooling. Thus, brief overviews of climate, thermal comfort conditions, and energy in building in Malaysia precede the chapter.

3.2 Climate

Climate is characterised and determined by spatial and temporal atmospheric variations and are termed as (Markus and Morris, 1980; Boucher, 1975; Battan, 1974): *global climate* that refers to the planet earth as a whole, *macroclimate* or *regional climate* as a condition for a region such as a state or a country on a scale up to 1000 km horizontally and 10 km vertically in a period of 1 to 6 months, *topoclimate* or *local climate* for an area such as a city for variations up to 10 km horizontally and 1 km vertically in a period of 24 hours, and lastly *microclimate* for limits of about 1 km horizontally and 0.1 km vertically also in a 24-hour period.

Climate describes long-term atmospheric conditions; for example a month, a season, or a year, and is associated with both seasonal and diurnal variations, while weather is short-term conditions that relates to diurnal variations (Markus and Morris, 1980; Battan, 1974; Trewartha, 1968). Thus, in the same locality, weather and climate differs only by temporal description in which both are expressed by the same spatial environmental elements; which are solar radiation, sunshine, cloud, temperature, humidity, precipitation, and wind (Martyn, 1992; Boucher, 1975; Trewartha, 1968; Griffiths, 1966).

There are several different schemes of climate classification but the most referred ones are that of Köppen and Thornthwaite, which were used by others with appropriate modifications (Martyn, 1992; Boucher, 1975; Battan, 1974; Trewartha, 1968; Critchfield, 1966; Griffiths, 1966). However, the basis of all schemes is the characteristics and distribution pattern of the prevailing environmental or climatic elements, which typically are temperature and moisture or precipitation. The world climate is generally categorised into three main types, namely tropical, temperate, and cold, and are further subdivided with other locality specifications. The boundaries for the climate groups and subgroups depend on the degree of complexity or simplicity of the classification. Nonetheless, a climate can be generalised over a certain geographical location. The type of climate for Malaysia and the climatic analysis for building design with respect of thermal comfort and energy are described in the following section.

3.2.1 Climate of Malaysia

Malaysia is made up of two physical parts: i) a Peninsular Malaysia and (ii) a portion of the northern part of Borneo Island. The country comprises of twelve states in the Peninsular and two states on the Borneo Island. It lies between latitude of 1° to 7° N and longitude of 99° to 120° E with a total land area is about 333,000 km^2. The Peninsular is bounded by large bodies of water; South China Sea on the East, Straits of Malacca on the West, and Straits of Johore on the South.

Lying within the region of 15° North of the equator, Malaysia is in the tropical rainforest zone and the climate is generally classified as hot-humid (ASEAN, 1990) according to Köppen classification (Trewartha, 1968; Griffiths, 1966), or warm-humid equatorial (Ali et al., 1993; Koenigsberger et al., 1980; Evans, 1979; Givoni, 1976) due to the different definitions of temperature range. The classification for hot humid is defined as mean temperature above 18 °C while the warm humid is for a temperature range of 21 °C to 32 °C. By these temperature definitions, both the hot-humid and warm-humid classifications actually fall in the same temperature range. Therefore, in this thesis the climate of Malaysia is classified as warm-humid to make a distinction with the hot-arid dessert climates with higher temperatures of above 33 °C (De Wall, 1993; Koenigsberger et al., 1980) and the term is also more referred to in climatic building designs.

Malaysia is situated in the tropical climatic zone where heat and humidity are the dominant problem. The Malaysian Meteorological Service (Malaysia, 1998) describes the general climatic characteristics of Malaysia as follows: Abundant sunshine and solar radiation, uniform temperature, high humidity, heavy rainfall, and light and variable wind. The amount of solar radiation received and the length of sunshine hours are affected by the cloud cover. On the average, the sunshine hours are 6 hours per day. The temperature is high and uniform throughout the year. The annual variation is less than 2 °C and diurnal variation of 5 °C to 12 °C. Daytime temperature are high around 26 °C to 32 °C while night-time temperature is lower in the range of 21°C to 24 °C. Relative humidity is high with a monthly mean of 70 % to 90 %. Rainfall is heavy with annual average of 2000 mm to 3500 mm. Wind is generally light and variable and is affected by the land and sea breezes. The wind flow pattern is influenced by four monsoons. From middle of May or early June to September, the Southwest monsoon blows light wind of below 15 knots from southwest. From November to March, Northwest monsoon blows north-easterly wind across the South China Sea. It brings heavy rains and strong winds of up to 30 knots to the east coast states. There are two inter-monsoon seasons with light and variable wind.

An understanding of the prevailing climatic conditions is pertinent to the climatic design strategies to be adopted. These conditions will influence the thermal performance of the building and eventually the state of thermal comfort experienced by the occupants. The main climatic elements that affect building designs and human thermal comfort are solar radiation, air temperature, humidity, wind, and precipitation (Koenigsberger at al., 1980; Markus and Morris, 1980; Givoni, 1976). Among those, solar radiation is the most dominant element as it is the source of solar energy, which is the single most important control of weather and climate (Griffiths, 1976; Trewartha, 1968; Griffiths, 1966; Battan, 1974). It affects the air temperature and humidity, which are the primary determinant of thermal comfort (Fanger, 1972). Wind is unique due to its ability to reduce air temperature by flushing the heat and to provide comfort ventilation (Givoni, 1976).

Local weather data is the fundamental information needed by designers in decision-makings on climatic design strategies to predict the indoor climate and energy consumptions. The performance assessments of those design decisions are now possible via whole-building analysis using numerical simulations on computers. The building simulation softwares require an input of a specific type of climatic data in a certain format. Several standardised typical weather data sets have been developed to provide the needed climate database for various commercial computer softwares and are briefly described in the next section.

3.2.2 Typical weather data set

Computer simulation programmes usually allocate an input of a year of hourly local climate data with variations in weather parameters. The needed weather parameters may consists of some of the following data that are available from the Malaysian Meteorological Service (Malaysia, 1998); dry bulb temperature (DBT), wet bulb temperature (WBT), relative humidity (RH), sunshine hours, global radiation, rainfall, cloud cover, and wind speed and direction; or may also need dew point temperature, atmospheric pressure and diffuse radiation (Clarke, 2001; Crawley and Huang, 1997).

In U.S.A and United Kingdom (U.K), several organisations are involved in the collection, compilation, and processing of long term measured weather data of up to 30 years for various design applications (CIBSE, 2004; ITEM, 2004; NCDC, 2004; RReDC, 2004). These data are also processed into typical weather data sets of the respective locations that are specifically designed for energy simulation computer programs. Among the most notable type of data sets are *Test Reference Year* (TRY), *Typical Mean Year* (TMY), and *Weather Year Energy Calculations* (WYEC) (Clarke, 2001; Crawley and Huang, 1997). These are hourly weather data to describe the local climate. Each type differs by the processing concepts and techniques (Crawley and Huang, 1997; RReDC, 2004) with some variations among organisations and countries (Clarke, 2001).

It was reported that the concept and technique for developing TMY and WYEC were more comprehensive, thus would produce a more accurate predictions than TRY (Clarke, 2001; Crawley and Huang, 1997). However, a study conducted in several locations in U.S.A. to compare the variations in energy predictions using the above mentioned typical weather data sets had concluded that the performances were comparable in cooling-dominated locations (Crawley and Huang, 1997).

For the climate of Malaysia, at the time of this review, only two types of typical weather data sets have been established; TRY (Reimann, 2000) and Model Year Climate (MYC) data (Zain-Ahmed, 2000). These were developed from 21 years (1975 to 1995) weather data for Subang (latitude 3° 7', longitude 101° 33' E, 17 m above sea level) measured at the Subang meteorological station (Zain-Ahmed, 2000). The measured data were hourly values for DBT (°C), WBT (°C), RH (%), cloud cover (oktas), wind speed (ms^{-1}) and wind direction (degree from North), solar irradiation ($MJm^{-2}day^{-1}$), and sunshine hours (hr). These weather data represents the region of Klang Valley situated in the state of Selangor that is located in the Peninsular.

a) **TRY**: Reimann (2000) constructed TRY for computer building simulation programme TSBI3. The data consisted of the following weather parameters; cloud cover, DBT, absolute humidity, diffuse solar radiation, beam solar radiation, and wind speed. However, only five years of measured diffuse solar radiation data were available (1991-1995). It was reported that development of TRY required at least 10 years of weather data, thus the remaining diffuse data were analytically deduced. Table 3.1 shows the TRY data for Klang Valley.

Table 3.1: TRY for Klang Valley
(source: Reimann, 2000)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1993	1995	1991	1980	1990	1983	1981	1987	1985	1977	1986	1984

b) **Model Year Climate (MYC)**: Zain-Ahmed (2000) established a MYC data using the MYC analysis technique. This technique produced the best model year to represent the climate condition of a particular region from at least 20 years of data. Unlike the technique for TRY that selects a whole year to represent the weather data for each month, MYC technique identified a year to represent each weather parameter for each month. The MYC data is shown in Table 3.2 and Table 3.3 shows the MYC annual mean daily data.

Table 3.2: MYC model years (1975-1995)
(source: Zain-Ahmed, 2000)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
DBT	1975	1994	1991	1987	1976	1975	1984	1979	1977	1995	1990	1984
WBT	1986	1975	1976	1985	1980	1975	1993	1980	1989	1983	1986	1976
RH	1993	1978	1975	1976	1975	1984	1977	1977	1986	1990	1977	1981
Cloud Cover	1995	1980	1981	1995	1995	1979	1976	1995	1978	1990	1979	1988
Wind Speed	1989	1985	1983	1975	1993	1995	1989	1981	1976	1979	1992	1992
Wind Direction	1991	1992	1980	1991	1987	1980	1981	1975	1992	1990	1986	1993
Solar Irradiation	1980	1979	1976	1984	1980	1985	1986	1984	1984	1984	1981	1975
Sunshine Hrs	1994	1994	1985	1978	1979	1977	1990	1993	1986	1979	1986	1985

Table 3.3: MYC annual mean daily data
(source: Zain-Ahmed, 2000)

No	Climate Parameters	Annual Mean value
1	DBT	27.6°C
2	WBT	24.2°C
3	RH	83%
4	Cloud Cover	7 oktas
5	Wind Speed	1.2 ms^{-1}
6	Wind Direction	127 degrees
7	Solar Irradiation	16.4 MJm^{-2} day^{-1}
8	Sunshine Hours	6.2 hours

3.3 Thermal comfort

Climatic and thermal designs of buildings have been discussed in sections 2.2 and 2.3 with respect to heat exchanges in building. These are due to heat transfer processes, and thermal effects of building materials and constructions for practical applications of the appropriate thermal designs. The primary aim is to design for optimum thermal and energy performances. These are mainly related to the building energy needs to provide an acceptable level of indoor thermal comfort.

This section gives a brief overview of the thermal comfort theory, indices, and studies done in the Malaysian climate. A thorough and comprehensive review on the area is not discussed for two reasons.

Firstly, the computer software to be used in this study and is described in section 5.4 has a module (***Tas Ambiens***) for thermal comfort simulation. The ***Tas Ambiens*** module uses the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices that are universally recognised. The module uses a two-dimensional (2D) computer fluid dynamic (CFD) modelling to analyse the thermal comfort condition for a given one-hour period. These are computed by specifying the boundary conditions of the selected spaces. For that reason, only brief descriptions of thermal comfort indices are given in section 3.3.2.

Secondly, several studies have been conducted to evaluate the indoor thermal comfort conditions in buildings in Malaysia. The studies have considered all the latest developments in the area of thermal comfort. Extensive reviews on the established thermal comfort studies and standards in various climatic regions have been done. Despite of the availability of various universally recognised indices from many studies in other countries, national benchmarking was deemed necessary. The findings of the national thermal comfort studies have led to recommendations for the thermal comfort requirements for the climate of Malaysia. Accordingly, these are all summarised and tabulated for easy referencing, and are briefly discussed in section 3.3.3. These findings are valid for the people who are acclimatised to the weather in Malaysia and could be considered for the thermal comfort assessment for the local context.

3.3.1 Definition and Theory

Thermal comfort is defined as *that condition of mind which expresses satisfaction with the thermal environment* (BS EN ISO 7730, 1995; ASHRAE 55, 1992) or *the sensation of complete physical and mental well-being* (Koenigsberger et al., 1980). Thus, it is recognised that physical and psychological as well as physiological parameters influence a person's sensation of thermal comfort (ASHRAE, 1981).

The physiological aspect involves the thermoregulatory system of the body with a complex heat exchange between the body and the surrounding. The fundamental condition to be achieved is the heat balance experienced by the body that can be simply stated as:

$$\text{Heat production} = \text{heat dissipitation} \qquad \text{Equation 3.1}$$

And the heat balance equation can be written as (Fanger, 1972);

$$H_{met} - E_d - E_{sw} - E_{re} - L = K = R + C \qquad \text{Equation 3.2}$$

where;

H_{met} = internal heat production in the human body

E_d = heat loss by water vapour diffusion through the skin

E_{sw} = heat loss by evaporation of sweat from the surface of the skin

E_{re} = latent respiration heat loss

L = dry respiration heat loss

K = heat transfer from the skin to the outer surface of the clothed body (conduction through the clothing)

R = heat loss by radiation from the outer surface of the clothed body

C = heat loss by convection from the outer surface of the clothed body

The physiological mechanisms to achieve the heat balance are also affected by the physical factors that consist of environmental and individual variables, which are (BS EN ISO 7730, 1995; Fanger, 1972):

a) Environmental variables

- Air temperature
- Mean radiant temperature
- Air velocity
- Humidity

b) Individual

- Activity level or metabolic rate
- Thermal resistance of clothing (clo-value)

The sensation of thermal comfort is the combined effects of the above physical parameters that can consist of many different combinations. The four environmental variables are independent and uncontrolled in the natural environment and have been a great challenge to the researchers in the field. Many methods and approaches have been performed to establish standardised easy-to-use scales referred to as 'thermal indices' that combine the effect of the four variables.

3.3.2 Indices

Various thermal comfort indices obtained from numerous empirical and analytical studies are adequately elaborated in many specific references for each study.

Among the mostly used indices that accounted for certain combinations of environmental parameters as well as the individual parameters are (BS EN ISO 7730, 1995; Olgyay, 1992; ASHRAE, 1981; Koenigsberger et al., 1980; Markus and Morris, 1980; Evans, 1979; Givoni, 1976; Fanger, 1972; Straaten, 1967): *Predicted Mean Vote* (PMV), *Predicted Percentage of Dissatisfied* (PPD), new *Effective Temperature* (ET), *Corrected Effective Temperature* (CET), *Equatorial Comfort Index* (ECI), and *Standard Effective Temperature* (SET). These are single-figure indices that have some limitations in practical applications, such as allowances for the effect of humidity at lower temperatures or the cooling effect of air movement at high humidity level.

The PMV and the PPD were developed by Fanger (1972) to evaluate the thermal sensation of people in a given environmental condition. These standards are adopted by the British Standards Institution (BSI) (BS EN ISO 7730, 1995).

The PMV is an index that predicts the mean value of votes on the thermal sensation of a large group of people. It uses a 7-point scale shown in table below:

Table 3.4: PMV 7-point thermal sensation scale
(source: BS EN ISO 7730, 1995)

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

The PMV can be calculated using an equation that includes the different combinations of metabolic rate, clothing, air temperature, mean radiant temperature, air velocity, and air humidity. Due to its complexity and comprehensiveness, the PMV can be determined using a computer programme and tables. These are available in the BS EN ISO 7730 (1995) document. These can be referred and adopted for the local context.

The PPD index predicts the percentage of people dissatisfied with the given thermal environment. This can be determined from the votes for the PMV index. It gives the percentage of the people who are likely to feel hot, warm, neutral, cool, or cold on the 7-point thermal sensation scale shown in Table 3.4.

Abdul Rahman (1999) and Szokolay (1990, 1997) reported on discrepancies and inconsistencies among the various indices when subjected to internal and external climates that differed from the environment in the respective. The PMV-PPD indices were reported to be satisfactory for conditioned buildings but not for naturally ventilated buildings. Thus, adaptation to building usage using local climatic data was suggested. Nevertheless, within the given limitations, the later revised indices are considered as valid to provide a quick guide for thermal comfort assessments (Koenigsberger et al., 1980).

To allow for more consideration on the independent effect of the environmental parameters, comfort zone plotted on bioclimatic charts (Olgyay, 1992) and psychrometric charts (Szokolay, 1990; Givoni, 1976; ASHRAE, 1981) are also used for thermal comfort assessment. Comfort zone is defined as *the range of environmental conditions in which at least 80 % of the people would feel comfortable* (Koenigsberger et al., 1980).

3.3.3 Thermal comfort for Malaysia

The main causes of discomfort in Malaysia are the high humidity, and low and unreliable wind speed (Sapian et al., 2001). Table 3.5 summarises some of the latest findings on thermal comfort for the climate of Malaysia.

Table 3.5: Thermal comfort studies for Malaysia

Source	Temperature range (°C)	Humidity range (%)	Building condition	Sample
(S. Ahmad and Ibrahim, 2003)	* 25.1 – 30.1 T_n: 27.6 ** 24.4 – 26.9 T_n: 26.9	77	Field study Non residential * NV; V_{air}= 0.37 ms^{-1} ** Combined	College-aged students Clo-value: 0.56 – 0.64
(SIRIM, 2001)	23.0 – 26.0	60 – 70	Non-residential A/C	No information
(Sapian et al., 2001)	26.0 – 29.5	75 – 90	Field study Residential NV V_{air}= 0.5–1.0 ms^{-1} needed for comfort	No information
(Ismail and Barber, 2001)	20.3 – 28.9 T_n: 24.6	44 – 77	Field study Non- residential NV V_{air}= 0.15 ms^{-1}	Office workers Clo-value: 0.55 – 1.36 V_{air} : 0.1ms^{-1}
(Zain-Ahmed, 2000)	24.5 – 28.0 Optimum: 26.3°C @ 73%	72 – 74	Field study Non- residential NV; V_{air}= 0.6 –1.0 ms^{-1} A/C; V_{air}= 0.1ms^{-1}	College-aged students Clo-value: 0.50 – 1.20
(Abdul Rahman, 1999)	* 24.2 – 29.2 T_n: 26.7 ** 23.0 – 28.0 T_n: 25.5 *** 23.7 – 28.7 T_n: 26.2	50	Empirical model Non- residential V_{air}= 0 ms^{-1} * NV ** AC *** Combined	MYC data
(Abdulshukor and Young, 1993)	25.5 – 29.5 Optimum: 28.2°C @ 50%	45 – 90	Controlled climate chamber	College-aged students V_{air} : 0.1ms^{-1} Clo-value : 0.6

These were field studies for non-residential buildings in natural ventilation (S. Ahmad and Ibrahim, 2003; Ismail and Barber, 2001; Zain-Ahmed, 2000), mixed-mode ventilation (S. Ahmad and Ibrahim, 2003), and air-conditioned (Zain-Ahmed, 2000). There were also a field study for residential building in natural ventilation (Sapian, 2001), an empirical model study for non-residential using MYC data for natural and mixed-mode ventilation as well as air conditioned (Abdul Rahman, 1999), and a controlled climate chamber study (Abdulshukor and Young, 1993). There is no information on the type of study for the recommended indoor design condition for non-residential buildings in Malaysia (SIRIM, 2001).

Two other studies have plotted the comfort zone on bioclimatic chart (Zain-Ahmed, 2000) and psychrometric chart (Zain-Ahmed, 2000; Abdul Rahman, 1999) for naturally ventilated buildings in Malaysia using the MYC data.

Zain-Ahmed (2000) plotted the comfort zone on Olgyay's bioclimatic chart, Givoni's building bioclimatic chart, and Szokolay's control potential zone. The Givoni's and Szokolay's charts were produced on psychrometric chart. It was concluded that the design strategies needed were ventilation with air movement of greater than 0.1 ms^{-1} for 50 % of the time, dehumidification for 100 % of the time, and lastly cooling for 43 % to 60 % of the time.

Abdul Rahman (1999) proposed a comfort zone for naturally ventilated buildings plotted on psychrometric chart using Szokolay's procedure. The chart is shown in Figure A1.0 in Appendix A. The boundary for comfort was extended for air movement provision of 1.0 ms^{-1} to 1.5 ms^{-1} and humidity of up to 90 %. For air movement less than 1.0 ms^{-1}, thermal comfort can be satisfied within the range of DBT 25 °C with RH 65 % to 32 °C with RH of 12 %. The range for DBT can be extended up to about 35 °C with 0 % RH to 26.5 °C with 90 % RH with air movement of 1.0 ms^{-1}. If the air movement is 1.5 ms^{-1}, the comfort zone can be further extended to DBT 37 °C with 0 % RH to 27.5 °C with 90 % RH. The MYC weather data in table 3.3 shows that the annual mean for DBT is 27.6 °C and for RH is 83 %. Thus, an air movement of at least 1.0 ms^{-1} is required to attain thermal comfort in natural ventilation.

3.4 Energy in building

One of the primary concerns of the studies on building designs discussed in Chapter 2 was the energy needed for operation of buildings with due concerns on the depletion of natural energy resources, local environmental impact, and global climate change. Thus, despite of the current developments towards renewable and cleaner energy resources, it is highly imperative for end users of energy in all sectors to consume energy efficiently.

For the building sector, this calls for *Energy Efficiency* (EE) in building that is greatly influenced by the architectural design, building services, and finally the users' behaviour (Baker and Steemer, 2000) in proportion of 25 %, 25 %, and 50 % respectively (Australia, 2003b). Among these, building design has the most enduring effect, thus has to be made right from the outset of design planning and process. Energy assessment in building could commence as early as the pre-design stage via appropriate simulation modelling tools as well as after completion of the construction by means of energy auditing. EE is a term used to describe the practice of using energy wisely and productively that can be achieved by using currently available technologies and/or effective management of energy usage (Ibrahim et al., 2002).

3.4.1 Eight Malaysian Plan (Year 2001-2005)

Among the development thrusts in the ***Eight Malaysia Plan*** (8^{th} MP) are sustainable development on resources and environmental issues, and enhancing the quality of life (Malaysia, 2001a). The strategies include; sustainable utilisation of energy and concerns on the consequent environmental impacts that entail to *Energy Efficiency* (EE) programmes such as energy audits coupled with environment friendly measures; and housing development programmes that include provision for quality housings with lower cost but better comfort that lead to related research in construction technology and design concepts.

3.4.2 Energy audit and standard

In the year 2002, the industrial, commercial, and residential sectors respectively consumed about 52.2 %, 28.4 % and 18.2 % of the total energy sales of 60,054 GWh in the Peninsular (Malaysia, 2003a). Thus, the industrial and commercial sectors have been the focus for EE programmes (Malaysia, 2002a, 2002b, 2001a). Amongst others are energy audit as a low-cost measure and building insulation as high-cost or long-term measure (Ibrahim et al., 2002).

One of the EE programmes implemented by the Government of Malaysia is Energy Audit in Government Building (EAGM) managed by Malaysia Energy Center (PTM) that began in 2001 (Kasbani, 2004; Malaysia, 2002a). Kasbani (2004) reported that the following activities have transpired from the programme; a *Guideline and Technical Reference on the energy audit procedure* document was produced to assist the auditing process, 12 government offices had been audited, several EE measures were proposed, several buildings have received ASEAN Energy Awards, and 55 government offices had undergone an ASEAN Benchmarking programme.

Prior to this, in 1989, the then Ministry of Energy, Telecommunications, and Posts had prepared a *Guidelines for Energy Efficiency in Buildings* (Malaysia, 1989). This was then revised into *Code of Practice on Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings* in **MS 1525:2001** (SIRIM, 2001).

In the U.S.A, United Kingdom (U.K), Denmark, and Australia, EE for houses are being promoted, implemented, or incorporated in the Building Codes to educate and create awareness as well as complying and supporting towards sustainable development (Australia, 2004b; Denmark, 2004; NEF, 2004; U.S.A, 2004b; Australia, 2003a).

At the time of writing, in Malaysia the EE programmes and documentations are available only for non-residential buildings. The only EE document for residential building was published by CETREE (2002) and is a guide on the user's behaviour for EE at home. Although the residential building only uses 18.2 % of the national energy consumption (Malaysia, 2003a), the impact of urbanisation on the energy demand and the related environmental issues must not be underestimated.

Zain-Ahmed (2000) reported a study by Ramatha (1995) on the breakdown of energy consumption in residential sectors as follows: 25.3 % for lighting, 8.3 % for air conditioning, 10.1 %, for fan, and 47.9 % for household electrical appliances. Masjuki et al (2001) reported that the number of residential room air conditioner had increased from 13 251 units in the year 1970 to 253 399 units in 1990. It was predicted that the number would increase to 956 115 units in the year 2010 and 1 511 276 units in 2020. This reported and predicted increase on the number of air conditioning units showed that active cooling has and would become a necessity while it was once a pure luxury in domestic buildings. The installations of air conditioning units are becoming common sights in most of the housing estates in the urban areas. While the failure of the modern housing to respond to the climate was blamed, nature imposes limitations on the indoor thermal comfort conditions in Malaysia (Abdul Rahman, 1994; Hanafi, 1991).

3.4.3 EE projects

The *Low Energy Office* (*LEO*) building of the Ministry of Energy, Communications, and Multimedia built in Putrajaya demonstrates the commitment of the Government towards EE and sustainability in the built environment (Ibrahim et al, 2002). The project was granted design support from the Danish Agency for Development Assistance – *DANIDA* (formerly known as DANCED) (Malaysia, 2003b). It is intended to be a showcase for EE with the integration of the best EE measures, which are optimised to achieve the overall best cost/effective solution.

The Public Works Department (PWD) New Quarters Design (NQD) programme is the first EE project for residential building that is initiated by the Government, and at the time of writing is the only one. The programme started in December 2000 as a sustainable development project under the 8th MP. It is to adopt all the principles of sustainability, and it was officially launched in November 2002 (Jaffar, 2004). The design concepts are briefly explained in section 3.7.4(b).

3.5 Housing in Malaysia

Residential houses in Malaysia can be classified into two main categories; traditional and modern. The traditional house refers to the Malay traditional house built in the villages to meet the socio-economic and cultural needs using the locally available material, thus attuned to the local environment (Chen, 1998; Killmann et al., 1994; Gibbs, 1987; Lim, 1987). The traditional houses that had evolved over generations have been gradually transformed into modern houses. These are houses built with new design concept and construction material introduced from the west during the colonial period and has become a symbol of status (Chen, 1998; Lim, 1987).

The escalating housing demand instigated by industrialisation during the late 1970s has transpired in the emergence of a new generation of commercially mass-produced modern houses (Chen, 1998). According to Chen (1998), since then the housing development have proliferated to meet the demands due to urban migration, predominantly in the Klang Valley. The house forms have also departed from the traditional type into single or double storey link/terrace houses, low-rise and high-rise flats, apartments and condominiums, as well as bungalows, with totally different planning concepts and spatial arrangements.

The housing need is ever-increasing (Malaysia, 2001b) as the urban population is growing in tandem with the country's economic growth in various sectors (Malaysia, 2002c). In Census 2000 the country's population was 23.27 million with 5.57 million living quarters, and the urban population has increased to 62.0 % from 50.7 % in 1991 (Malaysia, 2001c, 2001d, 2001e). Houses are provided by the public sector encompassing of the Government agencies such as the PWD and the Ministry of Housing and Local Government (MHLG), and the private sectors that comprise of licensed developers. These housing providers carried out the so-called formal housing activities, whereby the planning of the townships and the associated houses are subjected to the approval by the relevant authorities before being marketed (Yahya and Ramachandran, 2001). In the public sector, the MHLG is directly involved in the low-cost housing (Malaysia, 2001b, 2001c) while the PWD is responsible for the design and construction of Government Residential Buildings (GRB) since 1986 (Malaysia, 1995).

The GRB is also referred as Government Standard Quarters (Malaysia, 1995) and has been known to the public as PWD quarters. These quarters are designed and built to comply with the standards set by the government. These are standards on the building form and size of built-up area, the quality of building materials for the interior and exterior finishes, and mechanical and electrical works according to the category of the quarters that are classified as Class A, B, C, D, E, F, G and H (Malaysia, 1995, 2000). The building forms are bungalows, semi-detached, and low-rise apartments of several sizes. The built-up area is biggest for class A with 860 m^2 and smallest for class H with 76.4 m^2. Guidelines are given for building materials for the roof, ceiling, floor, walls, and doors and windows. The materials of high grade are for quarters class A, medium grade for class B, C, and D, and utility grade for class E, F, and G. These ranges from composite sheets to concrete tiles for the roof; timber strip to chipboard for the ceiling; wood, stones to ceramic for the floor; wood, glass, stones to bricks for the wall, aluminium frames for the window frames; and glass door to wooden door. Guidelines for the mechanical and electrical works are provisions for lighting, water heater, and air conditioning systems.

In the 8th MP, the housing industry in Malaysia is also developing in line with the principles of Agenda 21 of the Rio Summit (Malaysia, 2001b), which is a global declaration for sustainable development worldwide (United-Nations, 1992). Principle 1 in the agenda proclaimed that 'human beings are at the centre of concerns for sustainable development'. The PWD is the first government body to publicly declare their commitment to take the challenge of sustainability in built environment through the PWD-New Quarters Design (PWD-NQD) programme.

3.6 Climatic design of houses in Malaysia

This section presents the literature on climatic suitability of traditional and modern houses based on references of Yahya and Ramachandran (2001), Chen (1998), Killmann et al. (1994), Lim (1987), and Gibb (1987).

3.6.1 Traditional house

The predominant features of traditional Malay house are detached, arranged in random orientation throughout the village, elevated above ground, and constructed using locally available material, which are lightweight with low thermal capacity. The house form, and construction materials and methods are generally similar throughout the country but with some variations in the roof designs. Thus, the houses are identified mainly by their roof shapes that can be classified into four basic forms; *bumbung panjang*, *bumbung lima, bumbung perak,* and *bumbung limas* as depicted in Figures 3.1 to 3.4. Regional variations of *bumbung minangkabau* and *bumbung gajah menyusu* are illustrated in Figures 3.5 and 3.6.

Roof eaves are normally large for extra protection from rain and sun. The original material for roof covering was thatched local palm leaves in the natural dark hues. These were gradually replaced by new roofing materials such as galvanized iron (commonly known as zinc), shingles, or tiles as a symbol of status and also due to its durability and easy maintenance. No-ceiling high roof with decorative openings at the gable provides ventilation for the roof space as well as daylighting. It allows hot air to be released, which in turn creates the temperature gradient for air movement.

The walls and floors are made of wood with the naturally dark hues. These are lightweight materials with low thermal capacity and shorter time-lag, thus do not store heat. They respond quickly to the changes of the external climate, therefore the indoor climate follows very closely to the variations of the outdoor condition. Full-length windows, veranda, and raised floors maximises the benefits of wind for extra thermal comfort while the minimal indoor partitions assist good indoor air movement and ventilation.

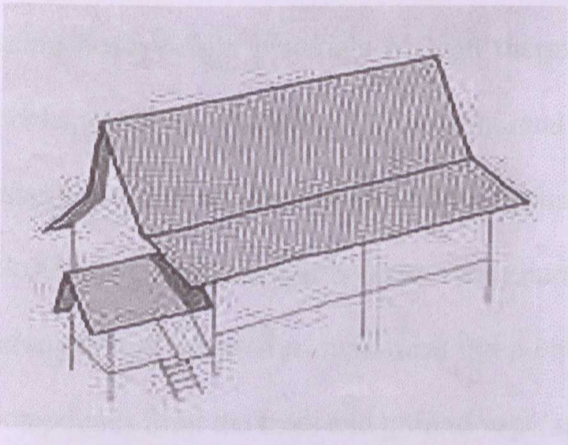

Figure 3.1: Bumbung Panjang
(source: Lim, 1987)

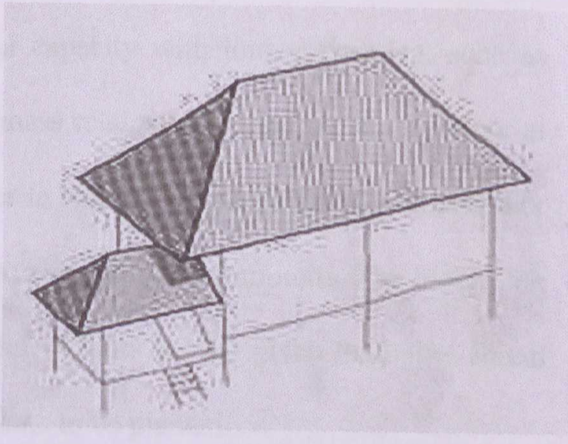

Figure 3.2: Bumbung Lima
(source: Lim, 1987)

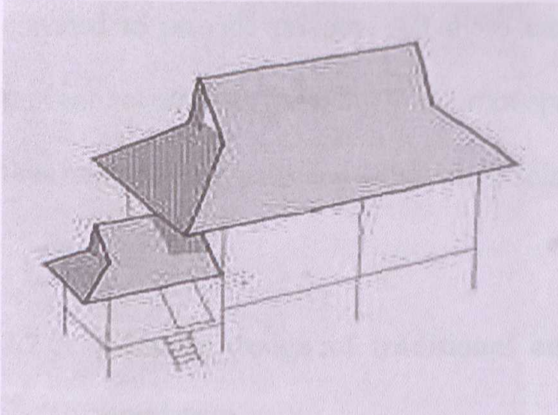

Figure 3.3: Bumbung Perak
(source: Lim, 1987)

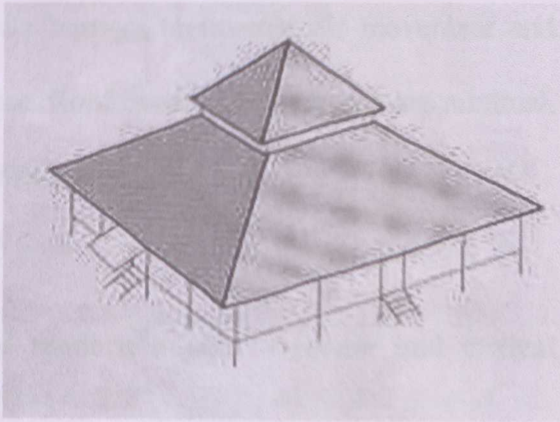

Figure 3.4: Bumbung Limas
(source: Lim, 1987)

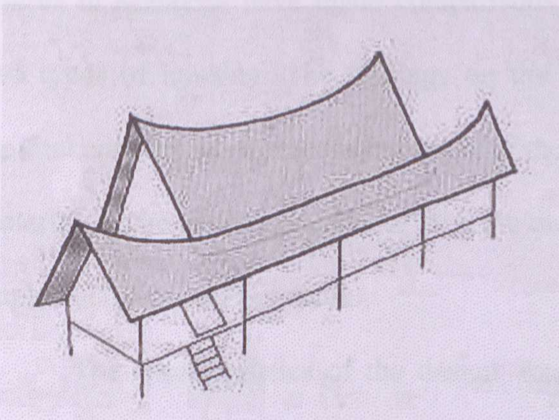

Figure 3.5: Bumbung Minangkabau
(source: Lim, 1987)

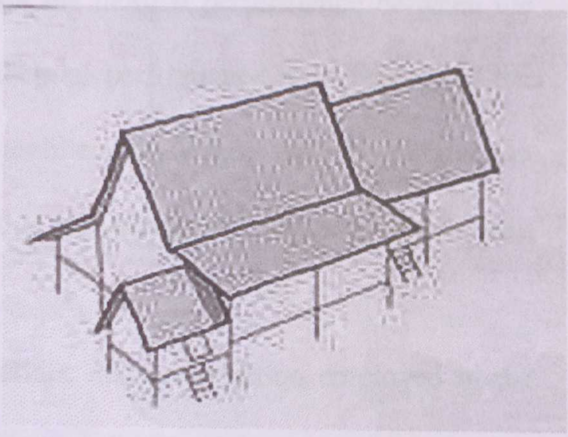

Figure 3.6: Bumbung Gajah Menyusu
(source: Lim, 1987)

3.6.2 Modern house

In contrast to the traditional house, modern houses are constructed on ground using heavyweight materials of high thermal capacity with longer time-lag, such as bricks, concrete, and tiles. The high thermal mass retained heat and radiate it indoor at later hours. The mass-produced modern houses in housing estates are mostly attached or clustered such as the link houses, flats, apartments, and condominiums. The blocks are arranged and oriented to maximise the number of units for the given land size. Small compounds limit the trees and ground vegetations to be planted.

Full internal partitions are used to separate rooms, ceilings are installed to separate the roof space from the living spaces underneath, and glazed windows are elevated to provide privacy. All these create barriers to internal air movement and prevent hot air from escaping to the roof space. Roof eaves and overhangs are minimal, thus exposing the walls and windows to solar radiation.

3.7 Climatic design of traditional and modern houses – review and critical analysis

Studies done on the climatic suitability of traditional and contemporary modern houses in Malaysia have made comparisons on the thermal performance between the two types of housing. The findings on the thermal performance with respect to the thermal comfort were analysed in terms of the architectural designs and the construction material. Some of the concepts of climatic design and energy efficiency have also been implemented in real practices.

The characteristics of the design, materials, and construction employed in the traditional houses as shown and discussed in the preceding sections were said to display adaptations to the climate, which has evolved from centuries of experiences and observations (Zain-Ahmed, 2000; Harith, 1997; Abdul Rahman, 1994; Hanafi, 1991; Lim, 1987). However, despite all the climatic design features, it was concluded that it would be difficult to achieve thermal comfort throughout the day merely by natural means due to high indoor temperature and relative humidity (Abdul Rahman, 1994; Zain-Ahmed, 2000; Jones et al., 1994).

On the contrary, the architectural designs of contemporary modern houses have been criticised as climatically unresponsive (Zain-Ahmed, 2000; Davis et al., 2000; Davis and Shanmugavelu, 1999; Harith, 1997; Abdul Rahman, 1994; Hanafi, 1991; Lim, 1987) due to the unsuitable characteristics that were partly due to cost constraints. These are the arrangements to maximise the number of units on the available plot with no consideration given to the sun path; the introduction of floor-to-ceiling interior partitions for privacy disrupt the indoor airflow for good ventilation; the insulated roofs with ceiling – whilst was believed to moderate the daytime radiation from the roof also inevitably traps the indoor heat during night-time, coupled with poor ventilation have elevated night-time indoor temperature above the outdoor; inadequate shading from trees while the size of the roof eaves, overhangs and other shading devices are left to the minimum. It was concluded that the full floor-to-ceiling compartmental interior, the internal layout, and the orientation that disregard the sun path and wind direction cause large areas of the building envelope to be exposed to solar radiation, and reduced the wind flow in the locality. The night-time thermal performance is further exacerbated by the heavyweight building materials of high thermal capacity with longer time-lag, which release the daytime stored heat later in the evening. This could last throughout the night depending on the amount of heat stored and the duration of time-lag that is influenced by the thickness or thermal capacity of the envelope. However, modern mass-produced commercial building materials have been preferred owing to its availability, durability, fire safety, and aesthetic appeal.

Consequently, the suggestions and recommendations for climatic designs are listed below (Davis and Nordin, 2002a; Zain-Ahmed, 2000; Ahmad, 2000; Ibrahim et al., 1999; Harith, 1997; Abdul Rahman, 1995, 1994; Hanafi, 1991; Lim, 1987).

- *Provision for ventilation*: external and internal layout to maximise air movement; large opening size of 40 % – 80 % of wall area.
- *Walling material and construction*: lightweight; insulated lightweight; light colour.
- *Roofing covering material and construction*: heavyweight; lightweight; low thermal capacity; light colour; reflective; radiant barrier; insulation; roof ventilation; no ceiling; double roof.

Field studies using data logging systems on various types of contemporary modern unconditioned houses have identified the climatic elements for unsatisfactory indoor thermal condition; namely high indoor temperature (Davis, 2000; Harith, 1997; Jones et al., 1994; Abdul Rahman, 1994; Hanafi, 1991), high indoor humidity (Harith, 1997; Abdul Rahman, 1994; Hanafi, 1991), and low indoor air speed (Harith, 1997; Abdul Rahman, 1994). The data analyses of field studies and simulations via computer modelling, and two projects in real practice are presented and discussed in the subsequent sections.

3.7.1 Field data monitoring

Abdul Rahman (1994) performed simultaneous indoor environmental monitoring on two traditional Malay houses with thatched dried palm leaves roof and zinc roof (galvanised iron); and three modern contemporary mass-produced houses classified as: double-storey cluster link with corrugated roof, walk-up flats with no exposed roof, and single-storey terrace with clay tiles roof. Data for the traditional houses showed indoor daytime T_{max} of 34 °C to 36 °C (2 °C to °4 C higher than the external air temperature) that is well above the thermal comfort temperature (T_{tc}) range of 23.8 °C to 30.1 °C obtained from studies in naturally ventilated (S. Ahmad and Ibrahim, 2003; Abdul Rahman and Kannan, 1997) and combined (Zain-Ahmed, 2000) spaces. The night-time indoor temperature dropped close to the external air temperature of 23 °C to 26 °C and was below the T_{tc} range. For both traditional houses, the average temperature difference (T_{diff}) between the external and internal was about 2.5 °C. However, at night-time the house with the zinc roof was about 1 °C cooler due to its higher emissivity compared to the thatched palm leaves. The RH ranged from 50 % to 90 % and the air speed was less than 0.2 ms^{-1}. As for the contemporary houses; the indoor daytime were lower – T_{max} of 32 °C to 33 °C with a time-lag of 2 hours to 5 hours and indoor-outdoor T_{diff} up to 2.5 °C, night-time temperature was high at about

30 °C, RH ranged from 50 % to 90 %, and the air speed were between 0.1 ms^{-1} to 0.2 ms^{-1} and reached 0.5 ms^{-1} aided with fan. In conclusion, the results show that the daytime temperature of both houses was above the T_{tc} range, however the traditional house provided better night-time thermal condition. At the time of writing, this is the most comprehensive data collection on thermal performance of traditional and modern houses in the country.

Harith (1997) conducted field study monitoring and computer simulation to evaluate the thermal performance of traditional and modern houses. The field data analyses of the traditional house with asbestos sheet roofing showed daytime T_{max} of 32.4 °C (0.8 °C higher than the external air temperature) that is above the mentioned T_{tc}. The indoor T_{mean} was 27.4 °C with night-time temperature close to the external air temperature of 23.6 °C, which was slightly below the lower T_{tc} range. The indoor RH ranged from 66 % to 96 % and the airflow reached a maximum of 0.58 ms^{-1}. The T_{max} in the modern houses roofed with corrugated cement tiles was 32 °C to 32.4 °C with a time-lag of about 4 hours, and the RH ranged from 61 % to 78 %. Although the RH is lower compared to that in the traditional house, the overall indoor temperature was higher. Similar to the findings of Abdul Rahman (1994), it was concluded that both houses were thermally uncomfortable during daytime but traditional house performed better at night.

The above findings show that in the traditional houses, the indoor daytime T_{max} was up to 5.9 °C above the upper limit of T_{tc} but at night, it was slightly below the lower limit. Therefore, the indoor daytime temperature could be unbearably hot when the solar radiation is at its peak. It cools down quickly after sunset but it could go well below the comfort temperature. This was mainly due to the lightweight building materials of low thermal capacity with negligible thermal mass, thus responded quickly to the changes of the external climate. They do not store heat and the time-lag is very short. Thus, the traditional building materials are suitable during night-time to take advantage of the cooler external temperature, but the usage are threatened by scarcity, maintenance, durability, and fire hazard.

In the modern houses, the T_{max} was up to 3.8 °C above the upper limit of T_{tc} and the minimum night-time temperatures were barely within the comfort temperature range. Many occupants in the concrete modern houses experience discomfort during most of the early evening to early morning hours mainly due to the higher humidity and lack of air movement and ventilation. These were among the causes of discomfort identified in all the studies and were deduced to be the consequences of improper design and inappropriate building materials. The RH recorded were as low as 50 % during daytime and as high as 90 % at night-time while the indoor air speed was up to only 0.3 ms^{-1} (Harith, 1997) even with the aid of fans (Abdul Rahman, 1994). The proposed comfort zone by Abdul Rahman (1999) shows that to be thermally comfortable with airflow of less than 1.0 ms^{-1} the upper RH limit must be in the range of 45 % to 65 %, which means that the indoor condition in these houses would never be in the comfort zone in natural ventilation during daytime.

It was concluded that the overall thermal performance of contemporary modern houses was worse than the traditional house. Despite the different building materials used in the traditional and modern houses, the daytime performance in modern houses were similar – an average of 2.5 °C higher than the external temperature but occurred later in the afternoon due to time-lag, but at night the traditional building materials provided a more favourable indoor condition (Abdul Rahman, 1994; Jones et al., 1994). These analyses were from field data recorded in different house forms at different localities and during different periods that were subjected to variations in external weather conditions. However, due to the nominal annual weather disparities in

Malaysian climate, the similarity in the findings could be used as an indication of the general performance of the two categories of houses.

3.7.2 Numerical simulation via computer modelling

Dynamic numerical simulations and whole-building analyses via computer modelling performed concurrently with the above empirical studies using suitable thermal softwares of FACET/APACHE (Harith, 1997) and HTB2 (Abdul Rahman, 1994) showed similar temperature and RH profiles on both types of houses despite of some discrepancies among the measurements. Apart from the accuracy and limitations of the softwares, the inconsistency of the assumptions on the internal conditions and the thermophysical properties of the building materials could be another underlying factor. More comprehensive computer simulation investigations were carried out using HTB2 (Hanafi, 1991), Bsim2000 (Davis and Nordin, 2002a), TSBI3 (Reimann, 2000), and Tas (Zakaria, 2002; Zakaria and Woods, 2002a, 2002b) as numerical evaluation tools to predict the sensitivity of the indoor thermal environment in contemporary modern houses towards various building conditions such as ventilation and thermal designs of the envelope.

Hanafi (1991) conducted parametric studies using HTB2 to investigate the appropriate thermal design of walls and roof based on a simple one-storey detached single-space dwelling and later applied the most favourable elements to a more complex two-storey detached multiple-space dwelling. Both the traditional and modern constructions were considered and evaluated in terms of the thermal performance using the Corrected Effective Temperature (CET) as the thermal comfort index. The findings on choice of the design elements for the single space dwelling and the application on the multiple space dwelling are summarised below.

- *Space ventilation*: Optimum rate was identified as 30 ach, which was equivalent to an air movement of 0.45 ms^{-1} and produced 15 hours of comfort.
- *Solar shading*: Shading on wall and window reduced the CET T_{max} by 1.2 °C.
- *Roof insulation and ceiling option*: Glassfibre insulation was applied to corrugated asbestos cement sheet roof and asbestos cement sheet was used for the ceiling. Uninsulated roof with no ceiling performed the worst while the use of ceiling had resulted in a less favourable condition. The benefit of roof insulation was confirmed but that of the ceiling was doubted.
- *Wall construction*: The walling configurations were uninsulated lightweight, insulated lightweight and heavyweight. The effect of thermal mass and time-lag were demonstrated by a lower T_{max} with one hour delay in heavyweight wall. Uninsulated lightweight wall was the least satisfactory while the lightweight insulated resulted in a comparable performance with the heavyweight walls and was therefore recommended.
- *Roof covering materials*: The materials used were the asbestos cement sheeting, concrete tiles, traditional clay tiles, traditional shingles, and thatched palm. There was no significant effect in terms of indoor air temperature, but with respect to the mean radiant temperature, thatched and shingles produced the most favourable results while zinc gave the highest daytime T_{max} due to its higher k-value but the lowest value in the morning owing to its lower emissivity. Despite the better thermal performance of thatched and shingles, they were less durable and more vulnerable to dilapidation, and thus new roofing materials with higher reflectivity and insulating property were recommended.
- *Application to multiple-space dwelling*: The most desirable elements were applied to the multiple-space dwelling with higher ventilation rate and corrugated asbestos cement sheet as the roof covering to account for the practicality of the

implementation. The simulation of the improved construction showed a more satisfactory indoor condition by the reduction of the discomfort hours. Whilst total comfort still could not be achieved, the following conclusions were made with respect to construction features to reduce heat gains and heat built up in the building: provision for better air movement, adequate solar shading, roof insulation and no ceiling, and lightweight wall with insulation.

At the time of this review, Hanafi's work is the most comprehensive numerical simulation studies on thermal design of traditional and modern building envelope.

Harith (1997) used FACET/APACHE to predict the thermal impact of several building parameters on traditional and modern houses. These are summarised below.

- *Space ventilation*: Optimum rate was identified as 35 ach.
- *Roof ventilation*: Reduced indoor temperature by 0.1 °C and the impact was concluded to be insignificant.
- *Ceiling emissivity*: ε of 0.01 reduced the internal air temperature by 0.2 °C and ceiling surface temperature by 1.2 °C.
- *Ceiling insulation*: A 100 mm glass wool lowered indoor T_{max} by 0.9 °C with vented roof space and 1.4 °C if sealed. It was concluded to be beneficial regardless of roof space ventilation.
- *Higher thermal mass wall*: Reduced the indoor air temperature up to 0.5 °C with vented roof space and gave a difference of 0.1 °C between vented and sealed roof space.
- Venting of roof space was highly recommended irrespective of other thermal design measures.

Reimann (2000) performed numerical simulations on roof designs of the Universiti Putra Malaysia (UPM)-Thermal Comfort House (TCH) that used RapidWall building system that is discussed in section 3.7.3. Software Heat2 that is a steady-state

2D computer program was used to determine the U-values of the existing steel frame lightweight RapidWall roof and several modified RapidWall roof with additional RB, insulation and ventilation rates. The results were as follows: the use of aluminium foil as RB lowered the U-value by 13 % and thus was recommended for less insulated roof; ventilated air cavity of 100 ach beneath the roof covering reduced the U-value by 13 %, thus was also recommended for poorly insulated roof. A more comprehensive TSBI3 software was later used to determine the impact on the cooling load. The result showed that the additional 100 mm insulation had a nominal energy impact with 7 % reduction in cooling load.

Davies and Nordin (2002a) investigated the benefits of five thermal design elements, individually and combined, on a single-storey semi-detached house using BSim2000. Evaluations were based on the T_{max} in the living room. The elements and respective analysis are summarised below.

- *Colour:* Changing red metal roof to white lowered T_{max} by 0.3 °C.
- *Wall thermal mass*: Higher thermal mass cement rendered brick wall reduced T_{max} by 0.3 °C over the lightweight Rapidwall building system.
- *Roof thermal mass*: Changing the roofing material from highly insulated Rapidwall roofing system (red metal) to the commonly used concrete tiles increased T_{max} by 3.5 °C.
- *Infiltration rate*: Lowering the rate from 3 ach to 0.5 ach reduced T_{max} by 0.4 °C.
- *Nightime mechanical ventilation*: The rate of 28 ach reduced night temperature by 1 °C and daytime temperature by 0.2 °C.
- When a combination of the identified elements was constructed, T_{max} was predicted to be 28 °C with electricity consumption of 10 $kWhm^{-2}year^{-1}$ to run the night-time mechanical ventilation system.

Zakaria and Woods (2002a, 2002b) performed parametric simulations of thermal design of roof on a two-storey linked house using **Tas** (EDSL, 1989). Evaluations were based on the T_{max} in the living room on the upper floor. Roofing material was concrete tiles and dark colour with $\alpha = 0.9$ was taken as the base-case. The roof parameters investigated and the analyses are summarised below.

- *Colour*: changing roof colour from $\alpha = 0.9$ to 0.3 reduced T_{max} by 1.0 °C.
- *Insulation*: 200 mm insulation reduced T_{max} by 1.1 °C.
- *Roof ventilation*: 100 ach reduced T_{max} by 0.9 °C and 10 ach was identified as the optimum, which lowered it by 0.8 °C.
- *Roof pitch*: increasing the pitch from 22° to 45° lowered T_{max} by 0.3 °C. It was concluded that light coloured high pitch roof was the best while dark coloured low pitched was the worst.

Using the same software and house model, Zakaria (2002) performed another simulation study to investigate the effect of orientation and roof colour on surface solar gain (SSG) and indoor temperature with the following results:

- *SSG*: SSG of the roof was 86 % of the total SSG for the whole envelope. Orientation altered the SSG of the roof by only 0.3 % while that of the other parts of the envelope by 32 % to 38 %. Light coloured roof lowered the roof SSG by about 65 %.
- *Temperature*: orientation affects the temperature in living spaces up to 2 °C and the light coloured roof altered it by 0.7 °C.

In conclusion, the above analyses from both physical and numerical studies have confirmed certain benefits of space and roof ventilation, roof insulation, lighter roof colour, higher pitch with bigger roof volume, ceiling insulation and higher thermal mass walls. On the contrary, the above findings stirred some doubts on the benefits of ceiling and uncertainties on the optimum type of wall and roof constructions as both the lightweight and heavyweight have the advantages and disadvantages. In all the above studies, the evaluations were based on either very few identified variables or only several preset values. Thus, the optimum values were not identified except for space and roof ventilations. The cost analysis for the economic benefits would be of interest to many end-users. Therefore, it is imperative to identify the optimum values for all the design parameters and the interactive impacts on the indoor thermal environment. In addition, it is worth mentioning that the above investigations were performed using different commercial computer thermal programs on various design configurations in variable external climatic conditions. Nevertheless, the data show some consistent patterns on the prediction of the performance. Apart from space ventilation, the temperature modifications due to the above design considerations were quite nominal which gave minimal improvements on the thermal comfort conditions. The intricacy of improving the thermal comfort conditions mainly due to high humidity and other limiting factors have eventually led many households to resort to air conditioner systems to alleviate the thermal stress as reported by Masjuki et al (2001). Therefore, additional analysis for the energy performance is prudent and this calls for a more comprehensive study on the thermal designs of contemporary modern house.

3.7.3 Research projects

In search of suitable building materials, the research group at the Centre of Thermal Comfort Studies in Universiti Putra Malaysia (UPM) had conducted a research on a new building system for thermally comfortable and energy efficient houses in Malaysia (Davis, 2000; Davies et al., 2000). The Rapidwall building system, a technology from Australia, was used for the wall and roof of a prototype low-cost house dubbed as UPM Thermal Comfort House (UPM-TCH) shown in Figure 3.7. The system consisted of pre-fabricated lightweight load hollow walls made from gypsum that is reinforced with fibreglass. The voids were filled with 75 mm rockwool insulation. Initial comparison study with a normal single-storey terrace house showed a lower peak hour temperature of about 3 °C. It was reported that the house could be kept within the comfort zone with the use of 6.4 kWh of electricity per day to run an air-conditioner unit and a whole-house fan ventilating system. However, a later computer simulation study using computer software as discussed in the previous section revealed that this building system had a peak indoor temperature of 0.3 °C higher than the usual cement rendered walls, thus concluded the contemporary walls to be more suitable than the Rapidwall system (Davis and Nordin, 2002a). There seemed to be an inconclusive finding on the aptness of the building material for the country – should it be lightweight or medium weight or heavyweight?

Figure 3.7: UPM-TCH (1999)

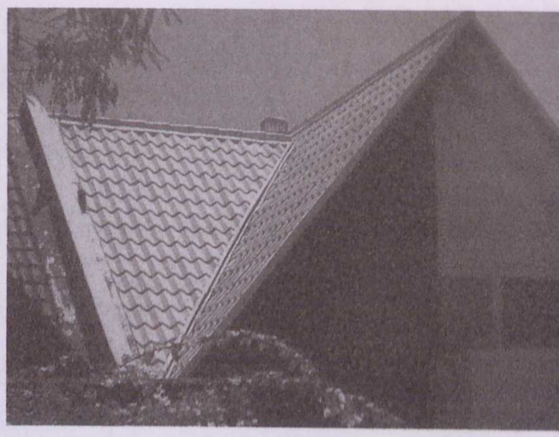

Figure 3.8: UPM Cool Roof (Davis and Nordin, 2002b)

Another study done by this research group was the UPM Cool Roof (Davis and Nordin, 2002b) shown in Fig 3.8. The outer layer of roof was constructed from white metal tiles, insulated with reflective aluminium foil and rockwool insulation. It was reported that the UPM Cool Roof had successfully reduced the thermal discomfort unit from one to 18 units in the living spaces and 66 units in the roof space. Using the UPM definition of thermal discomfort units (Davis and Shanmugavelu, 1999), these are equivalent to the average temperature difference of 0.1 °C to 0.5 °C for the living spaces and 2.8 °C in the roof space, and the peak hour temperature in the roof space was reduced by 13 °C. However, energy evaluation was not included. While this product appears to have demonstrated a promising solution to the thermal problem in Malaysian houses, an exhaustive research is desperately needed to establish information that is more scientific and the necessary database for further development on the product or for other related products.

3.7.4 Projects in real practices

This section presents two housing projects that were initiated with the concepts of energy efficiency and sustainability.

a) Beris Dam Resettlement project in Kedah

A core house for the *Beris Dam Resettlement* housing project was designed by the then Department of Architecture of the Universiti of Malaya with the concept of Low Energy Architecture encompassing energy efficiency and sustainability issues (Woods and Ahmad, 2000). Several prototype houses constructed at Paya Pahlawan are depicted in Figure 3.9. Figures 3.10 to 3.12 show some of the 600 houses constructed at Sungai Pau.

Figure 3.9: Prototype houses at Paya Pahlawan

Figure 3.10: Site at Sungai Pau

Figure 3.11: The completed house

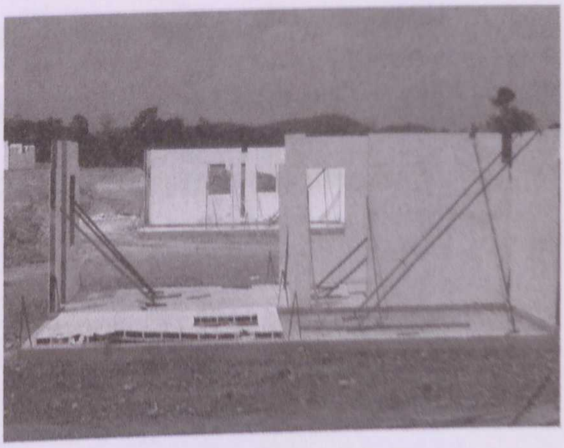

Figure 3.12: Rapidwall building system

Figure 3.11 shows Rapidwall building system was used for the ground floor and the lower part of the upper floor where wooden wall was used for the remaining part upper. Unlike in the study at UPM, the voids in the wall panels were left hollow as can be seen in Figure 3.12 – perhaps to cut cost. Referring to findings from the UPM-TCH discussed earlier, the evaluations of the building system have shown some inconsistencies in the performance. Thus, a Post Occupancy Evaluation (POE) of the building performance on the thermal, energy, and social aspects would provide valuable information. Apart from looking the climatic suitability of the material as a component, a study on the thermal design of a construction to function as a whole-building system must be considered to make it suitable and applicable for all needs and purposes.

b) Public Works Department (PWD) – New Quarters Design (NQD)

The existing standards and guidelines of the PWD quarters mentioned in the preceding section 3.5 are only on the infrastructure and quality of building materials. There are no guidelines on sustainable development in terms of design and construction with respect to human comfort and energy efficiency as well as the resources.

To respond to the call by the global community on green or sustainable development, the PWD of Malaysia has initiated the PWD-NQD programme as mentioned in section 3.5. Among the design criteria in the principles of sustainable development to be adopted in the design process were human comfort, energy efficiency and renewable energy, building shape and orientation, and the characteristics of the building envelope with the following details and provisions (Jaffar, 2004):

i) Human comfort

- good daylighting, ventilation, air quality
- good security and safety
- thermal control on temperature and radiation

ii) Energy efficiency and renewable energy

- utilisation of natural energy resources such as daylight and natural ventilation
- low energy and energy efficient electrical fixtures and building systems
- utilisation of renewable energy technologies such as photovoltaic, solar heating, and rain water harvesting

iii) Building shape and orientation

- long axis of building in north-south orientation and avoid it from east-west
- shading devices at required locations

iv) Building envelope

- material for good thermal performance and insulation
- construction with consideration on Overall Thermal Transfer Value (OTTV) and Roof Thermal Transfer Value (RTTV)
- design with minimum external wall to volume ratio, and light colour to minimise the absorption of solar radiation

Translating these in terms of thermal design, it means considerations on the solar thermal impact on the building envelope to maximise the indoor thermal comfort with minimum energy consumption.

In addition to the existing standards and guidelines on infrastructure and building materials stated in section 3.5, the PWD-NQD designs have also undergone the JKR ISO 9001 standard procedures that involved three stages of design evaluations based on the new criteria (Jaffar, 2004). The first stage was evaluation by the experts from Tenaga National Berhad, Economic Planning Unit, Selangor State Development Board, and the PWD. The second stage was evaluation by the top management personnel of PWD and directors from headquarters and states. The final stage was evaluation by all the PWD district engineers. Out of the four criteria mentioned above, an analyses of the design evaluations revealed that the designers have paid the least attention to criteria (ii) and (iv), which are the energy efficiency features and building envelope considerations.

3.8 Summary and conclusion

The lack of EE documentations and guidelines for residential buildings could be due to the low consumption of only 18.2 % of the national energy. However, the previous research findings on the thermal condition of contemporary modern houses should be taken as early warnings on the energy and environmental implications by the domestic sector.

The studies done by the previous researches have identified the causes that have diminished the ability of modern houses in Malaysia to provide quality housing with respect to thermal and energy performances. Physical and numerical investigations have been performed to ascertain the appropriate climatic design strategies for residential buildings in the country. These were the architectural design and planning, material, construction, and building systems for the walls and roofs. The parameters were form and layout, space and roof ventilation, usage of ceiling, lightweight materials, heavyweight materials, thermal insulation, and colour of envelope. However, these studies by researchers in the country are only the tip of an iceberg compared to those done for other climates in other countries as discussed section 2.3.3. More detail and comprehensive studies on many aspects of building design are needed to establish the groundwork for further development towards providing quality housing as outlined in the 8th MP. This includes researches for quantification of the identified design strategies and parameters for wide ranging built environment applications for it to be used for guidelines and standards.

Working towards the nation's and country's aspirations for Vision 2020 (Malaysia, 1994), the Government is leading the implementation of some sustainability development concepts with EE strategies in built environment. The design evaluations on the PWD-NQD have revealed the need for more systematic research to materialise the concept. The country is still at the teething stage towards this implementation, thus tremendous efforts, commitments, and collaborative work among academics, government bodies, and various private sectors would be needed.

To that end, this study takes the challenge by pursuing a research on thermal design of roof. The research framework and methodology adopted are fully explained in the next chapter.

CHAPTER 4: RESEARCH METHODOLOGY

4.1 Introduction

The research issues discussed on the global and national reviews in the preceding chapters have clearly justified the need for a study on thermal design of roof for modern houses in Malaysia. This research explores the thermal design of the roof for modern residential buildings by evaluating the dynamic whole-building thermal and energy performances. Referring to the research process illustrated in Figure 1.1 on page 6, this chapter elaborates on the theoretical framework. The research issues and statement are stated in section 4.2 and 4.3 respectively. The aim, objective, and outcome of the research are listed in section 4.4. The scope of research is explained in section 4.5 followed by the analysis in section 4.6. The scope of research determined the research approach to be employed and the options are discussed in section 4.7. Lastly, a brief overview of the execution of the selected research approach is given in section 4.8.

4.2 Research issues

Recapitulating the discussions on the building designs and the relevant research findings in Chapter 2 leads to the following research issues regarding the climatic designs and the implication on space cooling needs, and EE measures for residential buildings in Malaysia

a) EE documentations and guideline

EE programmes have been identified as one of the strategies toward sustainable development in the 8th MP. Since the commercial and industrial buildings are the major consumers of energy, the Government has shown more interest on programmes for non-residential buildings. The PWD-NQD programme is making a debut in government sponsored EE project for residential buildings. The guidelines and documents (SIRIM, 2001; Malaysia, 1989) mentioned in section 3.4.2 are providing the much needed references for immediate practices and current researches. However, from the stage of literature review until the preparation of this thesis, similar guidelines and references for non-residential buildings are still not available and the compilation of the relevant technical data for Malaysia is very much lacking.

In the year 2000, 4.6 million residential buildings in the Peninsular (Malaysia, 2001e) consumed only 16.8 % of the national energy consumption and it has increased to 18.2 % in 2002 (Malaysia, 2003a). While the overall percentage is small, the impact of higher living standards due to socio-economic development and the savings that could be generated with EE measures must not be misjudged. Moreover, it is essential to establish Malaysian standards and guidelines for this building type in the aspirations of materialising Vision 2020. Other developed countries such as U.S.A, U.K., Denmark, and Australia have established and are continuously revising the building energy codes to comply with the global agreement and concerns on the energy and environmental issues as was mentioned in section 2.2 and 3.4.2. The standards and benchmarking must take into account the climatic factors, needs of the society, and the cultural diversity.

The compilation of the relevant databases is the first step towards further researches in the related area. Whilst the residential buildings appear to have a nominal short-term consequence on the national energy consumption, the long-term impact on the mindset of future generations must not be underestimated, since this is the type of building aspired by every single energy-environment conscious citizen of a developed country.

b) Climatic designs of modern houses

The discussions on the climatic building design and energy in building in the preceding chapters have demonstrated that studies on residential buildings have been of interest to many researches – local and abroad. At the national level, the literature search has found several studies conducted on the thermal and energy performances of residential buildings. Traditional houses were reported to display the adaptation to the climate by means of the architecture design and type of material. On the contrary, the contemporary modern houses were criticised of being not climate-responsive. However, it was concluded that generally both the traditional and modern houses exhibited limitations on the thermal comfort level that could be attained. The shortcomings were mainly due to the building material of traditional houses, while for modern houses the constraints of architectural design and planning were identified as the major factors.

The concept of formal housing as introduced by the government to address the housing needs and to ensure proper planning of townships towards Vision 2020 has transpired in the emergence of contemporary mass-produced modern houses provided by both public and private developers. In due time, this type of houses is also going through some transformation in many aspects in respond to the socio-economic development. Thus, the quality of modern houses is of great concern, amongst others studies to improve the thermal and energy performances of these houses are highly imperative.

c) Recommended climatic design features

The design characteristics recommended in Chapter 2 can be classified as architectural and planning, and envelope construction; and both have cost implications. However, the architectural design and planning such as form, size, orientation, and external and internal layout are subjected to more constraints in term of the project development as a whole. On the other hand, the construction of the envelope could be given a more individual attention and prioritised according to the degree of impact on the overall building performance.

For low-rise buildings in equatorial region such as Malaysia, the roof is the major source of heat gain. Thus, several features have been recommended by many researchers and have been extensively studied in certain countries as mentioned in section 2.3.3. Among others were; light surface colour, lightweight material, roof space ventilation, ceiling, and thermal insulation for roof and ceiling including radiant barriers. Some of these features have also been investigated for houses in Malaysia as discussed in section 3.7. However, a more comprehensive study on thermal design of the roof to quantify the optimum values and the interactive impact on thermal and energy performances would provide valuable information for studies on residential buildings in Malaysia.

4.3 Research statement

The thermal and energy performances are determined by the heat exchanges of the building. These exchanges are influenced by the building response to the local climate. Control of the heat exchanges can be achieved via proper thermal design of the building envelope. For buildings in lower latitude regions, vis-a-vis the Equator, the roof has been said to be the major source of heat gain. This heat gain would be more significant in low-rise residential buildings. Thus, appropriate thermal design of the roof would be able to moderate the thermal impact from the local climatic conditions. This research explores the thermal design of the roof for a Public Works Department New Quarters Design (PWD-NQD) double-storey bungalow by evaluating the dynamic whole-building thermal and energy performances.

4.4 Aim, objectives, and outcome of research

The aim was set to address the research issues and statement. The research objectives were actions to be done to achieve the aim and these were documented as the research outcome.

a) Aim

- To identify the thermal design of roof assembly for optimum whole-building thermal and energy performances for low-rise detached residential buildings in Malaysia.

b) Objectives

- To quantify the optimum roof thermal parameters for best thermal performance.
- To apply the combined optimum roof thermal parameters and evaluate whole-building thermal and energy performances.
- To analyse the roof thermal design options pertaining to the thermal impact and cooling energy needs.

c) Outcome

- To contribute to recommendations for thermal design of the roofs for low-rise detached residential buildings in Malaysia.

4.5 Scope of research

This covers the type and model of building, materials, and constructions of the envelopes, roof parameters, and the investigation tool. The details are elaborated in Chapter 6.

a) Type and model of building

The national review in Chapter 3 has revealed the need for the establishment of an appropriate database on the thermal and energy performances for residential buildings in Malaysia. Reports on urbanisation and the housing scenario in the country have concluded that modern houses are the contemporary housing type. Many of the previous studies have identified various thermal and energy related problems with this type of house. The rapid development of the country and the escalating demands for houses have indeed made these problems as issues that need to be addressed at the national level.

The Government have initiated and embarked in implementing some of the recommendations and suggestions proposed by researchers and professional practitioners as mentioned in section 3.4. At the time of selecting the house model for this study, the PWD-NQD programme was the only housing project that promoted the concept of EE in buildings. Therefore, this research is very opportune to evaluate the designs that have been given careful considerations on EE and sustainability features as mentioned in section 3.7.4 (b). These features and the existing guidelines mentioned in section 3.5 are qualitative descriptions. These have to be quantified for the purpose of performance evaluations. Therefore, it is very timely to produce and compile the necessary technical details to support the programme. Even though all the architectural designs have been finalised, the findings of this research could still be of benefit for this programme and others in the future.

In the PWD-NQD programme, there are 28 building design types comprising of bungalow, semi-detached, low-rise, and medium-rise and mixed development apartments (Jaffar, 2004). Since the research is to study the thermal design of roof, the most appropriate type of design is a low-rise building as the ratio of roof surface area to total building surface area is higher. A double-storey [1]bungalow design was chosen, as this type is a detached building that would eliminate the thermal effects due the adjacent dwellings. The bungalows are in the categories of Class B, C, D, and E with respective floor areas of 345 m^2, 288 m^2, 188 m^2, and 135 m^2. To evaluate the significance of the overall thermal impact on the building, the smaller size would be a better option. The Class D bungalow was chosen as it is the intermediate size compared to the others to enable future comparison studies with the next bigger Class C and the smaller Class E bungalows.

These quarters have been designed to comply with the standards and guidelines set by the Malaysian government as mentioned in section 3.5 and are used for all government quarters throughout the country. Thus, any findings from this research would give direct contribution to the government of Malaysia in particular, and the population of Malaysia in general. With regards to the EE and sustainability features mentioned in section 3.7.4 (b), the findings could be set as a guide for the performance evaluations for the other designs of the PWD-NQD. These can also be used as a reference to benchmark the thermal performance and energy rating to the housing industry in Malaysia. Certainly, adaptations must be made to consider the possible disparity in thermal responses for other types of house form.

In conclusion, contemporary modern house is the most appropriate type of residential building to be studied, and a PWD-NQD Class D double-storey bungalow was chosen as the house model for this research. The model for the real house and the internal layout are shown in Figures 4.1(a) to 4.1(d).

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[1] Bungalow in Malaysia implies stand-alone building which could be one or two-storey.

Figure 4.1(a) Front view

Figure 4.1(b) Perspective

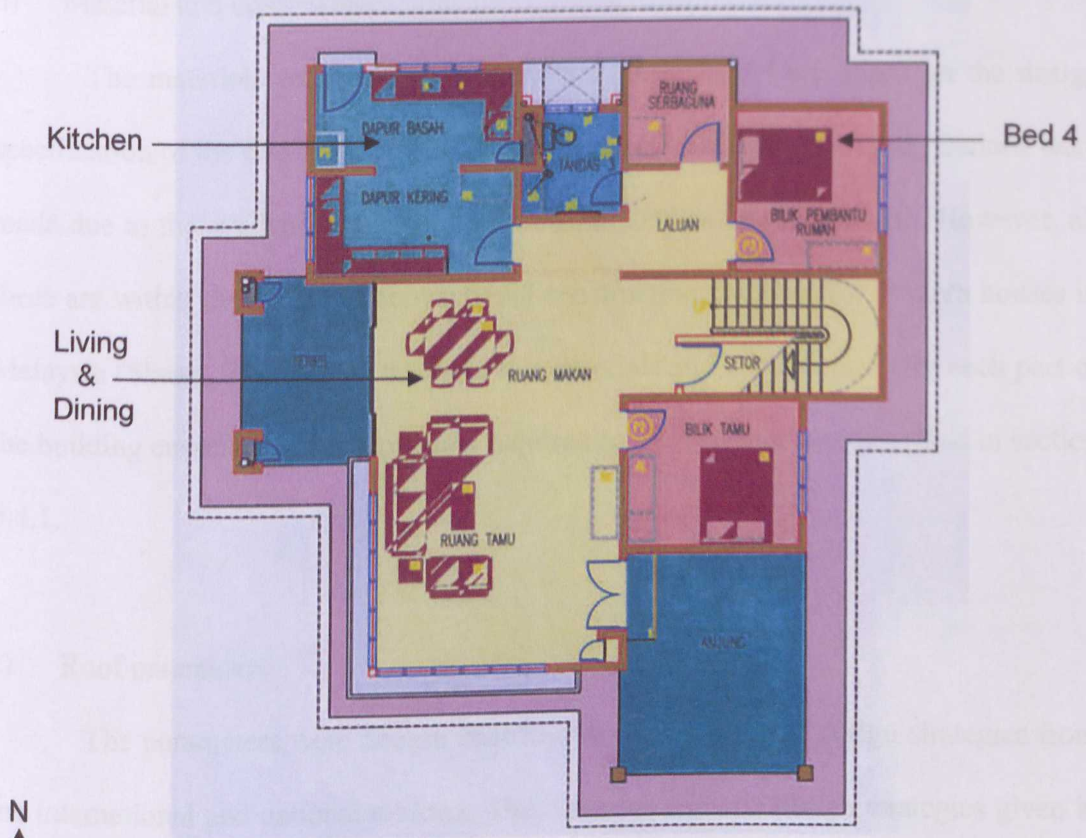


Figure 4.1 (c) Floor plan of ground floor

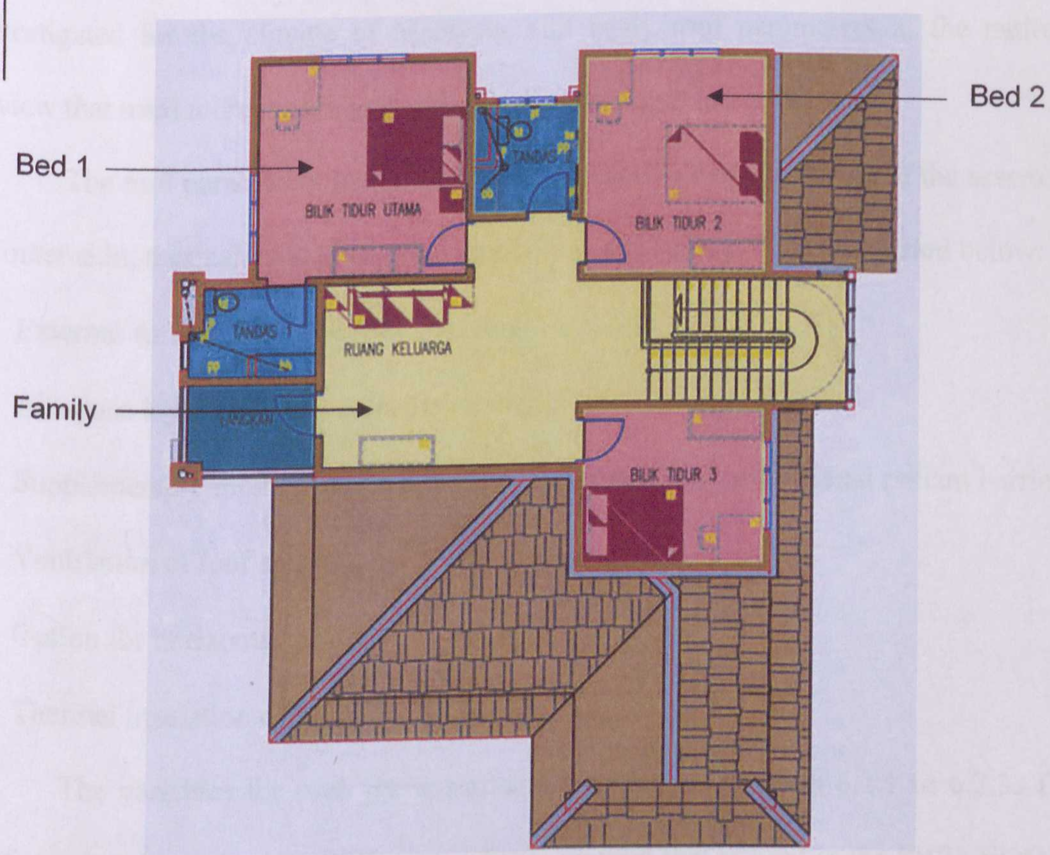


Figure 4.1 (d) Floor plan of upper floor

Figure 4.1: Building model of PWD-NQD (courtesy PWD of Malaysia) (scale 1:100)

b) Material and construction

The materials and constructions for the house model are based on the design specification of the real PWD-NQD house (Malaysia, 2002e). Some modifications were made due to the availability of the required input details for the database. However, all these are within the norms of conventional construction practices for modern houses in Malaysia (Shaari, 2001). The details of the materials and constructions for each part of the building envelope as the input data required by the software are described in section 6.4.1.

c) Roof parameters

The parameters were chosen based on the recommended design strategies from the international and national reviews. These are the climatic design strategies given in Chapter 2, roof parameters in the previous international studies that need to be investigated for the climate of Malaysia, and lastly roof parameters in the national review that need more extensive studies as discussed in Chapter 3.

The roof parameters identified for this research are the attributes of the assembly of outer skin, thermal insulation, roof ventilation, and ceiling. These are listed below:

- External surface colour of roof covering
- Air space layer beneath the roof covering
- Supplementary thermal insulation material beneath the conventional radiant barrier
- Ventilation of roof space
- Option for horizontal ceiling
- Thermal insulation over the horizontal ceiling

The variables for each parameter are described in sections 6.2.1 to 6.2.3. The roof construction is based on the conventional method that is used in the PWD-NQD as shown in Figure 4.2. The use of aluminium lining as radiant barrier has become a standard feature and concrete roof tiles in an assortment of colours is becoming the most common roof covering for PWD-NQD (Jaffar, 2002) as well as in conventional practices for other residential buildings (Shaari, 2001). Therefore, the radiant barrier and the other types of roofing material were not considered as a parameter of study.

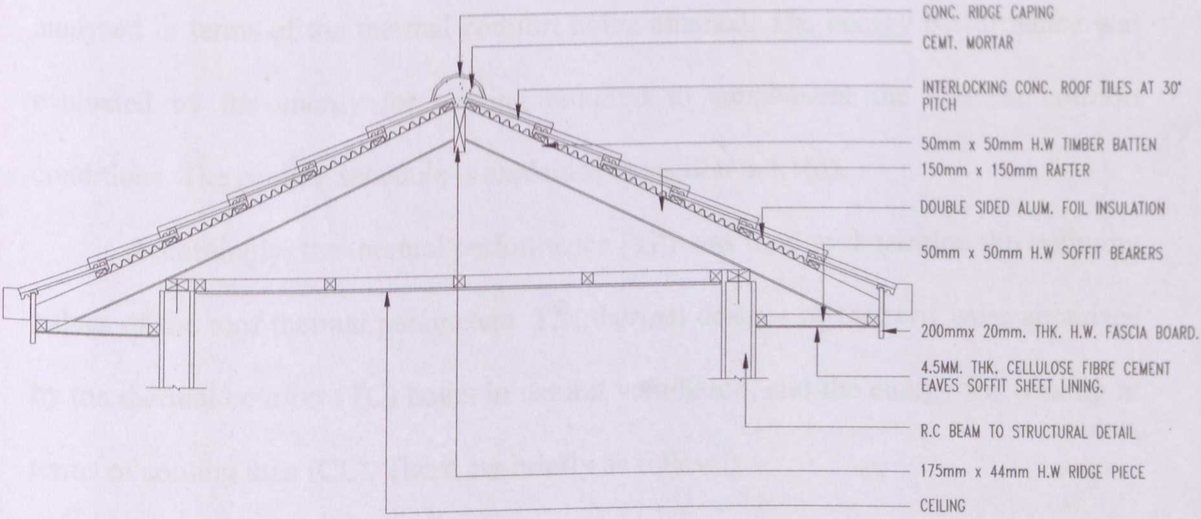


Figure 4.2 Roof detailing of PWD-NQD
(Malaysia, 2002e)

d) Investigation tool

This was determined from the research approach employed. The options and the selection of the most befitting technique are discussed in the next section. The scope of this study is to utilise a commercially available tool to perform the identified assessments within its capacities and limitations. The selected investigation tool for the research was a thermal design computer software **Tas** (EDSL, 1999). The selection of the tool and an overview of **Tas** are described in section 5.3 and 5.4.

4.6 Analysis

The roof thermal designs were appraised by the dynamic whole-building thermal and energy performances. In general, domestic buildings in Malaysia are naturally ventilated. Hence, the thermal performance was evaluated by the indoor temperature variations due to the thermal impact by the ambient weather conditions. It was also analysed in terms of the thermal comfort hours attained. The energy performance was evaluated by the energy for cooling required to supplement the thermal comfort conditions. The cooling schedule is explained in section 6.4.1(d).

Accordingly, the thermal performance (TP) was used to determine the optimum values of the roof thermal parameters. The thermal designs of the roof were appraised by the thermal comfort (TC) hours in natural ventilation, and the energy for cooling in terms of cooling load (CL). These are briefly as follows:

- TP – based on the maximum indoor air temperature. The air temperature was used, as it is the basis for the comfort zone used in the evaluation. The mean indoor air temperature was also used in certain parts of the analysis.
- TC – based on the recommended comfort zone (CZ) for Malaysia shown in Figure A1.0 in Appendix A.
- CL – the sensible CL was used as an indication to the pattern of the energy consumption

The evaluations were performed to analyse the dynamic whole-building thermal and energy performances due to the thermal impact by the ambient weather conditions. Therefore, the impact from individual roof element such as the roof/ceiling surface temperature were not analysed separately.

One of the criteria for selecting **Tas** as the thermal design software as mentioned in section 5.3.1 was the TC assessment using the PMV and PPD indices. However, the selected software has a limitation of a one-hour TC analysis, in which a 24-hourly individual data input would be required. The model would be individually simulated for each hour to obtain a daily TC evaluation. This means for each design, an hourly data consisting of the required boundary conditions have to be manually entered and has to be repeated for a total of 24-hourly period. Considering the number of design options to be evaluated, the manual entry of the needed data was considered impractical. Moreover, the PMV-PPD indices were reported to be unsuitable for naturally ventilated buildings as mentioned in section 3.3.2

For that reason, it was decided that the findings from the previous thermal comfort studies in Malaysia would be the most fitting reference to be adopted. The appraisal for the TC conditions was TC hours. This can be obtained from a comfort zone chart for Malaysia. At the time of analysing the data, the comfort zone chart for Malaysia proposed by Abdul Rahman (1999) is the most appropriate method to be used. It was constructed using the MYC data that was used as the climate data in this research. Thus, it would be valid for the evaluation performance.

4.7 Research approach

The aim of the research is to identify the thermal design of roof assemblage for optimum whole-building thermal and energy performances for low-rise detached residential buildings in Malaysia. To perform the tasks in order to meet the objectives, several roof parameters and variables were considered. A range of permutations of these variables and parameters were executed to identify and quantify the optimum design strategies and the pragmatic design options. These were done by parametric studies, whereby a base-case design was identified and only one parameter was then varied at a time. The design alternatives were explored and the thermal performance of each design option was evaluated to determine the affect of a particular variable on the thermal performance of the building. To that end, the main criterion for the selection of the approach was the ability to investigate the thermal responses and the energy impacts of the various roof configurations.

Three possible approaches for data collection and analyses were identified as listed below and are explained in the following sections:

- Approach 1: Field study and test house
- Approach 2: Field study and numerical simulation
- Approach 3: Numerical simulation

In the final analysis, Approach 3 was chosen, as it was the most viable approach within the approved time and funding constraints. The experimental procedures for the approaches are briefly discussed, and the strengths, weaknesses, and limitations are included.

4.7.1 Approach 1 (an alternative): Field study and test house

Approach 1 would consist of two parts: Part A would be an empirical study on a real PWD-NQD and to be referred as the base-case. Real data would be collected using a suitable monitoring and data logging system. Part B would be the investigations for the optimum thermal design of roof. For part B, a test house would be constructed with a few options for the roof parameters. The monitoring would be repeated and all the data would be analysed and compared.

The fundamental drawback of the approach is the limitation on design options to be studied. No doubt this approach would give the opportunity to record measurements in the real practical situation. However, the uniqueness of the real situations would make it very difficult to control the parameters under study. There are many uncontrollable variables that could influence and impose limitations on the findings. Among these are weather conditions, and human factors such as the occupants' activities and occupancy schedules. The external weather conditions might vastly change during the periods of the physical experiments. The influence of human factor could be minimised by choosing an unoccupied house. Nevertheless, it would not satisfy the main criterion for the selection of approach as the cost and time will impose limitations on the design options. In addition to all the above limitations, Part A could not be conducted because at the time of selecting the research approach, the building had not been constructed yet.

To summarise, among the shortcomings of this approach are no real building for Part A and limited design options for part B. Time and budget would impose constraints on the number of design options to be investigated. Therefore, this approach could not be considered.

4.7.2 Approach 2 (an alternative): Field study and numerical simulation

It would consist of three parts: Part A would be an empirical study on a real PWD-NQD, and Part B and Part C of would be numerical simulations on computer. Part A would be a study on the base-case design as in the alternative Approach 1. Part B would be a numerical simulation study of the base-case using suitable thermal design computer software. The simulation and the empirical results would be analysed and compared. Lastly, Part C would be the investigations for the optimum thermal design of roof using the thermal design computer software. All the identified design options would be modelled and the proposed designs could be evaluated.

The comments and limitations for the field study in Part A are as mentioned in the alternative Approach 1. The numerical simulation in Part B would serve as a comparison with the empirical findings in Part A. Since there was no real PWD-NQD building, Part A and Part B cannot be performed. Thus, this approach was excluded as well.

4.7.3 Approach 3 (the selected approach): Numerical simulation

Approach 3 that is numerical simulation was selected as the research approach. It was totally by numerical simulation using an identified thermal design computer software. The simulations were performed on the base-case design and all the selected design options. The design options were selected based on the performance evaluation of the parametric analyses.

The deciding factor on the selection of the research approach was that at the time of the selection, the building to be studied had not been constructed yet. This had eliminated the possibility of employing the alternative approaches described above. Secondly, the main criterion for the research approach chosen was the ability to collect the data for all the possible thermal designs of the roof. Apart from the fact that the building had not been constructed, the alternative approaches could only be conducted with limited design options. The computer numerical simulation approach would enable all the possible design options to be modelled and analysed. Variables could be selected and controlled. These were parametric studies whereby evaluations were made by comparing the performance among the chosen designs. All other parameters were kept constant, thus any inaccuracy would be consistent for all the models throughout the evaluation process.

The only drawback is that there were no comparisons to the actual performance in the real situation because there was no real building at the time of the investigation. Nevertheless, this is the best approach to explore various roof thermal designs options. Moreover, the analyses involve the computations of numerous dynamic heat transfer processes. The emergence of sophisticated as well as simplified computing thermal software opens up a horizon for realistic exploration on building designs and performance evaluations. The outcome of the PWD-NQD design evaluation mentioned in section 3.7.4 has substantiated the need for computer simulations to aid the decisions at the early design stage, due to the relatively fast output and flexibility of simulating permutated designs before being drawn on the blueprint.

In essence, this project is a comparative study of the performance of suitable thermal designs of the roofs for low-rise detached residential buildings using a PWD-NQD double storey bungalow as a case study.

The usage of computer software as a simulation tool for the performance assessments in research as well as in design process is discussed in Chapter 5. A pilot study was done to test the reliability of the software chosen for this study. This is explained in section 5.4.7.

4.8 An overview of the execution of the selected approach

After selecting the research approach, several tasks were carried out before the actual investigations could be performed. These were carried out in three stages; the first stage was selection of a suitable thermal design software to be used as the experimental tool, the second was learning and setting-up of the software to perform the experiments, and lastly was the execution of simulation modelling using the identified computer thermal software. The process for each stage is briefly as follows:

a) **Selection of the thermal design software**: The potentials of commercially available computer-modelling software are compiled from the Internet and discussions with the users. A qualitative analysis was performed based on the required criteria. Lastly, after considering all the related factors, the most appropriate one was selected. Details and discussions on the selection are presented in Chapter 5.

b) **Learning and setting-up of the software**: The tasks involved learning of the software and setting-up of the required database. The learning part included understanding of the basic principles, its operation and limitations, the type of analyses, the required input data, and the generated output data. The setting-up consisted of the general set-up, the preparation of the specific databases, and the input data. The general set-up involved the selection of the weather data and the design day. The databases prepared were the local climate, internal conditions, and the material and construction of the building envelopes. The input data were the house model and the attributes of the envelope as well as the internal conditions. These are elaborated in section 6.4.

c) **Numerical simulation via computer modelling**: Numerical simulations were performed for each model of the design options. Results were analysed and performance assessments were evaluated. Conclusions were drawn and design recommendations were proposed. Details of the experimental process and design are presented in Chapter 6, and the results and analysis in Chapter 7.

4.9 Summary and conclusions

The research issues are the EE documentations and guidelines for residential buildings, the climatic designs of modern houses, and the recommended climatic design features. The findings of the previous researches in Malaysia and other countries with similar climate are the basis of the research aim, objectives, and the parameters of study. The research outcome is to contribute to recommendations for the thermal design of the roofs.

At the time of selecting the building model, the PWD-NQD programme was the only housing project that promoted the concepts of sustainability and EE for residential buildings. This research took the opportunity to support the programme by using a PWD-NQD as the case-study. A double-storey bungalow was chosen as the house model. The findings would provide the compilation of some technical design details that could contribute towards recommendations for thermal design of the roof for low-rise detached residential buildings.

This research explores the thermal design of the roofs for the PWD-NQD double-storey bungalow by evaluating the dynamic whole-building thermal and energy performances. The research employed a numerical simulation approach using suitable computer thermal design software as the experimental tool.

The selection and overview of the suitable software are presented and discussed in the next chapter. It also includes the developments and the applications of computer-modelling software as simulation tools for building performance assessments.

CHAPTER 5: SIMULATION TOOL – PERFORMANCE ASSESSMENT, SELECTION AND OVERVIEW

5.1 Introduction

The core discussions in this chapter are the selection and overview of the thermal design computer software to be used as a simulation tool to meet the research aim and objectives. It also highlights the evolution and applications of the building simulation technology in building performance assessments in research and real practices to verify its use as a valid research approach. An overview of the selected software outlines the conceptual operation, the required input data, and the generated output data.

5.2 Building simulation technology

This section presents the development of computer-modelling software to demonstrate the tremendous efforts that have been devoted by researchers and professionals to turn numerical simulation into a state-of-the-art approach in building design process. The application of numerous computer simulation tools in many aspects of building performance assessments verified the validity and reliability of this numerical experiment method as a research approach.

5.2.1 The development

Research in computer design started after 1930 whereby the applications of computer modelling and simulation were mainly for military purposes following World War II and for almost two decades thereafter (Martin, 1968). It was then extended to other disciplines with the invention of commercial computers for scientific and business applications in the mid-twentieth century (Martin, 1968). The groundwork of formulating the computer-modelling software as simulation tools in the architectural design, engineering services, operation, and management of building started in 1960s (Augenbroe, 2002). Since then, the advancements and innovations in the digital technology had caused dramatic improvements in the computing power and versatility of the applications, thus emerging as the state-of-the-art technique in appraising and predicting building performances (Augenbroe, 2004, 2002; Hensen, 2002, 2001; Al-Homoud, 2000; Cole, 1998; Clarke, 1993; Clarke and Maver, 1991). The developments of the hardware have enabled the refinements of computing codes and techniques that allowed more complicated problems to be studied. Consequently, the applications of the building performance simulations have been extended from the thermal and energy application in 1970s to the more sophisticated applications for lighting, airflow using Computational Fluid Dynamics (CFD), moisture flow, and acoustic in late 1980s and 1990s (Augenbroe, 2002; Hensen, 2002).

The pursuit for more superior, accurate and reliable, yet friendly and simplified software is an on-going challenge to researchers and designers in building performance simulation field. Research on integrated design tools (Amor et al., 1990; Athientis et al., 1990); integrated thermal simulation software with airflow (Tuomaala and Rahola, 1995); CFD (Bartak et al., 2002; Zhai et al., 2002); HVAC Systems (Riederer et al., 2002; Chow, 1998; Rousseau and Mathews, 1993); and visual, acoustic, energy and environmental building simulation (Citlerlet and Hard, 2002) were developed to facilitate holistic performance assessments so as to make this technique acceptable and practical to the practitioners (de Wilder et al., 2002; Morel and Faist, 1993; Amor et al., 1993; Mathews and Richards, 1993). The fascination to materialise computer-simulations as an easy-to-use and a friendly tool in real practices has further encouraged the formulation of simplified computer tools (Gratia and de Herde, 2002; Ellis and Mathews, 2001; Yezioro and Shaviv, 1996; Szokolay and Ritson, 1982). Advanced mathematical algorithms for daylighting (Miguet and Groleau, 2002), thermal (Laouadi, 2004; Beausoleil-Morrison, 2002; Boyer et al., 1996), airflow (Musy et al., 2002), estimation techniques (Chen and Atnienitis, 2003) and optimisation models (Ali et al., 2002) were formulated to increase the precision of computing capability and the consistency of output data. New improved methodological techniques for daylighting (Glaser and Ubberlohde, 2002) and optimisation methods (Coley and Schukat, 2002; Bouchlaghem and Letherman, 1990) were developed to assist and enhance the preparation and analysis processes. And last but not least, new approaches for the performance assessments of life cycle analysis (Mithrarafne and Vale, 2004; Cole, 1998) and energy performance (Botsaris and Spyridon, 2004; Pedrini et al., 2002; Al-Homoud, 2000) were introduced to broaden the applications.

New generations of computer simulation tools for buildings are progressively being developed and improved at various energy-related research centres to keep up to the challenges of the commercialisation to meet the demands of the end-users (U.S.A, 2004b, 2004c; CSIRO, 2003; FSEC, 2003; U.S.A, 2003). These research centres and several other international organisations such as the International Building Performance Simulation Association (IBPSA, 1986), International Energy Agency (IEA, 2004), and American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) are also responsible in promoting and assuring quality in the discipline as well as serving as platforms to disseminate knowledge. Part of the activities carried by the IEA is monitoring the validation of the commercially available simulation software.

Those remarkable efforts in the past have paved the way to the current progress towards establishing building performance simulations as a promising research method. The involvements and commitment of many researches, professional and internationally organised bodies in supporting the development and the establishment of the discipline, and the applications in many aspects of built environment and building industry have verified the validity of the simulation method for research and real practical practices, and the usage of computer software as an effective tool in many decision-making processes in the building industry. These applications are further elaborated in the following section.

5.2.2 The application

Computer software has become a powerful design tool in the decision-making processes to optimise the performances of the building envelope and the required building services systems at the design stage. The predictions of the performances could be projected under a range of anticipated external and internal conditions. Numerous building performance assessments are of interest to building designers, engineers and the end-users. Amongst others are the impact of building heat transfer on indoor environmental conditions for human comfort and health such as thermal, visual, acoustical, airflow and indoor air quality; energy supply systems such as renewable energy, heating and cooling power systems; building services systems such as Heating Ventilating and Air Conditioner (HVAC) systems and Energy Management Systems (EMS); and last but not least is EE and sustainability in the built environment which include construction, operation and maintenance.

Depending on the scope and levels of assessment to be investigated in the studies, the list of parameters and variables, and their permutations to be considered could be endless. Modelling via the physical experiment method would be subjected to various temporal, spatial, and financial constraints that would consequently impose limitations on the scope and depth of the investigations. Due to the complexity of the process and the mathematical computations, or the interplay of large a number of parameters, or time-factor, and/or cost factor, numerical experiment via computer modelling would be the best method to conduct a comprehensive study in the areas of interest in a controlled environment (Holm and Kuenzel, 2002; Hyde and Docherty, 1997; Lomas, 1996; Forwood, 1983; Turner and Szokolay, 1982; Shaviv and Shaviv, 1978). All the physical interactions between the external and internal parameters of the building and systems as well as within the building and systems must be accounted for in all the design options. A good and suitable design tool would be able to consistently compute all the mathematical formulations for all the design options only at the cost of the tool and the competency of the user. It is thus an economical method using a very resourceful tool to assist and support the researchers and building professionals on many aspects at various stages of the life of a building.

The use of the computer technology as predictive tools could facilitate designers in much decision making at the design stage (Capeluto et al., 2003; Gratia and De Herde, 2003; Coley and Schukat, 2002; Tahat et al., 2002; Shaviv and Shaviv, 1978), retrofit options (Gratia and De Herde, 2004b; Gratia and De Herde 2004c; Coley and Schukat, 2002; Noble and Barthakur, 1998) and performance assessments (Burnett and Yaping, 2002; Holm and Kuenzel, 2002; Shaviv et al., 2001; Hyde and Docherty, 1997; Elnahas, 1994; Kaushik and Chandra, 1982) have clearly indicated that confidence has been established in the reliability of the numerical simulation technique for the application in real situations.

The *LEO* building that is the showcase of Malaysia on EE building mentioned in section 3.4.3 was designed with the aid of a computer-simulation **Energy 10** software to assist the decisions in the optimisation of the building designs and energy systems. Numerical simulations were performed during the planning and the design stages to support the design decisions and to predict the building energy consumptions.

5.3 Thermal design software

A broad range of building simulation tools is available with various levels of user-friendliness, modes of operation, computational capabilities as well as limitations, and prices. The search for a suitable commercially available building analysis software for the thermal design of buildings was done via Internet surveys (U.S.A, 2004b, 2004c, 2004d, 2003; FSEC, 2003), literature reviews cited in the preceding sections, and informal discussions with several users (Harith, 2001; Pedrini, 2001; Reimann, 2001; Tang, 2001).

Several keywords were used to short-list the selection; these were thermal and energy analysis, dynamic whole-building analysis, thermal comfort, airflow, residential building, and portable personal computer (PC) platform with graphical user interface facility. The last criterion was the final determining factor since the design process in this study was to be applied on other building designs with the intention to demonstrate simplicity and user-friendliness. Besides the criteria mentioned above, the information obtained from users were indispensable since they provided the insight of the respective software from their hands-on personal and professional experiences. Finally, the commercial software that best satisfies the six listed criteria were reduced to five choices and are briefly described below. The overviews given were based on the information obtained from the above resources at the time of the selection.

a) **VisualDoe3.0**: An energy simulation program for residential and commercial buildings with graphical interface facility. Runs on PC with Microsoft-Windows 95, 98 and 2000. Uses DOE-2.1E calculation engine for energy analysis. Requires whole-building plan and has CADD files import facility. Libraries for input data are available and new ones can be created. Performs multi-zones whole-building analysis for quick evaluation of energy savings for building design options. Oriented for actively conditioned buildings. Target users are architects, engineers, energy analysts, and utility personnel.

b) **Bsim2000**: A building simulation package for energy, daylight, thermal, and indoor climate analysis with graphical interface facility. Runs on PC with Microsoft-Windows 9x and NT/2000. Uses upgraded tsbi3 program with more new features. Requires whole-building plan with computer aided design (CAD) import facility. Libraries for input data are available and new ones can be created. The calculations on complex buildings with many thermal zones could be performed simultaneously. Evaluation of building design options for actively conditioned spaces with limited capacity for natural ventilation or mixed mode. Outputs are available in graphical and tabular forms. Target users are engineers, researchers, and students.

c) **Energy-10**: An energy simulation software for residential and small commercial building with floor area of less than 10,000 m^2. Runs on PC with MS-Windows 3.0/95/98/2000. Performs whole-building energy analysis, dynamic thermal and daylighting specifically designed for performance assessments in the very early stages of the design process. Simultaneous analyses are limited to only one or two zones. Very easy to use since it does not require the actual architectural building plans. Requires only four input data to generate two initial generic building descriptions for comparative evaluation of design options with base-case. Libraries for input data are available and new ones can be created. Evaluation of building design options for actively conditioned spaces. Outputs are available in graphical and tabular forms. Target users are designers, engineers, utility companies, and students.

d) **Integrated Energy System (IES):** An integrated whole-building simulation of building with the HVAC systems. Predicts building performance on thermal, energy, thermal comfort, lighting, airflow (3D CFD), plant, cost and life-cycle, and occupants evacuation. Runs on PC with MS-Windows except the airflow using CFD program. Requires whole-building plan with CAD import facility and creates models with or without CAD data. Libraries for input data are available and new ones can be created. Performs multi-zones whole-building analysis for indoor climate in natural ventilation and energy evaluation for actively conditioned spaces. Outputs are available in graphical and tabular forms. Target users are designers, engineers, building managers, building design consultants, researchers, and students.

e) **Tas**: A software package for dynamic whole-building analysis. Performs simulations on thermal, energy, plant, airflow (2D CFD), and thermal comfort performances. Runs on with MS-Windows NT 4.0 on Pentium PC with user interface facility. Requires whole-building plan with CAD import facility and creates models with or without CAD data. Libraries for input data are available and new ones can be created. Performs simultaneous multi-zones whole-building analysis for indoor climate in natural ventilation and energy evaluation for actively conditioned spaces. Outputs are available in graphical and tabular forms. Target users are building service engineers and architects.

Selection of the most appropriate modelling tool was crucial to ensure the needed computations to be within the boundaries and the capabilities of the operation of the selected software. Therefore, the next stage was the qualitative evaluation of the above identified thermal design software. This was to finalise the choice for the purpose of this research and is presented in the next section.

5.3.1 Evaluation of thermal design tools and selection of the appropriate software

The evaluation for selecting an appropriate computer simulation tool could be categorised into the quantitative and qualitative assessments (Ahmad, 1998). The quantitative evaluation is the comparison with the empirical results and is normally used as a validation procedure. The qualitative evaluation is the assessment on the features of the tools such as input data, output data, capabilities, limitations, and user-friendliness.

A qualitative evaluation was performed on the five short-listed software for the final selection. The building performances appraised were the thermal performance, energy performance, and thermal comfort. Detailed features specified in the evaluation were user friendliness, modes of operation, building type/size, ventilation mode, number of zones, availability of the required input data and the needed simulation outputs.

All the software has comparable capabilities and flexibilities in terms of user friendliness, input data such as default databases and the making of new ones, creation of building models and assignment of attributes, and analyses of simulation outputs for the energy performance. All has *AUTOCAD* import facility to assist with the drawing of the building plan and performed simultaneous multi-zones calculations except **Energy-10**. **Energy-10** does not require the actual building plan whereby hypothetical spaces are generated from the specified input data and are treated as one or two zone increments. Only **IES** and **Tas** are capable of simulating naturally ventilated spaces and **IES** ranked top in the list with a *3D Computational Fluid Dynamics* (CFD) as well as cost and life cycle analysis. **Tas** came second with a 2D CFD but is obtainable at a lower licence cost. A CFD analysis would assist the evaluation for indoor air movement for TC assessment, but since airflow is not the main focus of the study it was decided that a 2D CFD would be sufficient. Moreover, the TC conditions could be assessed via other techniques as discussed in section 4.6. Finally, after weighing up all the capabilities and limitations against the needed performance evaluations to meet the objectives of the study, **Tas** was resolved as the most appropriate software to be used for this research. The evaluation is summarised in Table 5.1.

Table 5.1: Summary of software evaluation

Rating: Poor (*); Limited (**); Good (***); Not available/applicable (NA)					
	VisualDoe3.0	Bsim2000	Energy-10	IES	Tas
1. Residential	***	***	***	***	***
2. Analysis					
a. thermal	NA	NA	NA	***	***
b. energy	***	***	***	***	***
c. whole-building	***	***	NA	***	***
d. thermal comfort	NA	NA	NA	***	***
e. airflow	NA	NA	NA	***	**
f. multi-zones	***	***	*	***	***
3. Ventilation					
a. natural	NA	NA	NA	***	***
b. active – a/c	***	***	***	***	***
c. mixed-mode	NA	NA	NA	***	***
4. User friendly					
a. PC	***	***	***	***	***
b. interface	***	***	NA	***	***
c. default database	***	***	***	***	***
d. new database	***	***	***	***	***

5.4 Overview of Tas

Tas has been commercially developed by the Environmental Design Solutions Limited (EDSL) since 1989 (EDSL, 1999). It is a software package for dynamic whole-building thermal and energy simulation. The programming language of C++ and the software runs on Pentium machines with Microsoft Windows NT 4.0. It has been sold as a software product and used for consultancy work by EDSL (Jones, 2003).

Tas comprises of four modules; **Tas Building Designer** for the dynamic building simulation in natural and forced airflow, **Tas Systems** for the Heating Ventilating Air Conditioner (HVAC) systems simulation, **Tas Ambiens** for the airflow and thermal comfort simulation using a two dimensional (2D) computational fluid dynamics (CFD) modelling, and **Report Generator** (**RG**) for post-processing facility to increase the range of outputs for the analysis and/or display of outputs to meet the various needs of the users. User guide for all the modules is available in reference manuals and tutorials. Detail information on the theoretical formulation, technical scope, and capabilities are available in the references and website (EDSL, 1999). All the modules have undergone the validation exercise by the IEA (EDSL, 1999).

Built-in databases of climate, internal conditions, and building material and construction are available in the software while new ones can be added. The building can be modelled using either interactive or batch simulation in natural or mixed-mode ventilation. The interactive simulation is a one-day simulation and the outputs can be viewed in graphical or tabular forms. The batch simulation is a simulation over a specified period and the outputs can be viewed using the report generation facilities in the **RG** module.

The software requires several input data that must be entered and the needed simulation outputs could be selected. Results can be exported to other software for further analyses, such as *MS-Excel*, *Lightscape* for daylighting analysis or *Cymap* for building services.

The flowchart in Figure 5.1 summarised the building thermal design sequence of **Tas**. The features for each module are explained in the following sections and the details of each input data used in this research are elaborated in section 6.4.1.

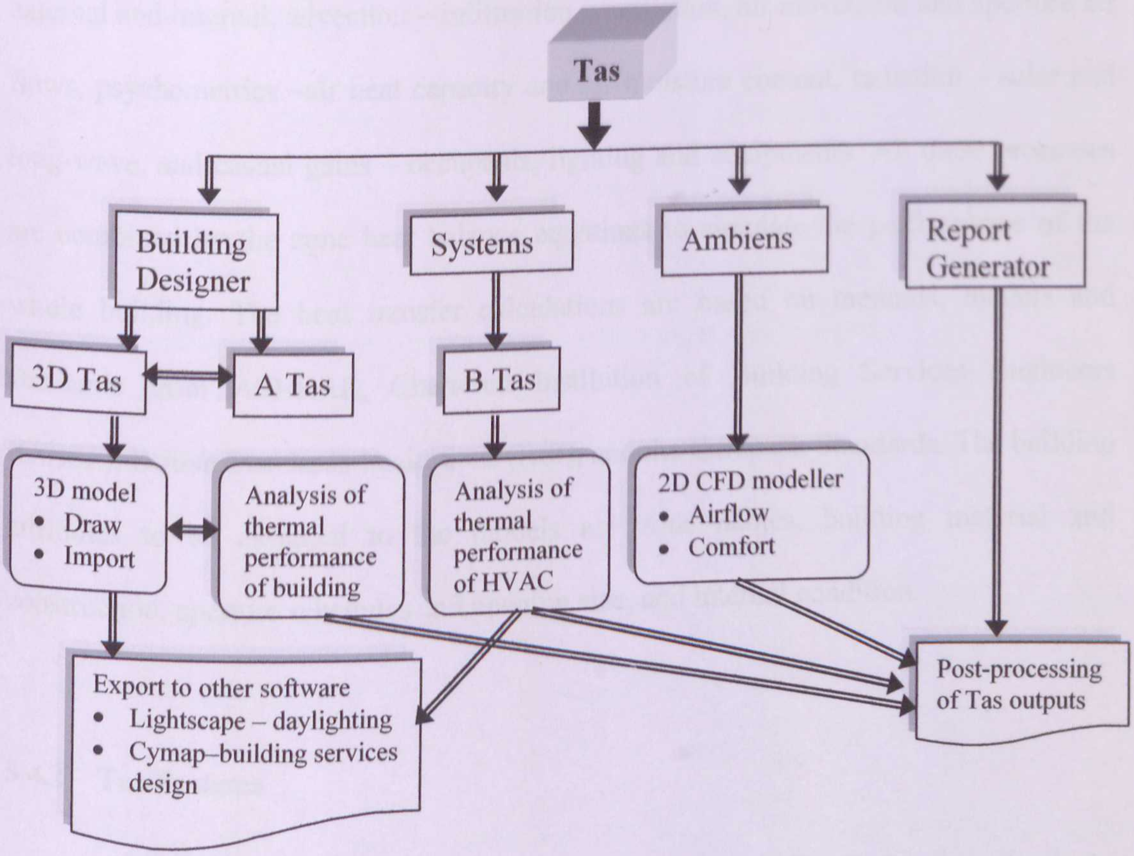


Figure 5.1: Thermal design sequence of **Tas**

5.4.1 Tas Building Designer

This module has two programmes; ***3D-Tas*** and ***A-Tas***.

a) ***3D-Tas*** – 3D Modelling programme: It creates a model and prepares data for the thermal simulation by ***A-Tas***. Buildings can be drawn or imported from CAD files and the model can be viewed in 3D along with display of shadows. The model saved in ***3D-Tas*** could be retrieved and linked to the ***A-Tas*** module for thermal analysis.

b) ***A-Tas*** – Building analysis programme: ***A-Tas*** performs dynamic simulations to evaluate the thermal performance of buildings. The hourly thermal state of the building due to numerous thermal processes occurring in the building throughout the simulation period is continuously analysed. The various heat and moisture transfer processes occurring around and within the building are accounted from conduction, convection –

external and internal, advection – infiltration, ventilation, air movement and aperture air flows, psychometrics –air heat capacity and air moisture content, radiation – solar and long-wave, and casual gains – occupants, lighting and equipments. All these processes are combined by the zone heat balance equations to simulate the performance of the whole building. The heat transfer calculations are based on methods, models and standards from ASHRAE, Chartered Institution of Building Services Engineers (CIBSE), British Standards Institutions (BSI), and the European Standards. The building attributes to be assigned to the models are zone names, building material and construction, aperture schedules and opening size, and internal condition.

5.4.2 Tas Systems

This module uses ***B-Tas*** as the software for the HVAC Systems Analysis program. It simulates the thermal performance of heating and air conditioning systems. There are basically three stages in the applications. The first stage is the system assembly where the schematics of the HVAC systems are assembled from the selected system symbols and the control links are set. The second stage is the parameter where the control settings and performance characteristics for each component are set. The final stage simulates the system's performance.

5.4.3 Tas Ambiens

This is a 2D CFD modeller. It simulates airflow and temperature across a 2D section of an internal space for comfort assessment. The index used for the thermal comfort assessment is the Percentage of People Dissatisfied (PPD) based on the Predicted Mean Vote (PMV).

5.4.4 Report Generator

It is a post-processing facility to increase the simulation outputs. The facilities are used to customise the format of **Tas** output; as a post-processor for further analysis such as the analysis of energy systems and economics; and as an interface between **Tas** and other software packages such as a spreadsheet and word processing.

5.4.5 Input data

The software requires several input data that must be entered and the needed simulation outputs could be selected. The required input data are:

a) **Weather data**: A weather database of 365 days with parameters of global solar radiation (Wm^{-2}), diffuse solar radiation (Wm^{-2}), cloud cover (0-1), dry bulb temperature (°C), relative humidity (%), wind speed (ms^{-1}) and wind direction (degree east of north).

b) **Building design**: The design can be drawn or imported using the CAD links facility. The building attributes are assigned from the relevant databases.

c) **Building material and construction**: These databases can be created and require the input of the thermophysical properties of the materials and the layering of construction components. An envelope can be composed of constructions of up to 12 layers comprising of an opaque material, a transparent material or a gas.

d) **Zones**: Zone numbers are assigned to a space or a group of spaces. This identifies the space/s for the thermal and energy analyses. A building can have a maximum of 60 zones and each zone can have individual internal climate and operation schedule.

e) **Aperture schedules**: This controls the schedule and the opening size of apertures. It provides an hourly 24-hour schedule for Weekday, Saturday and Sunday.

f) **Internal condition** (IC): This database contains information on the occupancy and the equipment schedules. It describes the internal activities within the zones that contribute to the internal heat gains. The input data are the set-point temperature and relative humidity, heating and cooling operating schedule in four intervals, and a 24-hour occupancy schedule in eight intervals. The occupancy schedule table requires the input of the period of occupancy, infiltration and ventilation rate, and heat gains from lighting, occupants, and equipments.

5.4.6 Output data

Among the automatically generated simulation outputs are: temperature – air, mean radiant and resultant; relative humidity (RH); airflow; surface outputs – temperature and solar gain; heating and cooling loads; building services performance; load breakdown; and thermal comfort assessment.

The generated outputs for the interactive data can be viewed directly on the screen in a graphical form or viewed in tabular form that can be exported for further analysis. For batch simulation, the outputs can be viewed using the report generator facility. These generated outputs can also be exported for further analysis. Other user-specified data analyses can be performed using the **RG** facility.

5.4.7 Pilot study

A pilot study was done to test the reliability of **Tas** as the software to be used for the simulation. The house model used was a real existing double-storey terrace house.

Although this is a different type of house compared to the selected detached PWD-NQD, it is a low-rise building where the thermal impact of the roof would be significant. This type of house was purposely selected to compare the findings for evaluating the reliability and validity of the simulation output data. Thermal simulations were done using the roof parameters of interest. Similar assumptions were made on the input data for the IC as well as the building materials and constructions. The findings have been briefly summarised in section 3.7.2. Due to the different configuration of the house, the findings in the pilot study showed a greater thermal impact of the roof compared to that for the PWD-NQD double-strorey bungalow that are presented and discussed in Chapter 7. Nonetheless, the pattern persists and was concluded to be consistent with the findings of the other research using other thermal design software.

5.5 Other users

In U.K the **Tas** users ranges from individuals to practising companies as well as academic institutions and research centres (Jones, 2003). **Tas** has also been successfully used for numerous building performance evaluations in other countries of varying climatic conditions and these are summarised below.

Gratia and De Herde (2003) used **Tas** for parametric studies to evaluate the strategies for designing a low energy office building in the climate of Belgium. It was a double skin façade building proposed by the IEA in a subtask for performance of solar façade components. The double skin façade was a relatively new architectural design concept and has been applied to only very few buildings. Thus, with the little experience on the expected performance, numerical simulation technique was employed to investigate on the advantages to be exploited and the cautions to be taken. Among the design strategies modelled were form, thermal insulation, control of internal gains, window area and orientation, type of glazing, natural ventilation, and thermal mass. The recommended practices for each design strategy were suggested. The insulation was found to be beneficial to reduce the heating load in winter but the trapped internal gains had adverse effect in summer. The heating and cooling loads were evaluated on eight types of days during the four seasons with the external air temperature ranged from 0 °C on a sunny winter day to 26.7 °C on a sunny autumn day (Gratia De Herde, 2004c). The performance in natural ventilation was studied on a sunny summer day with external temperature ranging between 11.4 °C to 23.3 °C (Gratia De Herde, 2004b) and detailed strategies were qualitatively analysed (Gratia De Herde, 2004a).

Tahat et al. (2002) used **Tas** for design decisions to construct a two-storey flat-roofed detached house in a Mediterranean climate. The summer time temperature ranged from 26 °C at night to 39 °C during daytime with RH of about 48 %. In winter, the temperature ranged from -1 °C to 10 °C with RH of about 75 %. The aim was to reduce the heating and cooling energy consumption. Among the design parameters considered were building fabric specification, building orientation, shape, and aspect ratio of building, window-to-wall area ratio, and thermal insulation. The selected parameters were initially individually optimised and later were done collectively. The U-value and time-lag were considered in the technical specification for the construction of the envelope. The house was built as close as possible to the theoretical design. The measured experimental data agreed with the predicted numerical data and the house performed much better than typical similar house type. There was only several days of overheating heating in summer and during winter the average indoor temperature was between 15 °C to 19 °C without supplementary heating. It was concluded that the house performed as a low energy house and was recommended to other countries in the Mediterranean climate.

Gorgolewski et al. (1996) evaluated the predicted energy savings for retrofitting of thermal insulation, double-glazing, ventilation controls, and sunspaces for high-rise housing in the U.K. It was found that the space heating load on the first floor was lower than that for the tenth floor. Hence, the design strategies should be depends on the floor levels. For individual renovation measures, the space heating loads were mainly affected by the infiltration rates, followed by glazing, and wall insulation had the least effect. However, the combination of several envelope-insulation measures could generate more savings than the sum of the savings by individual measure.

Tassiopoulou et al. (1996) studied the energy efficient design strategies of two traditional dwellings in the warm-temperate climate of Greece. **Tas** was used to study a dynamic simulation of the heat transfer processes in the buildings. The building thermal and energy performances were simulated with building usage as was originally intended and when adapted for modern living. Realistic assumptions were made on the occupancy pattern, space heating schedules, and the type of ventilation for the occupied spaces. These were to represent the typical Athenian dwelling as well as adaptations for contemporary life style. From the findings, it was concluded that the traditional dwellings responded well to the climate. However, adaptations for modern living standard such as modified central-heating system and added thermal insulation led to higher heating load in winter and the tendency for overheating in summer. Thus, appropriate evaluations were suggested to be considered in the refurbishments of historic dwellings.

Grindley and Hutchinson (1996) calibrated **Tas** using the weather data of New Mexico in U.S.A with measured diurnal ambient temperature ranged from 4 °C to 35 °C. The building was enveloped with soil, and the walls were of high thermal mass made of re-cycled car tyres. Physical measurements of the air and mean radiant temperature were recorded and compared to the **Tas** simulation outputs. The building was also simulated using the weather data for the south-eastern region of U.K. Both the recorded and the simulated data showed the building was overheated in the summer.

The discrepancy between the measured and predicted mean radiant temperature was within +/- 1.2 °C. It was concluded that the correlation between the predicted and measured temperature was good and **Tas** was used for other performance assessments of the building.

Panayi (2004) used **Tas** to investigate the impact of several passive design strategies on energy consumption of dwellings in the climate of Cyprus. The design strategies were the insulations for the wall and roof, glazing, thermal mass for the wall, building orientation, and the optimum roof structure. The aim was to determine the impact of each parameter individually and the interaction among them in order to prioritise the investments for energy savings and cost. The heating and cooling energy were analysed for a detached house and an apartment in a three-storey flat house. Realistic assumptions were made on the typical constructions for the structural frame and the building envelope, and for the occupancy and household appliances schedules and usage pattern. The impact of each parameter was simulated individually to identify the best option for each parameter. The best measure for energy savings was added to the base-case model and this improved base-case model was simulated again with the addition of the other identified options. This was to determine the best combination, as the impact of the measures was not additive. From the findings, it was concluded that fabric insulation gave the most significant energy saving and the other measures led to a reduction on the overall energy consumption. It was reported that **Tas** has been validated for detached dwellings in the climate of Germany. The availability of the weather data for Cyprus and the assumptions made on the occupancy and appliances schedules for the heat gain calculations were considered as the limitation of the study.

5.5 Summary

Numerical modelling via computer simulation is becoming a state-of-the-art method for various building performance assessments. It has become almost ubiquitous in many design processes, in research and real practices. The immense researches in this discipline that entails from the advancements of computing and digital technology have revolutionized its applications. The validity and the confidence in the numerical computer simulations have been demonstrated in numerous applications in various fields.

Due to the nature of the investigations in this research, a numerical simulation via computer modelling was identified as the most suitable. A qualitative evaluation performed on selected thermal design software has chosen **Tas** to be the most appropriate simulation tool for the study. The selection was based on the computing capabilities, its limitations, the necessary input data, and the required output to perform the needed analyses as well as cost. Among these are:

- PC based
- User friendliness
- Ventilation: natural, artificial, mixed-mode
- Multi-zones thermal and energy analyses
- Thermal comfort assessment
- Airflow analysis – 2D CFD

All the programmes in **Tas** has been validated and used in consultation and research on a range of building performance evaluations in several countries with varying climatic conditions. Realistic assumptions were made and the evaluations were performed on various building types. Within the limitation of the available input data and computation capabilities, the findings were concluded to be valid and reliable.

CHAPTER 6: NUMERICAL SIMULATION – DESIGN, SET-UP AND EXECUTION

6.1 Introduction

This chapter explains the process for the numerical simulation via computer modelling. It comprises of configuration of the experimental design and models, the selection of the simulation day, the preparation of the input data, and finally the execution of the simulation.

6.2 Experimental Design

The experiment was designed to meet the aim and research objectives for this thesis. The scheme was parametric studies on hypothetical models of a real PWD-NQD house selected for the case study. The aim is to identify the thermal design of roof assemblage for optimum whole-building thermal and energy performances for low-rise detached residential buildings in Malaysia. The research objectives are to quantify the optimum roof thermal parameters, to apply the combined roof parameters and evaluate whole-building thermal and energy performances, and lastly to analyse the roof thermal design options pertaining to the thermal impact and cooling energy needs. The outcome is to contribute to recommendations for thermal design of the roofs for low-rise detached residential buildings in Malaysia

The investigations were divided into three parts: EXPERIMENT 1 was to quantify the optimum roof thermal parameters for the assembly of outer skin of roof, EXPERIMENT 2 was to evaluate the thermal impact of roof ventilation, and EXPERIMENT 3 was to appraise the use of ceiling.

The optimum variable for each parameter and the optimum construction for the models were determined by the reduction of peak and mean daily indoor temperature. This was to achieve the best thermal condition with viable construction technology and contemporary field practices in Malaysia. The values for the optimum parameters were within the bounds of reasonable practical construction.

The base-case roof design is as shown in Figure 4.2. The investigations in the following experiments were based on this design with appropriate modifications on the identified roof parameters as discussed in section 4.5(c). The experimental design and process for each part of the investigation are elaborated in the subsequent sections.

6.2.1 EXPERIMENT 1: Optimum assembly of outer skin of roof

This was to quantify the optimum roof thermal parameters for the assembly using three basic roof parameters based on the conventional contemporary practice by means of two experiments; 1A (Expt1A) and 1B (Expt1B). The roof parameters were the external surface colour of roof covering (C), thickness of air space (AS) beneath the roof covering, and the supplementary roof insulation (RIn) beneath the conventional radiant barrier. Each parameter in the base-case (BASE) model was varied in a number of small increments to quantify the optimum value. A number of trial simulation runs have been performed to make certain that the optimum values could be determined from the selected variable range. For that reason, several extreme variable values were included.

a) **External surface colour of roof covering (C):** The hues were indicated by the solar absorption coefficient (α) which was varied from 0.3 (C1) for light hue, to darker hues of 0.5 (C2), 0.7 (C3), and finally 0.9 (C4). α=0.9 was used for the (BASE) model due to the contemporary general preference for darker roof.

b) **Thickness of air space beneath roof covering (AS)**: The air space represented the thickness of the batten used in the construction. The batten dimension of 50 mm x 50 mm is used in the PWD-NDQ as shown in Figure 4.2. Thus, air space thickness (d) of 50 mm (AS2) was taken as the base-case (BASE). It was then reduced to 20 mm (AS1) to investigate the effect of a smaller air space, doubled to 100 mm (AS3), and finally an extreme of 200 mm (AS4) was used to analyse the magnitude of impact of the air space.

c) **Supplementary roof insulation (RIn)**: The conventional aluminium foil lining with no supplementary roof insulation (RIn00) was taken as the base-case (BASE) A supplementary insulation material (RIn) with the thickness (d) of 10 mm (RIn01) to 100 mm (RIn10) in an increment of 10 mm was added underneath the aluminium lining.

Thus, the roof attributes for the BASE model were: colour with α of 0.9 (C4); airspace of 50 mm (AS2) and aluminium insulation 0.25 mm (RIn00).

- **Expt1A** – individual parameters: This was to study the thermal impact of each parameter independently. Only one parameter was varied from the BASE model at a time and the optimum variable of each parameter (C, AS, RIn) was identified.
- **Expt1B** – combination parameters: This was to study the thermal impact of combined optimum variables on the spaces in the proximity. The optimum air space (AS) and supplementary roof insulation (RIn) were put together with all hue variations (C1, C2, C3 and C4). These models became the combined-optimum (COMBO) models with four ranges of solar absorptivities. These were considered to allow for personal preferences. Whilst providing the best environmental performance, the designs have to be aesthetically pleasing as well as socially and culturally acceptable.

The discussions of results and analyses for Exp1A and Expt1B are presented in section 7.3.1 and section 7.3.2 respectively.

6.2.2 EXPERIMENT 2: Roof ventilation (RV)

This was to evaluate the thermal impact of roof ventilation on the occupied spaces on the upper floor. It consisted of two experiments; 2A (Expt2A) and 2B (Expt2B).

- **Expt2A** – optimum RV rate: This was to quantify the optimum RV rate. The BASE model has a RV rate of 0 ach (RV00). It was then modelled with RV rates of 5 ach (RV01) to 50 ach (RV10) in increments of 5 ach and the optimum rate was identified.
- **Expt2B** – apply optimum RV: This was to determine the benefits of RV towards improving the indoor thermal environment. The optimum RV rate identified in Expt2A was applied to the COMBO models created in EXPERIMENT 1. The new models then became the combined-optimum with roof ventilation (COMBORV) models.

The discussions of results and analyses for Exp2A and Expt2B are presented in section 7.4.1 and section 7.4.2 respectively.

6.2.3 EXPERIMENT 3: Ceiling.

This was to appraise the usage of the horizontal ceiling that was intentionally designed as a thermal barrier between the roof space and the occupied spaces underneath. There were three experiments; 3A (Expt3A), 3B (Expt3B), and 3C (Expt 3C).

- **Expt3A** – no-ceiling (nc): This was to ascertain the benefit of using the horizontal ceiling. The ceiling in the COMBO and COMBORV models was removed. The models are named as COMBOnc and COMBORVnc.
- **Expt3B** – optimum ceiling insulation (CIn): This was to quantify the optimum CIn. The BASE model with no CIn (CIn00) was simulated to identify the optimum thickness (d) of insulation for the horizontal ceiling. An insulation material with a thickness of 10 mm (CIn01) to 100 mm (CIn10) in increments of 10 mm was horizontally laid above of the ceiling (the insulation was in the roof space) and the optimum CIn was identified.
- **Expt3C** – apply optimum CIn: This was to study the thermal impact of CIn. The optimum CIn identified in Expt3B was applied to the COMBO and COMBORV models. The models are named as COMBOCIn and COMBORVCIn.

The discussions of results and analyses for Exp3A, Expt3B and Expt3C are presented in section 7.5.1, section 7.5.2, and section 7.5.3 respectively.

6.2.4 Experimental models for roof

The needed roof models have been described together with the explanation of the purpose for each experiment. The models in EXPERIMENT 1 were to quantify the optimum roof thermal parameters for the assembly of outer skin of roof and consisted of two types: individual parameters and a combination of the optimum parameters (COMBO). For EXPERIMENT 2, the models were to quantify the optimum RV rate and its benefits on the COMBO models. In EXPERIMENT 3, the first part was to ascertain the benefits of horizontal ceiling on the COMBO and COMBORV models, the second part was to quantify the optimum thickness of CIn, and lastly was to study the benefits of the optimum CIn on the COMBO and COMBORV models.

All the models were decided following a pilot simulation of the anticipated models for EXPERIMENT 1 that was performed to investigate the thermal impacts of individual and combined parameters. The analyses showed that the cumulative thermal effects were not additive but were interactive. However, it would be superfluous to model all the possible combinations of the parameters. An educated selection of the permutations of the parameters and variables was prudent to avoid an endless list of experimental models. For that reason, each parameter in the base-case (BASE) model was varied in a number of small increments to quantify the optimum value. A number of trial simulation runs have been performed to make certain that the optimum values could be determined from the selected variable range. Consequently, several extreme variable values were included. Finally, only the optimum value of each parameter was added to the BASE model to produce the most befitting roof thermal design options for low-rise detached residential building in Malaysia. Therefore, the models used were decided based on the reasonable deductions from the output data for the optimum thermal and energy performances. Nevertheless, these models were sufficient to generate the data needed to produce the analyses and charts to contribute to recommendations for the thermal design of roofs for the PWD-NQD.

In summary, the experimental design has produced seven thermal design options for the roof, namely: COLOUR, COMBO, COMBORV, COMBOnc, COMBORVnc, COMBOCIn, and COMBORVCIn. Each design has four colour options to consider the colour preference. The roof thermal design options and the construction details of the assembly for each model investigated are sequentially listed in Table 6.1. The investigated roof parameters and variables are illustrated in Figure 6.1 while the detailing of the design options are depicted in Figures 6.2 to 6.8.

Table 6.1: Models for each experiment

Expt	Parameter	Variable	Model name	Construction attributes
1A Individual	Colour (C) (COLOUR)	α	C1	1. Colour: C1, C2, C3, C4 2. Air space: 50 mm(BASE) 3. RB: 0.25 mm *(note: BASE with variable C)*
		0.3		
		0.5	C2	
		0.7	C3	
		0.9	C4 (BASE)	
	Air space (AS)	d (mm)	AS1	1. Colour: C4 (BASE) 2. Air space: AS1 to AS4 3. RB: 0.25 mm *(note:BASE with variable AS)*
		20		
		50	AS2 (BASE)	
		100	AS3	
		200	AS4	
	Supplementary roof insulation (RIn)	d (mm)	RIn00 (BASE)	1. Colour: C4 (BASE) 2. Air space: 50 mm (BASE) 3. RB: 0.25 mm 4. Supp. insulation: RIn00 to RIn10 *(note:BASE with variable RIn)*
		0		
		10	RIn01	
		20	RIn02	
		30	RIn03	
		40	RIn04	
		50	RIn05	
		60	RIn06	
		70	RIn07	
		80	RIn08	
		90	RIn09	
		100	RIn10	
1B Combination	Optimum AS Optimum RIn All colours C (COMBO)	α	ComboC1	1. Colour: C1, C2, C3, C4 2. Air space: 50 mm 3. RB: 0.25 mm 4. Supp. insulation: 40 mm
		0.3		
		0.5	ComboC2	
		0.7	ComboC3	
		0.9	ComboC4	
2A Roof ventilation	Roof Ventilation (RV)	Rate (ach)	RV00 (BASE)	1. Colour: C4 2. Air space: 50 mm 3. RB: 0.25 mm 4. Roof ventilation: RV00 to RV50 *(note:BASE with variable RV)*
		0		
		5	RV05	
		10	RV10	
		15	RV15	
		20	RV20	
		25	RV25	
		30	RV30	
		35	RV35	
		40	RV40	
		45	RV45	
		50	RV50	
2B Apply optimum RV	Optimum AS Optimum RIn Optimum RV All colours C (COMBORV)	α	ComboRVC1	1. Colour: C1, C2, C3, C4 2. Air space: 50 mm 3. RB: 0.25 mm 4. Supp. insulation: 40 mm 5. Roof ventilation: 10 ach
		0.3		
		0.5	ComboRVC2	
		0.7	ComboRVC3	
		0.9	ComboRVC4	

Table 6.1 – continue

Expt	Parameter	Variable	Model name	Construction attributes
3A No Ceiling	Optimum AS Optimum RIn All colours C (COMBOnc)	α	ComboC1nc	1. Colour: C1, C2, C3, C4 2. Air space: 50 mm 3. RB: 0.25 mm 4. Supp. insulation: 40 mm 5. no ceiling
		0.3		
		0.5	ComboC2nc	
		0.7	ComboC3nc	
		0.9	ComboC4nc	
	Optimum AS Optimum RIn Optimum RV All colours C (COMBORVnc)	α	ComboRVC1nc	1.Colour: C1, C2, C3, C4 2. Air space: 50 mm 3. RB: 0.25 mm 4. Supp. insulation: 40 mm 5. Roof ventilation: 10 ach 6. no ceiling
		0.3		
		0.5	ComboRVC2nc	
		0.7	ComboRVC3nc	
		0.9	ComboRVC4nc	
3B Ceiling insulation	Ceiling insulation (CIn)	d (mm)	CIn00 (BASE)	1. Colour: C4 2. Air space: 50 mm 3. RB: 0.25 mm 4. Ceiling insulation: CIn00 to CIn10 *(note:BASE with variable CIn)*
		0		
		10	CIn01	
		20	CIn02	
		30	CIn03	
		40	CIn04	
		50	CIn05	
		60	CIn06	
		70	CIn07	
		80	CIn08	
		90	CIn09	
		100	CIn10	
3C Apply Optimum CIn	Optimum AS Optimum RIn All colours C Optimum CIn (COMBOCIn)	α	ComboC1CIn	1. Colour: C1, C2, C3, C4 2. Air space: 50 mm 3. RB: 0.25 mm 4. Supp. insulation: 40 mm 5. Ceiling insulation:20mm
		0.3		
		0.5	ComboC2CIn	
		0.7	ComboC3CIn	
		0.9	ComboC4CIn	
	Optimum AS Optimum RIn Optimum RV All colours C Optimum CIn (COMBORVCIn)	α	ComboRVC1CIn	1. Colour: C1, C2, C3, C4 2 Air space: 50 mm 3. RB: 0.25 mm 4. Supp. insulation: 40 mm 5. Roof ventilation: 10 ach 6. Ceiling insulation:20mm
		0.3		
		0.5	ComboRVC2CIn	
		0.7	ComboRVC3CIn	
		0.9	ComboRVC4CIn	

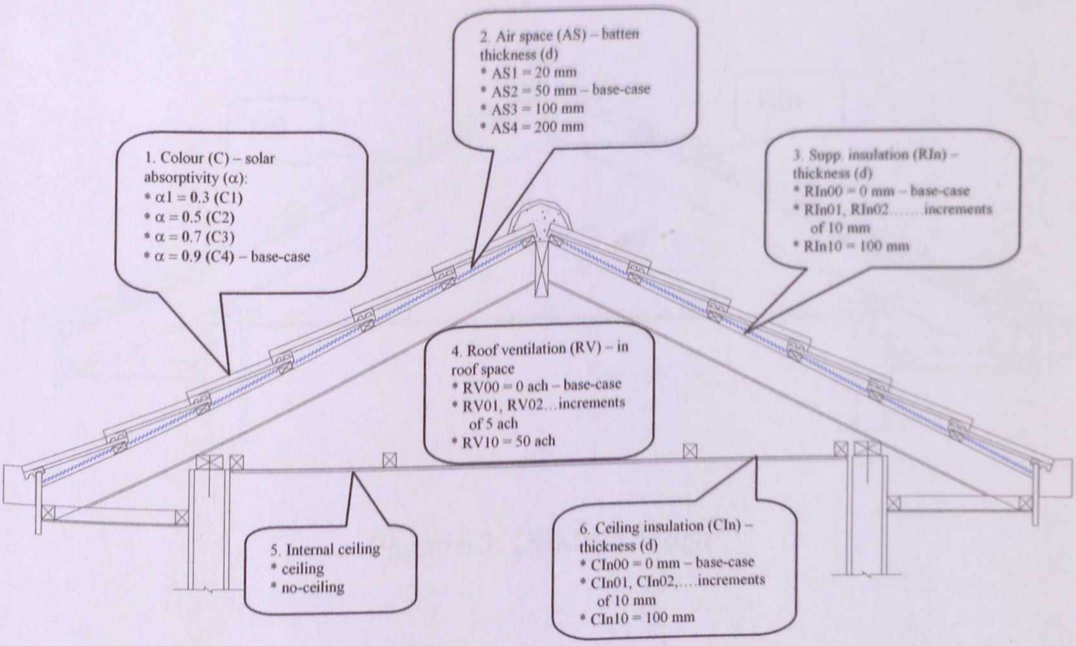


Figure 6.1: Roof parameters and variables

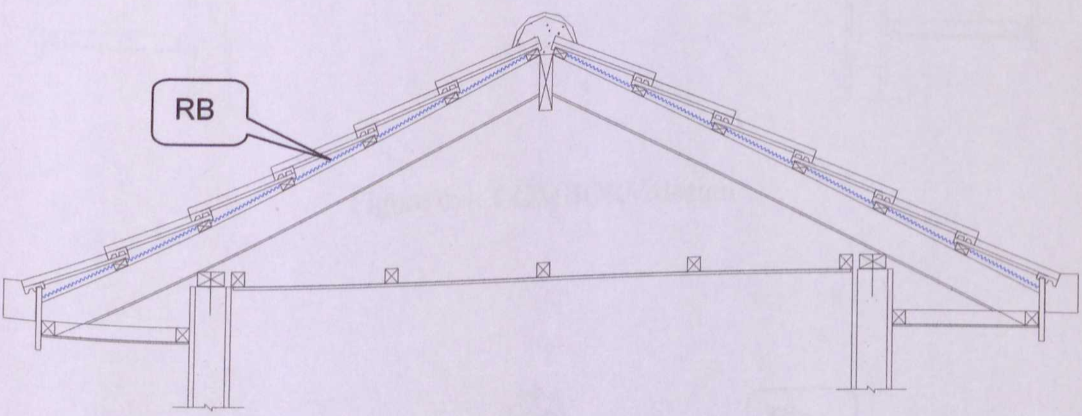
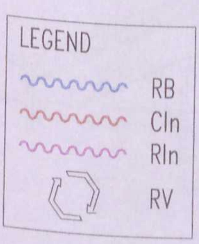


Figure 6.2: COLOUR design



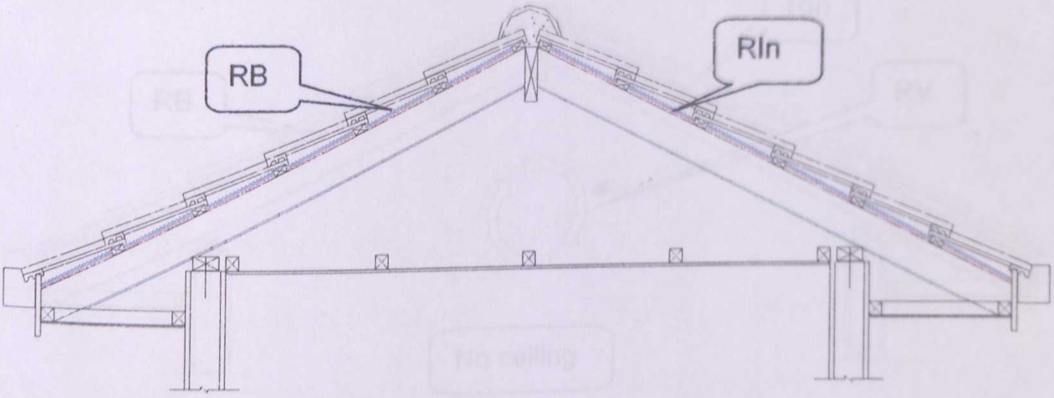


Figure 6.3: COMBO design

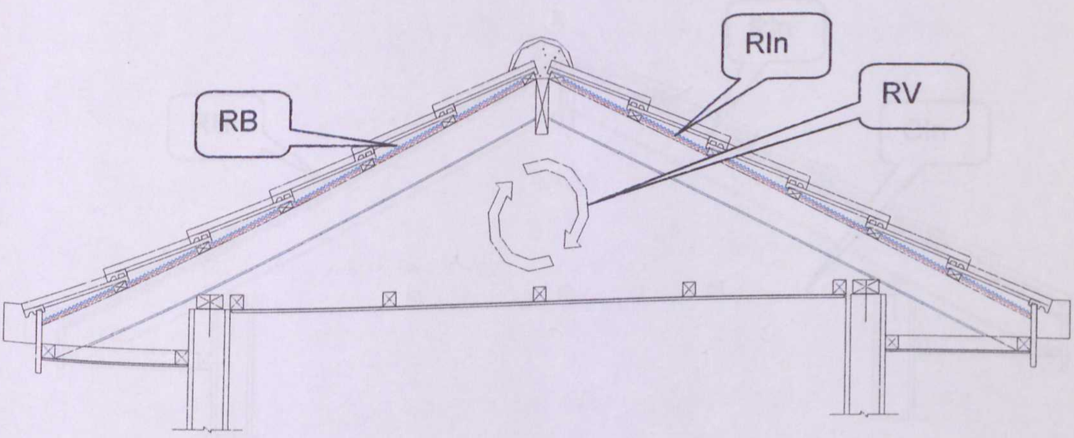


Figure 6.4: COMBORV design

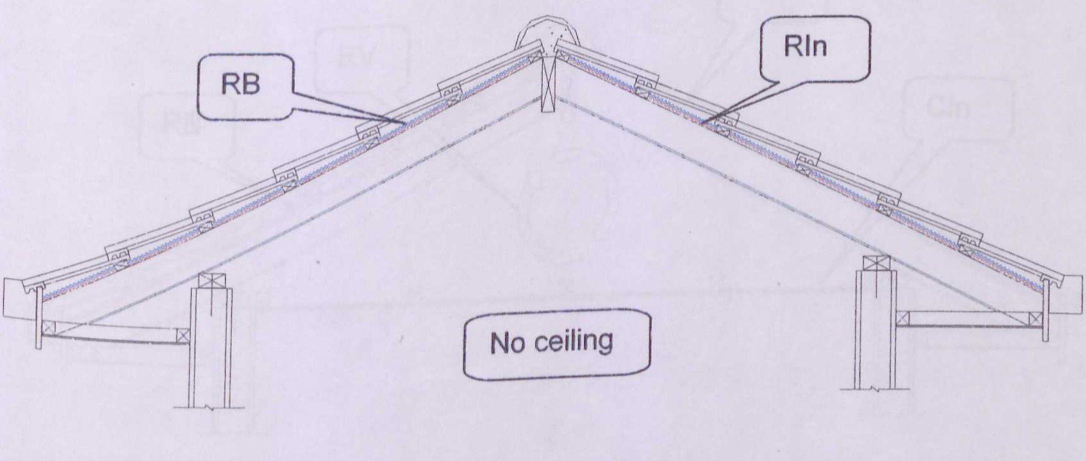


Figure 6.5: COMBOnc design

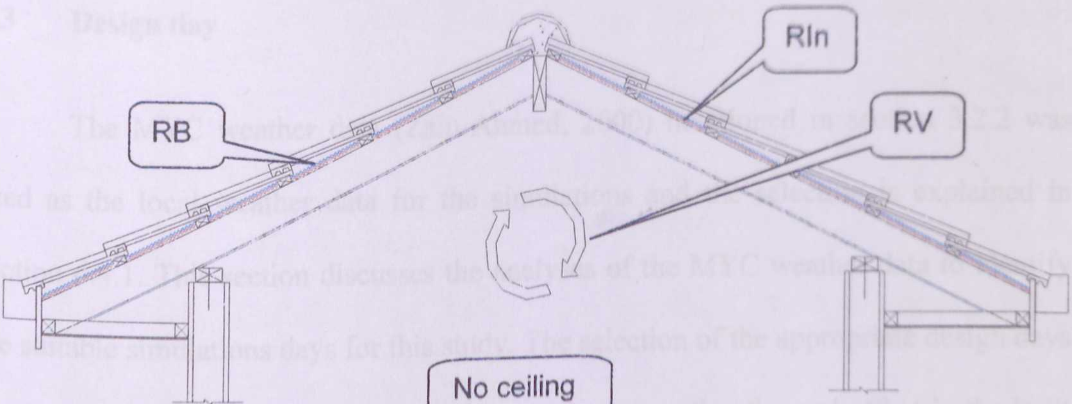


Figure 6.6: COMBORVnc design

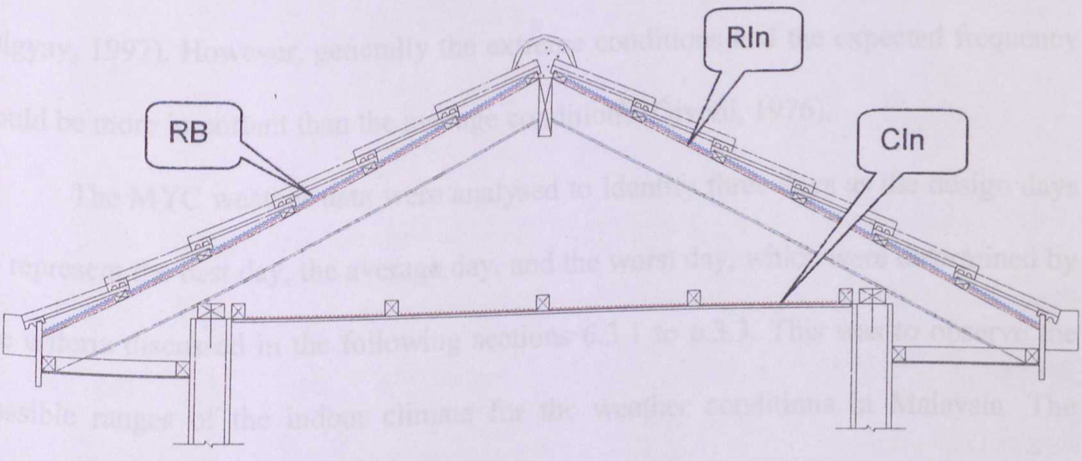


Figure 6.7: COMBOCIn design

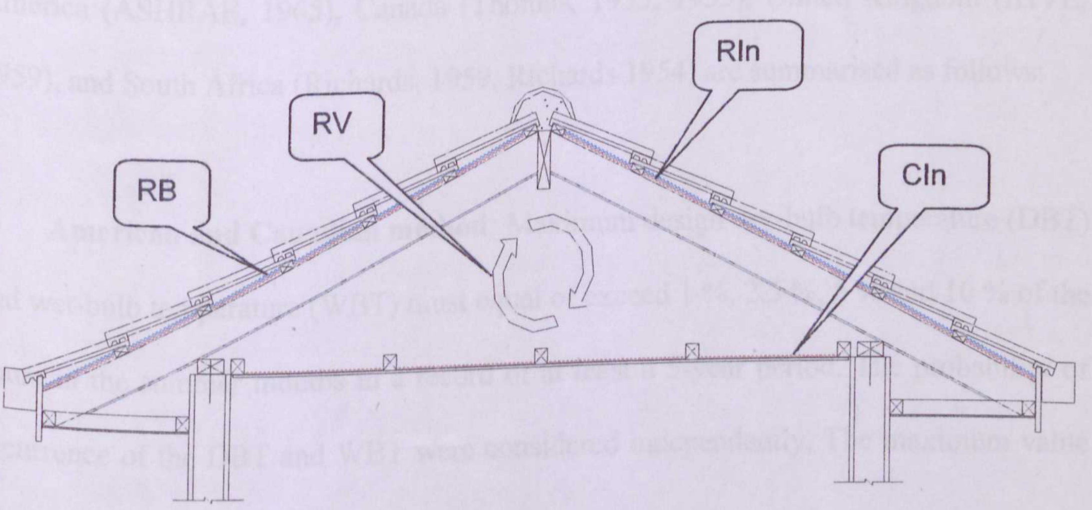


Figure 6.8: COMBORVCIn design

6.3 Design day

The MYC weather data (Zain-Ahmed, 2000) mentioned in section 3.2.2 was used as the local weather data for the simulations and the selection is explained in section 6.4.1. This section discusses the analyses of the MYC weather data to identify the suitable simulations days for this study. The selection of the appropriate design days for the design purposes are imperative due to the interactive thermal effect in the built environment. Information on the extreme weather conditions is pertinent for mechanical systems design while the typical or normal weather conditions are essential for architectural climatic design strategies (Straaten, 1967; Koenigsberger et.al, 1980; Olgyay, 1992). However, generally the extreme conditions and the expected frequency could be more important than the average conditions (Givoni, 1976).

The MYC weather data were analysed to identify three days as the design days to represent the best day, the average day, and the worst day, which were determined by the criteria discussed in the following sections 6.3.1 to 6.3.3. This was to observe the possible ranges of the indoor climate for the weather conditions in Malaysia. The selection of the weather elements for the design data practiced in the United States of America (ASHRAE, 1981); and as reported by Straaten (1967) for the United States of America (ASHRAE, 1965), Canada (Thomas, 1955, 1953), United Kingdom (IHVE, 1959), and South Africa (Richards, 1959, Richards 1954) are summarised as follows:

a) **American and Canadian method**: Maximum design dry-bulb temperature (DBT) and wet-bulb temperature (WBT) must equal or exceed 1 %, 2.5 %, 5 % and 10 % of the hours in the summer months in a record of at least a 5-year period. The probability of occurrence of the DBT and WBT were considered independently. The maximum value of solar radiation was used.

b) **British method**: For summer design data, the DBT was chosen from the month that has the highest average monthly maximum DBT. The WBT was produced from the association of the vapour pressure with the DBT.

c) **South African method**: The design data were selected based on the principle of the combined effect of the weather elements. However, the selection was based purely on the basis of air temperature, whereby the mean air temperature, humidity, and total and diffuse radiation were derived from twenty hottest days according to the highest daily maximum temperature. This was said to provide coincident values of four weather elements, but the variability and the independency of the various elements were not accounted for.

The selection of the weather data based on the independent probability of occurrence was appropriate for service engineers, but for thermal design of buildings, the designer must consider the thermal impact of the combined pertinent weather elements (Olgyay, 1992; Koenigsberger et al., 1980; Markus and Morris, 1980; Evans, 1979; Givoni, 1976; Straaten, 1967; Rogers, 1964). The significant weather elements are solar radiation, air temperature, humidity, and wind. Solar radiation is necessary for computing the maximum cooling load and thermal performance in natural ventilation (ASHRAE, 1981; Markus and Morris, 1980), and air temperature is the fundamental element for determining thermal comfort (ASHRAE, 1981; Markus and Morris, 1980; Fanger, 1972). While single element of air temperature could be used to observe a simplified pattern of relationships between indoor temperature and outdoor air temperature (Givoni et al., 2002; Givoni and Vecchia, 2001; Kruger and Dumke, 2001; Givoni, 1999) as well as residential energy consumption (Hart and de Dear, 2002), the application is only limited to similar data configurations.

From the established works and findings of previous studies as mentioned above, it was concluded that the most referred method was the American's (Givoni, 1976; Straaten, 1967; Rogers, 1964). The combined effect of the weather elements must be considered whereby the air temperature is the most prevailing element.

Therefore, for this thesis, the MYC weather data were analysed and the design days were selected based on the American method and the combined effect of three climatic elements. In order of significance, these were the DBT, RH, and solar radiation. The effect of the wind was considered as not significant due to the low and variable wind speed (Malaysia, 1998). The selected days must have the DBT with the probability of at least 1 %, 2.5 %, 5 %, or 10 % of occurring (ASHRAE, 1981). The coincident RH must have similar probability of occurrence and the extreme value of the solar radiation was used.

The daily maximum, minimum, mean, and the probability of occurrence of the three climatic elements were calculated for the whole year. Table 6.2 shows the daily maximum, minimum, and the mean for DBT and RH that have the probability of occurrence of at least 1 %. The values for the radiation are the total daily maximum, minimum and mean.

Table 6.2: Maximum, minimum and mean with occurrence of at least 1%

	Air temperature (°C)	Relative Humdity (%)	Global radiation (Whm^{-2})	Diffuse radiation (Whm^{-2})
Max	28.4	93	5820	2135
Min	25.2	74	4730	1508
Mean	26.7	83	5203	1915

The possible design days were firstly selected based on the temperature. Then the coincident RH of the days was checked for the probability of occurrence independently. The days were again selected based on the coincident maximum, minimum, and mean values of the DBT and RH. Lastly, the days with the highest global radiation were used as a guide to the selection. The coincident diffuse radiation was also used as a reference.

Preliminary simulations were done to observe a graphical distribution pattern of the indoor climate. The selected days were the design days that could be used as the representative days for the weather conditions in Malaysia. However, some of the days showed some abnormalities of the curves due to certain external weather condition, such as afternoon rain, high wind speed due to thunderstorm, and unusual high evening solar radiation. While these are quite normal daily phenomena during certain periods of the year, the days with the normal distribution graphs are preferred as the reference for the design decisions for the parametric studies. Thus, the final selection of the design days were based upon the indoor climate with the normal distribution curves.

6.3.1 Design day for the best day

Table 6.3 shows the probabilities for the low air temperature range. The lowest mean daily air temperature is 24.2 °C, but the probability of occurrence is less than 1 %. Thus, the next lowest air temperature of 25.2 °C with the probability of 1 % was chosen. The days with this minimum air temperature (T_{min}) were selected and are shown in Table 6.4.

The next criterion was the day with the lowest relative humidity (RH_{min}). Day 2 has the lowest RH of 73 % but has the probability of less than 1 % of occurrence individually, hence was discarded. None of the days has an RH of 74 % that is the minimum RH of at least 1 % of occurrence as listed in Table 6.2. Day 205 has the next lowest RH of 77 % with the probability of occurrence of 2.74 % and a greater value of solar radiation. Therefore, it was chosen to be the design day to represent the best day.

Table 6.3: Range of low air temperature and probability of occurrence

T_{min} (°C)	24.2	24.3	24.2	24.6	24.7	24.9	25.1	25.2
Probability T_{min} (%)	0.55	0.27	0.27	0.55	0.82	0.82	0.27	1.37

Table 6.4: Days for T_{min} and the design data for RH and solar radiation

T_{min} (°C)	Probability T_{min} (%)	Day	Date	RH (%)	Probability RH (%)	Global (Whm^{-2})	Diffuse (Whm^{-2})
25.2	1.37	2	2nd Jan	73	0.55	5247	1675
25.2	1.37	205	24th Jul	77	2.74	5447	1912
25.2	1.37	166	15th Jun	80	6.85	3945	1641
25.2	1.37	284	11th Oct	88	4.93	5157	1919
25.2	1.37	241	29th Aug	90	2.94	5152	1849

6.3.2 Design day for the average day

The average of the mean daily DBT is 26.7 °C, which occurs 24 days of the year with the probability of occurrence of 6.58 %. This is also the mode and the median of the mean daily DBT, which shows a uniform annual distribution. Table 6.5 shows the days with the coincident value of mean of the mean daily RH of 83 % that is the average RH of at least 1 % occurrence as listed in Table 6.2. The selected design day with the daily RH of 82 % is also shown. Days 296 and 301 have unusual temperature distribution curves, thus were not chosen as the representative day. The choice of day 304 was discarded because the solar radiation is less than the mean total daily. Therefore, other days with a RH of lower than 82 % and higher than 84 % were considered. The RH of 82 % is the mode with the probability of occurrence of 9.0 % and the probability of RH of 84 % is 8.22 %. The percentage difference from the mean value is 1.2 %. Six days were identified and day 292 was found to be the best representative day. The other days are either on weekends or the distribution curve is not normal.

Table 6.5: Days for T_{avg} and the design data for RH and solar radiation

T_{avg} (°C)	Probability T_{avg} (%)	Day	Date	RH (%)	Probability RH (%)	Global (Whm^{-2})	Diffuse (Whm^{-2})
26.7	6.58	292	19th Oct	82	9.0	5771	2082
26.7	6.58	296	23rd Oct	83	7.4	6225	1900
26.7	6.58	301	28th Oct	83	7.4	6305	2115
26.7	6.58	304	31st Oct	83	7.4	4764	1950

6.3.3 Design day for the worst day

Table 6.6 shows the probability for the high temperature range. The highest mean daily temperature is 29.0 °C but the probability of occurrence is less than 1 %. The highest temperature with the probability of at least 1 % is 28.4 °C. Thus, this was taken as the maximum mean daily temperature to be used as the design day to represent the worst day. Table 6.7 shows the days with this mean daily temperature and the corresponding RH.

Table 6.6: Range of high air temperature and probability of occurrence

T_{max} (°C)	29.0	28.9	28.7	28.6	28.5	28.4
Probability T_{max}	0.55	0.27	0.55	0.55	0.27	1.64

Table 6.7: Days for T_{max} and the design data for RH and solar radiation

T_{max} (°C)	Probability T_{max} (%)	Day	Date	RH (%)	Probability RH (%)	Global (Whm^{-2})	Diffuse (Whm^{-2})
28.4	1.64	290	17th Oct	84	8.33	5629	2432
28.4	1.64	76	17th Mar	85	7.12	5443	1781
28.4	1.64	114	24th Apr	85	7.12	4893	1748
28.4	1.64	66	7th Mar	90	2.74	5445	1993
28.4	1.64	62	3rd Mar	93	2.19	5928	1987
28.4	1.64	96	6th Apr	95	0.27	4707	1716

The maximum RH with the probability of occurrence of at least 1 % is 93 % as shown in Table 6.2. In Table 6.7, day 62 has the highest RH of 93 % at 2.19 % probability of occurrence and also has the highest solar radiation, but the curve of the indoor condition on day 66 is more representative. On day 62, both the DBT and RH are high from the hours of 0900 to 1800 hours. This pattern was observed for most of the days with RH of above 93 %. Although the indoor RH on day 62 is higher than day 66, the indoor temperature is lower. Since the design strategy is to minimise the heat gain and thus directly reducing the indoor temperature, choosing the day with the higher indoor temperature would be more appropriate than the higher RH. This is due to the fact that for building in natural ventilation, applying passive design strategies to control the heat gain is much easier than to control the humidity. Thus, day 66 is more suitable to be used as the design day to represent the worst day. A summary of the design days for the simulation and the corresponding design data is shown in Table 6.8.

Table 6.8: Summary of the design days

	Day	Date	Temp (°C)	Probability (%)	RH (%)	Probability (%)	Global (Whm^{-2})	Diffuse (Whm^{-2})
Best	205	24^{th} Jul	25.2	1.37	77	2.74	5447	1912
Average	292	19^{th} Oct	26.7	6.58	82	9.0	5771	2028
Worst	66	7^{th} Mar	28.4	1.64	90	2.74	5445	1993

6.3.4 Simulation day

The interactive simulation was used for the evaluation of thermal performance and thermal comfort while a 365-day batch simulation was done to analyse the energy performance.

a) **Interactive simulation:** The preceding discussion on the design days have suggested that the average weather conditions were sufficient for climatic design strategies while the extremes were required for the system designs. This mainly referred to climates with distinct seasonal variations whereby the architectural and the system designs must be optimised for all the weather disparities. However, in Malaysia the weather variations are very small as was mentioned in section 3.2.1. The findings on thermal comfort studies shown in Table 3.4 show that the comfort condition is mainly determined by the temperature and humidity. The MYC data shows that the mean daily

DBT ranges from 24.2 °C to 29.0 °C while the mean daily RH ranges from 72 % to 95 %. The differences between the extreme conditions for DBT and RH are 4.8 °C and 23 % respectively. The pilot runs on the BASE model have shown that the daytime temperature variations in the living spaces on the worst and the best day was about 1 °C to 3 °C and the RH variations were 4 % to 22 %. It could be inferred that it would not be necessary to analyse the design strategies for all the three design days. The design days have been selected based on the accepted levels of probabilities of occurrence. For the average day with mean daily DBT of 26.7 °C, the frequency of occurrence is 6.6 %, the frequency of higher DBT is 48.2 %, and the frequency of lower DBT is 45 %. Thus, choosing the average day as the design day for the study would mean that the indoor condition could be worse during 48.2 % of the year and better during 45 % of the year. The choice of the worst day as the design day would mean that the indoor condition could be worse during only 2.2 % of the year but could be better during 95.6 % of the year. Therefore, after analysing the general weather condition of Malaysia and the indoor thermal performance, it was finally concluded that the worst day (day 66; 7th March) would be used for the interactive simulation for the thermal performance and thermal comfort assessments.

b) **Batch simulation**: At least a week's data would be needed to predict the energy for cooling due to the different cooling schedule for each day-type listed in Table 6.9. However, a 365-day simulation was performed to account for the impact on the annual national energy consumption

6.4 Numerical Simulation

The experimental process comprised of three stages. The first stage was the preparation for the required data inputs comprising of the creation of databases and the setting-up of the experimental models. The models were then ready for the simulations in the natural and mixed-mode ventilation settings. In the second stage, interactive simulations were performed on the selected day in natural ventilation and batch simulations were performed for the selected period in natural and mixed-mode ventilation settings. Lastly was the retrieval of the simulation outputs for data analysis.

6.4.1 Preparation of input data – creation of databases

The required input data to create the relevant databases were climate, materials, constructions, internal conditions and calendars that have been briefly described in section 5.4.5. The details of the input data for each database are elaborated below.

a) Climate data

The options for the typical weather data sets were the TRY and MYC. These data sets have been described in section 3.2.2. The weather parameters needed by **Tas** are hourly values for solar radiation (Wm^{-2}), diffuse radiation (Wm^{-2}), dry-bulb temperature (°C), relative humidity (%), cloud cover, wind speed (ms^{-1}) and wind direction (degree East of North). TRY weather data has all the needed parameters but the diffuse solar data were obtained from an analytical deduction. This was because the MYC does not provide the needed diffuse solar data, but a five-year average hourly value for diffuse and direct solar radiation data were available. Apart from the critical comments about TRY data set mentioned in section 3.2.2, for this thesis it was preferred to use all measured values to ensure consistency of the computational error throughout the analyses.

To consider only measured data sets, the five-year average hourly diffuse solar data have to be used. These were initially used concurrently with the MYC global solar data. However, some of the diffuse data were higher than the global solar radiation data suggested in Table 3.2. This happened because the data were from different years. Due to the incompatibility of the five-year average hourly diffuse radiation data with the 21 years global data, both the diffuse and global radiation data must be taken from the same years. Thus, the global data used were the summation of the five-year average hourly direct and diffuse data. Therefore, the weather data used were as in Table 3.2 with annual average given in Table 3.3 except for the diffuse and global data with annual day average of 6.9 $MJm^{-2}day^{-1}$ and 18.7 $MJm^{-2}day^{-1}$ respectively. Despite the adjustments made on the MYC data, this was the latest and most comprehensive set of processed real climatic data available in the country at the time of this selection. The data represented the climatic characteristics for Klang Valley, which is going through a rapid transformation towards urbanisation. Thus, it could present the anticipated local climate in other urban areas. If the local climate were to have more favourable weather conditions, then the roof design options would be expected to perform better.

Although the PWD-NQD houses will be built at numerous sites in the country, it was not necessary to run the simulations using the weather data at the anticipated locations, as it would not contribute to the investigations for the optimum thermal design of roof. For this parametric study as discussed above, the site location must be invariant and the variables were only the roof thermal parameters. The minimal variations of the weather conditions in Malaysia as discussed in section 3.2.1 verified the use of the MYC data for the study.

The required weather parameters were entered into a programmed **Tas**-formatted Microsoft Excel worksheet and were exported to **Tas** climate database. The hourly data for day 66 (7^{th} of March) that was chosen for the interactive simulation is shown in Appendix B in Table B1.0.

b) Materials

The building materials used were based on the conventional contemporary building construction practices in Malaysia. Some of the materials were not listed in the database of the software, thus new materials had to be added. However, there was insufficient information on some of the thermophysical properties required for the input data. Therefore, some assumptions and deductions were made on the properties from several references available at the time of the preparation of this database (Kannan, 1991; Malaysia, 1989). The material was specified as opaque, transparent or gas. The needed inputs for the properties were the solar absorptance, emissivity, conductivity ($Wm^{-1}\,°C^{-1}$), density (kgm^{-3}), convection coefficient ($Wm^{-2}\,°C^{-1}$), specific heat capacity ($Jkg^{-1}\,°C^{-1}$), and vapour diffusion factor. The materials used for the construction are listed in (c) below.

c) Construction

The construction of the building envelopes were also based on the conventional contemporary building construction practices in Malaysia. However, due to the lack of available information on the needed input data, some of the materials and properties were selected from the default database. The selected values have been thoroughly checked and compared with the most relevant available data. Hence, within the limitation on existing documented references, to the best of knowledge from the literature and discussions with practitioners (Shaari, 2001), the input data could best represent the type of materials, constructions, and properties of the building materials used in conventional contemporary practices.

The details of the input data required by the software for the materials and constructions for each part of the building envelope for the base-case design are as follows:

- ground floor (from inside): 25 mm marble; 50 mm concrete screed; 125 mm concrete with 3 % moisture content; 75 mm crushed brick aggregate; 1000 mm sand
- external glass window: 10 mm clear float
- external door: 40 mm hardwood
- internal door: 35 mm plywood
- external and internal wall: 20 mm plaster; 115 mm common dry brick with 0% moisture content; 20 mm plaster
- ceiling: 4.5 mm asbestos free ceiling
- roof (from outside): 20 mm concrete roof tile; 50 mm air space; 0.05 mm aluminium foil underlined with 0.20 mm paper

The above input data and the corresponding thermophysical properties are given in Tables B1.1 to B1.8 in Appendix B. These are the specifications for the house model with the base-case roof design. For house models with the other roof design options, only the constructions for the roof and ceiling were varied while that for the other parts of the envelope were the same (refer to the diagrams in figures 6.1 to 6.8).

Table 6.9 below shows the **Tas** output of some of the thermophysical properties of the building elements for the base-case design.

Table 6.9: Thermophysical properties of building elements of BASE model

Building elements	U-value ($Wm^{-2} K^{-1}$)	Decrement Factor (μ)	Time-lag, (ϕ) (hours)
Ground floor	0.285	0.008	20.4
Wall	2.567	0.673	4.7
Window	5.445	1.000	0.0
External door	2.279	0.996	1.0
Outer skin of roof	1.261	0.973	0.6
Internal ceiling	2.606	0.994	0.2

d) Internal Condition (IC)

To model the response of the occupied building under realistic occupancy schedules, several assumptions were made on the IC of each zone. These were to simplify the complexity of the actual occupancy schedule and the usage pattern of heat generating household appliances that would contribute to the internal heat gains, which would affect the energy balance of the house. The internal conditions were set up with the assumption of intermittent occupancy due to the working and schooling hours. Inputs for the occupancy period had to be in whole number of hours. Thus, the hours were rounded off and averaged out for the short intermittent occupancy periods. This was to allow for realistic random uncontrolled movements of the occupants. Due to short occupancy period in the bathrooms, they are therefore considered to be unoccupied. The details of the assumptions on the occupants and the household appliances are given in Tables B2.0 and B2.1 in Appendix B.

The required input data were temperature and humidity setting, cooling schedules, and occupancy schedules with the predicted casual gains. The internal conditions for each zone were grouped into three day-types; *Weekday*, *Saturday* and *Sunday*. The input data for each day-type were different according to the anticipated occupancy schedules and activities. The data pages for the IC for each occupied zone on each day-type in the natural and mechanical ventilation setting are shown in Tables B2.2 to B3.9 in Appendix B.

i) *Temperature and humidity setting*: The set points for the temperature and relative humidity for the air-conditioned mode were 26 °C and 70 % respectively. These are the code of practice on EE for non-residential buildings (SIRIM, 2001). The set point for natural ventilation mode was zero.

ii) *Cooling schedules*: The cooling hours were set based on the thermal comfort condition during the occupancy period. In real practice, most residents limit the use of the cooling systems in the bedroom during sleeping hours – at night-time and sometimes during afternoon naps on weekends. The analyses of the thermal comfort hours also showed that the thermal conditions in the bedrooms were outside the comfort zone during those hours. Some houses also operate the cooling system in the family room during limited occupancy hours. It was included in the schedule to avoid underestimating the usage. The cooling hours of each of the four spaces and the total annual cooling hours are shown in Table 6.10. The table shows that at certain hours some of the spaces were simultaneously cooled.

iii) *Occupancy schedules*: Assumptions were made on the daily routine of the occupants in each zone and the operation of the commonly used household electrical appliances and equipments. The heat gains from the occupants depended on the activities (ASHRAE, 1981) which were resting, eating, and light work in seating or standing position. The appliances and equipments were rated based on the typical and recommended ratings for EE at home and office (CETREE, 2002; Malaysia, 2002d). However, no published literature was available for the sensible and latent gains from occupants and equipments in naturally ventilated residential buildings. Since the building was set to mixed-mode ventilation, it would be reasonable to refer to the heat gains in conditioned spaces in office and commercial buildings (ASHRAE, 1981;

Carrier, 1965). For the equipments, reference was made to the heat gains for hooded appliances and some adjustments were made based on the given recommendations. Similarly, the lighting power was also based on the code of practice on EE for non-residential buildings (SIRIM, 2001). The infiltration rate was determined by the configuration and type of the windows and doors in each space (ASHRAE, 1981).

Table 6.10: Cooling hours in the spaces on each day-type

	Weekday (hours)	Saturday (hours)	Sunday (hours)
Bedroom 1	0000-0600	0000-0600	0000-0600
	2200-2400		1500-1800
			2200-2400
Total daily (hr)	***8***	***6***	***11***
Bedroom 2	0000-0600	0000-0600	0000-0600
	2200-2400	2300-2400	1500-1800
			2200-2400
Total daily (hrs)	***8***	***7***	***11***
Bedroom 3	0000-0600	0000-0600	0000-0600
	2200-2400	2300-2400	1500-1800
			2200-2400
Total daily (hrs)	***8***	***7***	***11***
Family room	1500-1900	0	1500-1800
Total daily (hrs)	***4***	***0***	***3***
Annual total (hrs)	**7308**	**1040**	**1872**
		10220	

e) Calendar

The first day (1st of Jan) of the calendar was adjusted so that all the probable and intended simulation days for the interactive simulation fall on the same day-type. This was crucial for the analysis because the IC database was set into three day-types, as explained in (d) above. The parametric analyses required data generated from the same internal conditions. The calendar was set such that the worst day, best day, and the average day fall on *Weekday* day-type. The weekdays make up 71.5 % of the days in a year, for this reason simulations on weekdays would give a better representation of the whole-year building performance.

6.4.2 Preparation of input data – experimental model

The PWD-NQD bungalow Class D house model used in this study are illustrated in Figures 4.1 (a) to 4.1 (d). The total floor area of the house is 188 m^2 and the cooling floor area is 73.7 m^2. The first part was the preparation of the plan in ***3D-Tas***. The second part was the application of ***A-Tas*** to the models whereby the operational conditions and the relevant databases were assigned before it was ready for the simulation runs. An overview of the operations of ***3D-Tas*** and ***A-Tas*** modules was given in section 5.4.

a) ***3D-Tas*** module: The design was available in an AutoCAD file. It was imported into the **Tas Building Designer** module and was used as a template in ***3D-Tas***. Doors and windows were assigned according to the specifications, and the walls, floors and ceilings were assigned accordingly. Zone numbers were then given to all spaces. Assumptions were made on the usage of the spaces to simplify the final analyses of the data. The occupied living spaces are portrayed in Figures 4.1(c) and 4.1(d) and the location of the bedrooms (*Bed1*, *Bed2*, *Bed3*) and family room (*Family*) discussed in the analyses in Chapter 7 are shown. The regularly occupied living spaces were assigned to individual zones. These spaces were the three bedrooms and one family room on the upper floor, while that on the ground floor were the living and dining room, kitchen, and the maid's room. The unoccupied roof spaces were also assigned to individual zones to compare the indoor conditions profiles with the occupied spaces. The other less frequently occupied living spaces were grouped and assigned to the same zones to speed up the process of specifying the needed data inputs. These zones and the bathrooms were set as vacant with no occupant or casual gains. This is due to the limitations on the schedules for the internal condition that required a minimum occupancy period of one hour. The contributions for the internal heat gains from these spaces were minimal due to the infrequent and short occupancy periods.

b) ***A-Tas*** module: The building model in ***3D-Tas*** was then linked to ***A-Tas*** for the following data inputs and it was then ready for the execution of the simulations.

i) *General details*: A brief description of the model was made.

ii) *Zone names and groups*: Zone names were assigned and grouped to speed up the assignment of the internal conditions and the generation of simulation outputs.

iii) *Schedules*: The opening of the doors and windows were assigned. These were based on the ventilation mode of the respective spaces – natural or air-conditioned.

iv) *Construction details*: The constructions of doors, windows, walls, floors, ceilings, and roof were assigned from the construction database. The schedule and openable proportion were assigned to all the apertures according to the occupancy and operation schedule. These were hourly periods for day-type *Weekday*, *Saturday* and *Sunday*.

v) *IC:* The IC for all spaces was assigned for each day-type from the IC database.

vi) *Output specification*: The needed simulation outputs for each zone were specified.

The model was then ready for the simulation runs.

6.4.3 Execution of the simulation

Two types of simulations were executed on each model in EXPERIMENT 1, 2, and 3 as listed in Table 6.1. An interactive simulation, which is a one-day simulation on the selected day, which was 7th March (day 66) was performed in natural ventilation mode for the assessment on the TP and TC hours. A 365-day batch simulation was then carried out in mixed-mode ventilation for the energy performance. In the mixed-mode ventilation, the *Family, Bed1, Bed2* and *Bed3* on the upper floor were actively ventilated as scheduled in Table 6.10 using room air conditioner system while the other occupied spaces on the ground floor were naturally ventilated.

The simulations were performed on each experimental model in the sequence described in section 6.2 using the models listed in Table 6.1. These are summarised in the flowchart of experimental design and process in Figure 6.9.

6.4.4 Simulation output data – retrieval and analyses

The simulation outputs were selected based on the analyses to be performed. The interactive simulation outputs produced hourly data performance and were retrieved in a tabular format. The data were saved and exported to *Microsoft Excel* for further analyses of the maximum, minimum, mean values as well as the TC hours. The TP evaluations for the models in EXPERIMENT 1, 2 and 3 required the data output on indoor air temperature and RH. These data were also used to assess the TC hours. The batch simulation outputs were available in the project folder and were retrieved using the **RG** module for the needed analyses. The necessary outputs for the energy performance appraisal were the cooling load. All the required data were then ready to be processed for the needed analyses. The results are presented and discussed in the next chapter.

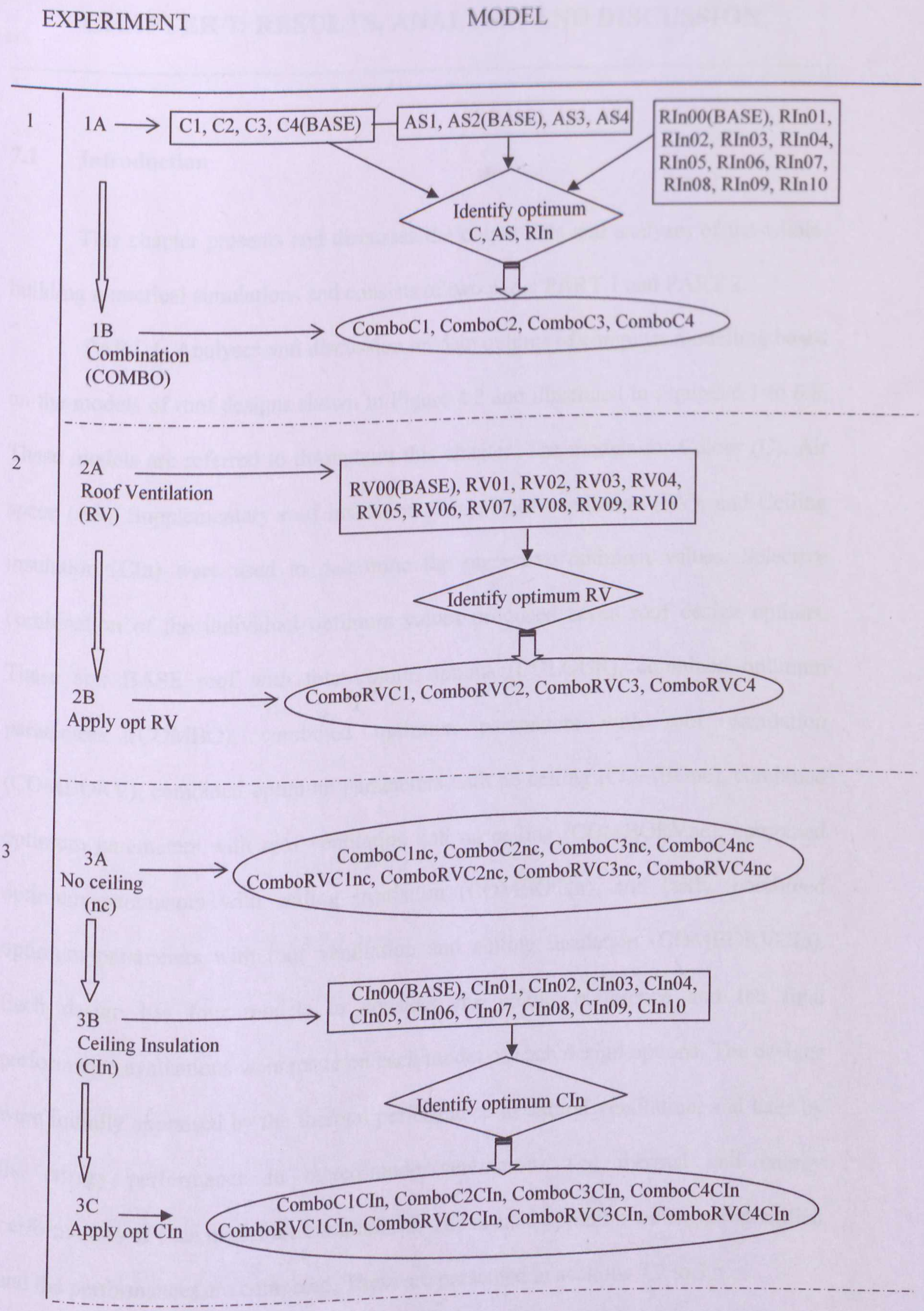


Figure 6.9: Flowchart of experimental design and process

CHAPTER 7: RESULTS, ANALYSIS AND DISCUSSION

7.1 Introduction

This chapter presents and discusses the output data and analyses of the whole-building numerical simulations and consists of two parts: PART 1 and PART 2.

PART 1: Analyses and discussion on data outputs of computer modelling based on the models of roof designs shown in Figure 4.2 and illustrated in Figures 6.1 to 6.8. These models are referred to throughout this chapter. The models for Colour (C), Air space (AS), Supplementary roof insulation (RIn), Roof ventilation (RV), and Ceiling insulation (CIn) were used to determine the respective optimum values. Selective combination of the individual optimum values produced seven roof design options. These are: BASE roof with four colour options (COLOUR), combined optimum parameters (COMBO), combined optimum parameters with roof ventilation (COMBORV), combined optimum parameters with no ceiling (COMBOnc), combined optimum parameters with roof ventilation and no ceiling (COMBORVnc), combined optimum parameters with ceiling insulation (COMBOCIn), and lastly, combined optimum parameters with roof ventilation and ceiling insulation (COMBORVCIn). Each design has four models to consider the colour preference and the final performance evaluations were made on each model of each design options. The designs were initially appraised by the thermal performance in natural ventilation, and later by the energy performance in mixed-mode ventilation. The thermal and energy performances of each model are summarised. The needed optimum values are identified and the performances are compared. These are presented in sections 7.2 to 7.5.

PART 2: Conclusions of the findings are summarised and presented in form of charts for comparative thermal and energy performance evaluations of the thermal design of roofs investigated in this study. These are presented in sections 7.8 to 7.10.

PART 1: SIMULATION OUTPUT DATA

The major findings obtained from the analyses in PART 1 are the optimum value for each roof thermal parameter, indoor thermal performance and thermal comfort hours, and the predicted energy savings based on the cooling load. The concern is more on the thermal condition in the occupied spaces. However, comparisons are made with the roof space to observe the temperature variations between the two spaces. This is to investigate all the possible benefits that could be exploited for the roof design options. The evaluation assessments and the details of the analyses are presented in the following sections.

7.2 Evaluation assessment and data presentation

Evaluation of the roof design options were based on whole-building appraisal of thermal performance (TP), thermal comfort (TC), and energy performance (EP) in terms of the following conditions:

a) **TP – T_{air}, T_{max}, T_{min}, T_{mean}, T_{diff}, RH**. These are the indoor environmental conditions on the selected simulation day (7th March) discussed in section 6.3. An hourly air temperature (T_{air}) and relative humidity (RH) are tabulated to determine the hourly TC condition in natural ventilation. T_{max}, T_{min}, T_{mean} are the day highest, lowest, and average T_{air} respectively. The extreme conditions (T_{max} and T_{min}) are of interest to observe the temporal benefits, but the overall impact (T_{mean}) is also considered. T_{diff} is used to quantify the advantages and disadvantages of the design options. T_{diff} refers to the temperature difference between the roof models in the discussion. In general, it is used to analyse the advantage or disadvantage between the models or designs, unless otherwise stated.

b) **TC – comfort zone (CZ).** An hourly TC hours in the occupied living spaces which are bedroom 1 (*Bed1*), bedroom 2 (*Bed2*), bedroom 3 (*Bed3*), and family room (*Family*), located on the first floor are determined from the CZ for Malaysia (Appendix A – Figure A1.0)

c) **EP – energy performance.** Analyses of annual sensible cooling load (CL) are used as an indication to the cooling energy needs by the models. The annual CL for each occupied space: bedroom 1 (*Bed1*), bedroom 2 (*Bed2*), bedroom 3 (*Bed3*), and family room (*Family*), located on the first floor and the total load for the building are recorded. A CL index (CLI) is introduced as a benchmark for the cooling energy demands, defined as the CL per square meter of cooled floor area.

Optimum values for RIn, RV, and CIn are identified from the TP by varying only one variable at a time from BASE. The whole house was naturally ventilated and the optimum values are determined by the reduction of T_{max} in *Family*. *Family* is used to represent the impact on the living spaces underneath the horizontal ceiling. This space was chosen as it is usually the most commonly used space and has the least exposed external wall. Therefore, the impact of other influences such as heat transfer through external walls and windows are minimal. Thus, roof is the major source of external heat gain compared to the other spaces.

The simulation outputs and analyses are presented in tables and graphs. For each model, a summary of indoor T_{max}, T_{min}, T_{mean}, RH, TC hour, and annual CL and CLI of living spaces on the first floor and roof space (*RSpace*) of the upper roof are tabulated and discussed. These are extracted from the tabulated hourly indoor thermal condition in Tables C1.0 to C2.0 that are placed in Appendix C. Graphs are used to show the T_{air} profiles in *Family* and *RSpace*, the T_{diff}, and the building annual CL. The thermal comfort hours in the two spaces are compared to investigate the impact of roof variations on the *RSpace* and occupied living spaces underneath which is separated by a horizontal ceiling. Comparisons are also made on the T_{max}, T_{mean}, and annual CL among the models.

7.3 EXPERIMENT 1: Identification of optimum assembly of outer skin of roof

These are the analyses for EXPERIMENT 1 described in section 6.2.1 that comprises of Expt1A and Expt1B. Exp1A was to analyse the impact of individual roof thermal parameters and subsequently the optimum values are identified. The parameters are external surface colour (C) of the roof covering, air space (AS) underneath the roof covering, and supplementary roof insulation (RIn) underneath the conventional insulation, and the designs are named as COLOUR, AS, and RIn respectively. Expt1B was to investigate the impact of combined optimum parameters with the entire colour options and named as COMBO. Colour refers to the hue of the roof covering determined by the solar absorptivity (α) and these are synonymously used throughout the chapter.

7.3.1 Expt1A: Individual roof parameters and identification of an optimum value

a) Colour (C)

An hourly TP (T_{air} and RH) and TC hour in the occupied living spaces for model C4 (BASE) of the COLOUR design are shown in Table 7.1. For the TC data, symbol X is used to show that TC cannot be achieved at that given hour, while the values of 1.0 ms^{-1} and 1.5 ms^{-1} refer to the required air movement to attain the TC condition. The table shows TC condition is achieved for two hours in *Bed1*, *Bed2*, and *Bed3*, and one hour in *Family* at 0007 and 0008 hours with provision of air movement of 1.0 ms^{-1} to 1.5 ms^{-1}. The hourly thermal comfort condition in the living spaces and the annual CL for the other models of the COLOUR design are shown in Table C1.0 in Appendix C. The hourly T_{air} profiles in *Family* for all the models are also illustrated in Figure 7.2.

Table 7.1: Thermal performance for C4 (BASE)

	Bed1			Bed2			Bed3			Family		
Hour	T_{air} (°C)	RH (%)	TC	T_{air} (°C)	RH (%)	TC	T_{air} (°C)	RH (%)	TC	T_{air} (°C)	RH (%)	TC
1	32.5	75	X	32.9	80	X	31.8	73	X	31.7	72	X
2	32.2	76	X	32.6	81	X	31.6	74	X	31.5	71	X
3	31.8	76	X	32.4	82	X	31.2	73	X	31.3	71	X
4	31.5	76	X	32.0	82	X	30.8	73	X	31.0	70	X
5	31.1	76	X	31.7	83	X	30.5	73	X	30.7	70	X
6	30.8	76	X	31.5	83	X	30.2	73	X	30.1	71	X
7	26.7	85	1.0ms^{-1}	27.7	81	1.5ms^{-1}	27.8	80	1.5ms^{-1}	27.2	83	1.0ms^{-1}
8	27.3	89	1.5ms^{-1}	27.7	87	1.5ms^{-1}	27.9	85	1.5ms^{-1}	28.4	83	X
9	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X
10	31.0	89	X	31.2	88	X	31.9	84	X	31.3	87	X
11	32.3	88	X	32.3	88	X	32.9	85	X	32.9	85	X
12	33.4	83	X	33.3	84	X	34.0	80	X	33.0	85	X
13	34.1	84	X	34.0	84	X	34.6	81	X	33.6	86	X
14	33.8	75	X	34.0	76	X	34.4	73	X	33.8	77	X
15	34.8	68	X	34.5	70	X	34.9	67	X	34.2	71	X
16	33.9	78	X	34.3	76	X	33.9	78	X	34.1	77	X
17	32.9	83	X	33.4	81	X	33.8	79	X	33.9	78	X
18	29.9	74	X	30.4	73	X	30.4	73	X	31.3	70	X
19	29.3	83	X	29.3	82	X	29.4	82	X	30.5	77	X
20	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X
21	28.3	85	X	28.6	83	X	28.6	83	X	32.6	69	X
22	28.7	82	X	29.6	78	X	29.5	78	X	30.7	73	X
23	33.0	67	X	32.1	72	X	31.4	71	X	31.0	70	X
24	31.9	72	X	32.2	75	X	31.3	72	X	31.2	69	X
Max	34.8	89		34.5	88		34.9	85		34.2	87	
Min	26.7	67		27.7	70		27.8	67		27.2	69	
Mean	31.3	79		31.6	80		31.4	77		31.6	76	
TC hour			2			2			2			1

Table 7.2: Summary of thermal and energy performances for COLOUR models

Model		Bed1	Bed2	Bed3	Family	RSpace	Annual CL (kWh)	CLI ($kWhm^{-2}year^{-1}$)
C4 (BASE; α=0.9)	T_{max} (°C)	34.8	34.5	34.9	34.2	43.4		
	T_{min} (°C)	26.7	27.7	27.8	27.2	28.0		
	T_{mean} (°C)	31.3	31.6	31.4	31.6	33.8		
	TC hrs	2	2	2	1			
	CL (kWh)	1933	1398	1399	3827		8556	143
C3 (α=0.7)	T_{max} (°C)	34.7	34.3	34.8	34.1	41.3		
	T_{min} (°C)	26.6	27.7	27.7	27.2	27.9		
	T_{mean} (°C)	31.2	31.5	31.3	31.5	33.0		
	TC hrs	2	2	2	1			
	CL (kWh)	1890	1355	1347	3726		8318	139
C2 (α=0.5)	T_{max} (°C)	34.6	34.2	34.7	34.0	39.2		
	T_{min} (°C)	26.6	27.6	27.7	27.1	27.9		
	T_{mean} (°C)	31.2	31.4	31.3	31.4	32.3		
	TC hrs	2	2	2	1			
	CL (kWh)	1847	1312	1294	3626		8079	135
C1 (α=0.3)	T_{max} (°C)	34.5	34.1	34.6	34.0	37.1		
	T_{min} (°C)	26.6	27.6	27.7	27.1	27.8		
	T_{mean} (°C)	31.1	31.4	31.2	31.3	31.5		
	TC hrs	2	2	2	1			
	CL (kWh)	1804	1269	1242	3527		7841	131

Table 7.2 shows a performance summary of the living spaces and *RSpace* for the models of the COLOUR design. Similar temperature pattern is obtained for each model and the TC hour in each living space is the same. T_{max} and T_{mean} are highest in *Bed3* and *Bed2* respectively while T_{min} is lowest in *Bed1*. These could be explained by the orientation of the bedrooms as shown in Figures 4.1 (c) and 4.1 (d). *Bed3* with the highest T_{max} is south facing and is exposed to both the morning and evening sun as well radiation from the lower roof. *Bed2* with the highest T_{mean} is north facing and located on the east, thus is exposed to the morning sun and the radiation from the lower roof. *Bed1* is also north facing but is located on the west and there is no lower roof within the perimeter, although is exposed to the evening sun it has with the lowest T_{min}. It could be deduced that the radiation from the lower roof has an impact on the indoor temperature of the spaces exposed to it. The T_{diff} between daytime T_{max} in *RSpace* and the living spaces is up to 3.1 °C for C1 to 9.2 °C for C4. However, the T_{diff} between T_{min} in all the

spaces are only up to 1.3 °C for all roof colours. This provides evidence of night-time radiant cooling of roof. While roofs with higher α become much more heated during dayime, at night all roofs cool down equally due to the same ε of 0.9 for all the colours. The roof colour has a more profound effect on CL than TP or TC conditions. The difference of annual CL between the darkest (BASE) and the lightest (C1) roof colour is 715 kWh, equivalent to 8.5 %. The CLI ranges from 143 $kWhm^{-2}year^{-1}$ for BASE to 131 $kWhm^{-2}year^{-1}$ for C1. The CL in *Family* is 45 % of the total annual CL even though the cooling hours is only 23 hours per week compared to 57 hours in *Bed1*, and 58 hours in *Bed2* and *Bed3*. This could be due to the cooling hours during daytime and the opening at the staircase. When the opening at the staircase was closed during the cooling hours, the CL for *Family* in the BASE model is reduced by 46 % but is still the highest compared to the bedrooms.

Figures 7.1 and 7.2 show the hourly T_{air} profiles in *RSpace* and *Family* for models of the COLOUR design set in natural ventilation. The external T_{max} and T_{min} is 34.1 °C and 24.6 °C respectively. T_{max} in *RSpace* is 43.4 °C for BASE and 37.1 °C for C1. In *Family* it lags about one to two hours with a peak of 34.2 °C for BASE and 34.0 °C for C2 and C1. Thus, T_{diff} between the external environment and *RSpace* ranges from 9.3 °C for C1 to 3.0 °C for BASE, while in *Family* it ranges from 0.1 °C to 0.2 °C.

Temperature profiles similar to Figures 7.1 and 7.2 were recorded for the models of other roof designs, thus are not mentioned or discussed in the rest of the analyses. However, information on the hourly indoor condition for each model can be obtained from the respective tables in Appendix C. Note that the pattern of the temperature profiles in *Family* and *RSpace* are consistent with the external temperature. The profiles in *RSpace* follow very closely with the external but the variations and fluctuations at certain hours in *Family* are due to the internal heat gains that are influenced by the occupancy schedule and activities.

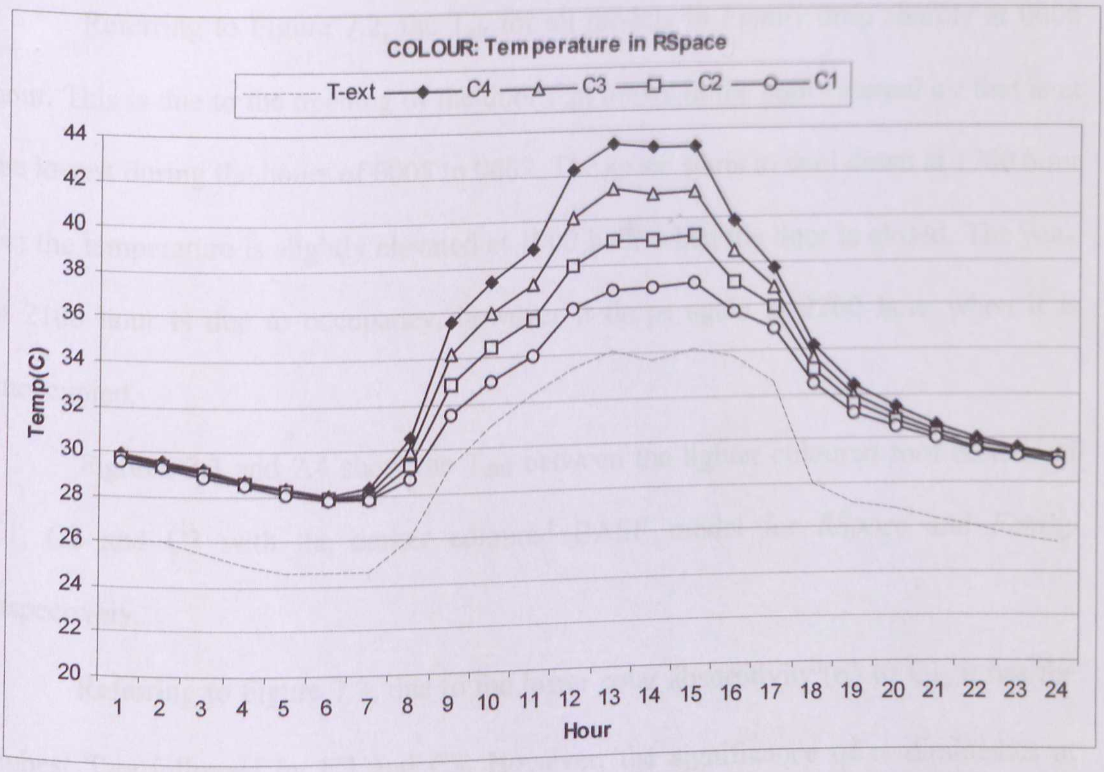


Figure 7.1: Indoor T_{air} in *RSpace* for COLOUR models

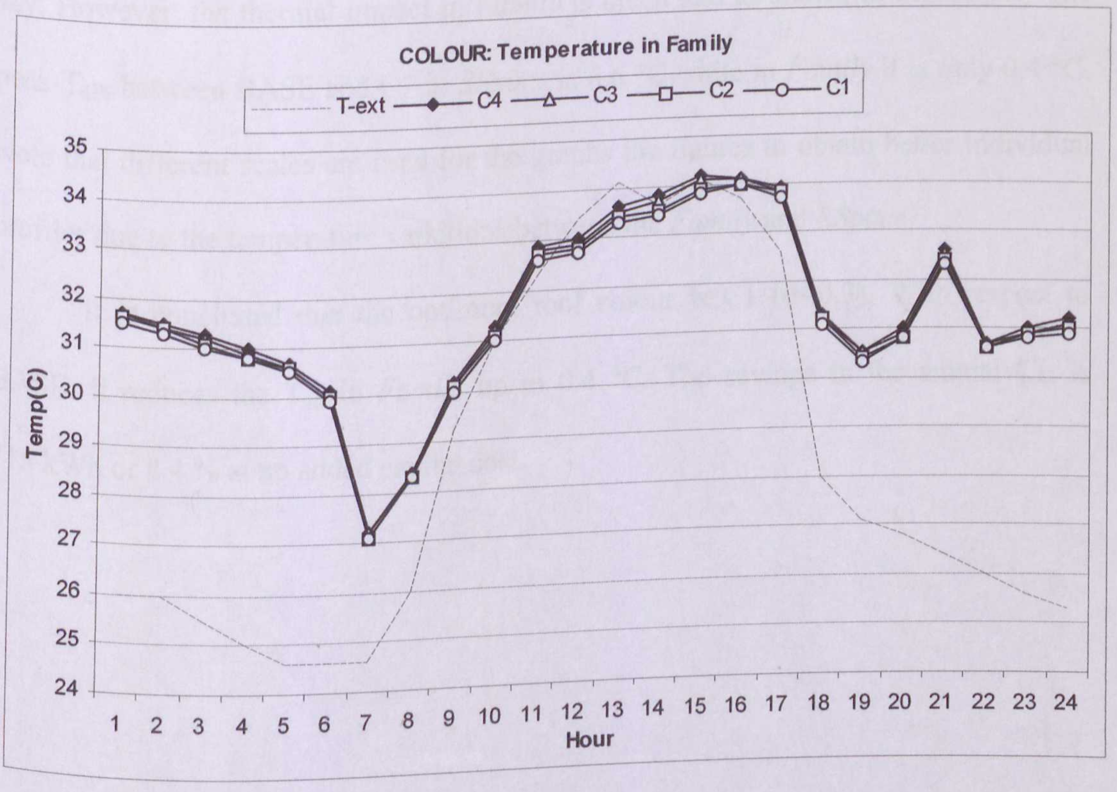


Figure 7.2: Indoor T_{air} in *Family* for COLOUR models

Referring to Figure 7.2, the T_{air} for all models in *Family* drop sharply at 0006 hour. This is due to the opening of the door that draws in the cool external air that is at the lowest during the hours of 0005 to 0007. The space starts to cool down at 1700 hour but the temperature is slightly elevated at 1900 hour when the door is closed. The peak at 2100 hour is due to occupancy, however it drops again at 2200 hour when it is unoccupied.

Figures 7.3 and 7.4 show the T_{diff} between the lighter coloured roof models of C1, C2 and C3 with the darker coloured BASE model for *RSpace* and *Family* respectively.

Referring to Figure 7.3, due to the lower solar absorptivity (α) of C1, it has the highest T_{diff} followed by C2 and C3. However, the significance of α diminishes at night-time as also shown in Table 7.2 and can been seen clearly in Figure 7.1. This is due to long-wave radiation exchange of the roofs having the same ε with cooler night sky. However, the thermal impact in *Family* is much less as shown in Figure 7.4. The peak T_{diff} between BASE and C1 in *RSpace* is 6.6 °C while in *Family* it is only 0.4 °C. Note that different scales are used for the graphs the figures to obtain better individual profiles due to the temperature variations between the *Family* and *RSpace*.

It is concluded that the optimum roof colour is C1 (α=0.3). With respect to BASE, it reduces the T_{air} in *Family* up to 0.4 °C. The savings in the annual CL is 715 kWh or 8.4 % at no added capital cost.

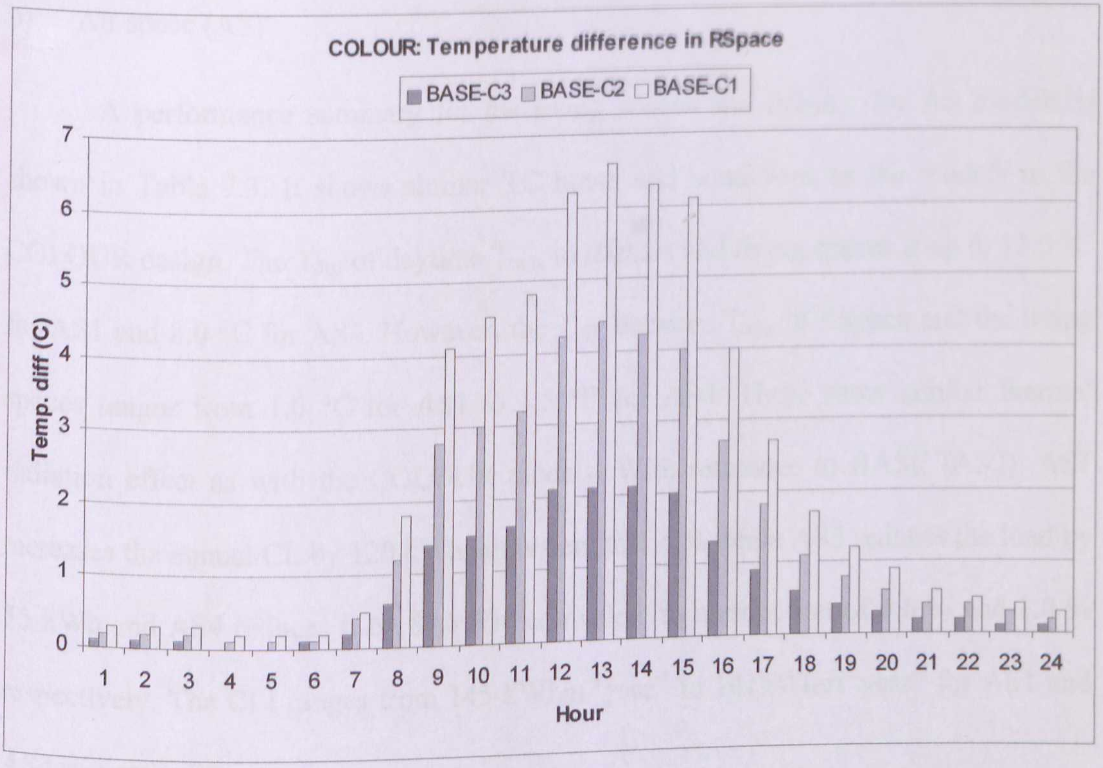


Figure 7.3: T_{diff} in *RSpace* between BASE and COLOUR models

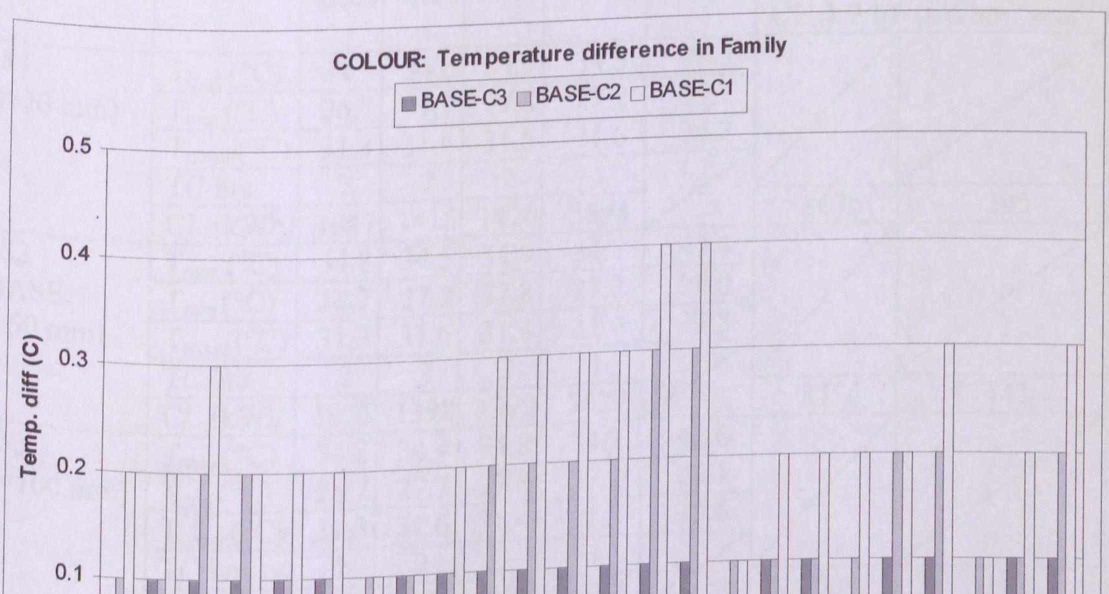


Figure 7.4: T_{diff} in *Family* between BASE and COLOUR models

b) Air space (AS)

A performance summary for the living spaces and *RSpace* for AS models is shown in Table 7.3. It shows similar TC hours and conditions as the models in the COLOUR design. The T_{diff} of daytime T_{max} in *RSpace* and living spaces is up to 11.0 °C for AS1 and 8.0 °C for AS4. However, the T_{diff} between T_{min} in RSpace and the living spaces ranges from 1.0 °C for AS1 to 1.5 °C for AS4. These show similar thermal radiation effect as with the COLOUR models. With reference to BASE (AS2), AS1 increases the annual CL by 120 kWh equivalent to 1.4 % while AS3 reduces the load by 55 kWh and AS4 reduces it by 87 kWh, equivalent to a reduction of 0.6 % and 1.0 % respectively. The CLI ranges from 145 $kWhm^{-2}year^{-1}$ to 141$kWhm^{-2}year^{-1}$ for AS1 and AS4 respectively.

Table 7.3: Summary of thermal and energy performances for AS models

Model		Bed1	Bed2	Bed3	Family	RSpace	Annual CL (kWh)	CLI ($kWhm^{-2}year^{-1}$)
AS1 (d=20 mm)	T_{max} (°C)	34.8	34.6	34.9	34.3	45.3		
	T_{min} (°C)	26.7	27.7	27.8	27.2	27.7		
	T_{mean} (°C)	31.3	31.6	31.5	31.6	34.2		
	TC hrs	2	2	2	1			
	CL (kWh)	1947	1415	1420	3894		8676	145
AS2 (BASE; d=50 mm)	T_{max} (°C)	34.8	34.5	34.9	34.2	43.4		
	T_{min} (°C)	26.7	27.7	27.8	27.2	28.0		
	T_{mean} (°C)	31.3	31.6	31.4	31.6	33.8		
	TC hrs	2	2	2	1			
	CL (kWh)	1933	1398	1399	3827		8556	143
AS3 (d=100 mm)	T_{max} (°C)	34.8	34.4	34.8	34.2	42.6		
	T_{min} (°C)	26.7	27.7	27.8	27.2	28.1		
	T_{mean} (°C)	31.3	31.6	31.4	31.5	33.6		
	TC hrs	2	2	2	1			
	CL (kWh)	1926	1390	1398	3797		8501	142
AS4 (d =200 mm)	T_{max} (°C)	34.7	34.4	34.8	34.1	42.1		
	T_{min} (°C)	26.7	27.7	27.8	27.2	28.2		
	T_{mean} (°C)	31.3	31.6	31.4	31.5	33.5		
	TC hrs	2	2	2	1			
	CL (kWh)	1922	1385	1383	3779		8469	141

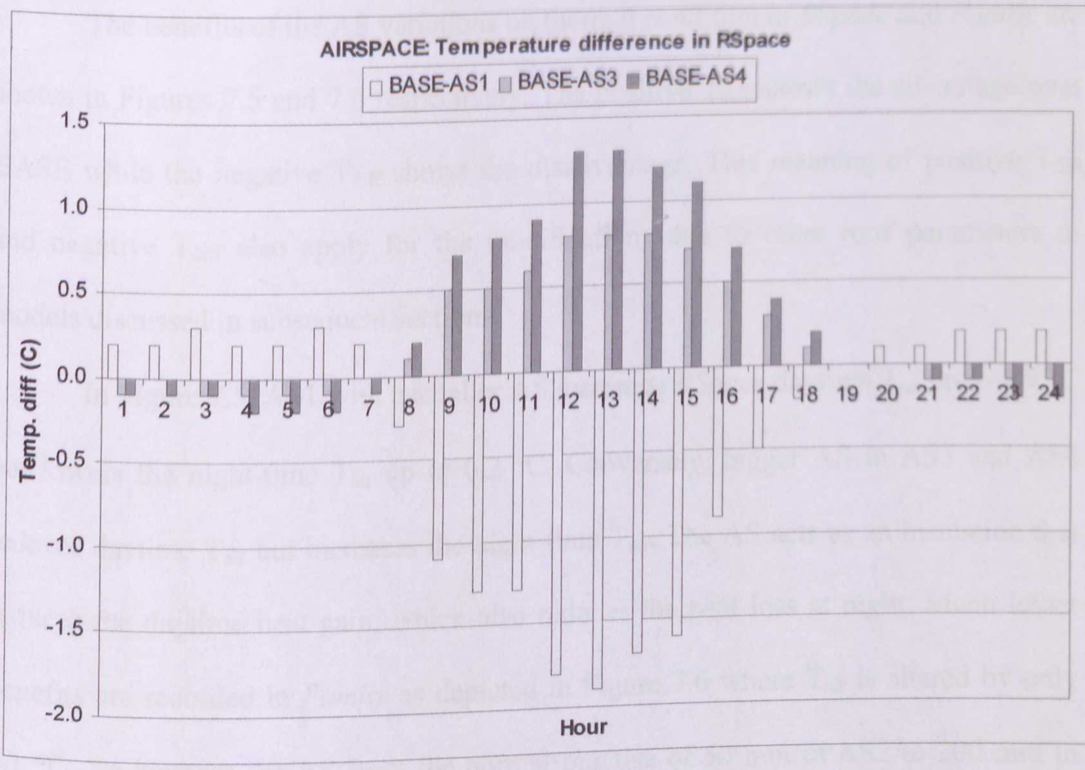


Figure 7.5: T_{diff} in *RSpace* between BASE and AS models

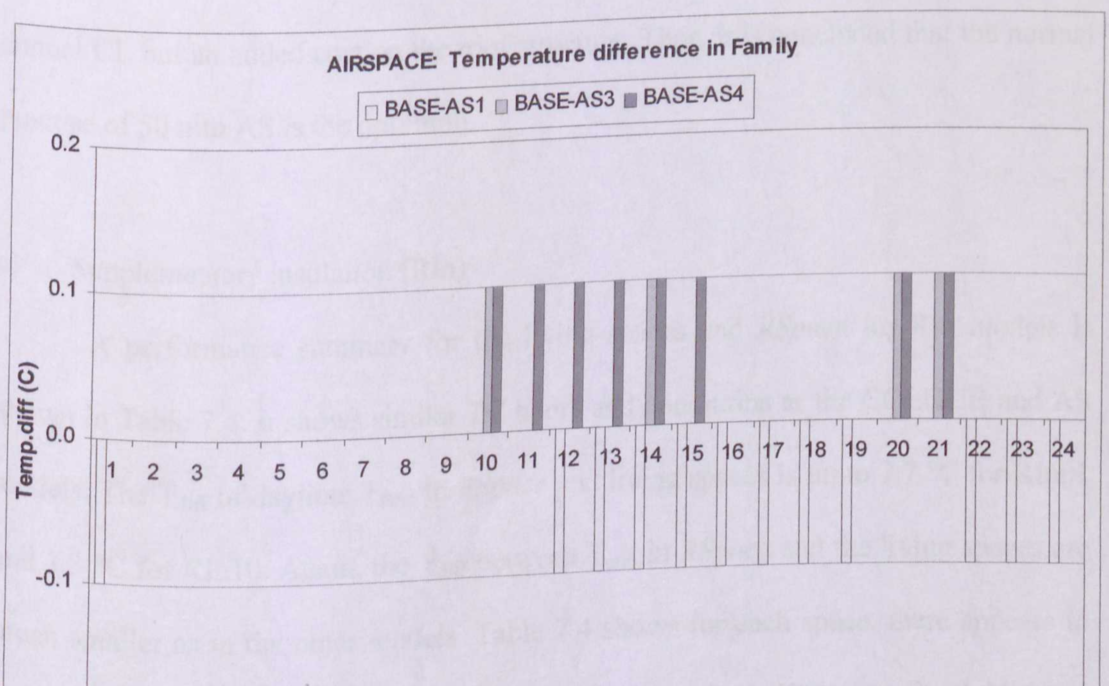


Figure 7.6: T_{diff} in *Family* between BASE and AS models

The benefits of the AS variations on thermal condition in *RSpace* and *Family* are shown in Figures 7.5 and 7.6 respectively. The positive T_{diff} shows the advantage over BASE while the negative T_{diff} shows the disadvantage. This meaning of positive T_{diff} and negative T_{diff} also apply for the modifications due to other roof parameters in models discussed in subsequent sections.

In Figure 7.5, AS1 with a smaller AS increases *RSpace* daytime T_{air} up to 1.9 °C but lowers the night-time T_{air} up to 0.2 °C. Conversely, bigger AS in AS3 and AS4 reduces daytime T_{air} but increases the night-time T_{air}. The AS acts as an insulation that reduces the daytime heat gain, which also reduces the heat loss at night. Much lesser benefits are recorded in *Family* as depicted in Figure 7.6 where T_{air} is altered by only 0.1 °C. To increase the AS from the normal practise of 50 mm in AS2 to 200 mm in AS4 would mean to quadruple the batten thickness that would have an effect on the design. However, this lowers T_{max} in *Family* by only 0.1 °C with 1.0 % reduction of annual CL but an added cost on the roof structure. Thus, it is concluded that the normal practise of 50 mm AS is the optimum.

c) Supplementary insulation (RIn)

A performance summary for the living spaces and *RSpace* for RIn models is shown in Table 7.4. It shows similar TC hours and conditions as the COLOUR and AS models. The T_{diff} of daytime T_{max} in *RSpace* and living spaces is up to 7.7 °C for RIn01 and 3.3 °C for RIn10. Again, the T_{diff} between T_{min} in *RSpace* and the living spaces are much smaller as in the other models. Table 7.4 shows for each space, there appears to be a minimum T_{max} that could be achieved in the natural ventilation mode. Additional insulation could not lower the temperature any further.

Table 7.4: Summary of thermal and energy performances for RIn models

Model		Bed1	Bed2	Bed3	Family	RSpace	Annual CL (kWh)	CLI ($kWhm^{-2}year^{-1}$)
RIn00 (BASE; d=0 mm)	T_{max} (°C)	34.8	34.5	34.9	34.2	43.4		
	T_{min} (°C)	26.7	27.7	27.8	27.2	28.0		
	T_{mean} (°C)	31.3	31.6	31.4	31.6	33.8		
	TC hrs	2	2	2	1			
	CL (kWh)	1933	1398	1399	3827		8556	143
RIn01 (d=10 mm)	T_{max} (°C)	34.7	34.4	34.8	34.1	41.8		
	T_{min} (°C)	26.7	27.7	27.8	27.2	28.2		
	T_{mean} (°C)	31.3	31.6	31.4	31.5	33.4		
	TC hrs	2	2	2	1			
	CL (kWh)	1923	1386	1383	3768		8459	141
RIn02 (d=20 mm)	T_{max} (°C)	34.7	34.3	34.8	34.1	40.7		
	T_{min} (°C)	26.7	27.7	27.8	27.2	28.4		
	T_{mean} (°C)	31.3	31.6	31.4	31.5	33.1		
	TC hrs	2	2	2	1			
	CL (kWh)	1912	1374	1369	3726		8382	140
RIn03 (d=30 mm)	T_{max} (°C)	34.7	34.2	34.7	34.1	39.9		
	T_{min} (°C)	26.7	27.7	27.7	27.2	28.5		
	T_{mean} (°C)	31.3	31.5	31.4	31.5	32.9		
	TC hrs	2	2	2	1			
	CL (kWh)	1905	1365	1358	3695		8322	139
RIn04 (d=40 mm)	T_{max} (°C)	34.6	34.2	34.7	34.0	39.3		
	T_{min} (°C)	26.7	27.7	27.7	27.2	28.6		
	T_{mean} (°C)	31.3	31.5	31.3	31.5	32.8		
	TC hrs	2	2	2	2			
	CL (kWh)	1898	1358	1349	3671		8276	138
RIn05 (d=50 mm)	T_{max} (°C)	34.6	34.2	34.7	34.0	38.8		
	T_{min} (°C)	26.7	27.7	27.7	27.2	28.6		
	T_{mean} (°C)	31.3	31.5	31.3	31.4	32.6		
	TC hrs	2	2	2	1			
	CL (kWh)	1893	1353	1342	3650		8239	137
RIn06 (d=60 mm)	T_{max} (°C)	34.6	34.2	34.7	34.0	38.4		
	T_{min} (°C)	26.7	27.7	27.7	27.2	28.6		
	T_{mean} (°C)	31.3	31.5	31.3	31.4	32.5		
	TC hrs	2	2	1	1			
	CL (kWh)	1889	1348	1337	3634		8208	137
RIn07 (d=70 mm)	T_{max} (°C)	34.6	34.2	34.6	34.0	38.1		
	T_{min} (°C)	26.7	27.7	27.7	27.2	28.7		
	T_{mean} (°C)	31.3	31.5	31.3	31.4	32.4		
	TC hrs	2	2	1	1			
	CL (kWh)	1886	1345	1332	3620		8183	136
RIn08 (d=80 mm)	T_{max} (°C)	34.6	34.2	34.6	34.0	37.8		
	T_{min} (°C)	26.7	27.7	27.7	27.2	28.7		
	T_{mean} (°C)	31.3	31.5	31.3	31.4	32.3		
	TC hrs	2	2	1	1			
	CL (kWh)	1883	1341	1328	3609		8162	136
RIn09 (d=90 mm)	T_{max} (°C)	34.6	34.1	34.6	34.0	37.5		
	T_{min} (°C)	26.7	27.7	27.7	27.2	28.7		
	T_{mean} (°C)	31.3	31.5	31.3	31.4	32.3		
	TC hrs	2	2	1	1			
	CL (kWh)	1881	1339	1325	3599		8144	136
RIn10 (d=100 mm)	T_{max} (°C)	34.6	34.1	34.6	34.0	37.3		
	T_{min} (°C)	26.7	27.7	27.7	27.2	28.7		
	T_{mean} (°C)	31.3	31.5	31.3	31.4	32.2		
	TC hrs	2	2	1	1			
	CL (kWh)	1879	1337	1322	3591		8128	135

Due to minimal temperature variation with each consecutive model, Figures 7.7 and 7.8 show the impact of RIn on *RSpace* and *Family* for only several selected models. Similar to the impact of COLOUR and AS, the advantage is more significant in *RSpace* than in *Family*. RIn10 reduces the T_{air} in *RSpace* up to 6.7 °C but *in Family* the reduction is up to only 0.3 °C. The T_{diff} in *RSpace* shows that additional RIn lowers the daytime T_{air} but increases the night-time T_{air}. However, the elevated night-time temperature is much less than the daytime reduction. Nevertheless, the minimal impact in *Family* necessitates the identification of an optimum thickness due to the cost of insulation material despite the continual reduction in CL. Therefore, whilst the impact on the TP and TC are nominal, it is prudent to consider the implication on CL. Figures 7.9 and 7.10 illustrate the technique used to determine the optimum thickness for RIn.

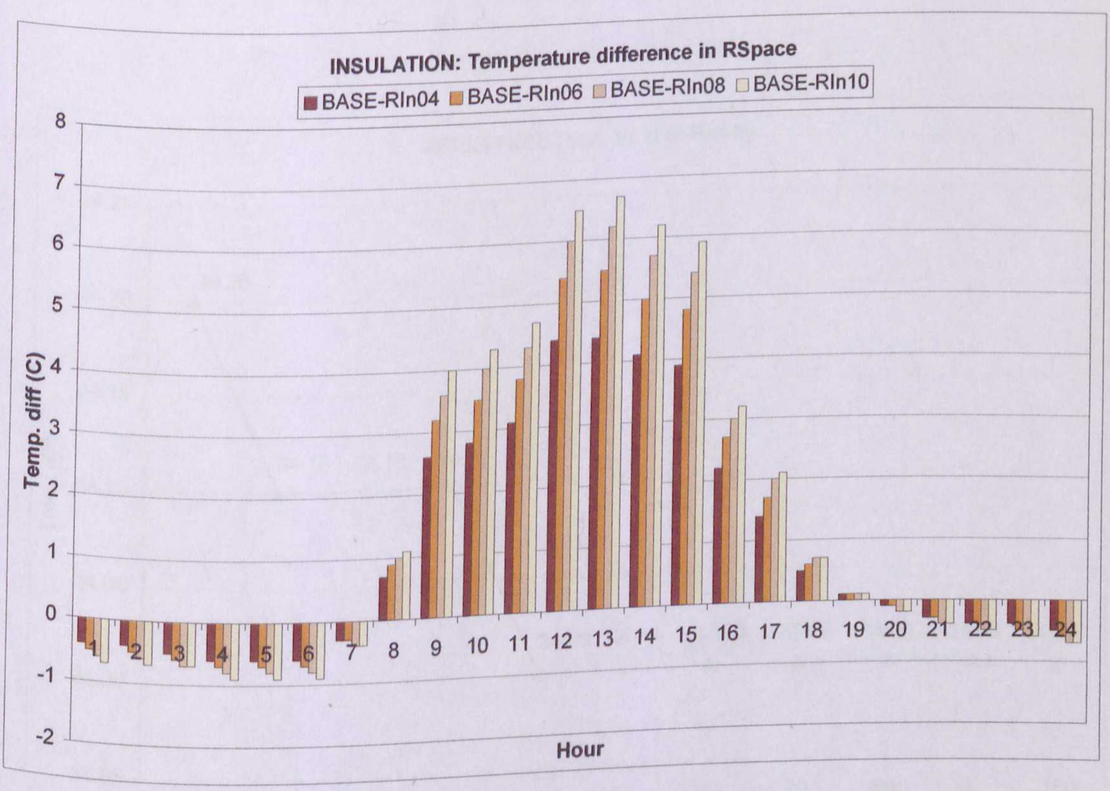


Figure 7.7: T_{diff} in *RSpace* between BASE and RIn models

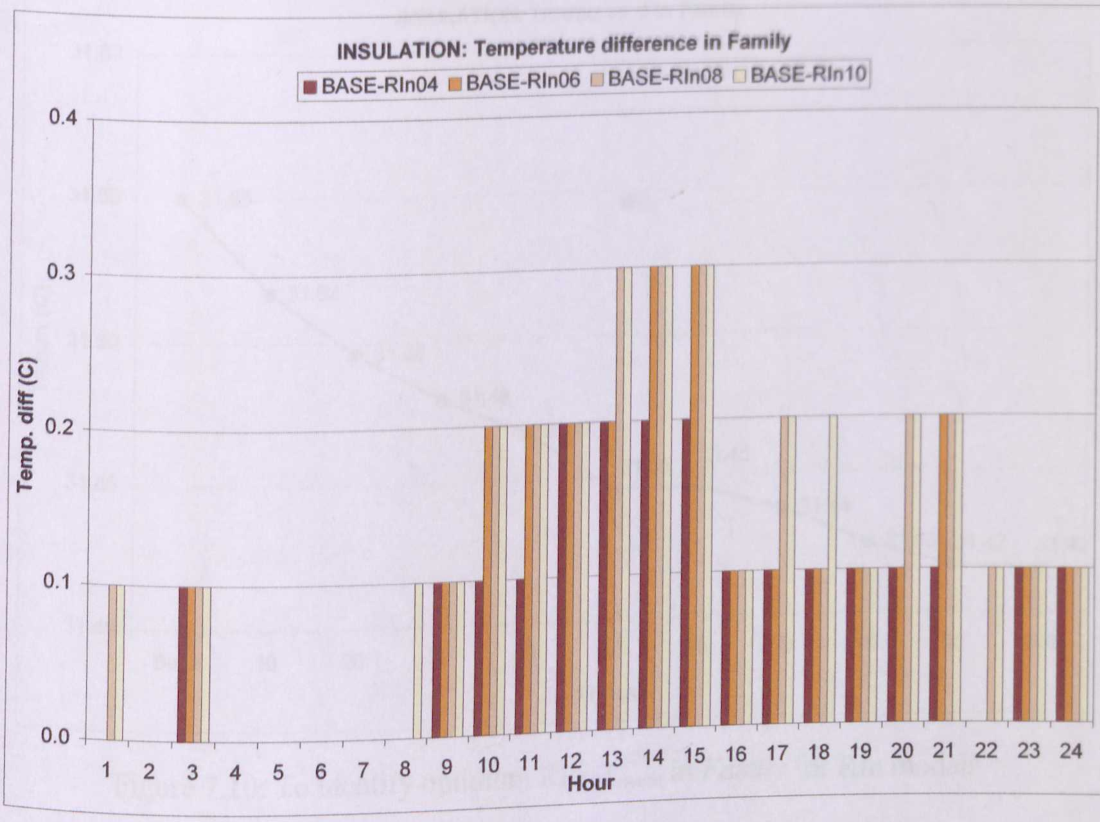


Figure 7.8: T_{diff} in *Family* between BASE and RIn models

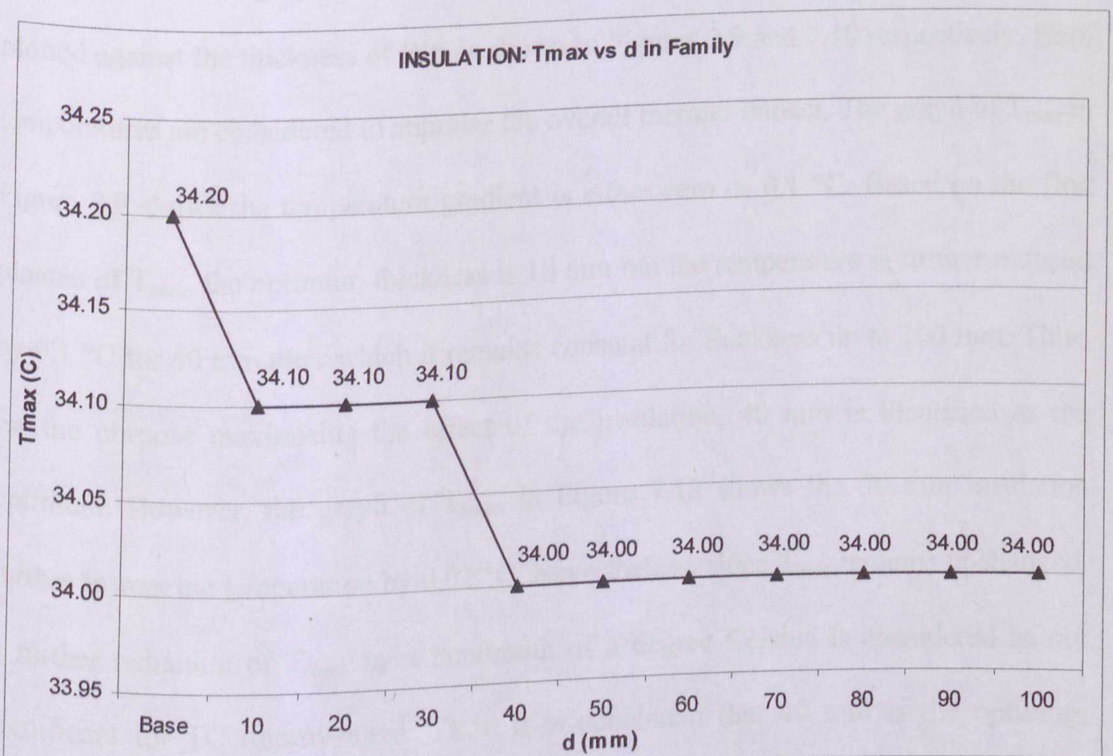


Figure 7.9: To identify optimum RIn: T_{max} in *Family* for RIn models

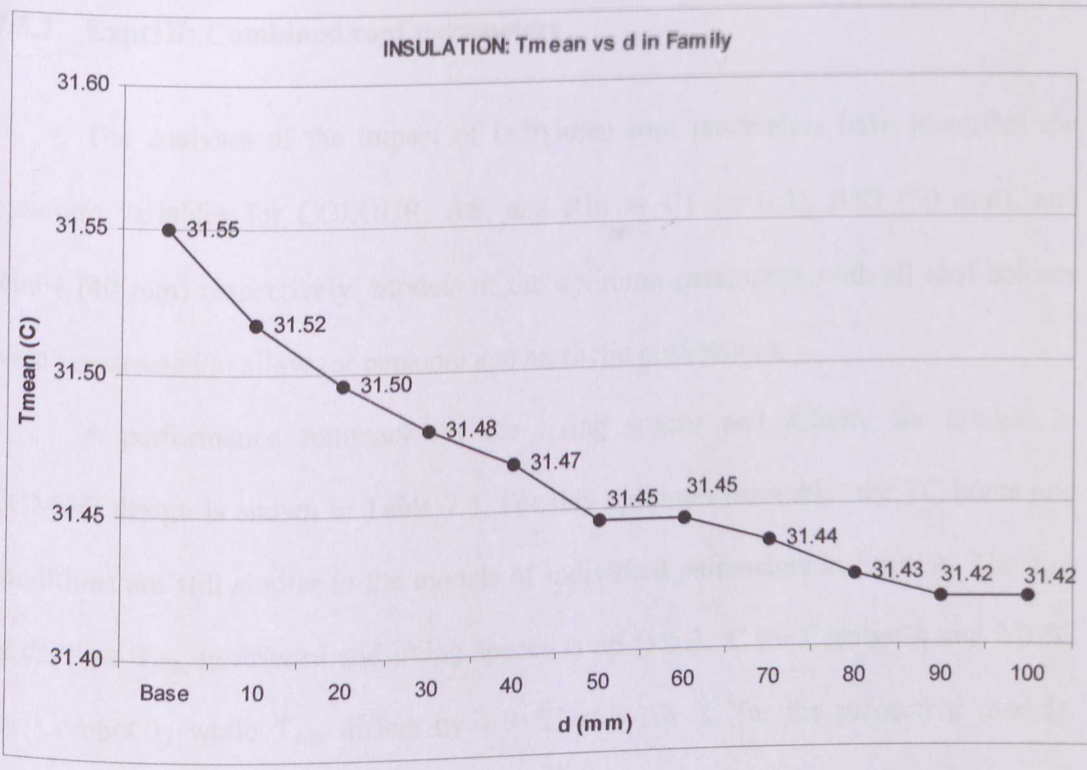


Figure 7.10: To identify optimum RIn: T_{mean} in *Family* for RIn models

To find the optimum thickness, T_{air} in *Family* was analysed to represent the impact on the living spaces on the upper floor. Graphs of daily T_{max} and T_{mean} are plotted against the thickness of RIn as shown in Figures 7.9 and 7.10 respectively. Both temperatures are considered to appraise the overall thermal impact. The graph of T_{max} in Figure 7.9 shows the temperature gradient is either zero or 0.1 °C. Based on the first plateau of T_{max}, the optimum thickness is 10 mm but the temperature is further reduced by 0.1 °C for 40 mm after which it remains constant for thickness up to 100 mm. Thus, for the purpose maximising the effect of the insulation, 40 mm is identified as the optimum. However, the graph of T_{mean} in Figure 7.10 shows the 50 mm insulation further lowers the temperature by 0.02 °C. Nevertheless, since T_{max} remains unchanged, a further reduction of T_{mean} by a hundredth of a degree Celsius is considered as not significant for TC improvement. Thus, it is concluded that 40 mm is the optimum thickness for RIn. With respect to BASE, Table 7.4 shows RIn04 with CLI 138 $kWhm^{-2}year^{-1}$ reduces the annual CL by 280 kWh or 3.3 %.

7.3.2 Expt1B: Combined roof parameters

The analyses of the impact of individual roof parameters have identified the optimum variables for COLOUR, AS, and RIn as C1 (α=0.3), AS2 (50 mm), and RIn04 (40 mm) respectively. Models of the optimum parameters with all roof colours were constructed to allow for personal and aesthetic preferences.

A performance summary for the living spaces and *RSpace* for models in COMBO design is shown in Table 7.5. For this optimum assembly, the TC hours and conditions are still similar to the models of individual parameters in Expt1A. The T_{diff} of daytime T_{max} in *RSpace* and living spaces is up to 5.3 °C for ComboC4 and 2.0 °C for ComboC1, while T_{min} differs by 1.9 °C and 1.7 °C for the respective models. Changing the roof colour from C4 (ComboC4) to C1 (ComboC1) reduces the annual CL by 409 kWh or 4.9 %.

Table 7.5: Summary of thermal and energy performances for COMBO models

Model		Bed1	Bed2	Bed3	Family	RSpace	Annual CL (kWh)	CLI ($kWhm^{-2}year^{-1}$)
ComboC1	T_{max} (°C)	34.5	34.1	34.5	34.0	36.0		
• C1	T_{min} (°C)	26.6	27.6	27.7	27.1	28.3		
• AS2	T_{mean} (°C)	31.2	31.4	31.2	31.3	31.5		
• RIn04	TC hrs	2	2	1	1			
	CL (kWh)	1822	1238	1258	3504		7867	131
ComboC2	T_{max} (°C)	34.5	34.1	34.6	34.0	37.0		
• C2	T_{min} (°C)	26.6	27.6	27.7	27.1	28.4		
• AS2	T_{mean} (°C)	31.2	31.4	31.3	31.4	31.9		
• RIn04	TC hrs	2	2	1	1			
	CL (kWh)	1847	1308	1288	3559		8002	133
ComboC3	T_{max} (°C)	34.6	34.2	34.6	34.0	38.2		
• C3	T_{min} (°C)	26.6	27.7	27.7	27.2	28.5		
• AS2	T_{mean} (°C)	31.2	31.5	31.3	31.4	32.3		
• RIn04	TC hrs	2	2	1	1			
	CL (kWh)	1873	1333	1319	3614		8139	136
ComboC4	T_{max} (°C)	34.6	34.2	34.7	34.0	39.3		
• C4	T_{min} (°C)	26.7	27.7	27.7	27.2	28.6		
• AS2	T_{mean} (°C)	31.3	31.5	31.3	31.5	32.8		
• RIn04	TC hrs	2	2	2	1			
	CL (kWh)	1898	1358	1349	3671		8276	138

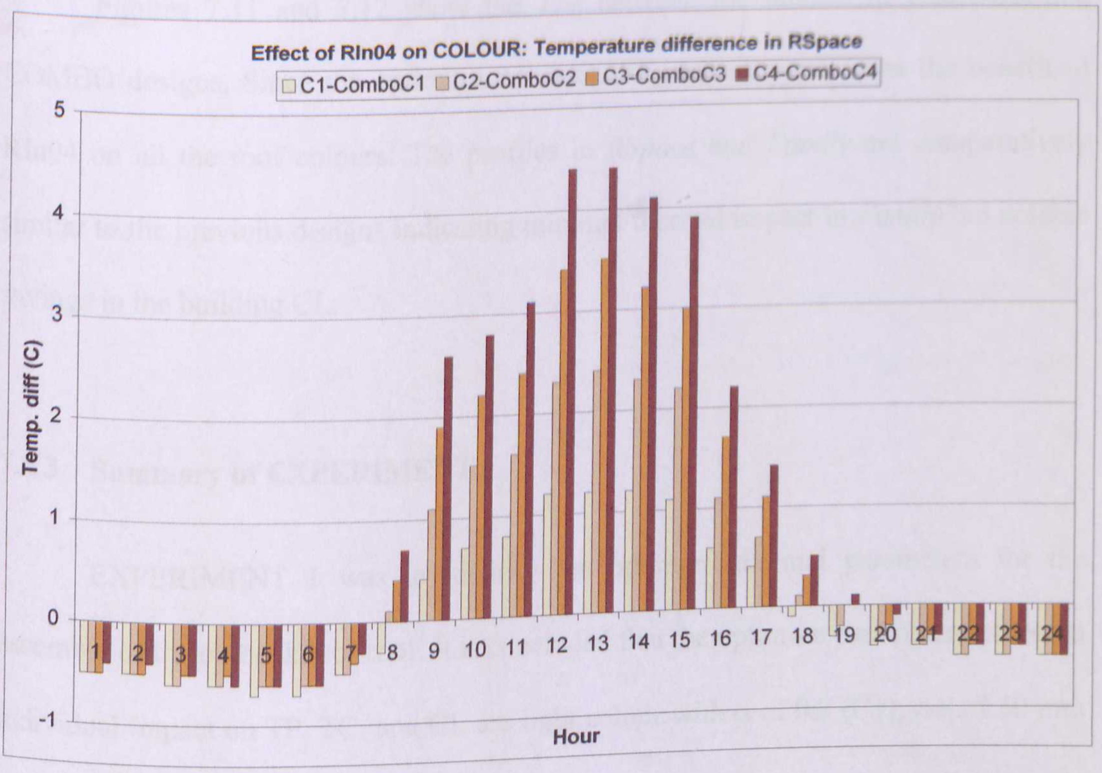


Figure 7.11: T_{diff} in *RSpace* between COLOUR and COMBO models

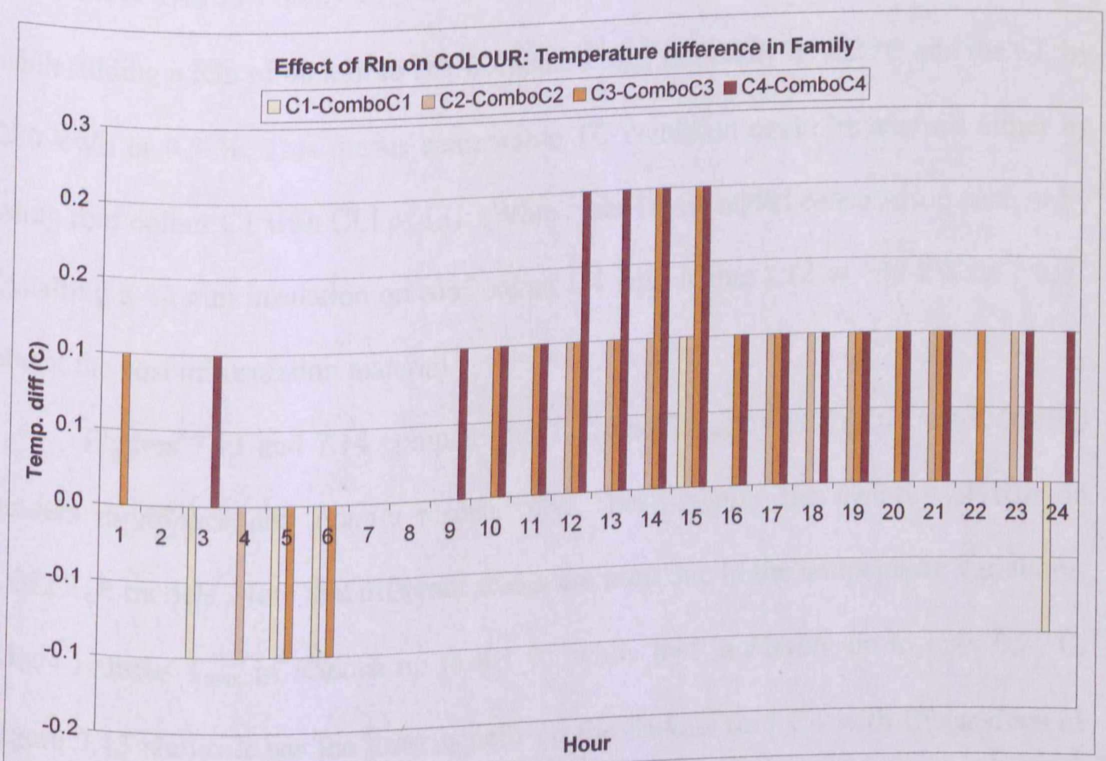


Figure 7.12: T_{diff} in *Family* between COLOUR and COMBO models

Figures 7.11 and 7.12 show the T_{diff} between the models in COLOUR and COMBO designs. Since the optimum AS is BASE, this also compares the benefit of RIn04 on all the roof colours. The profiles in *RSpace* and *Family* are comparatively similar to the previous designs indicating minimal thermal impact in *Family* but notable savings in the building CL.

7.3.3 Summary of EXPERIMENT 1

EXPERIMENT 1 was to identify the optimum thermal parameters for the assembly of the outer skin of roof. It is concluded that the optimum parameters based on individual impact on TP, TC, and CL are light colour with α of 0.3 (C1), AS of 50 mm (AS2), and RIn of 40 mm (RIn04).

Results for the individual models show changing the colour from C4 (BASE) to C1 reduces T_{max} in *Family* by 0.2 °C and the total annual CL by 715 kWh or 8.4 %, while adding a RIn of 40 mm to BASE reduces T_{max} in *Family* by 0.2 °C and the CL by 280 kWh or 3.3 %. This means comparable TC condition could be attained either by using roof colour C1 with CLI of 131 $kWhm^{-2}year^{-1}$ at no added construction cost, or by installing a 40 mm insulation on roof colour C4 with higher CLI of 138 $kWhm^{-2}year^{-1}$ and at the cost of insulation material.

Figures 7.13 and 7.14 compare the T_{max} and T_{mean} of COLOUR and COMBO models in *RSpace* and *Family* respectively. These signify the benefits of RIn on COLOUR models. Note that different scales are used due to the temperature variations. RIn04 reduces T_{max} in *RSpace* up to 4.1 °C while that in *Family* up to only 0.2 °C. Figure 7.15 shows it has the most benefit on the darkest roof C4 with CL savings of 280 kWh or 3.3 %. Whilst impeding daytime heat transfer thus lowering the daytime T_{max}, the insulation trapped night-time heat hence increasing the indoor temperature.

However, the reduction of daytime T_{max} is more considerable than the night-time temperature elevation. Nevertheless, the benefit depends on the occupancy pattern as well as the choice of ventilation. If the space were to be naturally ventilated, insulation would exacerbate the thermal condition. But if it were to be actively cooled, the insulation would reduce the CL.

It is concluded that COMBO models demonstrated an insignificant thermal improvement but noteworthy the impact on CL.

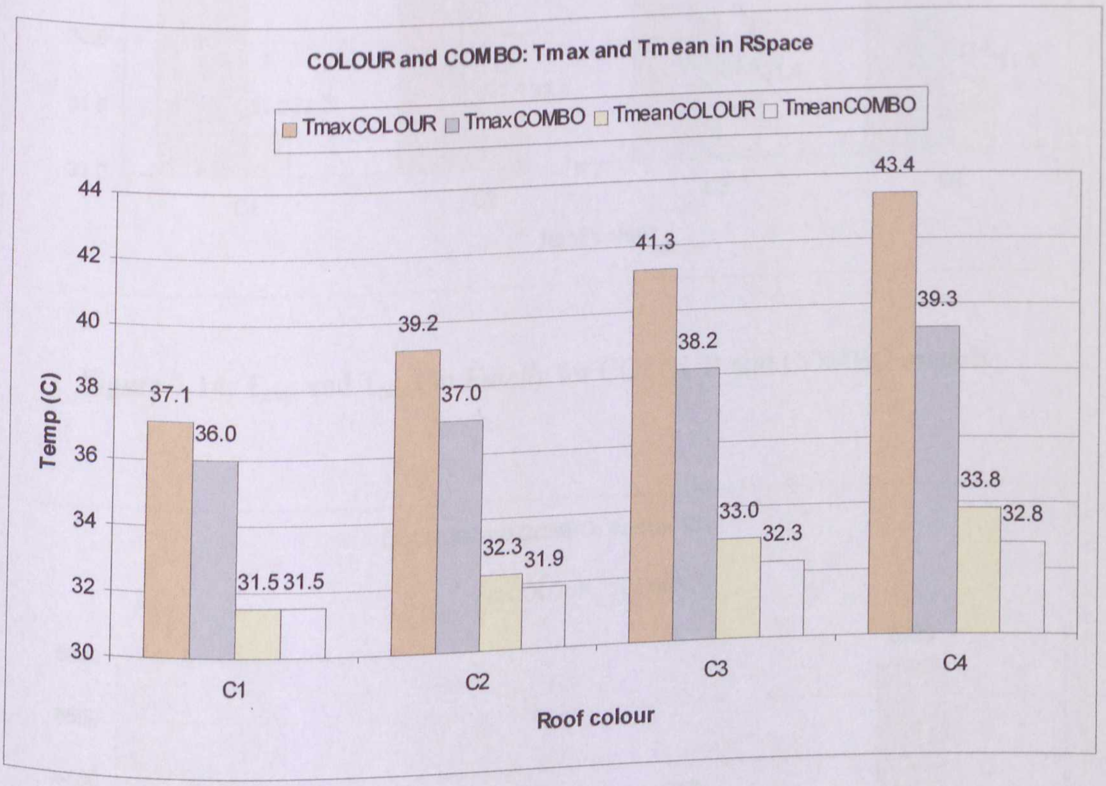


Figure 7.13: T_{max} and T_{mean} in *RSpace* for COLOUR and COMBO models

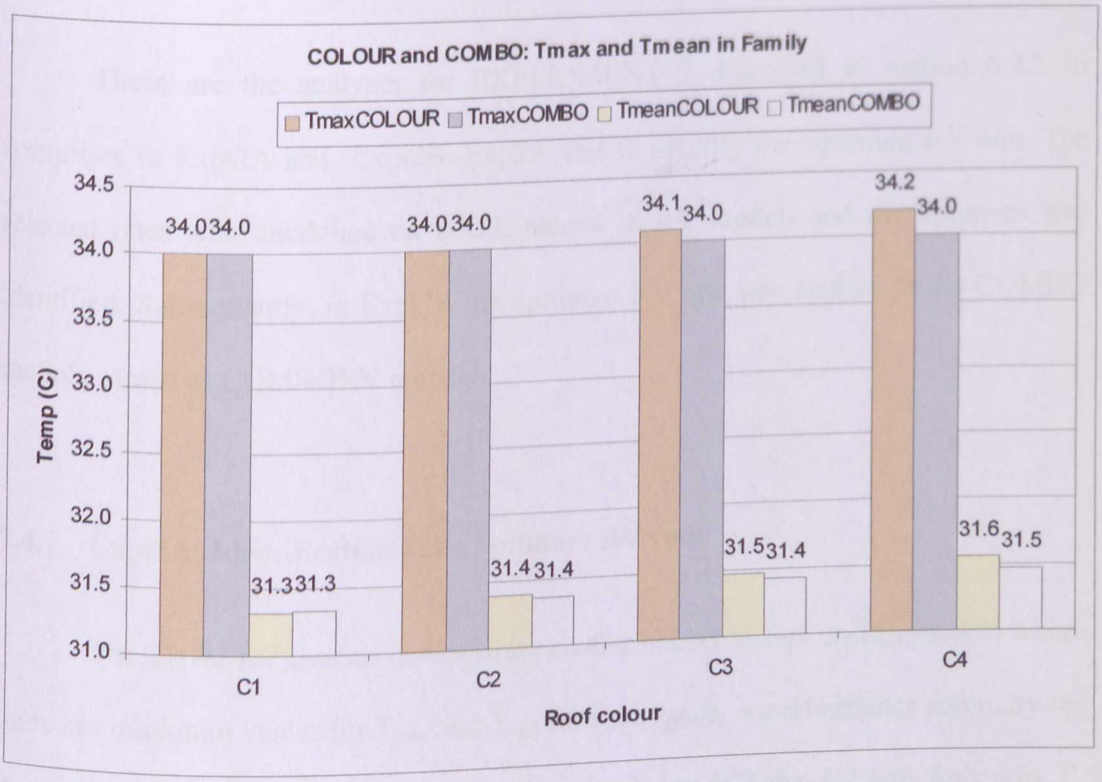


Figure 7.14: T_{max} and T_{mean} in *Family* for COLOUR and COMBO models

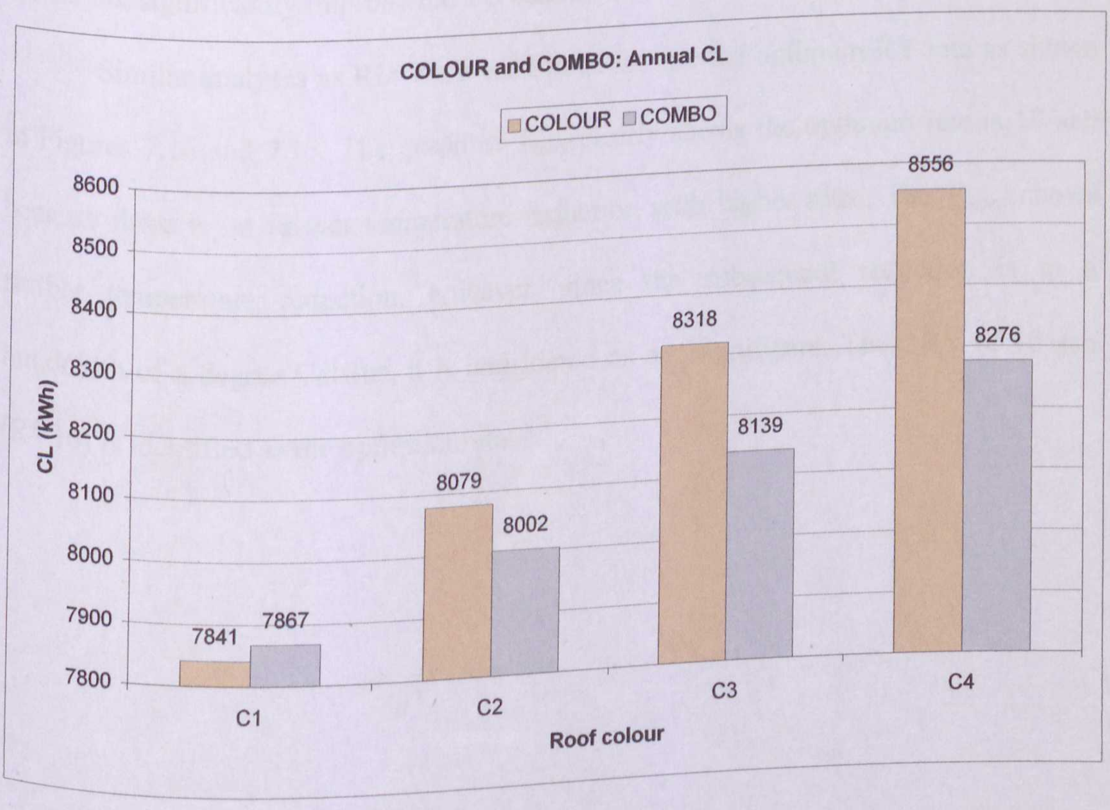


Figure 7.15: Annual CL for COLOUR and COMBO models

7.4 EXPERIMENT 2: Roof Ventilation (RV)

These are the analyses for EXPERIMENT 2 described in section 6.2.2. It comprises of Expt2A and Expt2B. Exp2A was to identify the optimum RV rate. The selected rates were modelled on BASE named as RV models and the optimum was identified. Subsequently, in Expt2B the optimum RV rate was applied to the COMBO models named as COMBORV models.

7.4.1 Expt2A: Identification of an optimum RV rate

The TP for RV models demonstrate similar impact as that on RIn models where there are minimum values for T_{max} and T_{min} for each space. A performance summary for the living spaces and *RSpace* for RV models are shown in Table C2.1 in Appendix C. The minimum indoor T_{air} indicates there is an optimum RV rate where higher rates would not significantly improve the TC condition.

Similar analyses as RIn were used to determine the optimum RV rate as shown in Figures 7.16 and 7.17. The graph of T_{max} clearly shows the optimum rate is 10 ach because there is no further temperature reduction with higher rates. The T_{mean} shows further temperature reduction, however, since the subsequent reduction is to a hundredth of a degree Celsius, it is considered as not significant. Thus, RV of 10 ach (RV10) is identified as the optimum rate.

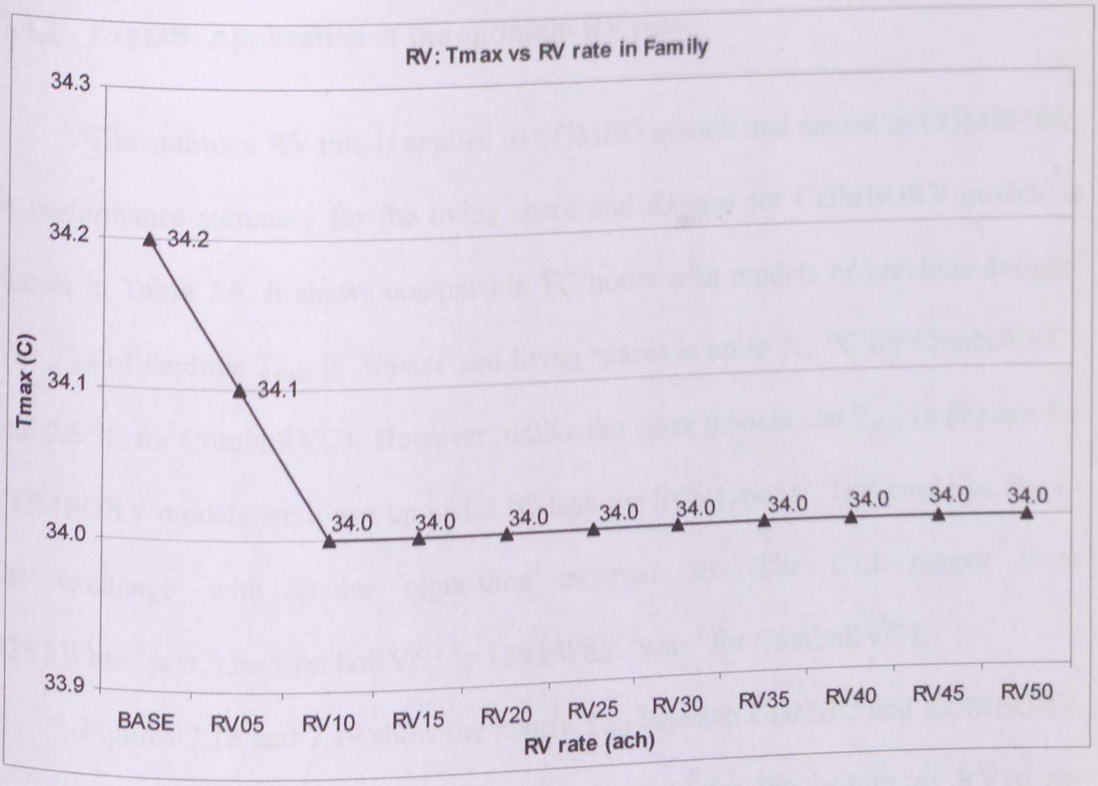


Figure 7.16: To identify optimum RV rate: T_{max} in *Family* for RV models

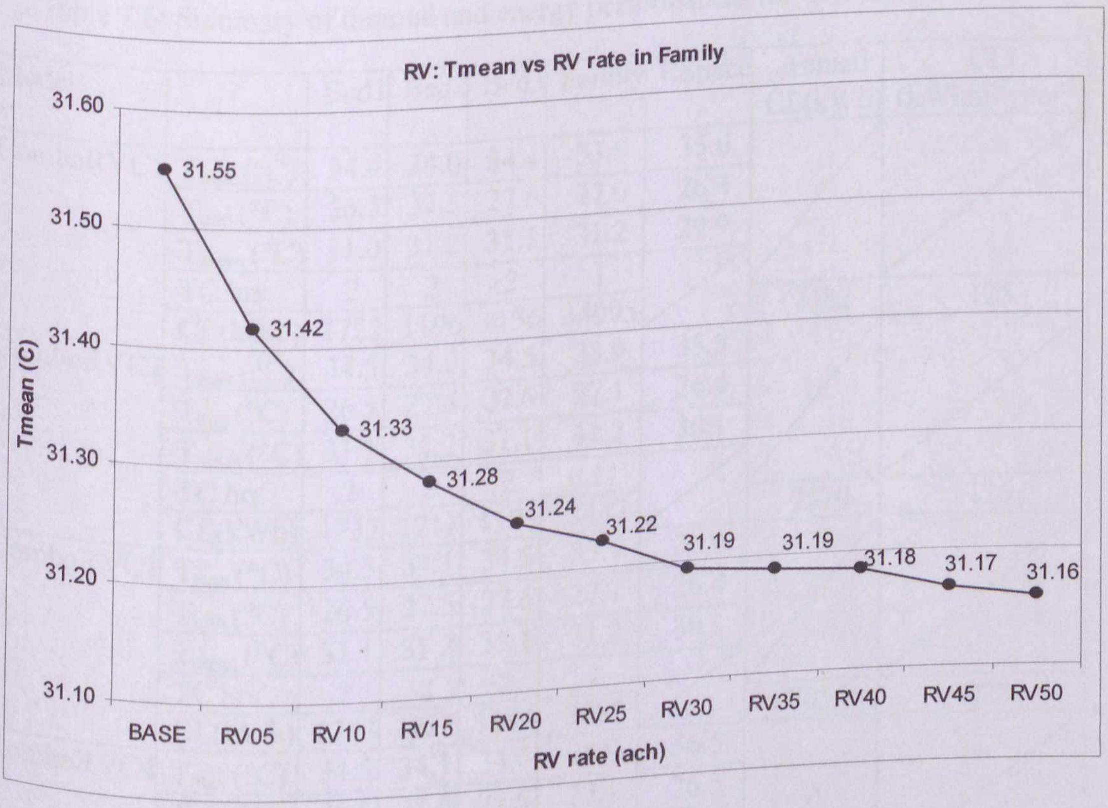


Figure 7.17: To identify optimum RV rate: T_{mean} in *Family* for RV models

7.4.2 Expt2B: Application of the optimum RV rate

The optimum RV rate is applied to COMBO models and named as COMBORV. A performance summary for the living space and *RSpace* for COMBORV models is shown in Table 7.6. It shows comparable TC hours with models of previous designs. The T_{diff} of daytime T_{max} in *RSpace* and living spaces is up to 1.1 °C for ComboRVC1 and 2.5 °C for ComboRVC4. However, unlike the other models, the T_{min} in *RSpace* for COMBORV models are lower up to 1.2 °C than the living spaces. This could be due to the exchange with cooler night-time external air. The CLI ranges from 125 kWhm^{-2}year^{-1} for ComboRVC1 to 129 kWhm^{-2}year^{-1} for ComboRVC4.

Figures 7.18 and 7.19 show the hourly T_{diff} between COMBO and COMBORV models in *RSpace* and *Family* respectively. It computes the benefit of RV10 on COMBO models that was up to 2.8 °C in *RSpace* and 0.4 °C in *Family*.

Table 7.6: Summary of thermal and energy performances for COMBORV models

Model		Bed1	Bed2	Bed3	Family	RSpace	Annual CL(kWh)	CLI (kWhm^{-2}year^{-1})
ComboRVC1	T_{max} (°C)	34.4	34.0	34.4	33.9	35.0		
	T_{min} (°C)	26.5	27.5	27.6	27.0	26.4		
	T_{mean} (°C)	31.0	31.2	31.1	31.2	29.9		
	TC hrs	2	2	2	1		7482	125
	CL(kWh)	1722	1196	1156	34095			
ComboRVC2	T_{max} (°C)	34.5	34.0	34.5	33.9	35.5		
	T_{min} (°C)	26.5	27.5	27.6	27.1	26.4		
	T_{mean} (°C)	31.1	31.2	31.1	31.2	30.1		
	TC hrs	2	2	2	1		7570	126
	CL(kWh)	1737	1211	1175	3447			
ComboRVC3	T_{max} (°C)	34.5	34.1	34.5	33.9	36.0		
	T_{min} (°C)	26.5	27.5	27.6	27.1	26.4		
	T_{mean} (°C)	31.1	31.2	31.1	31.2	30.3		
	TC hrs	2	2	2	1		7655	128
	CL(kWh)	1753	1227	1194	3482			
ComboRVC4	T_{max} (°C)	34.5	34.1	34.6	34.0	36.5		
	T_{min} (°C)	26.5	27.5	27.6	27.1	26.5		
	T_{mean} (°C)	31.1	31.3	31.2	31.3	30.5		
	TC hrs	2	2	2	1		7739	129
	CL(kWh)	1768	1242	1212	3518			

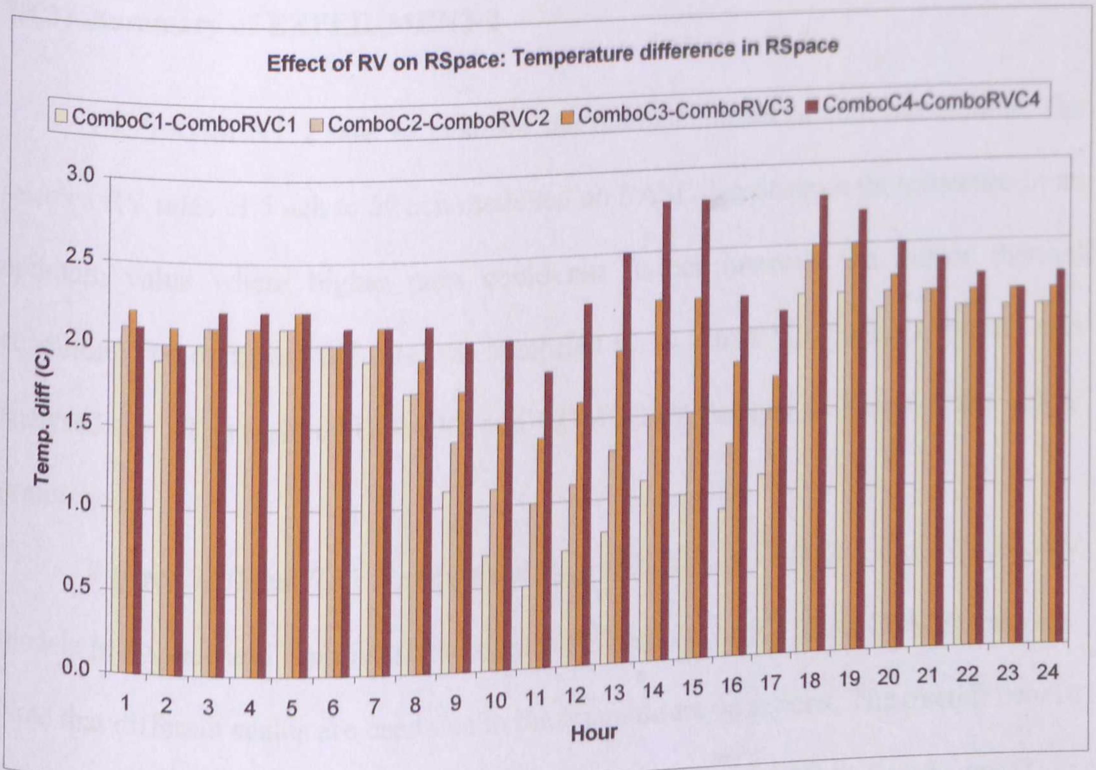


Figure 7.18: T_{diff} in *RSpace* between COMBO and COMBORV models

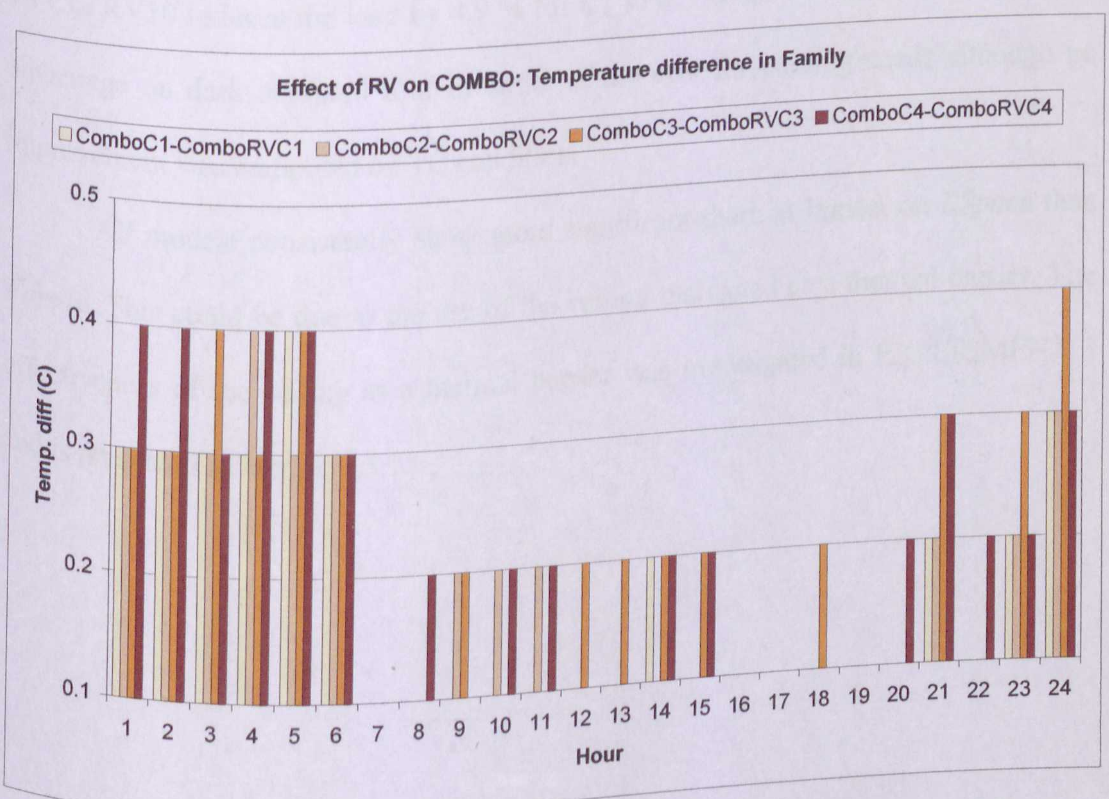


Figure 7.19: T_{diff} in *Family* between COMBO and COMBORV models

7.4.3 Summary of EXPERIMENT 2

EXPERIMENT 2 was to evaluate the thermal impact of roof ventilation. The selected RV rates of 5 ach to 50 ach modelled on BASE demonstrate the existence of an optimum value where higher rates could not further improve the indoor thermal condition. The optimum RV rate was identified as 10 ach (RV10) and the impact was analysed for all models of COMBO and COMBORV designs to consider the colour preferences.

Figures 7.20 and 7.21 compare the T_{max} and T_{mean} of COMBO and COMBORV models in *RSpace* and *Family*. These signify the benefits of RV10 on COMBO models. Note that different scales are used due to the temperature variations. The overall benefit on T_{max} and T_{mean} range from 1 °C to 2.8 °C in *RSpace* and 0.2 °C in *Family*, and T_{mean} in *RSpace* is lower than *Family* for all colours. Figure 7.22 shows more notable effect on CL. RV10 reduces the load by 4.9 % for C1 to 6.5 % for C4. Thus, it has the most advantage on dark coloured roof in terms of the cost for cooling needs although no improvement was computed on TC condition.

All models consistently show more significant thermal impact on *RSpace* than *Family*. This could be due to the use of the ceiling that acted as a thermal barrier. The effectiveness of the ceiling as a thermal barrier was investigated in EXPERIMENT 3 and is presented in section 7.5.1.

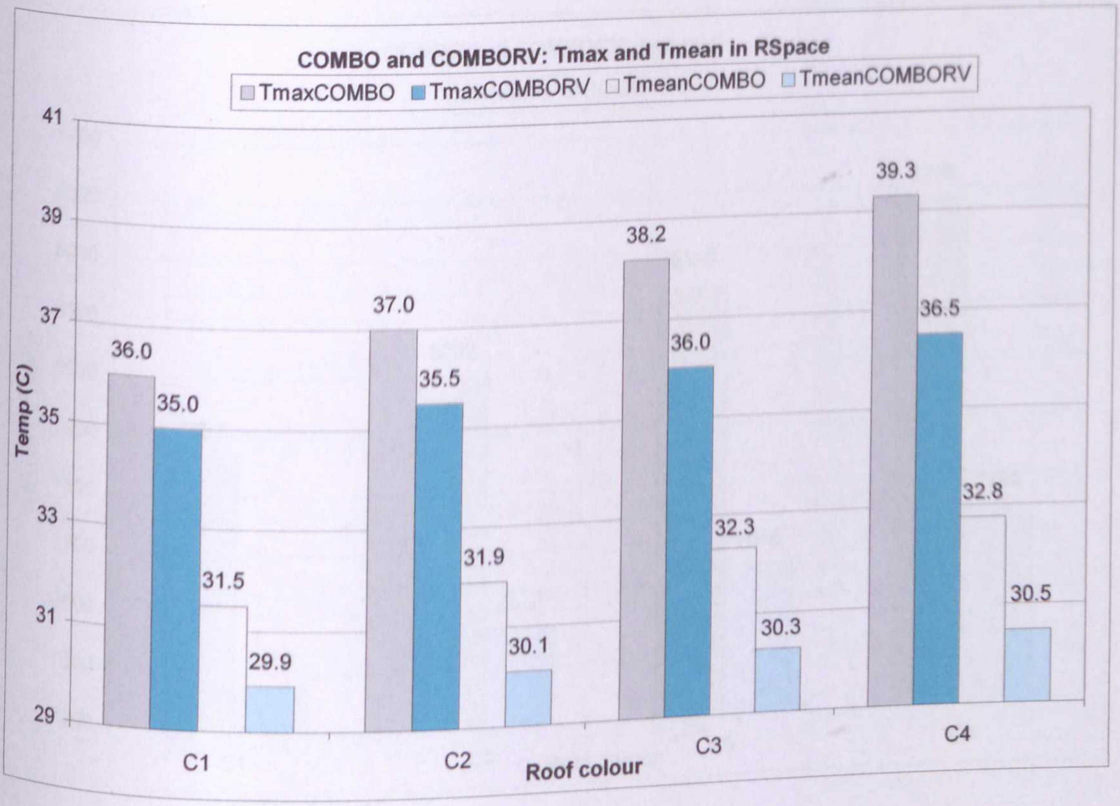


Figure 7.20: T_{max} and T_{mean} in *RSpace* COMBO and COMBORV models

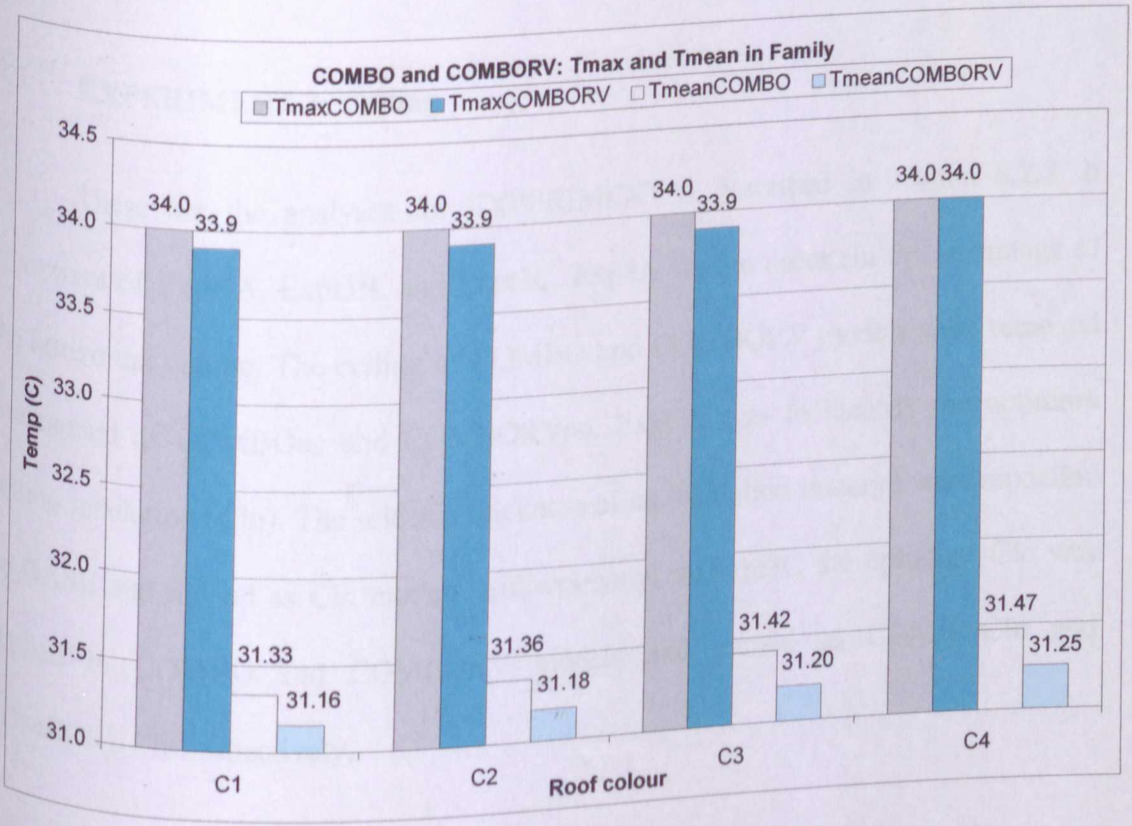


Figure 7. 21: T_{max} and T_{mean} in *Family* for COMBO and COMBORV models

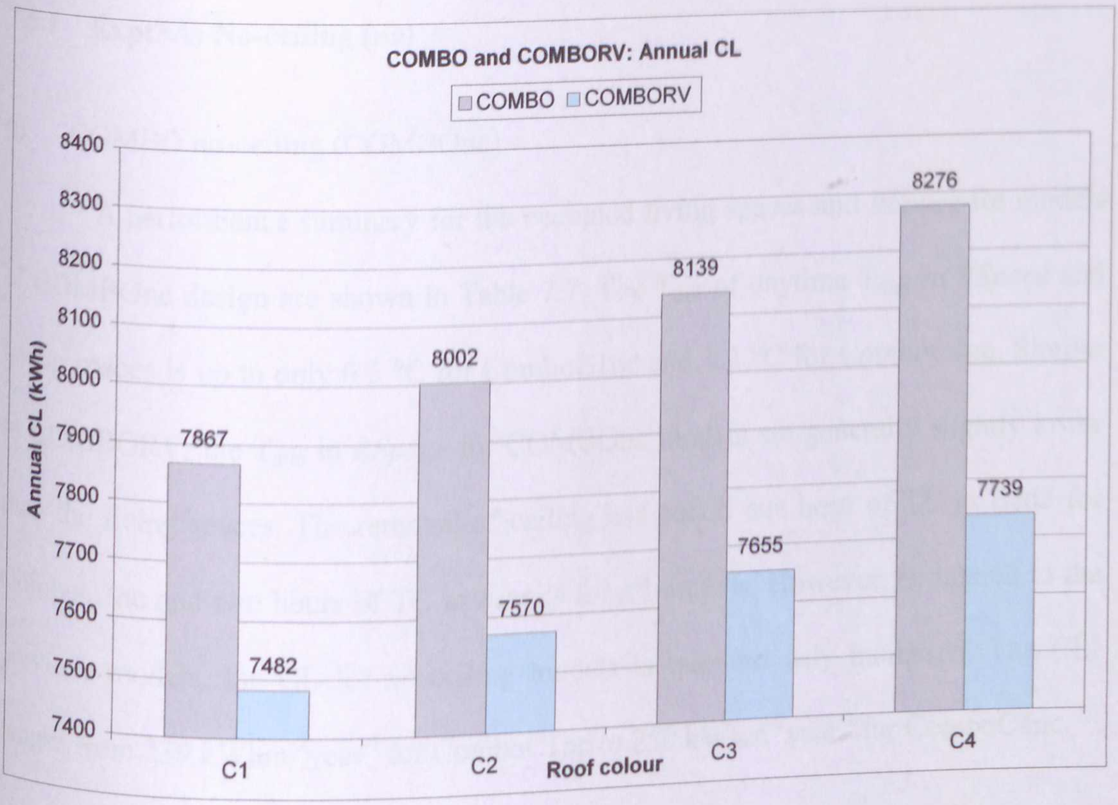


Figure 7. 22: Annual CL for COMBO and COMBORV models

7.5 EXPERIMENT 3: Ceiling

These are the analyses for EXPERIMENT 3 described in section 6.2.3. It comprises of Expt3A, Expt3B, and Expt3C. Exp3A was to ascertain the advantage of the horizontal ceiling. The ceiling of COMBO and COMBORV models were removed and named as COMBOnc and COMBORVnc. Expt3B was to identify the optimum ceiling insulation (CIn). The selected thickness of an insulation material were modelled on BASE and named as CIn models. Subsequently, in Expt3C the optimum CIn was applied to COMBO and COMBORV models and named as COMBOCIn and COMBORVCIn respectively.

7.5.1 Expt3A: No-ceiling (nc)

a) COMBO no-ceiling (COMBOnc)

A performance summary for the occupied living spaces and *RSpace* for models of COMBOnc design are shown in Table 7.7. The T_{diff} of daytime T_{max} in *RSpace* and living spaces is up to only 0.5 °C for ComboC1nc and 1.2 °C for ComboC4nc. Similar to COMBORV, the T_{min} in *RSpace* for COMBOnc models are generally slightly lower than the living spaces. The removal of ceiling has added one hour of TC in Bed3 for ComboC3nc and two hours of TC in *Family* for all models. However, compared to the previous models, the CL for no-ceiling models is tremendously increased. The CLI ranges from 239 $kWhm^{-2}year^{-1}$ for ComboC1nc to 250 $kWhm^{-2}year^{-1}$ for ComboC4nc.

Table 7.7: Summary of thermal and energy performance for COMBOnc models

Model		Bed1	Bed2	Bed3	Family	RSpace	Annual CL(kWh)	CLI ($kWhm^{-2}year^{-1}$)
ComboC1nc	T_{max} (°C)	34.2	34.0	34.4	34.0	34.5		
	T_{min} (°C)	26.6	26.3	27.3	26.6	26.8		
	T_{mean}(°C)	30.8	30.8	30.7	30.7	30.9		
	TC hrs	2	2	1	3		14357	239
	CL(kWh)	2237	1206	1472	9442			
ComboC2nc	T_{max} (°C)	34.2	34.0	34.6	34.1	34.7		
	T_{min} (°C)	26.6	26.3	27.3	26.6	26.8		
	T_{mean}(°C)	30.8	30.8	30.8	30.8	30.9		
	TC hrs	2	2	1	3		14574	243
	CL(kWh)	2258	1225	1505	9586			
ComboC3nc	T_{max} (°C)	34.2	34.0	34.9	34.2	34.9		
	T_{min} (°C)	26.6	26.4	27.4	26.6	26.8		
	T_{mean}(°C)	30.9	30.8	30.8	30.8	31.0		
	TC hrs	2	2	2	3		14793	247
	CL(kWh)	2279	1244	1537	9733			
ComboC4nc	T_{max} (°C)	34.2	34.1	35.2	34.2	35.3		
	T_{min} (°C)	26.6	26.4	27.4	26.6	26.8		
	T_{mean} (°C)	30.9	30.9	30.9	30.9	31.1		
	TC hrs	2	2	2	3		15011	250
	CL(kWh)	2300	1263	1569	9879			

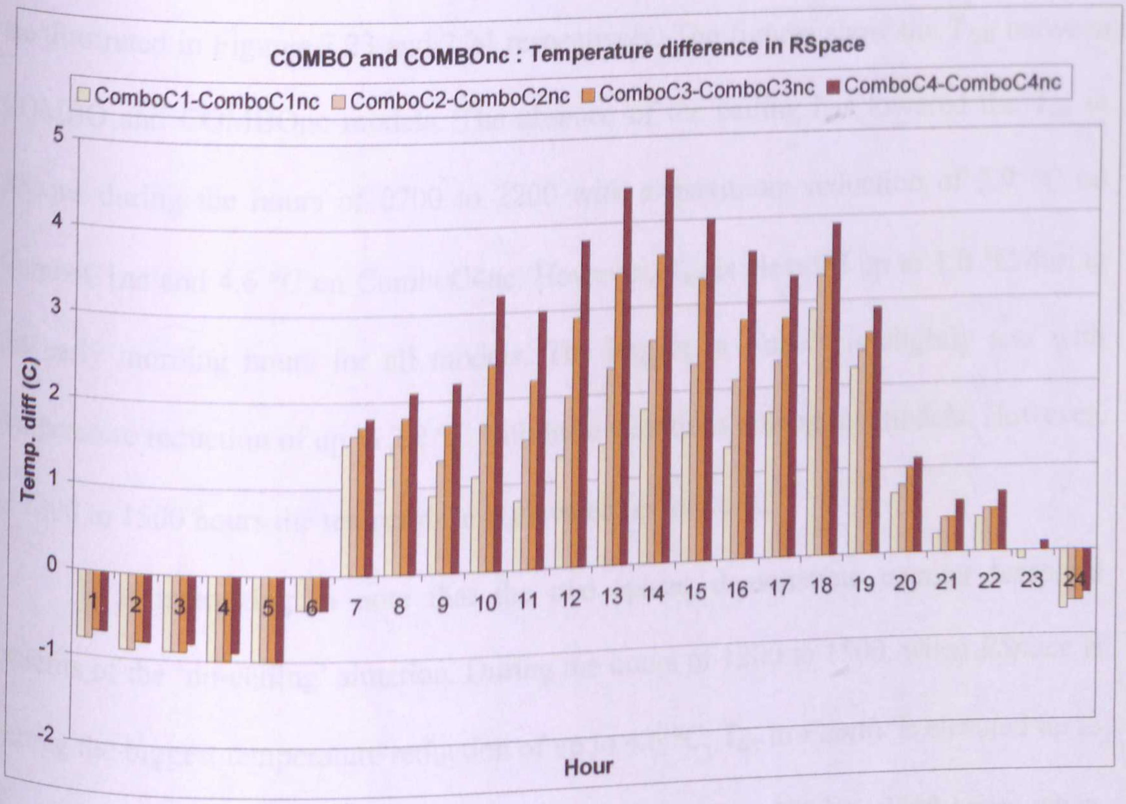


Figure 7.23: T_{diff} in *RSpace* between COMBO and COMBOnc models

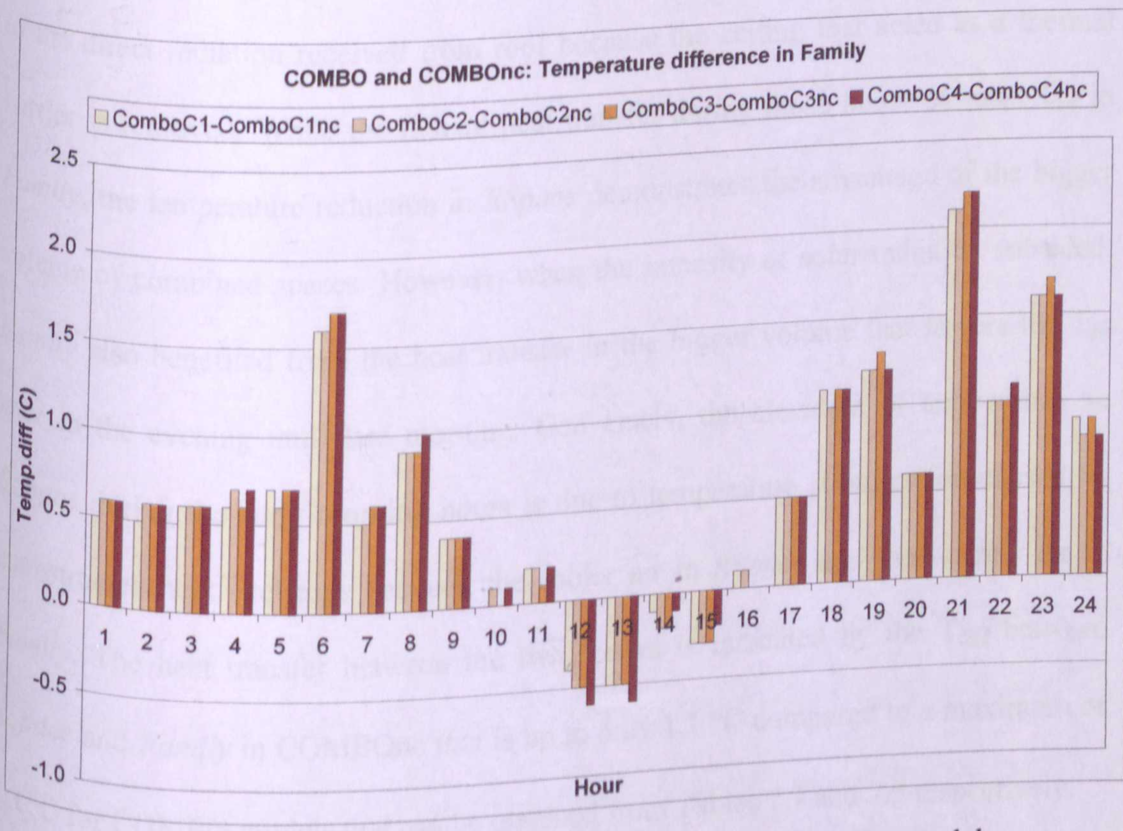


Figure 7.24: T_{diff} in *Family* between COMBO and COMBOnc models

The hourly modifications on T_{air} in *RSpace* and *Family* due to removal of ceiling are illustrated in Figures 7.23 and 7.24 respectively. The figures show the T_{diff} between COMBO and COMBOnc models. The absence of the ceiling has lowered the T_{air} in *RSpace* during the hours of 0700 to 2200 with a maximum reduction of 2.9 °C on ComboC1nc and 4.6 °C on ComboC4nc. However, T_{air} is elevated up to 1.0 °C during the early morning hours for all models. The impact in *Family* is slightly less with temperature reduction of up to 2.2 °C with little variations among the models. However, at 1200 to 1500 hours the temperature is elevated up to 0.6 °C.

It is interesting to note that the two spaces demonstrate counter temporal benefits of the 'no-ceiling' situation. During the hours of 1200 to 1500, when *RSpace* is getting the biggest temperature reduction of up to 4.6 °C, T_{air} in *Family* is elevated up to 0.6 °C. On the other hand, T_{air} in *RSpace* is elevated during 2200 to 0600 hours when *Family* is experiencing lower temperature. The afternoon T_{air} elevation in *Family* is due to the direct radiation received from roof because the ceiling that acted as a thermal barrier is removed. While the radiant heat transfer during those hours elevates T_{air} in *Family*, the temperature reduction in *RSpace* demonstrates the advantage of the bigger volume of combined spaces. However, when the intensity of solar radiation subsided, *Family* also benefited from the heat transfer in the bigger volume that lowers the T_{air} later in the evening until late morning. Conversely, the elevation of temperature in *RSpace* during the early morning hours is due to temperature stratification caused by unobstructed heat exchange between the cooler air in *RSpace* and the warmer air in *Family*. The heat transfer between the two spaces is indicated by the T_{diff} between *RSpace* and *Family* in COMBOnc that is up to only 1.1 °C compared to a maximum of 5.3 °C for COMBO models that can be obtained from Tables 7.7 and 7.5 respectively.

b) COMBORV no ceiling (COMBORVnc)

A performance summary for the occupied living spaces and *RSpace* for models of COMBORVnc design are shown in Table 6.8. The T_{diff} of daytime T_{max} in *RSpace* and living spaces is up to 0.5 °C for ComboRVC1nc and 0.9 °C for ComboRVC4nc. These are comparable to the temperature variations in the spaces for COMBOnc but with slight thermal improvement. Additional one to two TC hours is achieved in all living spaces for all roof colours. This lowers the CLI that ranges from 225 kWhm^{-2}year^{-1} for ComboRVC1nc to 234 kWhm^{-2}year^{-1} for ComboRVC4nc.

Table 7.8: Summary of thermal and energy performance for COMBORVnc models

Model		Bed1	Bed2	Bed3	Family	RSpace	Annual CL (kWh)	CLI (kWhm^{-2}year^{-1})
ComboRVC1nc	T_{max} (°C)	34.2	34.0	34.3	33.9	34.4		
	T_{min} (°C)	26.3	26.1	27.0	26.5	26.4		
	T_{mean} (°C)	30.4	30.4	30.4	30.4	30.3		
	TC hrs	3	3	3	3		13499	225
	CL (kWh)	2026	1028	1160	9285			
ComboRVC2nc	T_{max} (°C)	34.2	34.0	34.5	34.0	34.5		
	T_{min} (°C)	26.3	26.1	27.0	26.5	26.4		
	T_{mean} (°C)	30.4	30.4	30.5	30.4	30.4		
	TC hrs	3	3	3	3		13683	228
	CL (kWh)	2045	1044	1182	9412			
ComboRVC3nc	T_{max} (°C)	34.2	34.0	34.7	34.1	34.7		
	T_{min} (°C)	26.3	26.1	27.0	26.5	26.4		
	T_{mean} (°C)	30.4	30.4	30.5	30.5	30.4		
	TC hrs	3	3	3	3		13867	231
	CL (kWh)	2063	1060	1204	9540			
ComboRVC4nc	T_{max} (°C)	34.2	34.0	34.9	34.1	34.9		
	T_{min} (°C)	26.4	26.2	27.0	26.5	26.4		
	T_{mean} (°C)	30.5	30.4	30.6	30.5	30.5		
	TC hrs	3	3	3	3		14047	234
	CL (kWh)	2081	1075	1226	9665			

Figures 7.25 and 7.26 show the hourly modifications on T_{air} in *RSpace* and *Family* for 'no-ceiling' on COMBORV. The profiles are similar as the COMBO models but the RV has produced a different degree of impact because the RV brought in warmer daytime ambient air but cooler air at night. The daytime temperature reduction in *RSpace* is smaller but the night-time temperature elevation is bigger. The overall temperature reduction in *Family* is better during 2400 to 0500 hours.

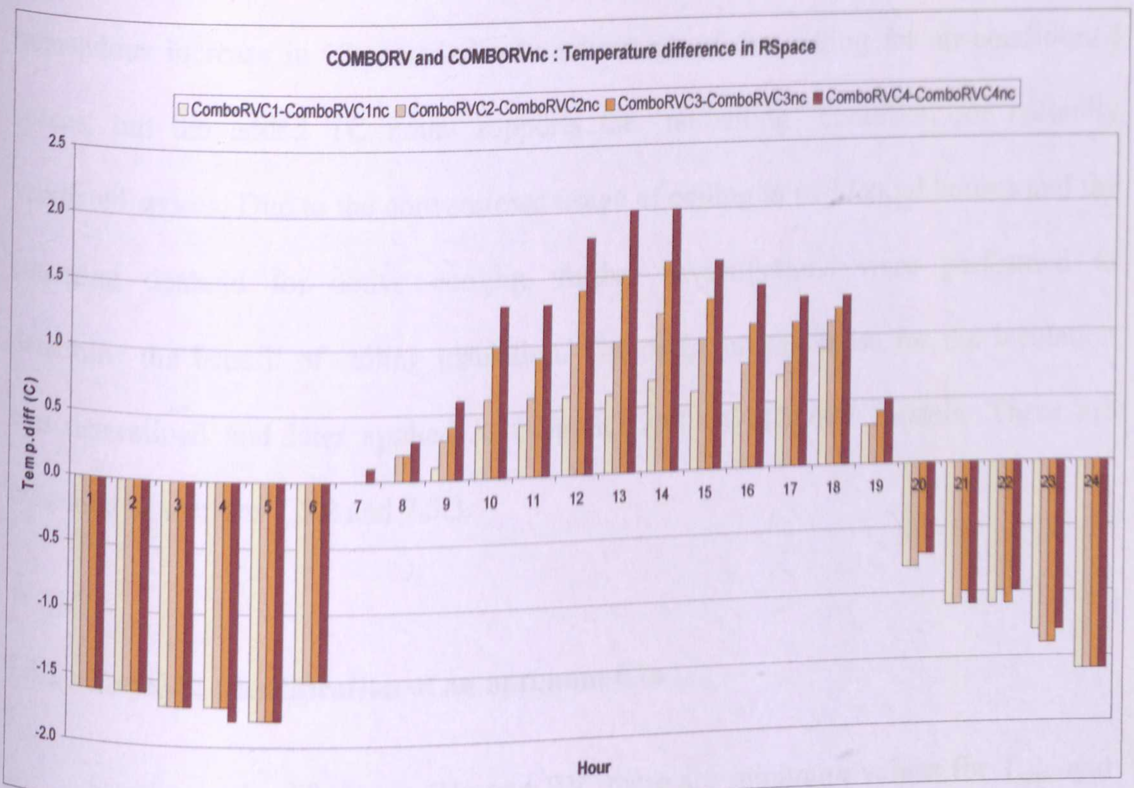


Figure 7.25: T_{diff} in *RSpace* between COMBORV and COMBORVnc

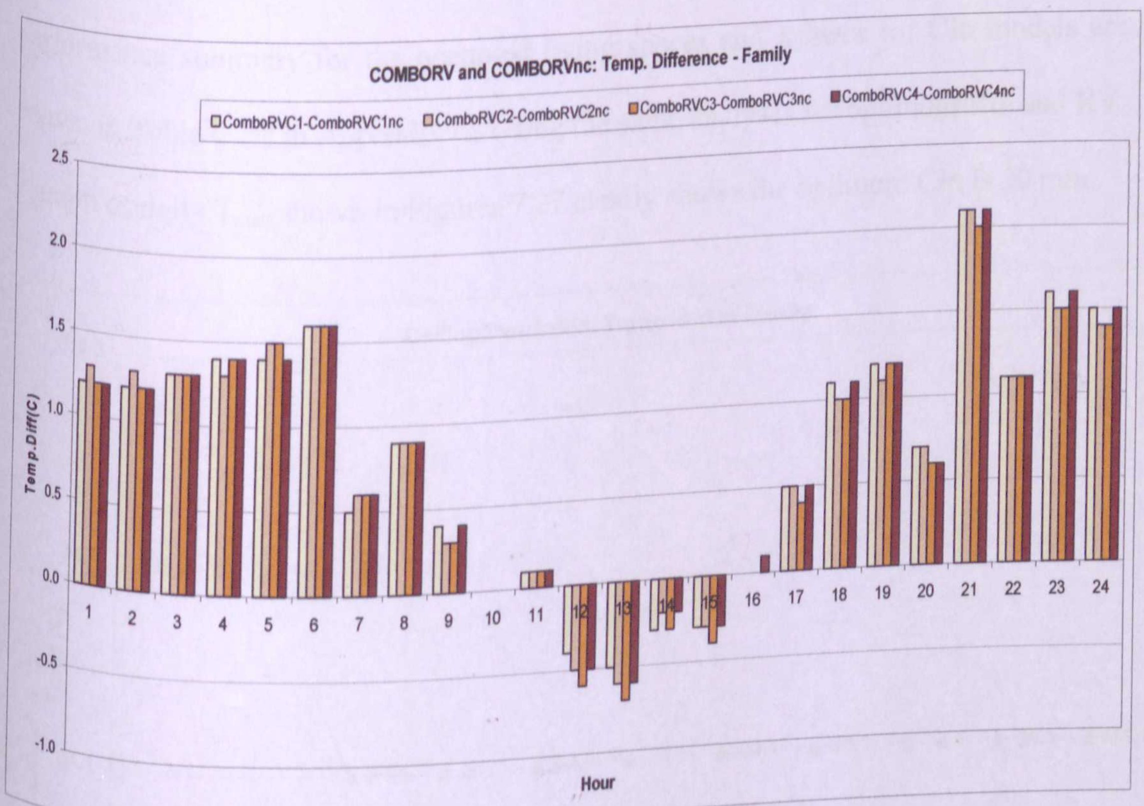


Figure 7.26: T_{diff} in *Family* between COMBORV and COMBORVnc models

In summary, both COMBO and COMBORV models demonstrate temporal benefits and adverse effects of the horizontal ceiling that acts as a thermal barrier. The tremendous increase in CL concludes an advantage of the ceiling for air-conditioned spaces, but the added TC hours supports the 'no-ceiling' condition for naturally ventilated spaces. Due to the conventional usage of ceiling in residential houses and the emerging demand for active cooling, further investigations were performed to determine the benefit of ceiling insulation. The optimum thickness for the insulation was determined and later applied to COMBO and COMBORV models. These are presented in sections 7.5.2 and 7.5.3.

7.5.2 Expt3B: Identification of an optimum CIn

Similar to the TP due to RIn and RV, there are minimum values for T_{max} and T_{min} for each space with the CLI of 142 kWhm^{-2}year^{-1} for CIn of 30 mm and thicker. A performance summary for the occupied living spaces and *RSpace* for CIn models are shown in Table C2.2 in Appendix C. Using the same analyses for optimum RIn and RV, a graph of daily T_{max} shown in Figures 7.27 clearly shows the optimum CIn is 20 mm.

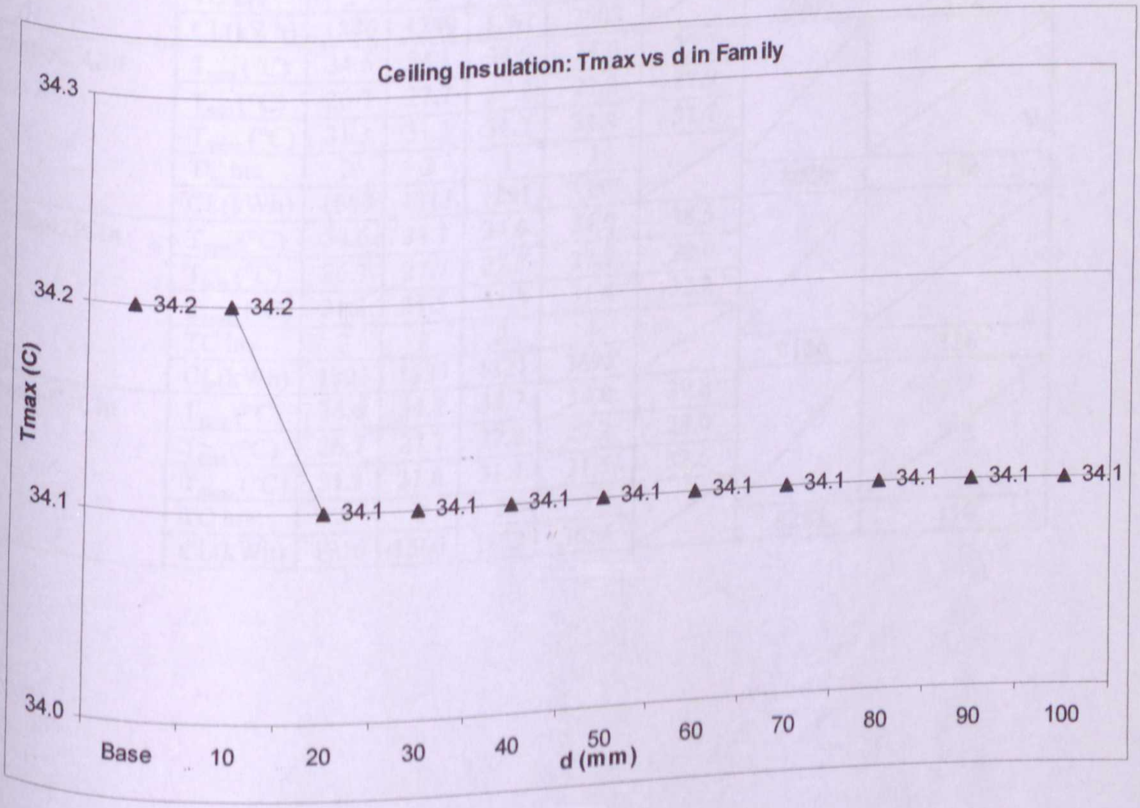


Figure 7.27: To identify optimum CIn: T_{max} in *Family* for CIn models

7.5.3 Expt3C: Application of the optimum CIn

The optimum CIn02 was applied to COMBO and COMBORV to investigate if it could further improve the indoor thermal condition.

a) COMBOCIn

A performance summary for the occupied living spaces and *RSpace* for models of COMBOCIn design is shown in Table 7.9. The TC hours and condition are similar to COMBO models. With the negligible thermal impact, the CL consumption is increased up to 0.5 % and the CLI ranges from 132 $kWhm^{-2}year^{-1}$ for ComboC1CIn to 138 $kWhm^{-2}year^{-1}$ ComboC4CIn.

Table 7.9: Summary of thermal and energy performance for COMBOCIn models

Model		Bed1	Bed2	Bed3	Family	RSpace	Annual CL(kWh)	CLI ($kWhm^{-2}year^{-1}$)
ComboC1CIn	T_{max} (°C)	34.5	34.1	34.6	33.9	36.1		
	T_{min} (°C)	26.7	27.6	27.7	27.2	27.8		
	T_{mean} (°C)	31.3	31.5	31.3	31.4	31.2		
	TC hrs	2	2	1	1			
	CL(kWh)	1846	1289	1261	3509		7906	132
ComboC2CIn	T_{max} (°C)	34.6	34.1	34.6	34.0	37.3		
	T_{min} (°C)	26.7	27.7	27.7	27.2	27.9		
	T_{mean} (°C)	31.3	31.5	31.3	31.4	31.7		
	TC hrs	2	2	1	1			
	CL(kWh)	1869	1313	1291	3557		8030	134
ComboC3CIn	T_{max} (°C)	34.6	34.1	34.6	34.0	38.5		
	T_{min} (°C)	26.7	27.7	27.7	27.2	28.0		
	T_{mean} (°C)	31.3	31.5	31.3	31.4	32.2		
	TC hrs	2	2	2	1			
	CL(kWh)	1893	1337	1321	3695		8156	136
ComboC4CIn	T_{max} (°C)	34.6	34.2	34.7	34.0	39.8		
	T_{min} (°C)	26.7	27.7	27.8	27.2	28.0		
	T_{mean} (°C)	31.3	31.6	31.4	31.5	32.6		
	TC hrs	2	2	2	1			
	CL(kWh)	1916	1360	1352	3655		8283	138

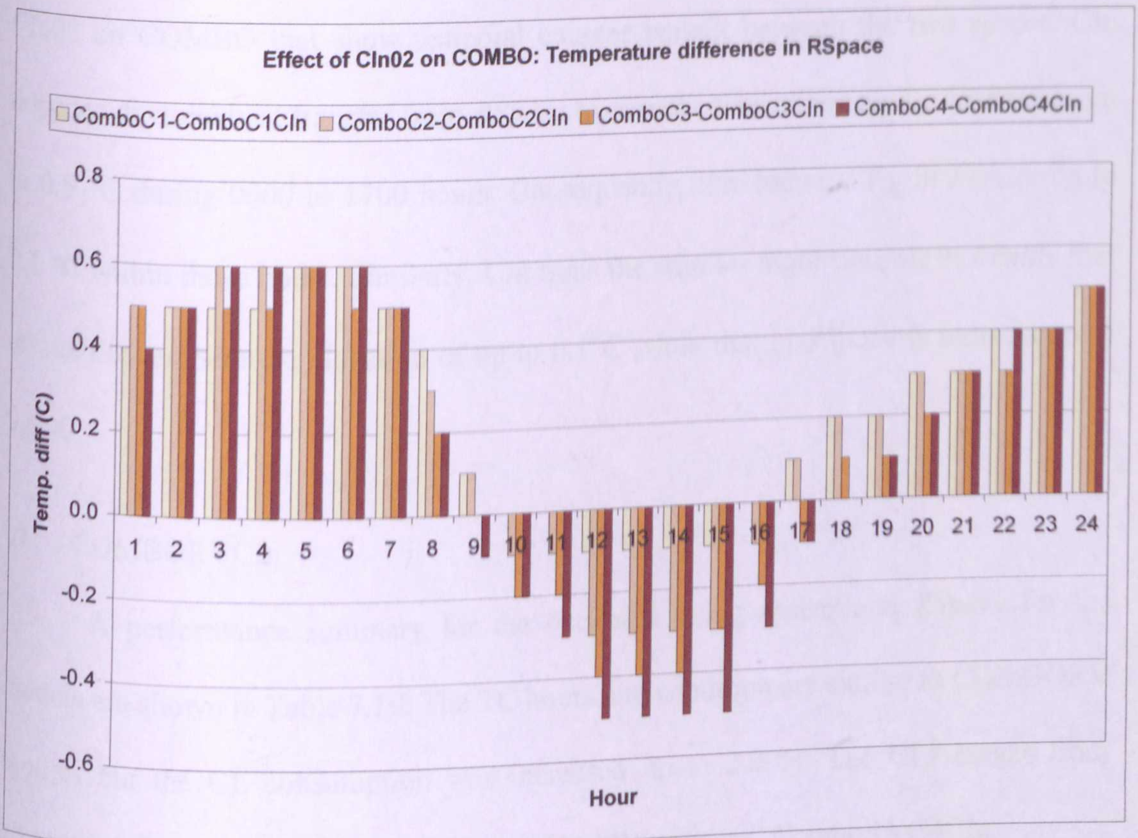


Figure 7.28: T_{diff} in *RSpace* between COMBO and COMBOCIn models

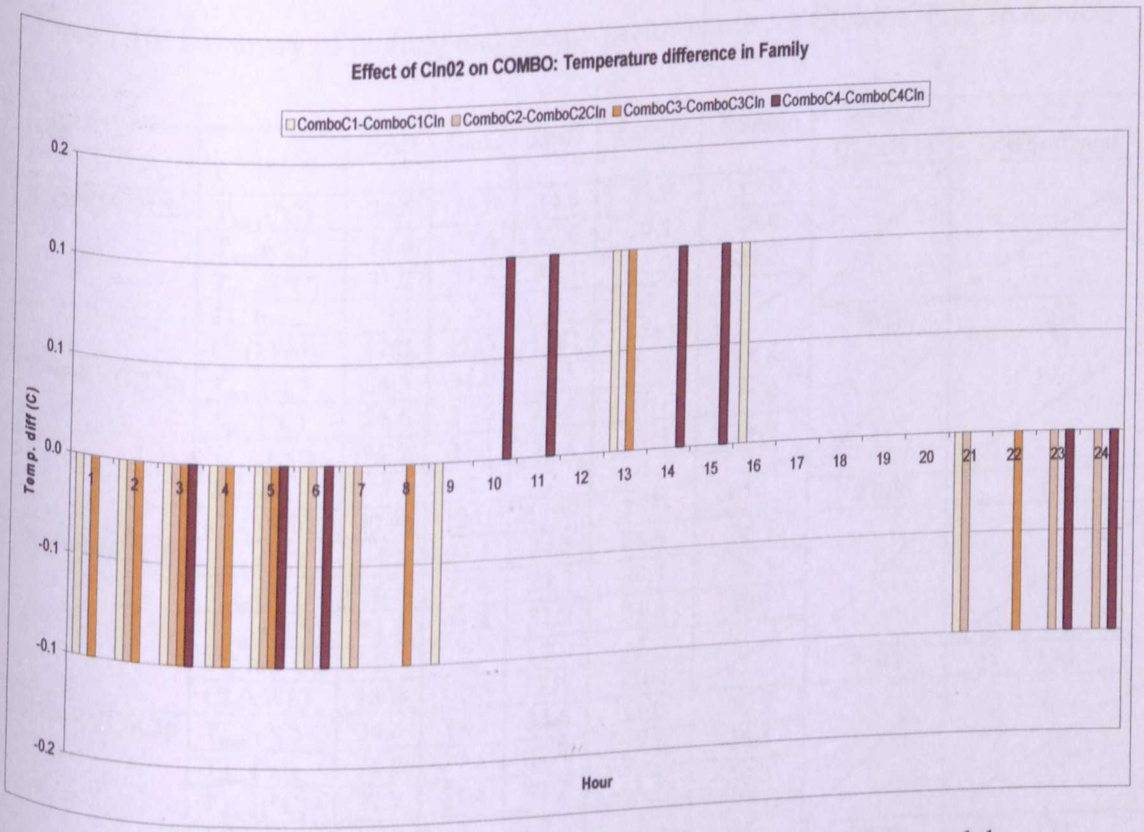


Figure 7.29: T_{diff} in *Family* between COMBO and COMBOCIn models

Figures 7.28 and 7.29 show the T_{diff} between the models of COMBO and COMBOCIn designs in *RSpace* and *Family* respectively. It computes the benefit of

CIn02 on COMBO that show temporal counter benefit between the two spaces. CIn impedes daytime heat transfer from *RSpace* to *Family*, thus elevating T_{air} in *RSpace* up to 0.5 °C during 0900 to 1700 hours. Consequently, this reduces T_{air} in *Family* up to 0.1 °C within those hours. Similarly, CIn traps the warmer night-time air in *Family* that resulted in temperature elevation of up to 0.1°C while that in *RSpace* is reduced up to 0.6 °C.

b) COMBORVCIn

A performance summary for the occupied living spaces and *RSpace* for the models are shown in Table 7.10. The TC hours and condition are similar to COMBORV models but the CL consumption was increased up to 2.0 %. The CLI ranges from 127 $kWhm^{-2}year^{-1}$ for ComboRVC1CIn to 131 $kWhm^{-2}year^{-1}$ ComboRVC4CIn.

Table 7.10: Summary of thermal and energy performance for COMBORVCIn models

Model		Bed1	Bed2	Bed3	Family	RSpace	Annual CL(kWh)	CLI ($kWhm^{-2}year^{-1}$)
ComboRVC1CIn	T_{max} (°C)	34.5	34.0	34.5	33.9	35.0		
	T_{min} (°C)	26.6	27.6	27.6	27.1	26.0		
	T_{mean} (°C)	31.2	31.3	31.1	31.3	29.7		
	TC hrs	2	2	2	1		7629	127
	CL(kWh)	1781	1227	1181	3440			
ComboRVC2CIn	T_{max} (°C)	34.5	34.0	34.5	33.9	35.6		
	T_{min} (°C)	26.6	27.6	27.6	27.1	26.0		
	T_{mean} (°C)	31.2	31.4	31.2	31.3	29.9		
	TC hrs	2	2	2	1		7708	128
	CL(kWh)	1794	1241	1199	3473			
ComboRVC3CIn	T_{max} (°C)	34.5	34.1	34.5	33.9	36.1		
	T_{min} (°C)	26.6	27.6	27.7	27.1	26.1		
	T_{mean} (°C)	31.2	31.4	31.2	31.3	30.1		
	TC hrs	2	2	2	1		7784	130
	CL(kWh)	1808	1255	1217	3504			
ComboRVC4CIn	T_{max} (°C)	34.5	34.1	34.6	34.0	36.7		
	T_{min} (°C)	26.6	27.6	27.7	27.1	26.1		
	T_{mean} (°C)	31.2	31.4	31.2	31.3	30.3		
	TC hrs	2	2	2	1		7858	131
	CL(kWh)	1821	1269	1235	3533			

Similar analysis as the COMBOCIn models to evaluate the impact of CIn02 on COMBORV indicates no added advantage. The T_{air} in *Family* cannot be reduced any further, however, the insulative property of the insulation has exacerbated the TP.

7.5.4 Summary of EXPERIMENT 3

EXPERIMENT 3 was to appraise the usage of the horizontal ceiling. The results in Expt3A show that the removal of the ceiling has a slight advantage on the TP and the TC, but has increased the annual CL up to 82 %. These impacts are due to the bigger volume of the combined spaces. Whilst the unobstructed heat exchange improves the TP and adds up to two hours of TC, it imposes great penalty on the needed CL. It is concluded that indoor thermal modifications could not outweigh the tremendous increase in the required CL. Nonetheless, an openable or removable ceiling could be considered as an alternative to the conventional type.

Expt3B identifies CIn of 20 mm (CIn02) as the optimum. Its application on COMBO and COMBORV models in Expt3C show negligible thermal modification but increases the CL up to 2.0 %. It is concluded that CIn has no added benefit on TP of TC, but has a CL penalty.

7.6 Summary and conclusion for PART 1

PART 1 is the analyses and discussion on the data outputs of the computer modelling on a number of identified thermal designs of roof. Whole-building analysis was performed to evaluate the impact of each model on thermal and energy performances of the house in this study. The thermal performance (TP) was appraised by the indoor environmental conditions and the thermal comfort (TC) hours in natural ventilation. These conditions are T_{air}, T_{max}, T_{min}, T_{mean}, and RH that represent the hourly air temperature, highest hourly temperature, lowest hourly temperature, average hourly temperature, and hourly relative humidity respectively. The energy performance is assessed by the needed cooling load (CL) to provide the desirable thermal comfort (TC) condition. Cooling load index (CLI) is introduced to appraise the cooling energy demand. It is defined as the annual CL per square meter of the cooled floor area.

The actual conventional roof using a roof covering with solar absorptivity (α) of 0.9 denoted as C4 was used as a base-case (BASE) roof model. Considering the personal and aesthetic preferences for colour, three other hues were also considered based on α of 0.7, 0.5, and 0.3; denoted as C3, C2, and C1 respectively. These are models for the COLOUR design. The BASE (C4) model was used to identify the optimum values of the following roof thermal parameters: thickness of air space (AS) underneath the roof covering, thickness of supplementary roof insulation (RIn) underneath the conventional radiant barrier, rate of roof ventilation (RV) in the roof space, and lastly the thickness of ceiling insulation (CIn) laid above the horizontal ceiling. These optimum values were determined by the T_{max} reduction in *Family*. This space was chosen to represent the impact on the living spaces underneath the ceiling due to its envelope configuration with regards to exposure to the external environment. Selective combination of the optimum values were later applied to the COLOUR design to create several other roof designs named as COMBO, COMBORV, COMBOCIn, and COMBORVCIn. Each design has four models with the external roof covering of colour C1, C2, C3 and C4. Each model was also simulated without the ceiling to investigate the benefit of its usage. The 'no-ceiling' models are named as COMBOnc and COMBORVnc.

The optimum values were found to be 50 mm for AS, 40 mm for RIn, 10 ach for RV, and lastly 20 mm for CIn. All models consistently show more significant thermal impact on *RSpace* than *Family*. This resulted in only slight modification on TP in

Family and the consequent TC improvement is negligible. However, the predictions on the needed CL reveal quite noteworthy energy implications.

The thermal modifications and CL demands on each design options are summarised as follows:

a) Choice of colour (COLOUR models)

- Temperature varies up to 6.6 °C in *RSpace* and 0.4 °C in *Family* with no improvement in TC hour.
- Light coloured roof reduces CL up to 8.4 % at no added capital cost. The CLI for C4 (BASE) is 143 kWhm^{-2}year^{-1} while the lightest hue (C1) is 131 kWhm^{-2}year^{-1}.

b) Use of 40 mm RIn on COLOUR models (COMBO)

- Daytime temperature is reduced up to 4.4 °C in *RSpace* but only 0.2 °C in *Family*. Night-time temperature is elevated up to 0.6 °C in *RSpace* and only 0.1 °C in *Family*. This is due to the property of insulation that impedes heat transfer, which is beneficial during daytime but unfavourable at night. Nevertheless, no changes on TC hour were computed.
- RIn has the most benefit on dark coloured roof with CL reduction of 3.3 % for ComboC4. CLI for ComboC1 remained at 131 kWhm^{-2}year^{-1} while that for ComboC4 is reduced to 138 kWhm^{-2}year^{-1}. However, the COMBO design has an added cost for the insulation.

c) Application of RV of 10 ach to COMBO models (COMBORV).

- Temperature is further reduced up to 2.8 °C in *RSpace* and 0.4 °C in *Family*. Additional one hour of TC is attained in one of the bedrooms.

- Similar to RIn, RV also has the most benefit on dark coloured roof. The CL reduction ranges from 4.5 % for ComboRVC1 to 6.5 % for ComboRVC4 with CLI of 125 $kWhm^{-2}year^{-1}$ to 129 $kWhm^{-2}year^{-1}$ for the respective models. COMBORV design has an additional cost for the devise or design to provide the required RV rate. The needed RV could be supplied by passive structural design, or assisted by a mechanism such as powered fan or wind-assisted vents.

d) 'No-ceiling' for COMBO and COMBORV models (COMBOnc and COMBORVnc)

- Removal of the horizontal ceiling exhibits temporal counter benefits between *RSpace* and *Family* that verifies its function as a thermal barrier. While the daytime T_{air} for COMBOnc is reduced up to 4.6 °C in *RSpace*, that in *Family* is elevated up to 0.6 °C from noon to 1500 hour. However, during the other hours T_{air} in *Family* is lowered up to 2.2 °C when on the other hand *RSpace* experiences a higher T_{air} of up to 1.0 °C from midnight to 0600 hour. Additional two hours of TC is achieved in *Family*. This is the effect of heat transfer in bigger volume and temperature stratification.
- However, the use of RV (COMBORVnc) has aggravated the TP in *RSpace* but in *Family* it gives an overall higher temperature reduction. These were due to the heat exchange with warmer daytime and cooler night-time external air. This resulted in an additional one to two hours of TC in all the spaces.
- Thus, whilst the daytime T_{air} elevation verifies the usage of ceiling as a thermal barrier, the added TC hours with 'no-ceiling' design implies otherwise.
- The CL is increased by 80 % to 83 % with CLI ranging from 225 $kWhm^{-2}year^{-1}$ to 250 $kWhm^{-2}year^{-1}$. Whilst removing the ceiling could provide some improvement in

TC condition, the tremendous increase in CL could not justify the 'no-ceiling' design if the space were to be cooled by active means.

e) Installation of CIn of 20 mm to COMBO and COMBORV models (COMBOCIn and COMBORVCIn)

- CIn demonstrates similar insulative effect as the RIn. However unlike RIn, CIn has a CL penalty of 0.5 % to 2.0 % on the COMBO and COMBORV designs.
- The CLI ranges from 127 $kWhm^{-2}year^{-1}$ to 138 $kWhm^{-2}year^{-1}$.
- It is concluded that CIn has no added benefit on TP of TC, but has a CL penalty.

The charts in Figures 6.30 to 6.35 show the overall impact of the models on the thermal and energy performances in *Family* with comparison to the BASE model. These can be concluded as follows:

- *Thermal improvement*: COMBORVnc provides the lowest T_{mean} with temperature variations of about 1.2 °C. The T_{max} temperature variations are only up 0.3 °C with any model from all the design options.
- *Energy savings*: The ComboRVC1 model in comparison to BASE achieves a CL savings of 12.6 %.

The predicted CL savings of 12.6 % per household can be translated into national electricity savings for the national interest as well as CO_2 reduction for the global interest on the environmental impact with regards to sustainable development. These are calculated as follows:

a) The facts, research findings, and assumptions are:

- **Facts**: 4.6 million living quarters in the Peninsular (Malaysia, 2001e) consume 16.8 % of the national energy consumption of 54, 254 GWh or equivalent to

9,093 GWh (Malaysia, 2001a); CO_2 emission in Malaysia is 0.62 ton per 1MWh of electricity generation (United-Nations, 2004).

- **Research findings**: The best roof option in this investigation reveals a potential CL savings of up to 12.6 % per household equivalent to 1074 kWh.
- **Assumption**: The CL savings of the modelled building applies to 10 % of the residential buildings which is equivalent to 0.46 million living quarters; the coefficient of performance (COP) for air-conditioning and mechanical ventilation (ACMV) system equipment is 2.6 (SIRIM, 2001).

b) The calculations for the energy savings and CO_2 reduction are:

- CL / COP = electricity load
- Electricity load savings per household: 1074 kWh / 2.6 = 413 kWh
- Residential sector savings: 413 kWh x 0.46 million = 190 GWh

  = 190 GWh / 9093 GWh = 2.1 %

- National savings: 190 GWh / 54, 254 GWh = 0.4 %
- CO_2 emission reduction: 190 GWh x (0.62 ton / 1MWh) = 117.8 kton

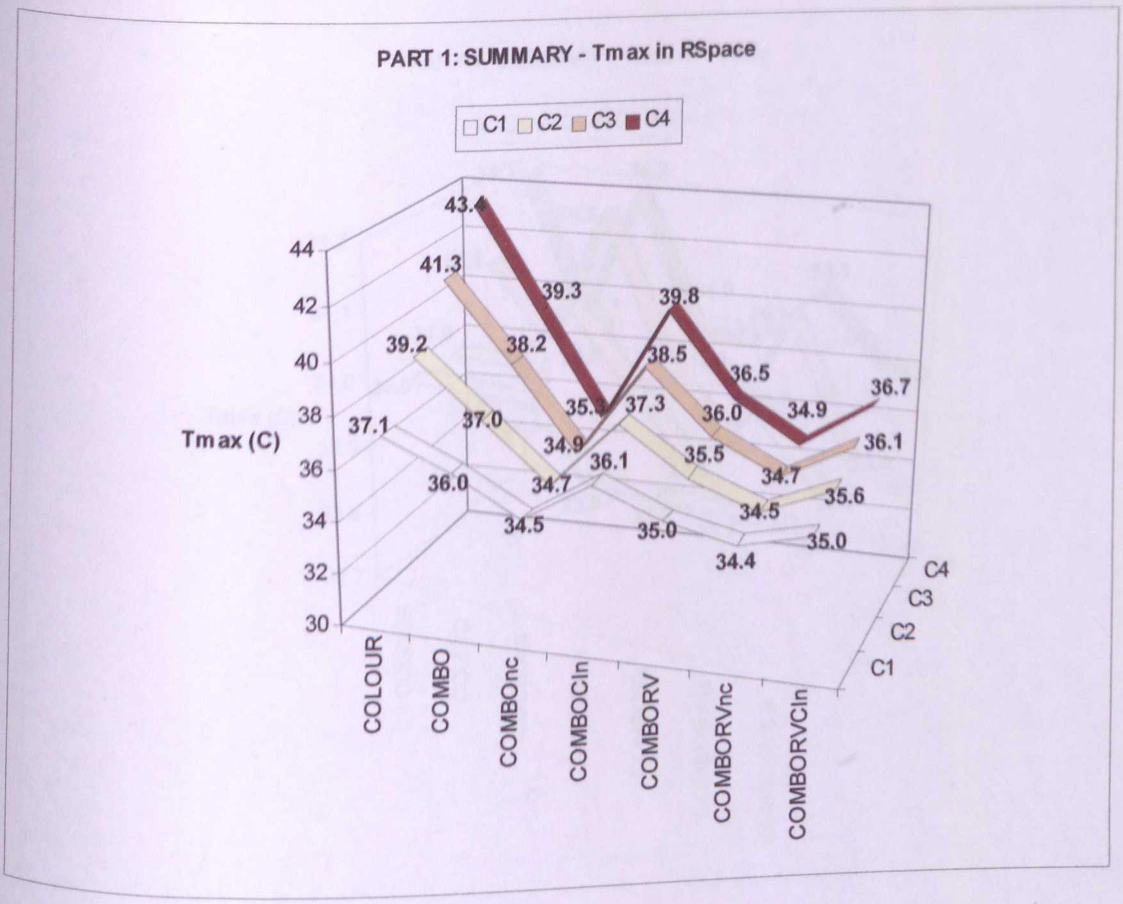


Figure 7.30: T_{max} in *RSpace* for all models

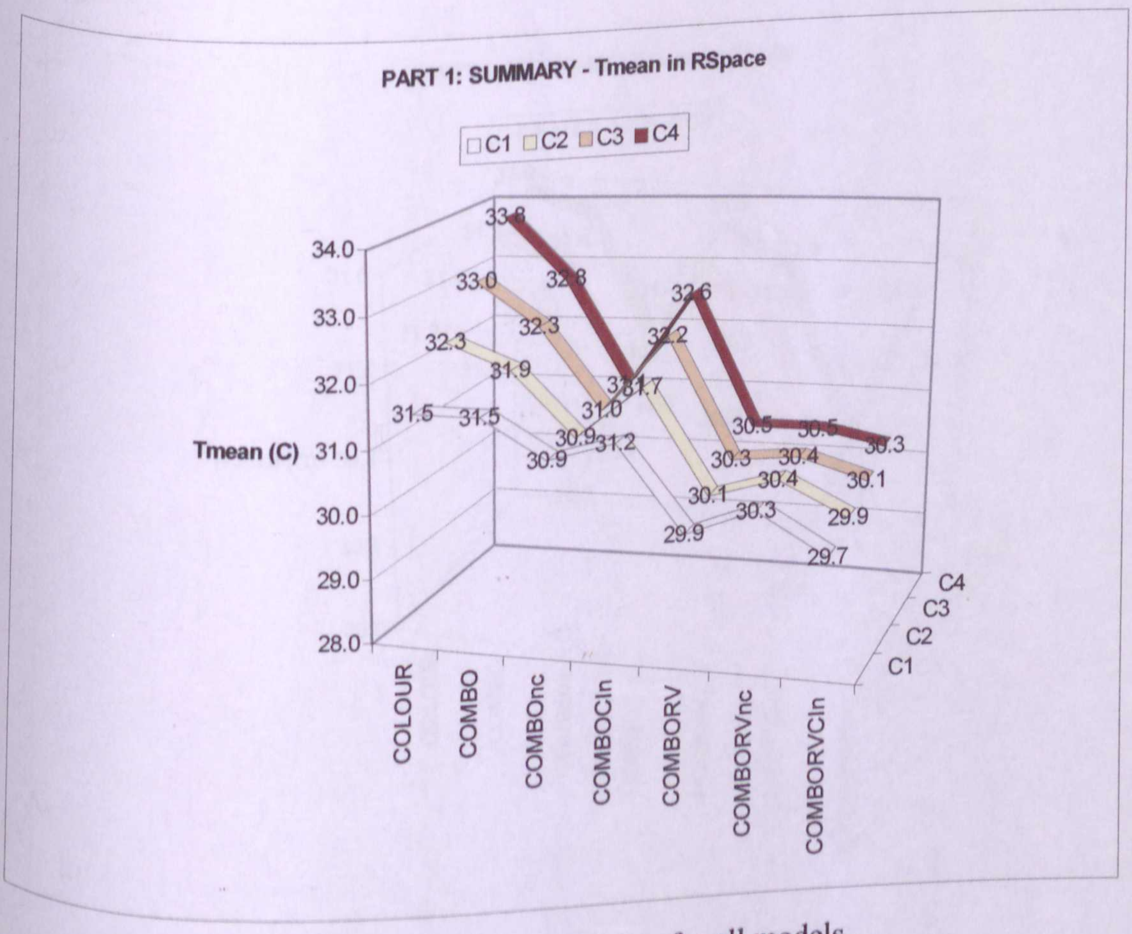


Figure 7.31: T_{mean} in *RSpace* for all models

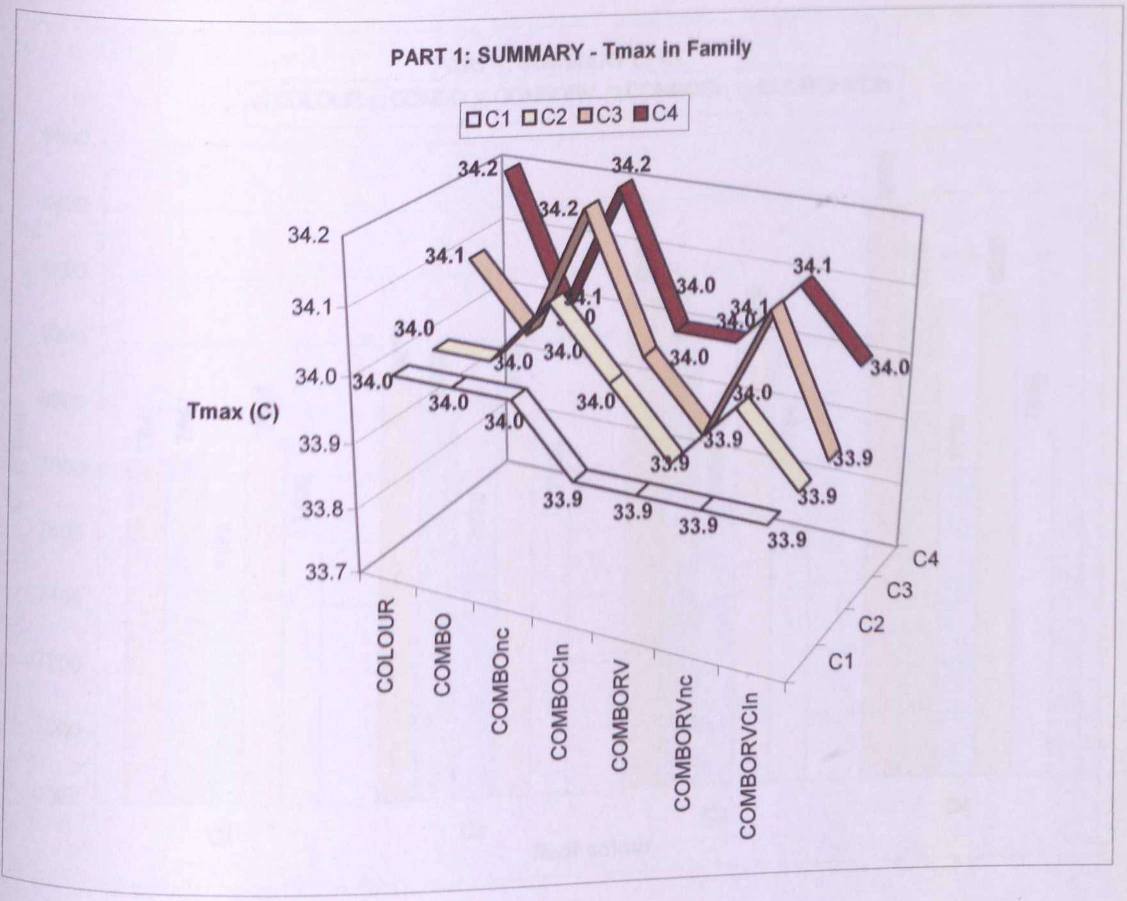


Figure 7.32: T_{max} in *Family* for all models

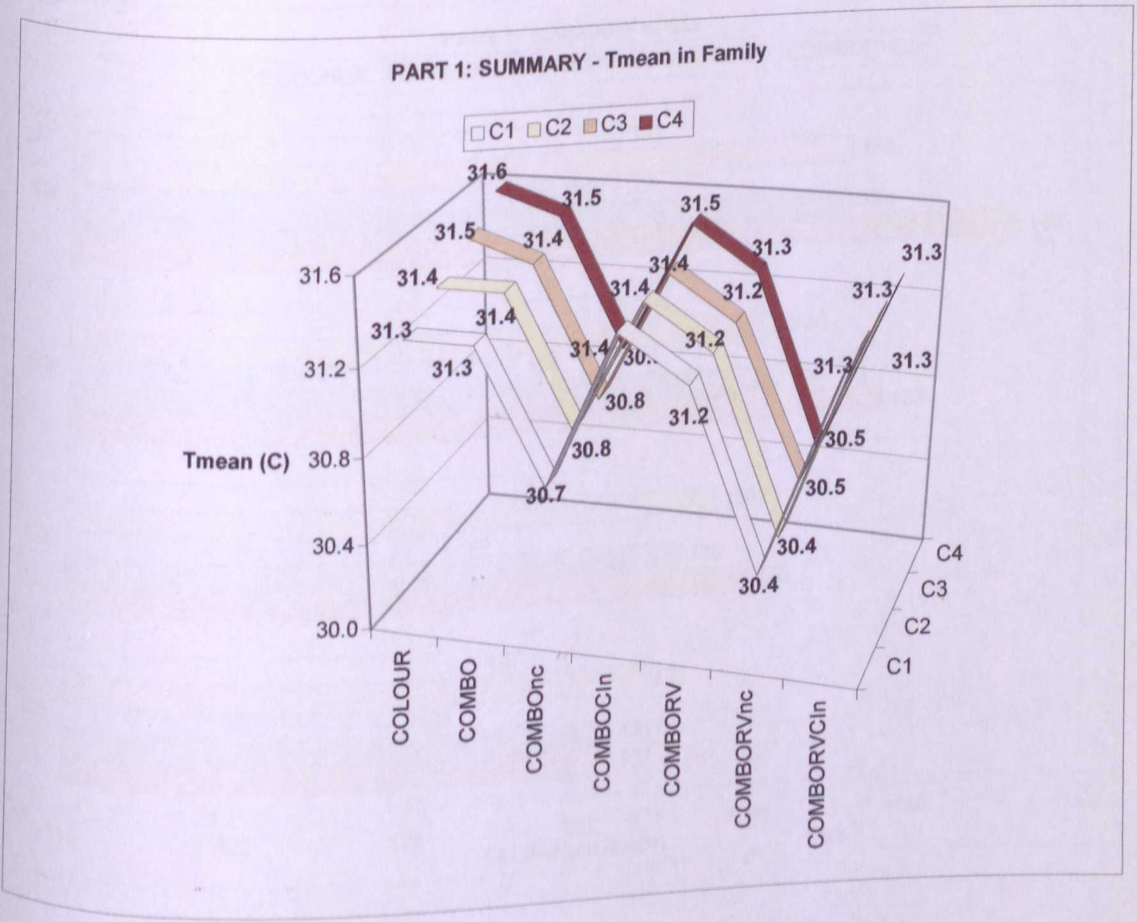


Figure 7.33: T_{mean} in *Family* for all models

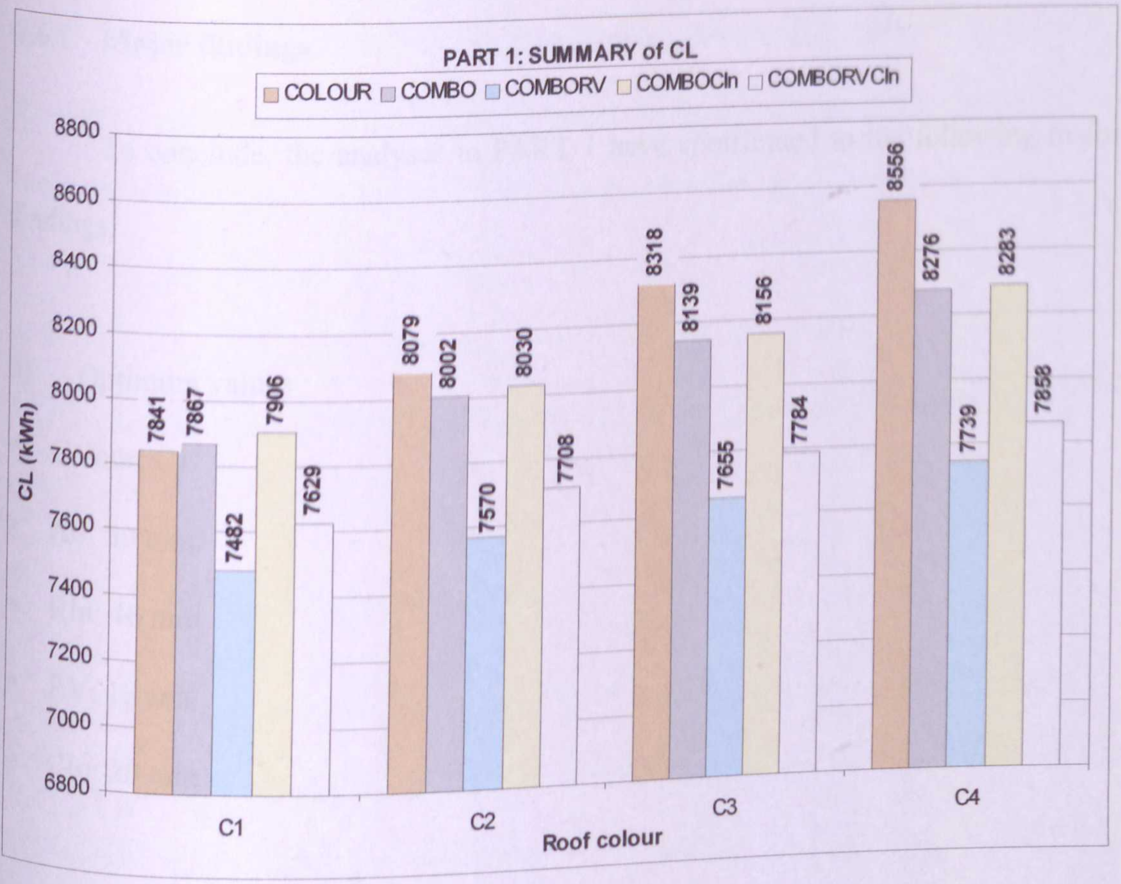


Figure 7.34: Summary of CL for all models

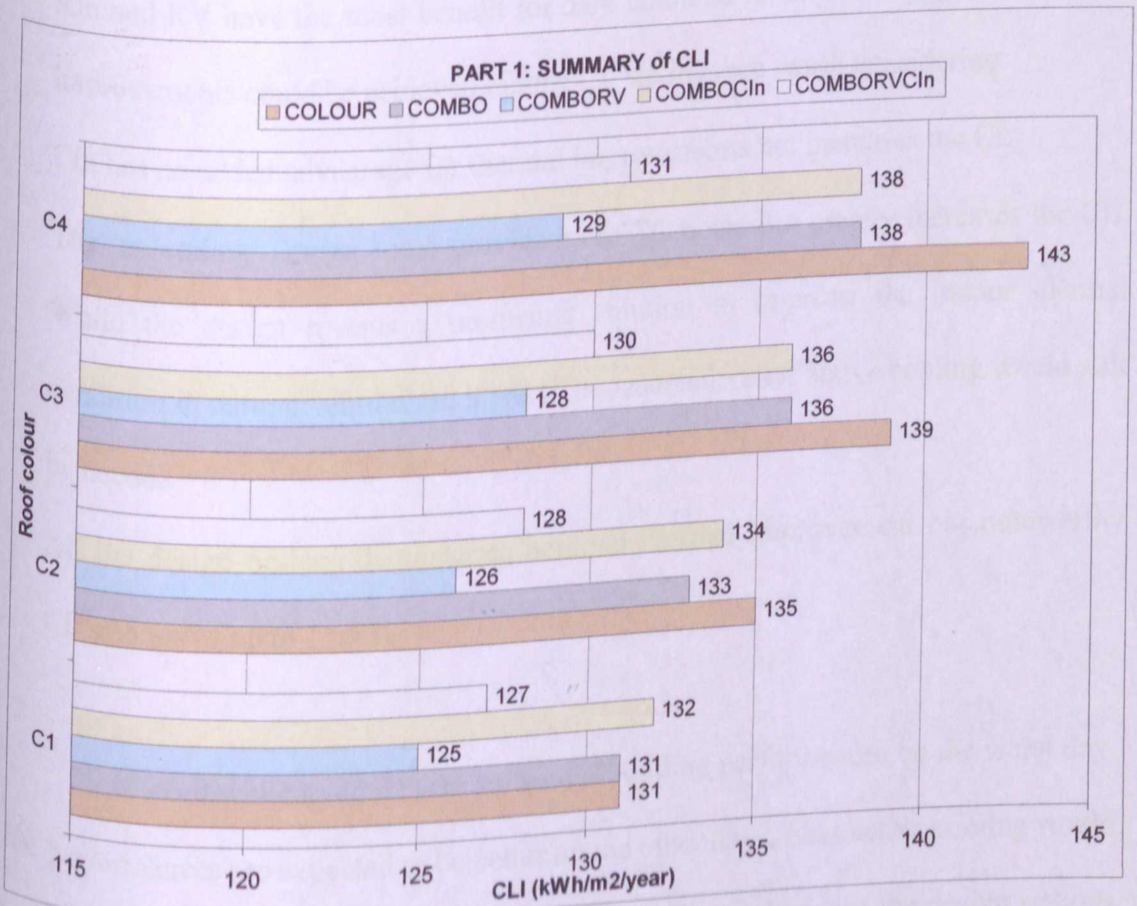


Figure 7.35: Summary of CLI for all models

7.6.1 Major findings

To conclude, the analyses in PART 1 have contributed to the following major findings:

a) Optimum values

- Colour: C1
- AS: 50 mm
- RIn: 40 mm
- RV: 10 ach
- CIn: 20 mm

b) Design options

- RIn and RV have the most benefit for dark coloured roofs. Some degree of thermal improvements could be achieved but the CL savings are worth considering.
- CIn has no added advantage for thermal improvements but increases the CL.
- The 'no-ceiling' design could provide more TC hours but greatly increases the CL. While the design reveals a promising solution to improve the indoor thermal condition in natural ventilation, it has to be reconsidered if active cooling would still be needed.
- All the design options demonstrate nominal thermal improvement but noteworthy CL savings of up to 12.6 %.

It is worthwhile to note these are whole-building performances on the worst day. The performances are expected to be better on the other days. Less active cooling would be needed with improved thermal condition. Thus, this implies that the design options could add more TC hours and generate CL savings of more than 12.6 %.

The findings in PART 1 are put together and presented in PART 2 as for comparative performance evaluations for decisions on roof designs for the house in this study. Similar analyses could be applied to other house designs.

PART 2: PERFORMANCE EVALUATIONS OF THERMAL DESIGN OF ROOF

7.7 Evaluation and data presentation

A compilation of the findings in PART 1 are presented in form of charts that displayed the appraisal on thermal and energy performances of the roof design options investigated in the study. The design options are COLOUR, COMBO, COMBORV, COMBOnc, COMBORVnc, COMBOCIn, COMBORVCIn.

7.8 Thermal performance: T_{max} and T_{mean}

Figures 7.36 and 7.37 can be used for decisions on the roof design to be adopted to optimise the indoor TP. The attributes for each design are as described in Table 6.1 and are also indicated on the charts. TC temperature (T_{tc}) is plotted to give a qualitative judgement on the comfort condition in the spaces.

Results in PART 1 have revealed that light colour gives the best overall performance. However, due to colour preferences, for either aesthetic appeal or maintenances, colour of the roof covering would become a deciding factor on the design options. Colour sensitivity on indoor T_{air} in *RSpace* and *Family* of each roof design are depicted as CHART 1A in Figure 7.36 and CHART 1B in Figure 6.37 respectively. The charts illustrate greater impact in *RSpace* than *Family* with higher sensitivity on T_{max} than T_{mean}. Figure 7.36 shows the sensitivity diminishes with the application of either

RV, or CIn, or both, and removal of the conventional horizontal ceiling. However, the 'no-ceiling' designs are the least sensitive to the choice of colour. This implies that for naturally ventilated spaces, the 'no-ceiling' design with RV (COMBORVnc) performs best followed by 'no-ceiling' without RV (COMBOnc) – with comparable performance by all colours. For designs with ceiling, RIn and RV would slightly modify the TP but with no significant TC improvement. The evaluation for the energy performance is presented in the following section.

CHART 1A

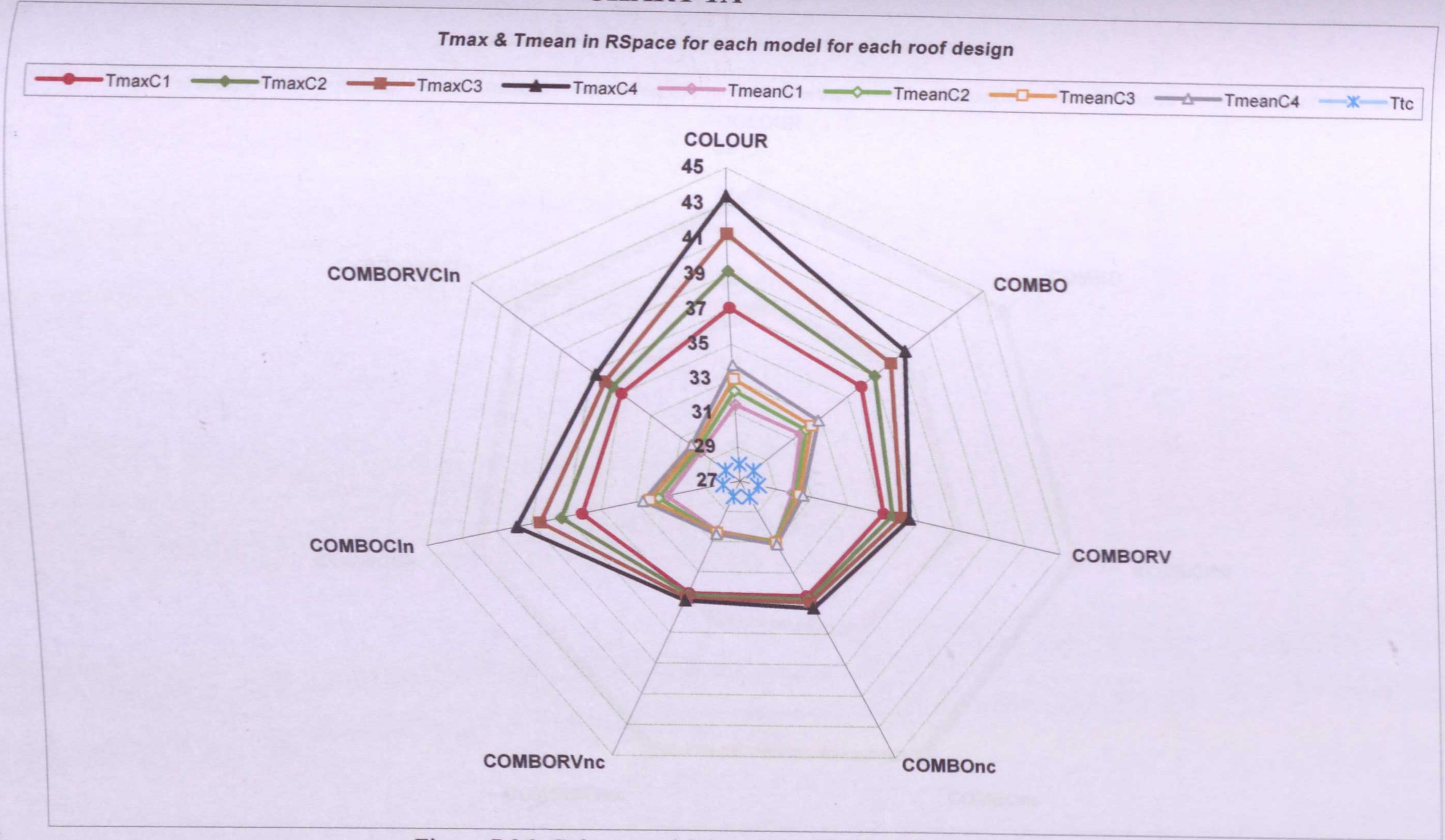


Figure 7.36: Colour sensitivity of roof design on TP in RSpace

CHART 1B

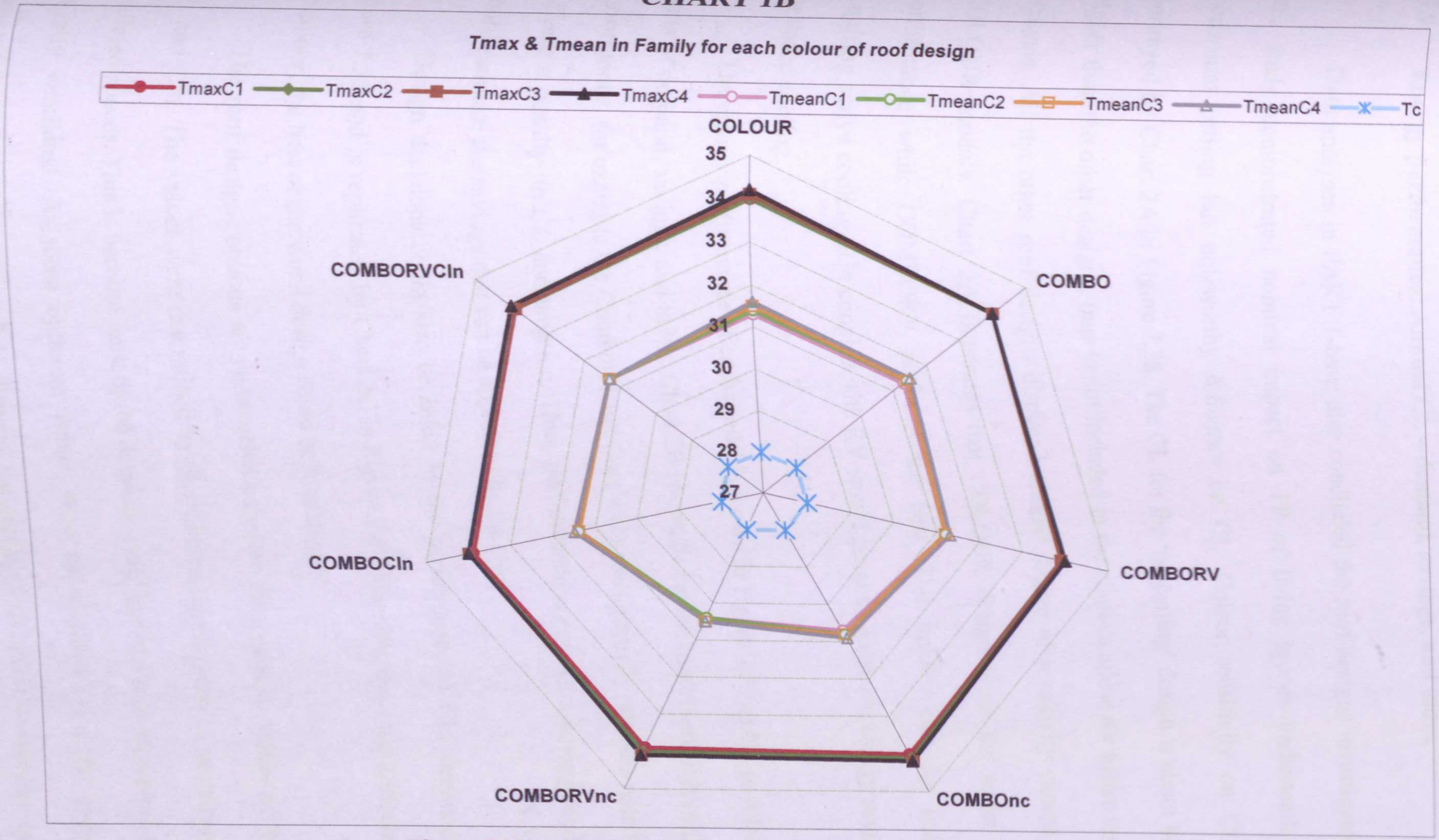


Figure 7.37: Colour sensitivity of roof design on TP in *Family*

7.9 Energy performance: Annual CL – demand, savings, and index

Data analyses in PART 1 have also concluded the roof designs investigated in this study demonstrated nominal impact on TP of living spaces underneath the horizontal ceiling but noteworthy influence on CL. Colour sensitivity on CL is portrayed by Chart 2A in Figure 7.38. The CL for the 'no-ceiling' design is about 80 % higher than the other designs, thus is not included in the chart to allow for better visual analysis. All the other roof designs display a similar degree of sensitivity except the COLOUR models. Chart 2A illustrates that COLOUR design gives the worst CL performance while COMBORV performs the best. This implies that for spaces requiring active cooling, RIn coupled with RV would generate a notable energy savings for space cooling.

The energy performance of each model is shown in Figure 7.39 as CL profiles in terms of demand, savings, and index. Chart 2B shows that some models exhibit similar performance, for example the ComboC4 and ComboC4CIn. Generally, models with CIn indicate a penalty on CL consumption. Thus, performance comparison among models would estimate the savings that can be appraised by the cost.

Design decisions could also be aided by the performance of CLI depicted in Figure 7.35 and is replicated by Chart 2C in Figure 7.40. Reading from the preference for colour, the best or the worst design could be predicted.

The roof designs options are constructed based on the optimum values of RIn, RV, and CIn. The values were determined by their thermal performances in naturally ventilated spaces. This is because most of the domestic buildings in Malaysia are mostly naturally ventilated. As these optimum values were not decided from the energy performance, Chart 2D in Figure 7.41 displays the predicted CL performance for each model of RIn, RV and CIn. The CL profiles are comparisons with the BASE model.

The performances of the design options are next discussed in relation to the thermophysical properties of the roof material and construction. These are however constrained to the limitation of the software to generate the computations for the individual roof components only.

CHART 2A

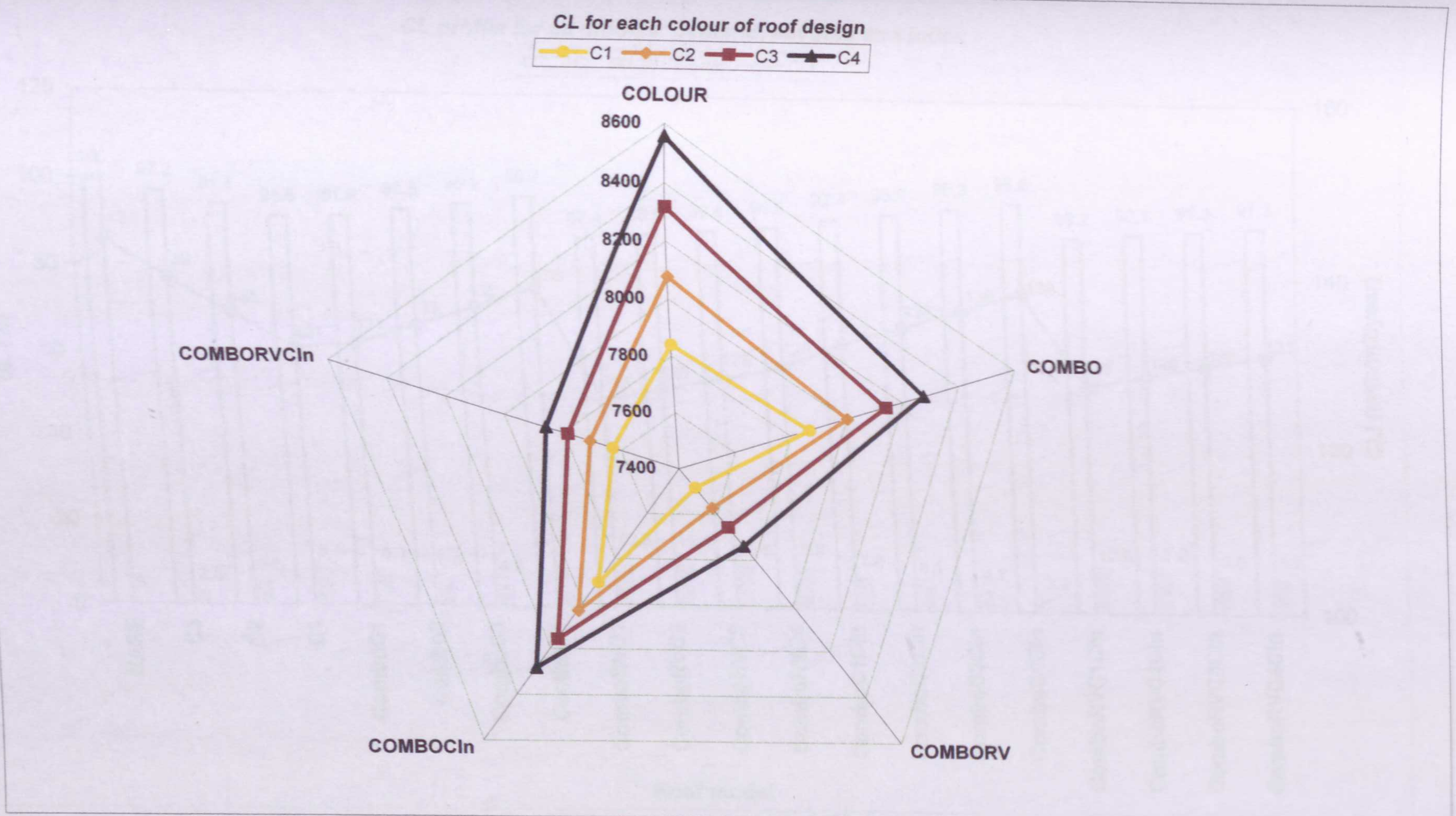


Figure 7.38: Colour sensitivity of roof design on building annual CL

CHART 2B

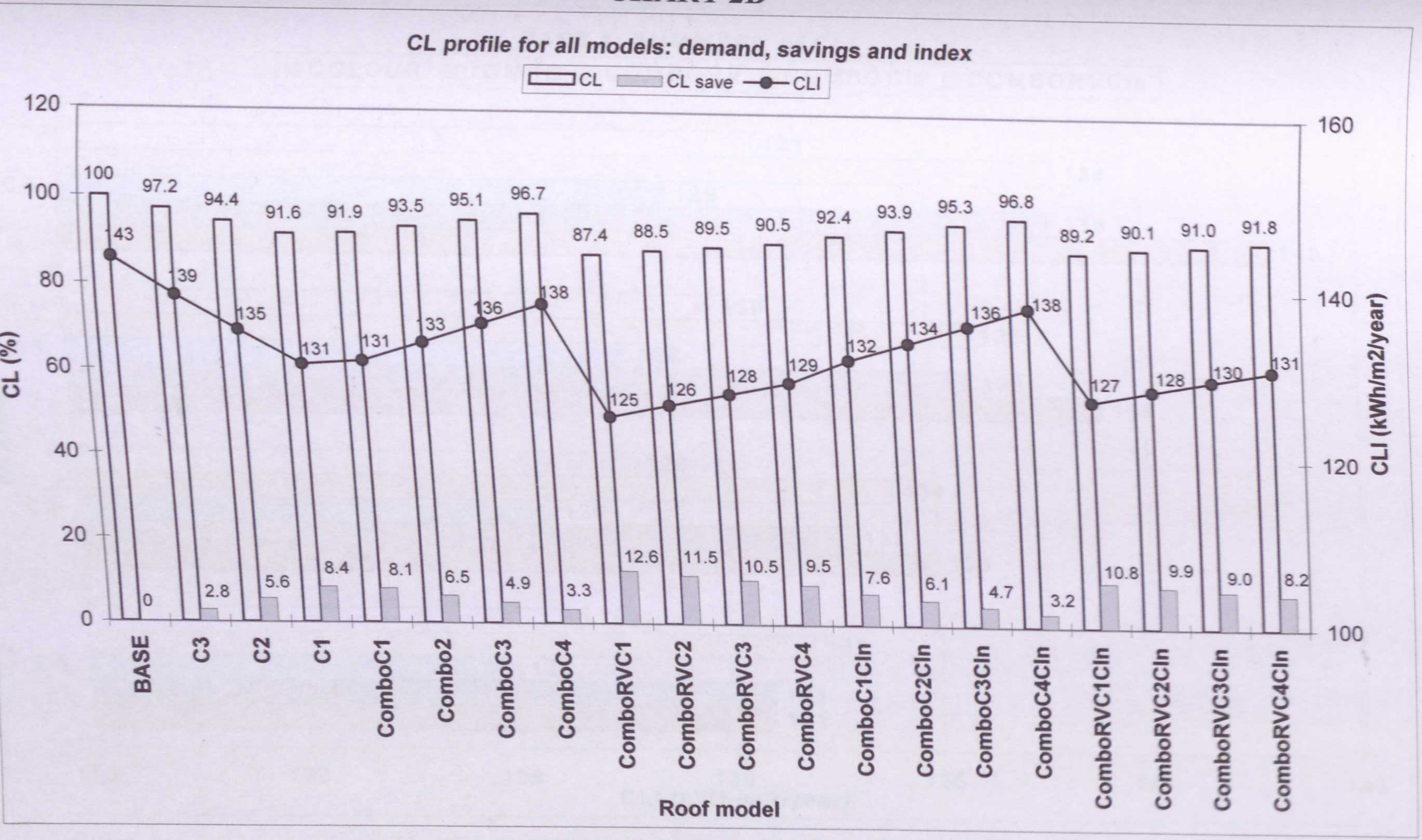


Figure 7.39: Energy performance for each model

CHART 2C

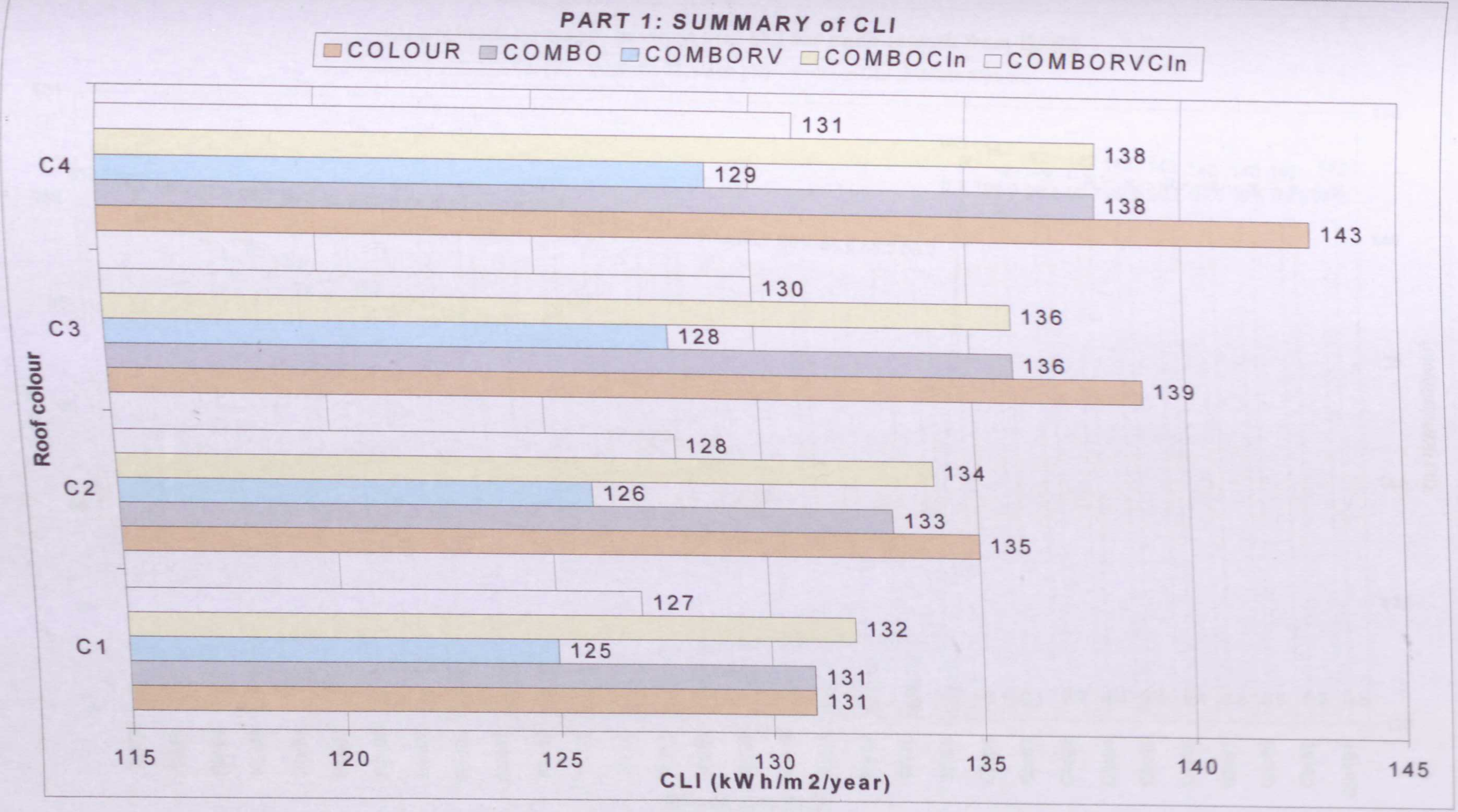


Figure 7.40: Colour sensitivity on CLI for each roof design

CHART2D

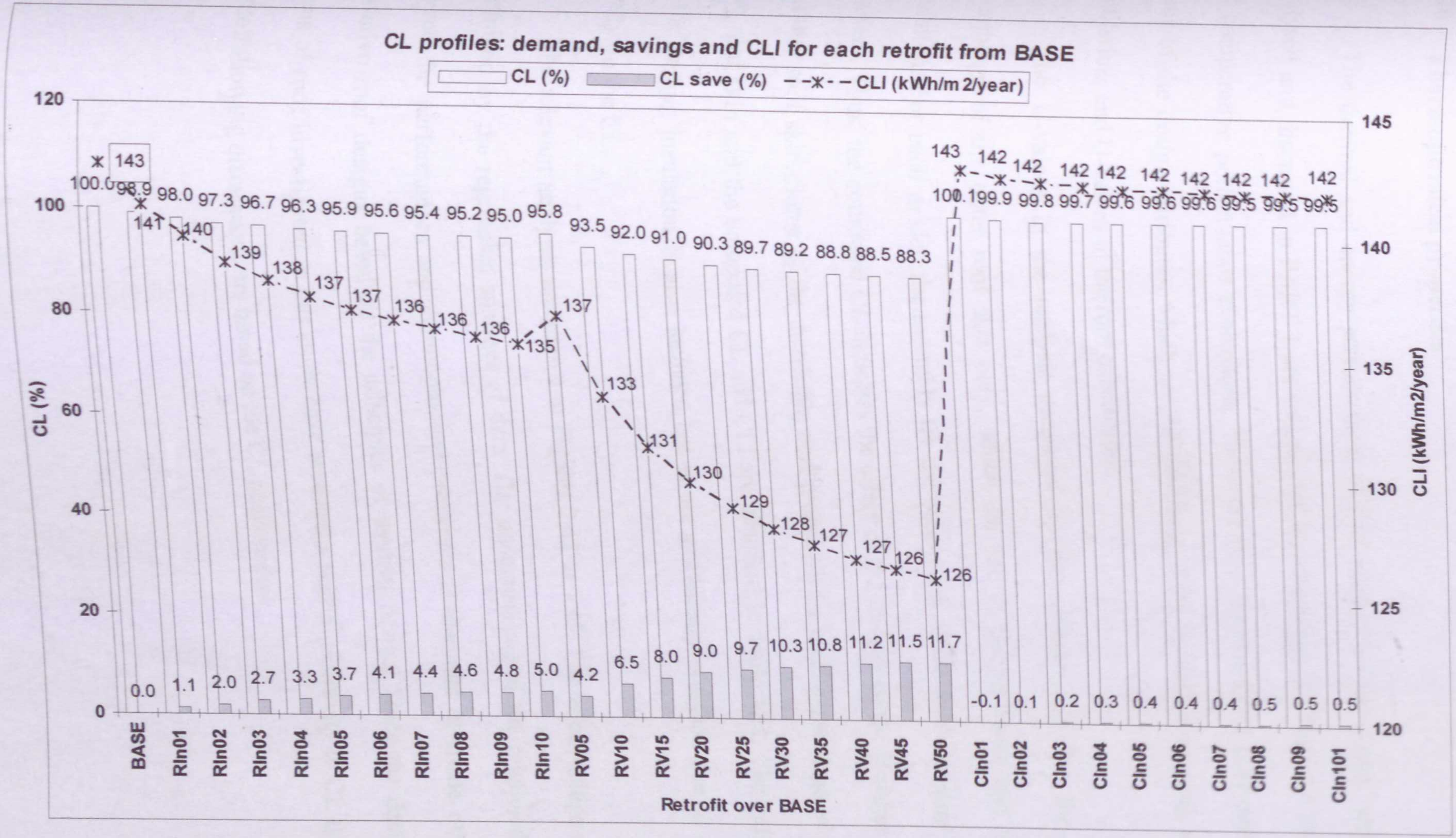


Figure 7.41: Energy performance for RIn, RV, and CIn models on based BASE

7.10 Thermophysical properties

The thermal and energy performances of roof models for the design options analysed and discussed in PART 1 are summarised and displayed in Charts 1A to 2D for comparative performance evaluations. These are now discussed and presented in terms of the design attributes, which are the thickness of the insulation material, roof ventilation, and U-values of the roof construction.

The U-values in the analysis computed by the software are that for the assemblage of the outer roof skin only, which are due to the air space and roof insulation. For each model, the assembly for the other parts of the roof structure are invariant. Thus, the computed CL indicates the effect of the changes of the U-value for the outer roof skin. Some of the thermophysical properties for each assemblage of the outer roof skin and the computed CL and CLI are tabulated in Table 7.11. The values for the ceiling insulation is also included but is not graphically analysed due to the penalty on the CL.

The relevant analyses are shown in Figures 7.42 to 7.45. The relationships are determined by the regression analyses of data. The understanding of the relationship between the performances and thermophysical properties is essential to create other innovative roof designs based on the principles of thermal design. Since the design options of roof investigated in this study have revealed a higher sensitivity to CL than TP, the following discussions are based on the CL performance.

Table 7.11: Analyses for selected roof parameters

Part	Model	d (mm)	U- value ($Wm^{-2}K$)	Decrement Factor	Time-lag (hr)	Annual CL (kWh)	CLI ($kWhm^{-2}year^{-1}$)
AS	AS1	20	1.695	0.974	0.5	8676	145
	AS2	50	1.261	0.973	0.6	8556	143
	AS3	100	1.097	0.973	0.6	8501	142
	AS4	200	1.011	0.973	0.6	8469	141
RIn	RIn00	0	1.261	0.973	0.6	8556	143
	RIn01	10	0.953	0.972	0.6	8459	141
	RIn02	20	0.766	0.971	0.6	8382	140
	RIn03	30	0.640	0.970	0.7	8322	139
	RIn04	40	0.550	0.969	0.7	8276	138
	RIn05	50	0.482	0.968	0.7	8239	137
	RIn06	60	0.429	0.967	0.8	8208	137
	RIn07	70	0.386	0.966	0.8	8183	136
	RIn08	80	0.352	0.965	0.9	8162	136
	RIn09	90	0.323	0.965	1.0	8144	136
	RIn10	100	0.298	0.964	1.0	8128	135
CIn	CIn00	0	2.606	0.994	0.2	8556	143
	CIn01	10	1.742	0.991	0.2	8565	143
	CIn02	20	1.204	0.991	0.2	8548	142
	CIn03	30	0.920	0.988	0.3	8538	142
	CIn04	40	0.744	0.986	0.3	8531	142
	CIn05	50	0.625	0.985	0.4	8525	142
	CIn06	60	0.539	0.984	0.4	8522	142
	CIn07	70	0.473	0.982	0.4	8519	142
	CIn08	80	0.422	0.981	0.5	8516	142
	CIn09	90	0.381	0.980	0.5	8514	142
	CIn10	100	0.347	0.979	0.6	8512	142

a) **Effect of colour**: The α of the roof covering directly determines the amount of solar radiation absorbed by the surface. Chart 2A in Figure 7.28 shows COLOUR design is the most sensitive to the choice of colour. However, the graphs in Figure 7.42 show that CL is linearly dependent on α for all roof designs. The variations of the degree of dependency are due to the U-value of the designs. Thus, the U-value does not change with α as it is a property of a construction. Therefore, it is concluded that CL is linearly dependent on the α of roof covering regardless of the modification on U-value by any design option.

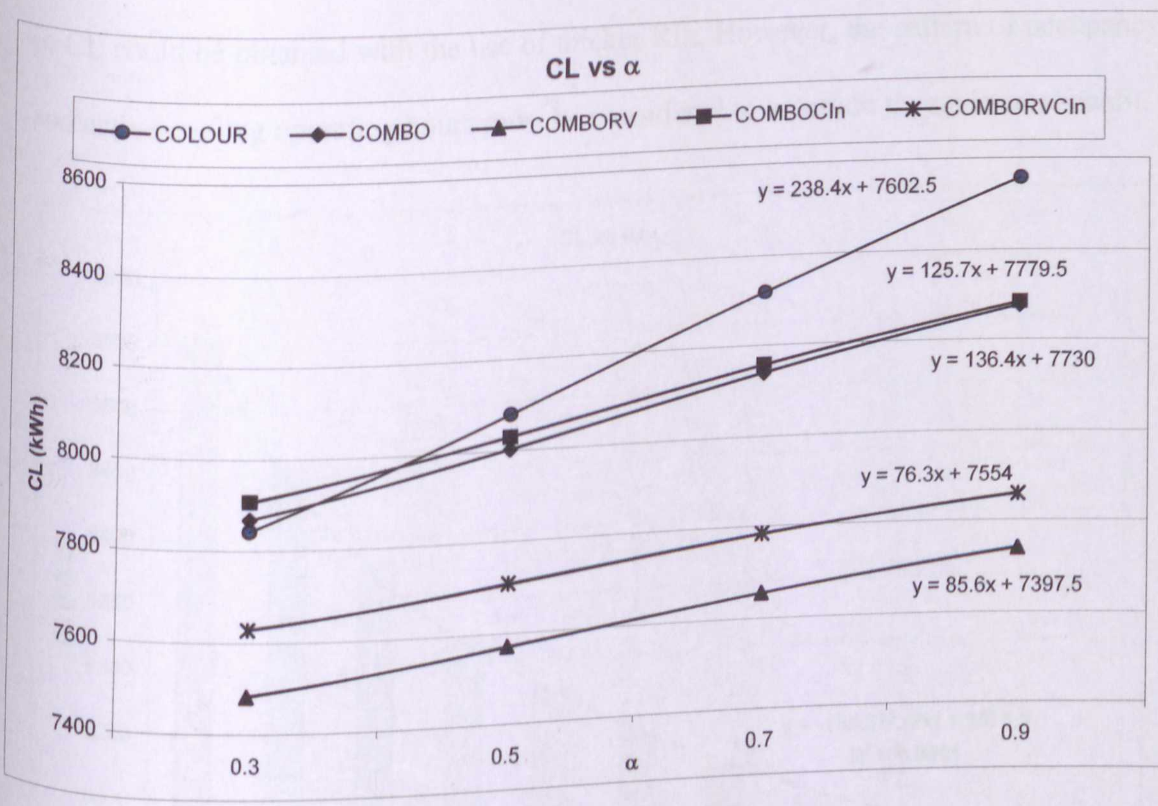


Figure 7.42: Effect of α on CL

b) **Effect of RIn**: The RIn used are made from conductive insulation material with *k value* of 0.04 $Wm^{-1}K^{-1}$ to supplement the reflective effect of the conventional aluminium foil that acted as radiant barrier. It impeded heat transfer and demonstrated a temporal benefit for naturally ventilated spaces as discussed in section 7.3.1 (c). It also lowered the U-value that reduces the CL of mechanically cooled spaces. The effect of U-value is analysed in item (d) of this section. The analyses in PART 1 have identified 40 mm as the optimum thickness that would optimise the TP in natural ventilation for the assumed occupancy pattern. The relation between thickness, d, of RIn investigated and the resulting CL is given by the equation in Figure 7.43. The graph shows further reduction in CL could be obtained with the use of thicker RIn. However, the pattern of occupancy and active cooling operating hours must be considered to ascertain the optimum benefit.

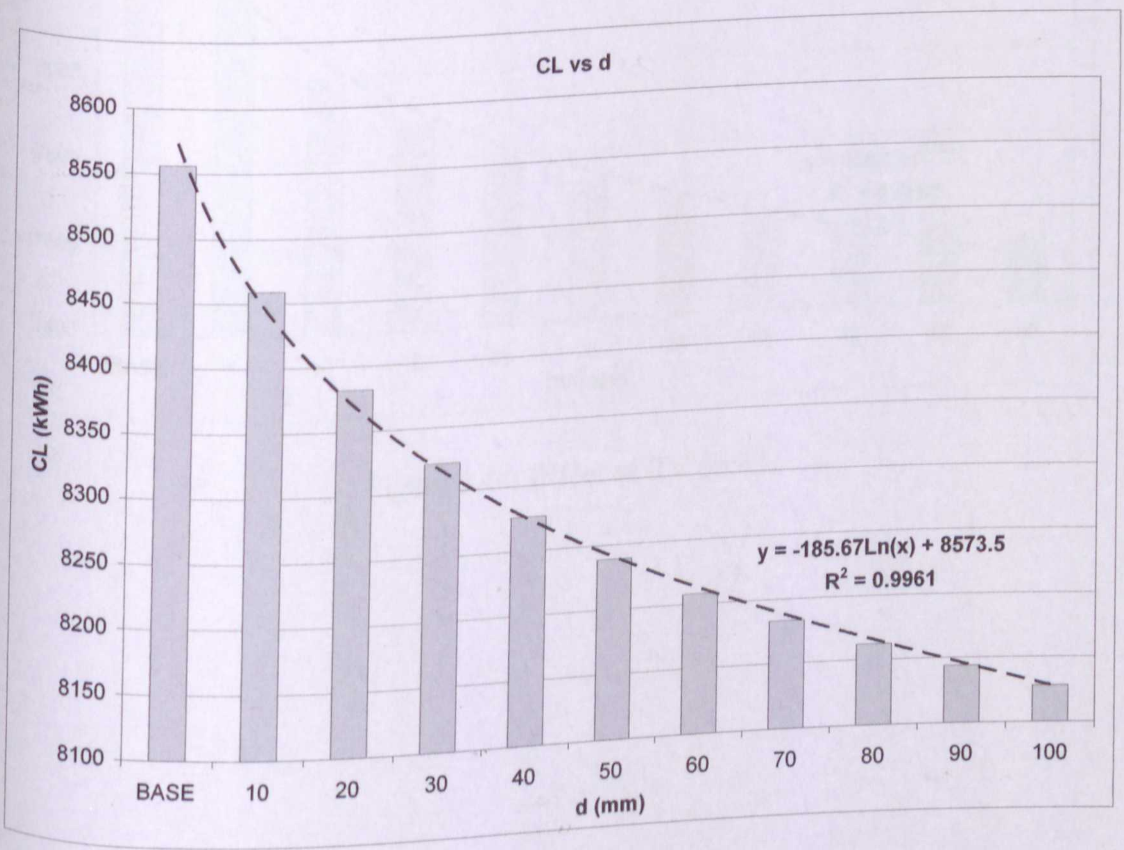


Figure 7.43: Effect of RIn on CL

c) **Effect of RV on CL**: The analyses in PART A have identified 10 ach as the optimum rate that would optimise the TP in natural ventilation for the assumed occupancy pattern. RV increased the air movement in *RSpace*, thus increasing the velocity of air near the underside of the roof surface. The relation between the investigated RV rate and the resulting CL is given by the equation in Figure 7.44. The graph shows further reduction in CL could be obtained with the use of higher rate.

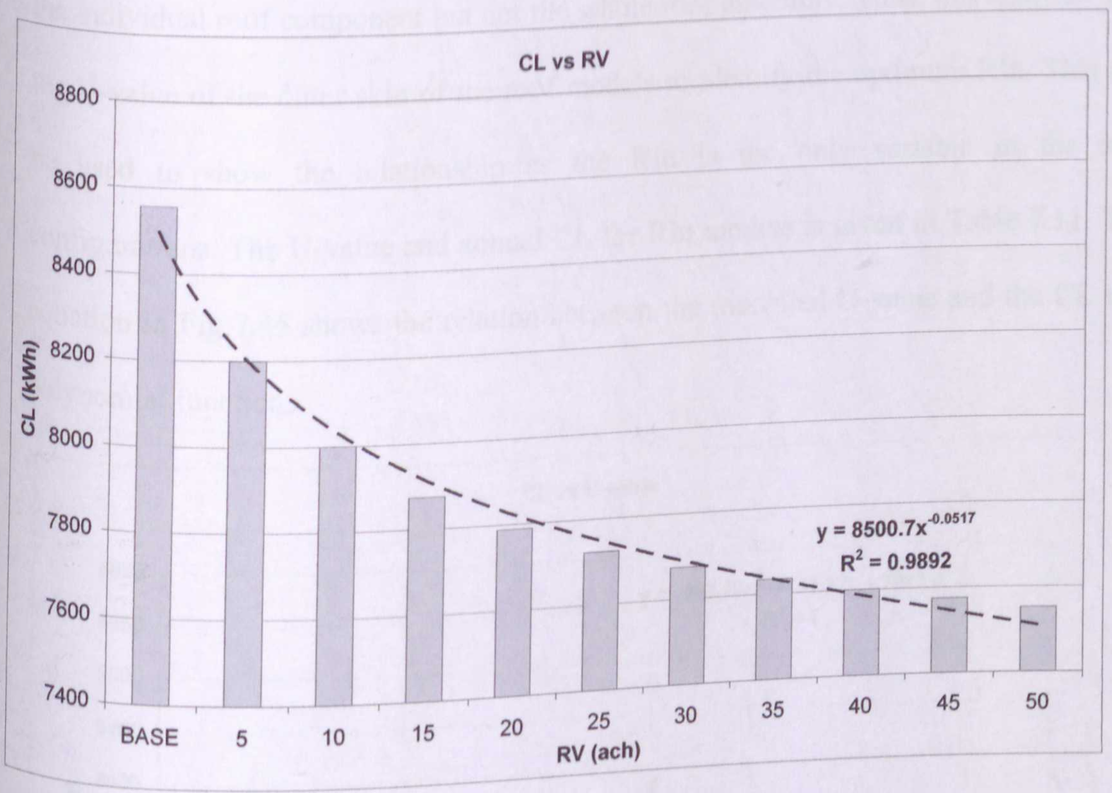


Figure 7.44: Effect of RV on CL

d) **Effect of U-value on CL**: The U-value of a building envelope depends on the material and thickness, construction, and the air film resistances, which are also influenced by the air movement near its surface. The U-value determines the heat transmission through envelope, thus influences the thermal and energy performances. Results in PART 1 have indicated the impacts on the thermal conditions are minimal but rather significant on the CL. The output of the software is limited to the U-value of only the individual roof component but not the whole roof assembly. Thus, this analysis uses the U-value of the outer skin of the roof models to identify the optimum RIn. This can be used to show the relationship as the RIn is the only variable in the roof configurations. The U-value and annual CL for RIn models is given in Table 7.11. The equation in Fig 7.45 shows the relation between the modelled U-value and the CL is a polynomial function.

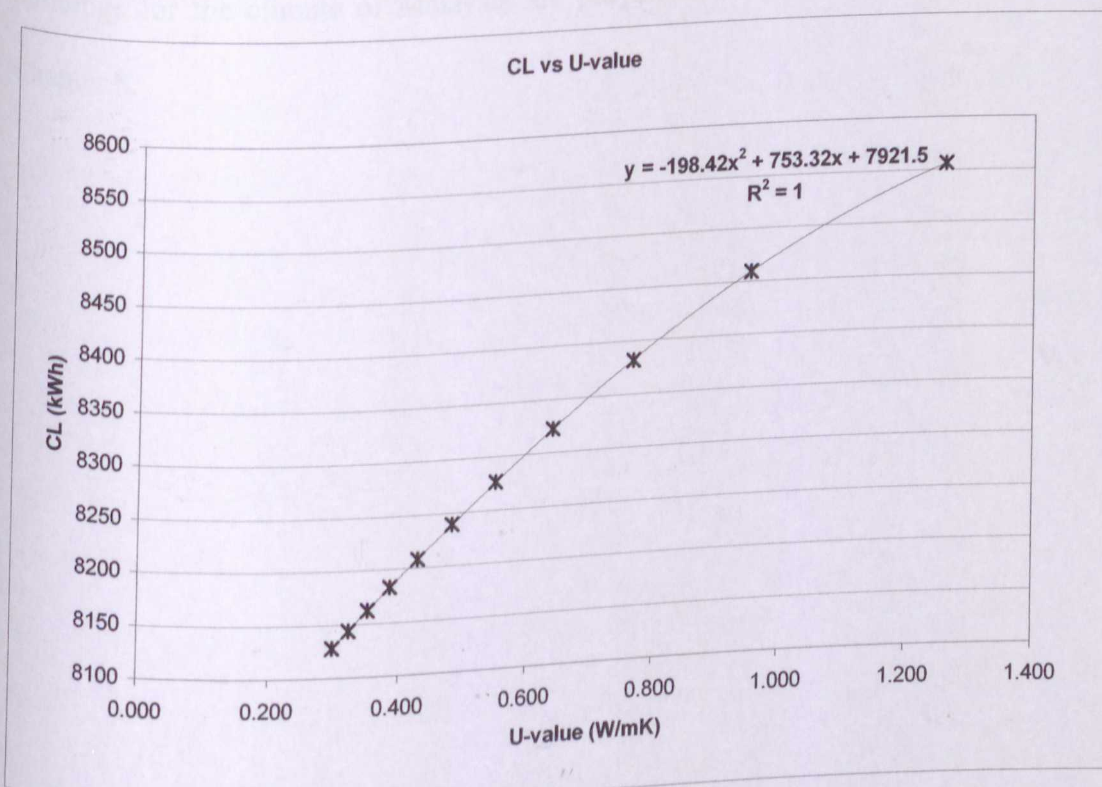


Figure 7.45: Effect of U-value of CL

7.11 Summary of PART 2

The findings in PART 1 have been summarised into graphs and charts in PART 2 to serve as comparative performance evaluations for decisions on the roof design based on thermal and energy performances of the whole-building. Although these are obtained from the appraisal of only seven design options for the house in the study, most of these findings are consistent with some of the previous international and national studies discussed in Chapter 2 and 3.

To conclude, the findings of this study have corroborated some of the previous research findings, and confirmed as well as questioned the aptness of some of the recommended roof designs for the climate of Malaysia. Therefore, several recommendations for thermal design of the roofs for low-rise detached residential buildings for the climate of Malaysia are put forward and are presented in the next Chapter 8.

CHAPTER 8: CONCLUSION AND RECOMMENDATION

8.1 Introduction

This chapter concludes the research findings. The research objectives are restated to relate to the important research findings and comparisons with the previous research are made. Recommendations for thermal design of the roofs for low-rise detached residential buildings in Malaysia are put forward as the research outcome. The significant contribution to knowledge is stated and limitations of study are clarified. Finally, suggestions for future work are made.

8.2 Conclusion

The research findings have addressed all the stated research objectives. The analyses on all the roof design options investigated lead to the conclusion of nominal thermal improvement but noteworthy CL savings of up to 12.6 % per household. Some other potential design alternatives are revealed, which could propel to a new paradigm in roof design and these are further discussed in section 8.3. The predicted CL savings could impose implications on the national energy consumption as well as the global environment.

These energy implications could be inferred from a projection analysis as follows: In the year 2000, 4.6 million living quarters in the Peninsular consumed 16.8 % of the national energy consumption. This is equivalent to the usage of 9,093 GWh of the total utilization of 54,254 GWh. If a CL savings of 12.6 % per household could be targeted with a realistic assumption that 10 % of the dwellings use active cooling with usage pattern assumed in the study, then this amounted to a total annual energy savings of 190 GWh. This is equivalent to a savings of 2.1 % by the residential sector that translates to a national savings of 0.4 %. This amount of energy savings corresponds to the country's CO_2 reduction of 117.8 kton.

While the savings and the environmental impact may appear very modest, these are non-trivial small benefits over the life span of many buildings. Small individual impacts may not be profound but repeating occurrences of many small effects could accumulate the advantages over time or accrue to permanent irreversible detrimental environmental effect.

To conclude, varying the roof design within the limited parameters of the conventional construction practices has little impact on thermal comfort condition in the spaces within the building. However, the small cooling load reductions when aggregated over a large number of buildings would be significant.

Summaries of design options performances are displayed as reference charts for comparative evaluations in sections 7.8 to 7.10. These could serve as a starting point to formulate other performance evaluations for decisions on roof design options as well as for other parts of the building envelope.

In the subsequent sections, the research objectives are restated to relate to the important research findings. The important research findings are summarised and recommendations for thermal design of the roofs for low-rise detached residential buildings in Malaysia are made.

8.2.1 Research overview

This research addresses the issue of thermal comfort and EE in residential buildings focussing on the design of the roof. Consequently, the aim is to identify the thermal design of roof assembly for optimum whole-building thermal and energy performances for low-rise detached residential buildings in Malaysia. The research objectives are:

- To quantify the optimum roof thermal parameters
- To apply the optimum roof thermal parameters and evaluate whole-building thermal and energy performances
- To analyse the thermal roof design options pertaining to the thermal impact and cooling energy needs.

The outcome is to contribute to recommendations for thermal design of the roof for low-rise detached residential buildings in Malaysia

The research employed a numerical simulation method using **Tas** as the experimental tool. The findings are summarised and compiled into charts for comparative analysis on the energy performance of the design options.

The roof design options investigated in this study were hypothetically constructed based on the conventional construction practices in Malaysia. The designs were appraised by the dynamic whole-building analyses on the thermal and energy performances. The thermal performance was evaluated on an identified worst day, which was the 7th of March (day 66) based on the analysis using the MYC data (refer to section 6.3) while the energy performance was based on whole-year consumption.

8.2.2 Important findings

The important findings to meet the research objectives are:

a) Optimum roof parameters

- External surface colour (C) – light
- Air space (AS) – 50 mm
- Supplementary thermal insulation (RIn) – 40 mm
- Roof ventilation (RV) rate – 10 ach
- Thermal insulation for ceiling (CIn) – 20 mm

b) Application of combined optimum roof parameters

Selective combination of the parameters produced seven design options, each with models of four hues to consider the colour preference. These are:

- COLOUR – conventional roof with four hue options. The darkest hue of C4 was used as the base-case model.
- COMBO – conventional roof with supplementary insulation beneath radiant barrier
- COMBORV – COMBO design with ventilated roof space
- COMBOnc – COMBO design without ceiling
- COMBORVnc – COMBORV design without ceiling
- COMBOCIn – COMBO design with ceiling insulation
- COMBORVCIn – COMBORV design with ceiling insulation

c) Thermal and energy performances of the design options

All the design options demonstrate more significant thermal impact in the roof space (*RSpace*) than the occupied spaces (represented by *Family*) underneath with little improvement on the thermal comfort (TC) conditions. However, noteworthy impact on the cooling load (CL) and cooling load index (CLI) were computed. The performance evaluations of all designs are compared with the conventional COLOUR design. The overall advantages of the design options are:

- Thermal modifications on T_{mean} in *Family* is up to 1.2 °C and an extra 2 hours of TC.
- CLI ranges from 125 $kWhm^{-2}year^{-1}$ to 143 $kWhm^{-2}year^{-1}$ with CL savings of up to 12.6 %.

d) The significance of each design options are:

- COLOUR – light colour gives the best thermal and energy performances with no added cost.

- COMBO – RIn has temporal benefit due to the property of insulating material that impedes heat transfer.
- COMBORV – RV shows a potential technique to reduce CL.
- COMBOnc and COMBORVnc – the 'no-ceiling design' reveals a promising solution to ameliorate the indoor thermal condition of naturally ventilated spaces. Due to the limitation of the software, a more detail performance evaluation of actively conditioned spaces is needed.
- COMBOCIn and COMBORVCIn – CIn has no computable benefit on the TC but imposes a penalty on the CL with an added construction cost.

Referring to the graphs in figures 7.32, 7.33 and 7.34:

- T_{max} is lowest for designs COMBOCIn, COMBORV, COMBORVnc COMBORVCIn with roof colour C1.
- T_{max} is highest for designs COLOUR, COMBO, and COMBOnc with roof colour C4.
- COMBORV is the best option for actively conditioned space.

8.3 Recommendations for thermal design of the roof

The findings of this research are consistent with the previous studies and recommendations discussed in Chapter 2 and 3, but with varying degree of impact owing to the microclimatic variations as well as different research techniques and investigation tools. These are the advantage of using light colour, the need for extra insulation, the use of ceiling, and the provision for roof ventilation. Within the scope and limitation of this study, the investigations have ascertained and verified the functionality of some recommended features and have also identified the unnecessary ones.

The charts and graphs in Figures 7.36 to 7.45 could assist the visual comparison for design evaluations. For general reference, the following conclusions can be drawn regarding the thermal parameters to be considered for thermal design of the roofs for low-rise residential detached buildings in Malaysia:

a) Colour – light:

The hue is an indicator of the solar absorptivity (α) that determines the amount of solar radiation absorbed. Thus, the roof colour would influence the amount of heat gain even though the U-value remains the same. Nonetheless, the colour option might not impose significant modification on the TC condition in the occupied living spaces, but the generated CL savings would need to be considered. Therefore, the roof can be designed to make use of other thermophysical properties of material or construction to reduce the colour sensitivity as demonstrated by the design options in Figure 7.42.

b) Thermal Insulation – yes and no:

- Underneath radiant barrier: yes
- On top of horizontal ceiling: No

The application of a conductive insulation underneath the conventional radiant barrier would not significantly alleviate the indoor thermal stress, which would necessitate the usage of active cooling. The insulation lowers the U-value and would contribute towards more efficient use of energy for cooling. However, its installation on top of the ceiling could aggravate the indoor thermal condition and increased the needed CL. The thermal resistance of the insulating material creates favourable as well as adverse effects on the indoor condition as it impedes heat transfer between the spaces.

Therefore, for each design alternatives a detail investigation on the overall performance is prudent to attain the desirable effect. This includes the identification for the optimum thickness and type of insulation material, as well as the temporal thermal impact and the consequent cooling needs. The identified optimum thickness for thermal insulation underneath the conventional radiant barrier is 40 mm. For insulation above the conventional horizontal ceiling, the optimum thickness is 20 mm.

c) Roof ventilation – yes and no:

- Design with ceiling – yes and no
- Design without ceiling – yes

For designs with the conventional horizontal ceiling, ventilating the roof space would not significantly improve the TC condition. An additional one to two extra TC hours could be attained, thus it would bring about some energy savings. Therefore, RV would be advantageous for actively conditioned spaces but its benefit for naturally ventilated spaces is doubted.

However, if the roof is designed without the ceiling, RV could appreciably improve the night-time TC condition as it draws in cooler ambient air. This would eliminate the need for active cooling thus entailing to more energy savings.

Hence, RV reveals a promising technique to reduce CL for designs with the conventional horizontal ceiling, but the optimum RV rate must be determined. The needed rate could be achieved by various active or passive means. An assessment to ascertain its performance in response to the microclimatic conditions is essential. The optimum rate identified is 10 ach.

d) Ceiling – yes and no:

- Design for natural ventilation: yes and no

- Design for active cooling: yes

The ceiling acts as thermal barrier to mitigate the impact of long-wave radiation from the roof. For naturally ventilated spaces, it would provide better thermal condition during daytime but could exacerbate the night-time condition as it traps the warmer indoor air that resulted from the internal gains. Thus, the ceiling is needed only during the day but not at night. At night, the 'no-ceiling' design not only allows the warmer air to move upwards from the occupied spaces to the roof space but also provide a bigger space for better thermal stratification. The cooler air in the roof space would sink to the occupied spaces underneath, thus lowering the indoor temperature.

However, if active cooling would still be needed, the impact on the required CL could be tremendous. Consequently, the usage would depend on the usage pattern of the spaces and detail assessment of the impact is necessary to optimise the need and performance.

The above recommendations generally indicate that thermal and energy performance evaluations would ascertain the advantages of the design options. This is due to the interactive effect of the relevant environmental factors with the whole-building design. These recommendations are based on the findings of this research that were subjected to various limitations. The implication of the findings and the limitations of study are used to suggest several suggestions for future work in the area.

The significant contribution to the body of knowledge for studies on residential buildings in Malaysia, the research limitations, and the suggestions for future works are discussed next to conclude this thesis.

8.3.1 Significant contribution to knowledge

The findings in this study have significant contributions to knowledge in the following ways:

- The optimum values for roof parameters recommended in literatures from international and national studies were systematically quantified. This is proven by the fact that all the cited references done so far for the Malaysian cases, only several selected values were investigated (refer to critical reviews of literature in section 3.7).
- The evaluations on the thermal and energy performances have ascertained the aptness and functionality of the all the parameters in the study. In addition to the descriptive evaluation of the roof design options, this study has actually transformed the performances into 'measureable quantities'. These are indicated by the performance appraisals of all the roof models as illustrated in the charts and graphs in PART 2 of the analyses presented in Chapter 7.
- The whole-building thermal and energy performances were simulated on a computer modelling tool that is used for the first time in the Malaysian climate. The consistency of the findings with previous research findings has proven that this modelling tool is suitable for the Malaysian climate.
- Since the PWD-NQD design is new and unique, all results in this study in itself is already a significant contribution to new knowledge, since it has not been done before by anyone. In addition, the performance evaluations on the proposed design options can be used as a reference for comparative analysis of roof designs generally as this design will be used widely throughout the country.
- The methodology and findings can be used as a basis for studies on other types of residential buildings.

8.4 Limitation of study

The findings of the research are based on the analyses of the generated output data from a computer-modelling software by numerical simulations on the house model using conventional building material and construction with realistic assumptions on some of the input data. Thus, the limitations of study are as follows:

a) **Type of building – double-storey detached house**: The quantification of the performances may apply only to this particular building configuration. The actual figures might differ, however based on the discussions and comparisons with the previous mentioned studies it is expected that the pattern of the performance will prevail for other building types.

b) **Assembly of material – conventional contemporary**: The performances obtained could be limited to the conventional contemporary practices employed. However, these are fundamentally determined by the thermal design of each building element. The thermophysical properties of the material and construction will determine the heat exchange of the building.

c) **Assumptions of input data – occupancy and household appliances**: The assumptions on the number of occupants, occupancy pattern and schedules, and the household appliances were realistically formulated. However, to some extent the findings would be affected by the occupancy pattern and total internal heat gains.

d) **Investigation tool – computer-modelling thermal design software**: The findings are predictions based on the input data that are 'partly real' such as the house model and 'partly assumed' such as the internal conditions. The accuracy of findings is determined by the capabilities of the computations. However, such errors of parametric analyses would be consistent for all the design alternatives.

8.5 Suggestions for future work

The findings have revealed some potential climatically responsive roof design alternatives that would be very fertile for further research in view of the tendency for "climate defiance" building design in contemporary practice in Malaysia. The following suggestions should be studied on several design configurations via empirical as well as numerical techniques.

a) **Ceiling**: There is a need to study dynamic ceiling systems whereby they are required during the day, but can be removed or opened at night. Further research would involve the practicality and reliability of any such mechanism. In addition, the roof configuration has to be reconsidered to accommodate to the 'no-ceiling' situation at night.

b) **Roof ventilation**: The advantage for naturally ventilated spaces with conventional design for ceiling is questionable but it reveals a promising technique for an EE measure. More detailed empirical studies would be needed to verify the benefits for naturally ventilated spaces in view of the increasing interest for the roof ventilation devices. This includes the architectural design as well as a mechanism that would respond to the local climatic conditions.

c) **Material and construction**:

- *Surface characteristics*: Only solar absorptivity was investigated in this study. Further studies should include the individual and combined effect of reflectivity and emmissivity.
- *New technology*: New materials as well as new construction techniques should be used to ascertain their climatic and cultural suitability.

Climatic design of buildings via appropriate thermal design techniques would pave a way for sustainable built environment. Building designs for sustainable development is paramount in current global concerns on the reduction of greenhouse gasses and pollutants as well as energy resources for our future generations. Reduced energy consumption in the domestic sector can play a significant role even if the actual reduction per unit is small. Where such gains can be achieved in the context of conventional design at little or no cost it is beholden on designers to convince clients of the desirability, both from a personal standpoint and the national good.

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APPENDICES

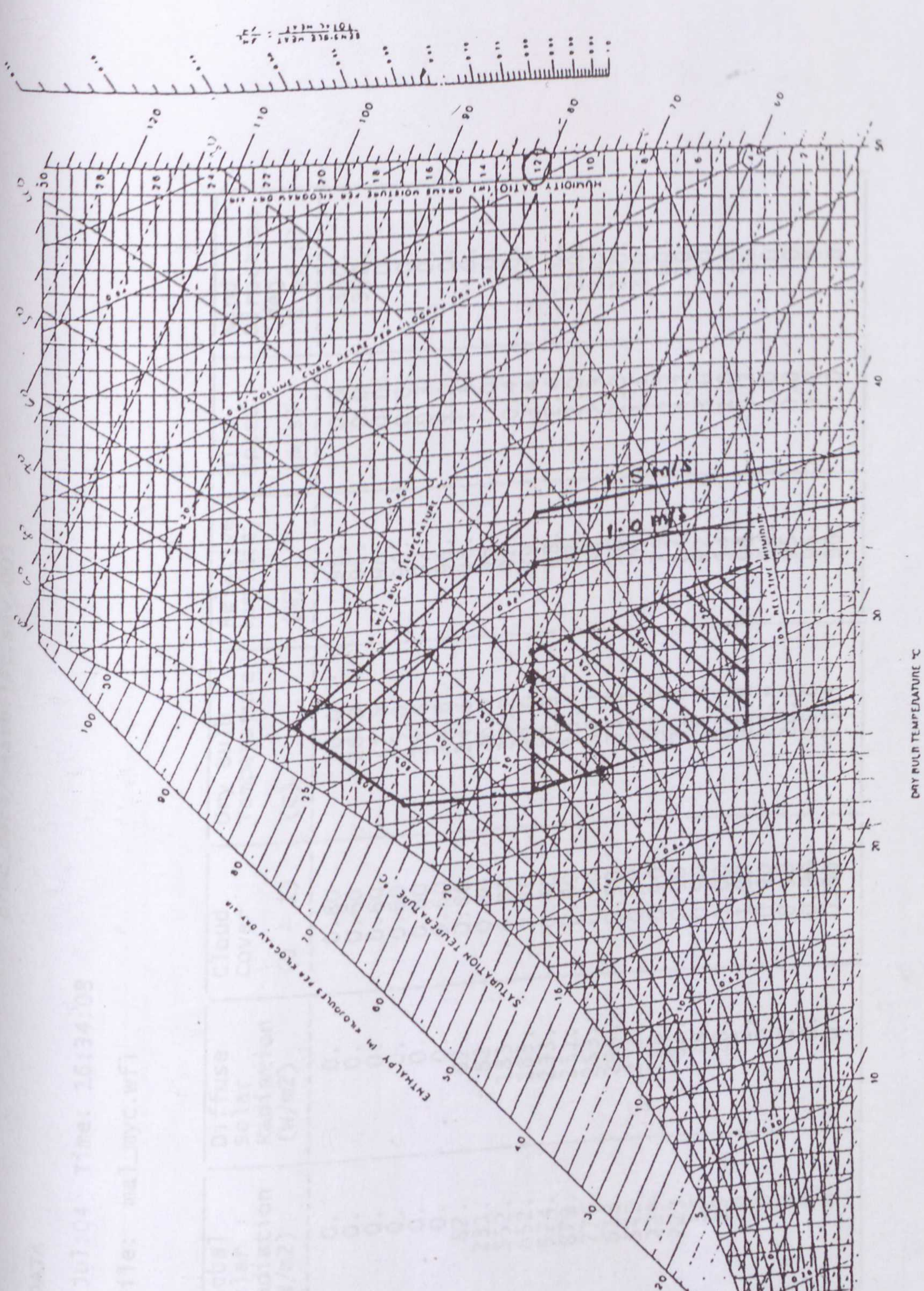
APPENDIX A (Abdul Rahman, 1999).

1) Figure A1.0: The Proposed Malaysian Comfort Zone

APPENDIX B (Tas simulation output data, this thesis)

1) Table B1.0: Weather data
2) Table B1.1: Opaque construction – ground floor
3) Table B1.2: Transparent construction – clear glass
4) Table B1.3: Opaque construction – plywood door
5) Table B1.4: Opaque construction – timber door
6) Table B1.5: Opaque construction – ext & int wall
7) Table B1.6: Opaque construction – ceiling
8) Table B1.7: Opaque construction – insulated ceiling
9) Table B1.8: Opaque construction – BASE roof
10) Table B1.9: Opaque construction: Combo roof
11) Table B2.0: House occupancy cshedule
12) Table B2.1: Common household appliances
13) Table B2.2: IC – living weekdays
14) Table B2.3: IC – living saturdays
15) Table B2.4: IC – living sundays
16) Table B2.5: IC – kitchen weekdays
17) Table B2.6: IC – kitchen saturdays
18) Table B2.7 IC – kitchen sundays
19) Table B2.8: IC – bed4 weekdays
20) Table B2.9: IC – bed4 saturdays
21) Table B3.0: IC – bed4 – bed4 sundays

Figure A1.0



The Proposed Malaysian Comfort Zone for Naturally Ventilated Buildings with extensions due to air velocity of 1m/s and 1.5m/s

(Abdul Rahman, 1999)

Table B1.0

WEATHER DATA

Date: 10:Jul:04 Time: 16:34:08

Weather File: mal_myc.wfl
Day: 66

Hour	Global Solar Radiation (W/m2)	Diffuse Solar Radiation (W/m2)	Cloud Cover (0 - 1)	Dry Bulb Temperature (C)	Relative Humidity (%)	Wind Speed (m/s)	Wind Direction (deg. E of N)
1	0.	0.	0.80	26.0	96.	0.0	350.
2	0.	0.	0.60	26.0	96.	0.0	350.
3	0.	0.	0.60	25.5	96.	0.0	0.
4	0.	0.	0.60	25.0	96.	0.0	0.
5	0.	0.	0.60	24.6	97.	0.3	0.
6	0.	0.	0.60	24.6	96.	1.0	0.
7	82.	62.	0.80	24.6	96.	1.5	0.
8	231.	62.	0.80	26.0	96.	0.0	0.
9	552.	183.	0.80	29.2	92.	0.4	10.
10	652.	185.	0.80	31.0	89.	3.4	0.
11	574.	233.	0.60	32.3	88.	2.4	0.
12	879.	251.	0.80	33.4	83.	2.0	320.
13	776.	253.	0.90	34.1	84.	2.3	330.
14	618.	283.	0.90	33.6	76.	2.0	350.
15	542.	211.	0.90	34.1	70.	1.5	320.
16	239.	136.	0.90	33.7	79.	4.5	90.
17	223.	88.	0.90	32.6	84.	4.7	20.
18	58.	28.	0.90	28.0	82.	3.0	70.
19	19.	18.	1.00	27.1	94.	1.0	10.
20	0.	0.	1.00	26.8	96.	0.3	10.
21	0.	0.	0.90	26.4	94.	0.0	0.
22	0.	0.	0.90	26.0	95.	0.0	0.
23	0.	0.	0.90	25.6	95.	0.0	0.
24	0.	0.	0.80	25.3	96.	0.0	0.

Table B1.1

Time Now	Date	Consultant	Program
15:28:47	09:Jul:04		A-Tas 8.40

DATABASE CONSTRUCTION

C-Code: ground/6 | Construction name: ground floor for Malaysia-marble

OPAQUE CONSTRUCTION

External Solar Absorptance	Internal Solar Absorptance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)	Time constant (hours)
0.760	0.450	0.910	0.950	0.297	128.0

Layer Number	M-Code & Material Name	Width (mm)	Conductivity (W/m C)	Density (kg/m3)	Specific Heat (J/kg C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside	am1stone/3 MARBLE *4	25.00	2.400	2600.0	840.0	-	38.000
2	am1concd/9 CONCRETE SCREED *3	50.00	1.280	2100.0	1000.0	-	34.000
3	am1concd/1 CONCRETE 3% m.c. 8 *3	125.00	0.870	1800.0	920.0	-	14.800
4	am1aggr/4 CRUSHED BRICK AGGREGATE *1	75.00	0.550	1580.0	1057.0	-	12.000
5	am1soil/7 SAND, DRY *2	1000.00	0.329	1515.0	796.0	-	99.000
6							
7							
8							
9							
10							
11							
12							

U VALUES (W/m2K): 0.283 (Wall) 0.285 (Roof) 0.278 (Internal) 0.285 (Ground Floor)

Table B1.2

Time Now	Date	Consultant	Program
13:33:03	09:Jul:04		A-Tas 8.40

DATABASE CONSTRUCTION

C-Code: glass/2 | Construction name: 10mm clear glass

TRANSPARENT CONSTRUCTION   External Blind? [No]   Internal Blind? [No]

Solar Trans-mittance	External Solar Absorptance (ext. surf.)	External Solar Absorptance (int. surf.)	Internal Solar Absorptance (int. surf.)	Internal Solar Absorptance (ext. surf.)	Light Trans-mittance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)
0.700	0.115	0.115	0.115	0.115	0.840	0.845	0.845	100.000

Layer Number	M-Code & Material Name	Width (mm)	Solar Tran.	Ext. Solar Refl.	Int. Solar Refl.	Ext. Emis.	Int. Emis.	Conductivity (W/m C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside	am1pilk/3 10MM CLEAR FLOAT	10.00	0.700	0.070	0.070	0.845	0.845	1.000	-	99999.000
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										

U VALUES (W/m2K): 5.329 (Wall) 6.227 (Roof) TOTAL SOLAR TRANSMITTANCE: 0.763 (Pilkington)

Table B1.3

Time Now	Date	Consultant	Program
14:41:59	09:Jul:04		A-Tas 8.40

DATABASE CONSTRUCTION

C-Code: door/2	Construction name: plywood door

OPAQUE CONSTRUCTION

External Solar Absorptance	Internal Solar Absorptance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)	Time constant (hours)
0.700	0.700	0.900	0.900	4.000	0.0

Layer Number	M-Code & Material Name	Width (mm)	Conductivity (W/m C)	Density (kg/m3)	Specific Heat (J/kg C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside	am1sheet/25 PLYWOOD 2 *4	35.00	0.140	530.0	2760.0	-	100.000
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							

U VALUES (W/m2K): 2.369 (Wall) 2.522 (Roof) 2.067 (Internal) 2.552 (Ground Floor)

Table B1.4

Time Now	Date	Consultant	Program
13:29:07	09:Jul:04		A-Tas 8.40

DATABASE CONSTRUCTION

C-Code: door/1	Construction name: timber door

OPAQUE CONSTRUCTION

External Solar Absorptance	Internal Solar Absorptance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)	Time constant (hours)
0.600	0.600	0.900	0.900	3.750	0.0

Layer Number	M-Code & Material Name	Width (mm)	Conductivity (W/m C)	Density (kg/m3)	Specific Heat (J/kg C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside	am1wood/6 HARDWOOD 2 *4	40.00	0.150	700.0	1420.0	-	11.420
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							

U VALUES (W/m2K): 2.279 (Wall) 2.421 (Roof) 1.998 (Internal) 2.448 (Ground Floor)

Time Now	Date	Consultant	Program
14:40:53	09:Jul:04		A-Tas 8.40

DATABASE CONSTRUCTION

C-Code: wallmal/5

Construction name: ext & int wall in Malaysia, a=0.4

OPAQUE CONSTRUCTION

External Solar Absorptance	Internal Solar Absorptance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)	Time constant (hours)
0.400	0.400	0.900	0.900	4.599	1.7

Layer Number	M-Code & Material Name	Width (mm)	Conductivity (W/m C)	Density (kg/m3)	Specific Heat (J/kg C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside	am1plast/31 a=0.4	20.00	0.530	1570.0	837.0	-	11.000
2	am1brick/10 BRICK COMMON DRY 0% m.c., RED *4	115.00	0.810	1760.0	920.0	-	8.000
3	am1plast/31 a=0.4	20.00	0.530	1570.0	837.0	-	11.000
4							
5							
6							
7							
8							
9							
10							
11							
12							

U VALUES (W/m2K): 2.567 (Wall) 2.748 (Roof) 2.216 (Internal) 2.784 (Ground Floor)

Table B1.5

Table B1.6

Time Now	Date	Consultant	Program
13:24:20	09:Jul:04		A-Tas 8.40

DATABASE CONSTRUCTION

C-Code: ceiling/7	Construction name: ceiling for malaysia + 20mm ins

OPAQUE CONSTRUCTION

External Solar Absorptance	Internal Solar Absorptance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)	Time constant (hours)
0.600	0.400	0.900	0.400	1.884	0.0

Layer Number	M-Code & Material Name	Width (mm)	Conductivity (W/m C)	Density (kg/m3)	Specific Heat (J/kg C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside	ceiling/1 asbestos free ceiling	4.50	0.250	1553.0	840.0	-	11.000
2	am1ins/3 GLASSWOOL 1 *2	20.00	0.039	24.0	920.0	-	1.500
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							

U VALUES (W/m2K): 1.301 (Wall) 1.382 (Roof) 1.204 (Internal) 1.277 (Ground Floor)

Table B1.7

Time Now	Date	Consultant	Program
13:21:33	09:Jul:04		A-Tas 8.40

DATABASE CONSTRUCTION

C-Code: ceiling/5

Construction name: ceiling for malaysia

OPAQUE CONSTRUCTION

External Solar Absorptance	Internal Solar Absorptance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)	Time constant (hours)
0.400	0.400	0.400	0.400	55.556	0.0

Layer Number	M-Code & Material Name	Width (mm)	Conductivity (W/m C)	Density (kg/m3)	Specific Heat (J/kg C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside	ceiling/1 asbestos free ceiling	4.50	0.250	1553.0	840.0	-	11.000
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							

U VALUES (W/m2K): 3.788 (Wall) 4.632 (Roof) 2.606 (Internal) 3.704 (Ground Floor)

Table B1.8

Time Now	Date	Consultant	Program
13:35:30	09:Jul:04		A-Tas 8.40

DATABASE CONSTRUCTION

C-Code: roofd/4	Construction name: roofd/4: a=0.9;20-50-0.25

OPAQUE CONSTRUCTION

External Solar Absorptance	Internal Solar Absorptance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)	Time constant (hours)
0.900	0.600	0.900	0.900	1.547	0.0

Layer Number	M-Code & Material Name	Width (mm)	Conductivity (W/m C)	Density (kg/m3)	Specific Heat (J/kg C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside	am1wood/10 WOOD *4	0.20	0.147	640.0	1420.0	-	11.420
2	am1metal/1 ALUMINIUM *3	0.05	204.000	2700.0	896.0	-	0.000
3	am1cav/23 50MM AIR (DOWNWARD FLOW)	50.00	-	-	-	0.500	1.000
4	rooftile/4 concrete rooftile, a=0.9	20.00	1.440	2402.0	879.0		34.000
5							
6							
7							
8							
9							
10							
11							
12							

U VALUES (W/m2K): 1.222 (Wall) 1.261 (Roof) 1.136 (Internal) 1.269 (Ground Floor)

Table B1.9

Time Now	Date	Consultant	Program
14:07:46	09:Jul:04		A-Tas 8.40

DATABASE CONSTRUCTION

C-Code: roofe/1 | Construction name: combi-01: roofe/1:C1-20-50-0.25+40

OPAQUE CONSTRUCTION

External Solar Absorptance	Internal Solar Absorptance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)	Time constant (hours)
0.300	0.600	0.900	0.900	0.598	0.0

Layer Number	M-Code & Material Name	Width (mm)	Conductivity (W/m C)	Density (kg/m3)	Specific Heat (J/kg C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside	am1ins/3 GLASSWOOL 1 *2	40.00	0.039	24.0	920.0	-	1.500
2	am1wood/10 WOOD *4	0.20	0.147	640.0	1420.0	-	11.420
3	am1metal/1 ALUMINIUM *3	0.05	204.000	2700.0	896.0	-	0.000
4	am1cav/23 50MM AIR (DOWNWARD FLOW)	50.00	-	-	-	0.500	1.000
5	rooftile/1 concrete rooftile, a=0.3	20.00	1.440	2402.0	879.0	-	34.000
6							
7							
8							
9							
10							
11							
12							

U VALUES (W/m2K): 0.542 (Wall) 0.550 (Roof) 0.525 (Internal) 0.551 (Ground Floor)

Table B2.0

No.of occupants: 2 full-time working parents, 4 school-age children, one full-time maid

The number of occupants in each space for each hour is listed in the table

Space/Hour		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Bed01	Week	2	2	2	2	2	2	1	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	2	2
	Sat	2	2	2	2	2	2	2	0	0	1	0	0	0	0	0	0	0	0	1	2	0	0	0	0
	Sun	2	2	2	2	2	2	2	2	0	0	0	0	0	0	0	1	1	1	0	2	0	0	2	2
Bed02	Week	2	2	2	2	2	2	1	0	0	0	0	0	0	0	0	1	1	1	0	2	0	0	2	2
	Sat	2	2	2	2	2	2	2	1	1	0	0	0	0	0	0	0	0	0	1	2	0	0	0	1
	Sun	2	2	2	2	2	2	2	1	1	0	0	0	0	0	0	1	1	1	0	2	0	0	2	2
Bed03	Week	2	2	2	2	2	2	1	0	0	0	0	0	0	0	0	1	1	1	0	2	0	0	2	2
	Sat	2	2	2	2	2	2	2	1	1	0	0	0	0	0	0	0	0	0	1	2	0	0	0	1
	Sun	2	2	2	2	2	2	2	1	1	0	0	0	0	0	0	1	1	1	0	2	0	0	2	2
Bed04	Week	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1		0	1	0	0	0	1
	Sat	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1
	Sun	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0
Kitchen	Week	0	0	0	0	0	1	1	1	0	0	0	1	1	1	1	0	0	0	0	0	1	1	1	0
	Sat	0	0	0	0	0	0	1	1	1	1	2	2	2	1	1	0	0	0	0	0	1	1	1	0
	Sun	0	0	0	0	0	0	1	1	1	1	2	2	2	1	1	0	0	0	0	0	1	1	1	0
Living	Week	0	0	0	0	0	0	3	0	0	0	0	0	0	0	4	0	0	0	0	0	6	0	0	0
	Sat	0	0	0	0	0	0	0	0	0	1	2	2	2	6	0	0	0	0	0	0	6	0	0	0
	Sun	0	0	0	0	0	0	0	0	2	2	2	2	2	6	4	0	0	0	0	0	6	0	0	0
Family	Week	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	2	2	2	0	0	6	0	0
	Sat	0	0	0	0	0	0	0	2	2	2	2	2	2	0	0	0	0	0	1	0	0	6	6	4
	Sun	0	0	0	0	0	0	0	0	2	2	2	2	2	0	0	3	3	3	0	0	0	6	0	0
Total	Week	7	7	7	7	7	7	7	1	0	0	1	1	1	1	5	5	5	4	3	7	7	7	7	7
	Sat	7	7	7	7	7	7	7	5	5	5	6	6	6	7	1	1	1	1	4	7	7	7	7	7
	Sun	7	7	7	7	7	7	7	5	7	5	6	6	6	7	5	7	7	7	0	7	7	7	7	7

Table B2.1

No	Eqpt/Space	Living	Kitchen	Family	Bed01	Bed02	Bed03	Bed04
1	Lamps	X	X	X	X	X	X	X
2	Fan	X	X	X	X	X	X	X
3	TV	X		X	X			
4	VCR/VCD/etc	X		X	X			
5	Computer			X				
6	Refrigerator		X					
7	Microwave		X					
8	Washing machine		X					
9	Cooker		X					
10	Kettle		X					
11	Toaster		X					
12	Food processor		X					
13	Clothing iron							X
14	Air conditioner			X	X	X	X	

Table B2.2

Building Name: AD9BASEnv *Building Data File:* AD9BASEnv.bdf.41 *Revision:* **
Time: 23:22:26 Date: 10:Jul:04 Consultant: Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
1. living	WEEKDAY	d09livnv/ 1	bungalow d09; living; weekdays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	6	1.000	0.000	0.000	0.000	0.000	0.236	0.000
2	1	1.000	0.000	20.000	5.930	7.345	2.359	0.000
3	7	1.000	0.000	0.000	0.000	0.000	0.236	0.000
4	1	1.000	0.000	0.000	7.905	9.793	2.359	0.000
5	4	1.000	0.000	0.000	0.000	0.000	0.943	0.000
6	1	1.000	0.000	20.000	0.000	0.000	0.943	0.000
7	1	1.000	0.000	20.000	11.858	14.689	2.359	0.000
8	3	1.000	0.000	0.000	0.000	0.000	0.236	0.000

Table B2.3

INTERNAL CONDITIONS

Building Name: AD9BASEnv   Building Data File: AD9BASEnv.bdf.41   Revision: **
Time: 23:24:24 Date: 10:Jul:04   Consultant: Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
1. living	SATURDAY	d09livnv/ 2	bungalow d09; living; saturdays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	9	1.000	0.000	0.000	0.000	0.000	0.236	0.000
2	1	1.000	0.000	0.000	1.976	2.448	2.359	0.000
3	3	1.000	0.000	0.000	3.952	4.896	2.359	0.000
4	1	1.000	0.000	0.000	11.858	14.684	2.359	0.000
5	5	1.000	0.000	0.000	0.000	0.000	0.943	0.000
6	1	1.000	0.000	20.000	0.000	0.000	0.943	0.000
7	1	1.000	0.000	20.000	11.858	14.689	2.359	0.000
8	3	1.000	0.000	0.000	0.000	0.000	0.236	0.000

Table B2.4

INTERNAL CONDITIONS

Building Name: AD9BASEnv   Building Data File: AD9BASEnv.bdf.41   Revision: **
Time: 23:25:41 Date: 10:Jul:04   Consultant: Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
1. living	SUNDAY	d09livnv/ 3	bungalow d09; living; sundays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	8	1.000	0.000	0.000	0.000	0.000	0.236	0.000
2	5	1.000	0.000	0.000	3.952	4.896	2.359	0.000
3	1	1.000	0.000	0.000	11.858	14.684	2.359	0.000
4	1	1.000	0.000	0.000	7.905	9.793	2.359	0.000
5	4	1.000	0.000	0.000	0.000	0.000	0.943	0.000
6	1	1.000	0.000	20.000	0.000	0.000	0.943	0.000
7	1	1.000	0.000	20.000	11.858	14.684	2.359	0.000
8	3	1.000	0.000	0.000	0.000	0.000	0.236	C.000

Table B2.5

INTERNAL CONDITIONS

Building Name: AD9BASEnv
Time: 23:30:58 Date: 10:Jul:04

Building Data File: AD9BASEnv.bdf.41
Consultant:

Revision: **
Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
2. kitchen	WEEKDAY	d09kitnv/ 1	bungalow d09; kitchen; weekdays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	5	0.750	0.000	0.000	0.000	0.000	18.405	0.000
2	3	0.750	0.000	20.000	5.521	5.828	58.900	20.859
3	3	0.750	0.000	0.000	0.000	0.000	38.650	10.429
4	4	0.750	0.000	0.000	5.521	5.828	58.900	20.859
5	5	0.750	0.000	0.000	0.000	0.000	38.650	10.429
6	3	0.750	0.000	20.000	4.601	4.601	38.650	10.429
7	1	0.750	0.000	0.000	0.000	0.000	18.405	0.000
8								

Table B2.6

INTERNAL CONDITIONS

Building Name: AD9BASEnv Building Data File: AD9BASEnv.bdf.41 Revision: **
Time: 23:32:01 Date: 10:Jul:04 Consultant: Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
2. kitchen	SATURDAY	d09kitnv/ 2	bungalow d09; kitchen; saturdays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	6	0.750	0.000	0.000	0.000	0.000	18.405	0.000
2	4	0.750	0.000	20.000	5.521	5.828	58.900	20.859
3	3	0.750	0.000	0.000	9.203	9.203	58.900	20.859
4	2	0.750	0.000	0.000	5.521	5.828	58.900	20.859
5	5	0.750	0.000	0.000	0.000	0.000	38.650	10.429
6	3	0.750	0.000	20.000	4.601	4.601	38.650	10.429
7	1	0.750	0.000	0.000	0.000	0.000	18.405	0.000
8								

Table B2.7

INTERNAL CONDITIONS

Building Name: AD9BASEnv   Building Data File: AD9BASEnv.bdf.41   Revision: **
Time: 23:32:30 Date: 10:Jul:04   Consultant: Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
2. kitchen	SUNDAY	d09kitnv/ 3	bungalow d09; kitchen; sundays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	6	0.750	0.000	0.000	0.000	0.000	18.405	0.000
2	4	0.750	0.000	20.000	5.521	5.828	58.900	20.859
3	3	0.750	0.000	0.000	9.203	9.203	58.900	20.859
4	2	0.750	0.000	0.000	5.521	5.828	58.900	20.859
5	5	0.750	0.000	0.000	0.000	0.000	38.650	10.429
6	3	0.750	0.000	20.000	4.601	4.601	38.650	10.429
7	1	0.750	0.000	0.000	0.000	0.000	18.405	0.000
8								

Table B2.8

INTERNAL CONDITIONS

Building Name: AD9BASEnv
Time: 23:33:07 Date: 10:Jul:04

Building Data File: AD9BASEnv.bdf.41
Consultant:

Revision: **
Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
3. bed4	WEEKDAY	d09b04nv/ 1	bungalow d09; bed04; weekdays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	5	0.500	0.000	1.000	6.383	4.255	4.256	0.000
2	10	0.500	0.000	0.000	0.000	0.000	1.064	0.000
3	2	0.500	0.000	0.000	7.979	7.979	4.256	0.000
4	2	0.500	0.000	0.000	0.000	0.000	1.064	0.000
5	1	0.500	0.000	20.000	6.915	5.851	4.256	0.000
6	3	0.500	0.000	0.000	0.000	0.000	1.064	0.000
7	1	0.500	0.000	1.000	6.383	4.255	4.256	0.000
8								

Table B2.9

INTERNAL CONDITIONS

Building Name: AD9BASEnv
Time: 23:33:34 Date: 10:Jul:04

Building Data File: AD9BASEnv.bdf.41
Consultant:

Revision: **
Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
3. bed4	SATURDAY	d09b04nv/ 2	bungalow d09; bed04; saturdays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	6	0.500	0.000	1.000	6.383	4.255	4.256	0.000
2	9	0.500	0.000	0.000	0.000	0.000	1.064	0.000
3	2	0.500	0.000	0.000	9.575	10.106	39.362	18.085
4	1	0.500	0.000	0.000	6.915	5.851	4.256	0.000
5	1	0.500	0.000	0.000	0.000	0.000	1.064	0.000
6	1	0.500	0.000	20.000	6.915	5.851	4.256	0.000
7	3	0.500	0.000	0.000	0.000	0.000	1.064	0.000
8	1	0.500	0.000	1.000	6.383	4.255	4.256	0.000

Table B3.0

INTERNAL CONDITIONS

Building Name: AD9BASEnv   Building Data File: AD9BASEnv.bdf.41   Revision: **
Time: 23:34:09 Date: 10:Jul:04   Consultant: Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
3. bed4	SUNDAY	d09b04nv/ 3	bungalow d09; bed04; sundays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	6	0.500	0.000	1.000	6.383	4.255	4.256	0.000
2	9	0.500	0.000	0.000	0.000	0.000	1.064	0.000
3	2	0.500	0.000	0.000	9.575	10.106	39.362	18.085
4	1	0.500	0.000	0.000	6.915	5.851	4.256	0.000
5	1	0.500	0.000	0.000	0.000	0.000	1.064	0.000
6	1	0.500	0.000	20.000	6.915	5.851	4.256	0.000
7	3	0.500	0.000	0.000	0.000	0.000	1.064	0.000
8	1	0.500	0.000	1.000	6.383	4.255	4.256	0.000

Table B3.1

INTERNAL CONDITIONS

Building Name: AD9BASEnv Building Data File: AD9BASEnv.bdf.41 Revision: **
Time: 23:34:41 Date: 10:Jul:04 Consultant: Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
7. bed1	WEEKDAY	d09b01nv/ 1	bungalow d09; bed01; weekdays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	6	0.750	0.000	1.000	7.101	4.734	2.367	0.000
2	1	0.750	0.000	20.000	3.846	3.254	5.326	0.000
3	11	0.750	0.000	0.000	0.000	0.000	0.592	0.000
4	1	0.750	0.000	20.000	3.846	3.354	5.325	0.000
5	1	0.750	0.000	20.000	7.692	6.509	5.325	0.000
6	2	0.750	0.000	0.000	0.000	0.000	0.592	0.000
7	1	0.750	0.000	20.000	7.692	6.509	5.325	0.000
8	1	0.750	0.000	1.000	7.101	4.734	2.367	0.000

Table B3.2

INTERNAL CONDITIONS

Building Name: AD9BASEnv Building Data File: AD9BASEnv.bdf.41 Revision: **
Time: 23:35:16 Date: 10:Jul:04 Consultant: Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
7. bed1	SATURDAY	d09b01nv/ 2	bungalow d09; bed01; saturday; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	7	0.750	0.000	1.000	7.101	4.734	2.367	0.000
2	2	0.750	0.000	0.000	0.000	0.000	0.592	0.000
3	1	0.750	0.000	0.000	3.846	3.254	2.959	0.000
4	8	0.750	0.000	0.000	0.000	0.000	0.592	0.000
5	1	0.750	0.000	20.000	3.846	3.254	5.325	0.000
6	1	0.750	0.000	20.000	7.692	6.509	5.325	0.000
7	4	0.750	0.000	0.000	0.000	0.000	0.592	0.000
8								

Table B3.3

INTERNAL CONDITIONS

Building Name: AD9BASEnv   Building Data File: AD9BASEnv.bdf.41   Revision: **
Time: 23:35:51 Date: 10:Jul:04   Consultant: Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
7. bed1	SUNDAY	d09b01nv/ 3	bungalow d09; bed01; sunday; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	8	0.750	0.000	1.000	7.101	4.734	2.367	0.000
2	7	0.750	0.000	0.000	0.000	0.000	0.592	0.000
3	3	0.750	0.000	0.000	3.550	2.367	2.367	0.000
4	1	0.750	0.000	0.000	0.000	0.000	0.592	0.000
5	1	0.750	0.000	20.000	7.692	6.509	5.326	0.000
6	2	0.750	0.000	0.000	0.000	0.000	0.592	0.000
7	1	0.750	0.000	20.000	7.692	6.509	5.326	0.000
8	1	0.750	0.000	1.000	7.101	4.734	2.367	0.000

Table B3.4

INTERNAL CONDITIONS

Building Name: AD9BASEnv   Building Data File: AD9BASEnv.bdf.41   Revision: **
Time: 23:36:19 Date: 10:Jul:04   Consultant: Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
8. bed2	WEEKDAY	d09b02nv/ 1	bungalow d09; bed02; weekdays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	6	0.500	0.000	1.000	10.620	7.080	3.540	0.000
2	1	0.500	0.000	20.000	5.752	4.867	4.425	0.000
3	8	0.500	0.000	0.000	0.000	0.000	0.885	0.000
4	3	0.500	0.000	0.000	5.752	4.867	4.425	0.000
5	1	0.500	0.000	0.000	0.000	0.000	0.885	0.000
6	1	0.500	0.000	20.000	11.504	9.735	4.425	0.000
7	2	0.500	0.000	0.000	0.000	0.000	0.885	0.000
8	2	0.500	0.000	1.000	10.620	7.080	3.540	0.000

Table B3.5

INTERNAL CONDITIONS

Building Name: AD9BASEnv   Building Data File: AD9BASEnv.bdf.41   Revision: **
Time: 23:36:55   Date: 10:Jul:04   Consultant: Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
8. bed2	SATURDAY	d09b02nv/ 2	bungalow d09; bed02; saturdays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	7	0.500	0.000	1.000	10.620	7.080	3.540	0.000
2	2	0.500	0.000	20.000	5.750	4.867	4.425	0.000
3	9	0.500	0.000	0.000	0.000	0.000	0.885	0.000
4	1	0.500	0.000	20.000	5.750	4.867	4.425	0.000
5	1	0.500	0.000	20.000	11.504	9.735	4.425	0.000
6	3	0.500	0.000	0.000	0.000	0.000	0.885	0.000
7	1	0.500	0.000	1.000	5.310	3.540	3.540	0.000
8								

Table B3.6

INTERNAL CONDITIONS

Building Name: AD9BASEnv   Building Data File: AD9BASEnv.bdf.41   Revision: **
Time: 23:37:22 Date: 10:Jul:04   Consultant: Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
8. bed2	SUNDAY	d09b02nv/ 3	bungalow d09; bed02; sundays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	7	0.500	0.000	1.000	10.620	7.080	3.540	0.000
2	2	0.500	0.000	20.000	5.752	4.867	4.425	0.000
3	6	0.500	0.000	0.000	0.000	0.000	0.885	0.000
4	3	0.500	0.000	0.000	5.752	4.867	4.425	0.000
5	1	0.500	0.000	0.000	0.000	0.000	0.885	0.000
6	1	0.500	0.000	20.000	11.504	9.735	4.425	0.000
7	2	0.500	0.000	0.000	0.000	0.000	0.885	0.000
8	2	0.500	0.000	1.000	10.620	7.080	3.540	0.000

Table B3.7

INTERNAL CONDITIONS

Building Name: AD9BASEnv   Building Data File: AD9BASEnv.bdf.41   Revision: **
Time: 23:38:52 Date: 10:Jul:04   Consultant: Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
10. family	WEEKDAY	d09famnv/ 1	bungalow d09; family; weekdays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	10	0.500	0.000	0.000	0.000	0.000	0.476	0.000
2	1	0.500	0.000	0.000	4.286	4.524	13.571	0.000
3	4	0.500	0.000	0.000	0.000	0.000	0.476	0.000
4	4	0.500	0.000	0.000	6.191	5.238	7.143	0.000
5	2	0.500	0.000	20.000	0.000	0.000	1.905	0.000
6	1	0.500	0.000	20.000	18.571	15.714	7.143	0.000
7	2	0.500	0.000	0.000	0.000	0.000	0.476	0.000
8								

Table B3.8

INTERNAL CONDITIONS

Building Name: AD9BASEnv Building Data File: AD9BASEnv.bdf.41 Revision: **
Time: 23:38:27 Date: 10:Jul:04 Consultant: Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
10. family	SATURDAY	d09famnv/ 2	bungalow d09; family; saturdays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	7	0.500	0.000	0.000	0.000	0.000	0.476	0.000
2	6	0.500	0.000	0.000	6.191	5.238	7.143	0.000
3	5	0.500	0.000	0.000	0.000	0.000	1.905	0.000
4	1	0.500	0.000	0.000	3.095	2.619	7.143	0.000
5	2	0.500	0.000	20.000	0.000	0.000	1.905	0.000
6	2	0.500	0.000	20.000	18.571	15.714	4.762	0.000
7	1	0.500	0.000	20.000	12.381	10.476	4.762	0.000
8								

Table B3.9

INTERNAL CONDITIONS

Building Name: AD9BASEnv   Building Data File: AD9BASEnv.bdf.41   Revision: **
Time: 23:37:51 Date: 10:Jul:04   Consultant: Program: A-Tas 8.40

Zone	Day type	IC - Code	Internal Conditions Description
10. family	SUNDAY	d09famnv/ 3	bungalow d09; family; sundays; nv

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	7	0.500	0.000	0.000	0.000	0.000	0.476	0.000
2	6	0.500	0.000	0.000	6.191	5.238	7.143	0.000
3	2	0.500	0.000	0.000	0.000	0.000	1.905	0.000
4	3	0.500	0.000	0.000	9.286	7.857	7.143	0.000
5	1	0.500	0.000	0.000	0.000	0.000	1.905	0.000
6	2	0.500	0.000	20.000	0.000	0.000	1.905	0.000
7	1	0.500	0.000	20.000	18.511	15.714	4.762	0.000
8	2	0.500	0.000	0.000	0.000	0.000	0.476	0.000

Table C1.0

Expt 1A: Colour - Thermal Performance, Thermal Comfort and Cooling Loads

	C4 (BASE)												C3											
	Bed1			Bed2			Bed3			Family			Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	
1	32.5	75	X	32.9	80	X	31.8	73	X	31.7	72	X	32.4	76	X	32.8	80	X	31.7	74	X	31.7	72	X
2	32.2	76	X	32.6	81	X	31.6	74	X	31.5	71	X	32.1	76	X	32.6	81	X	31.5	74	X	31.4	72	X
3	31.8	76	X	32.4	82	X	31.2	73	X	31.3	71	X	31.8	76	X	32.3	82	X	31.1	74	X	31.2	71	X
4	31.5	76	X	32.0	82	X	30.8	73	X	31.0	70	X	31.4	76	X	32.0	83	X	30.8	73	X	30.9	70	X
5	31.1	76	X	31.7	83	X	30.5	73	X	30.7	70	X	31.1	76	X	31.7	83	X	30.4	73	X	30.6	70	X
6	30.8	76	X	31.5	83	X	30.2	73	X	30.1	71	X	30.8	76	X	31.4	84	X	30.2	74	X	30.0	71	X
7	26.7	85	1.0m/s	27.7	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.5m/s	26.6	86	1.0m/s	27.7	81	1.5m/s	27.7	80	1.5m/s	27.2	83	1.5m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	86	X	28.3	83	X
9	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X	29.7	88	X	29.9	87	X	30.6	84	X	30.1	85	X
10	31.0	89	X	31.2	88	X	31.9	84	X	31.3	87	X	31.0	89	X	31.1	88	X	31.8	85	X	31.2	87	X
11	32.3	88	X	32.3	88	X	32.9	85	X	32.9	85	X	32.3	88	X	32.3	88	X	32.9	85	X	32.8	85	X
12	33.4	83	X	33.3	84	X	34.0	80	X	33.0	85	X	33.3	83	X	33.2	84	X	34.0	80	X	32.9	85	X
13	34.1	84	X	34.0	84	X	34.6	81	X	33.6	86	X	34.1	84	X	33.9	85	X	34.5	82	X	33.5	86	X
14	33.8	75	X	34.0	76	X	34.4	73	X	33.8	77	X	33.8	75	X	33.8	76	X	34.3	74	X	33.7	78	X
15	34.8	68	X	34.5	70	X	34.9	67	X	34.2	71	X	34.7	68	X	34.3	70	X	34.8	68	X	34.1	71	X
16	33.9	78	X	34.3	76	X	33.9	78	X	34.1	77	X	33.9	78	X	34.3	77	X	33.9	78	X	34.1	77	X
17	32.9	83	X	33.4	81	X	33.8	79	X	33.9	78	X	32.8	83	X	33.3	81	X	33.7	79	X	33.8	79	X
18	29.9	74	X	30.4	73	X	30.4	73	X	31.3	70	X	29.9	75	X	30.3	74	X	30.3	73	X	31.2	71	X
19	29.3	83	X	29.3	82	X	29.4	82	X	30.5	77	X	29.3	83	X	29.3	83	X	29.3	82	X	30.5	77	X
20	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X	29.8	81	X	30.5	78	X	30.5	78	X	30.9	76	X
21	28.3	85	X	28.6	83	X	28.6	83	X	32.6	69	X	28.2	85	X	28.5	83	X	28.6	83	X	32.5	69	X
22	28.7	82	X	29.6	78	X	29.5	78	X	30.7	73	X	28.7	82	X	29.5	78	X	29.5	78	X	30.7	74	X
23	33.0	67	X	32.1	72	X	31.4	71	X	31.0	70	X	32.9	68	X	32.0	73	X	31.2	72	X	30.9	71	X
24	31.9	72	X	32.2	75	X	31.3	72	X	31.2	69	X	31.8	72	X	32.1	75	X	31.1	72	X	31.1	69	X
Max	34.8	89		34.5	88		34.9	85		34.2	87		34.7	89		34.3	88		34.8	86		34.1	87	
Min	26.7	67		27.7	70		27.8	67		27.2	69		26.6	68		27.7	70		27.7	68		27.2	69	
Mean	31.3	79		31.6	80		31.4	77		31.6	76		31.2	80		31.5	81		31.3	78		31.5	76	
TC hours			2			2			2			1			2			2			1			1
CL (kWh)			1933			1398			1399			3827			1890			1355			1347			3726

	C4 (BASE)	C3
Total annual CL (kWh)	8556	8318
CL Index (kWh/m2)	143	139

Table C1.0 – continue

	C2													C1										
	Bed1			Bed2			Bed3			Family			Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.3	76	X	32.7	80	X	31.6	74	X	31.6	72	X	32.3	76	X	32.6	81	X	31.5	75	X	31.5	73	X
2	32.1	76	X	32.5	82	X	31.4	74	X	31.4	72	X	32.0	77	X	32.4	82	X	31.3	75	X	31.3	72	X
3	31.7	76	X	32.2	83	X	31.1	74	X	31.1	71	X	31.6	77	X	32.1	83	X	31.0	74	X	31.0	72	X
4	31.4	76	X	31.9	83	X	30.7	74	X	30.8	70	X	31.3	77	X	31.8	83	X	30.6	74	X	30.8	71	X
5	31.0	76	X	31.6	84	X	30.3	74	X	30.6	70	X	30.9	77	X	31.5	84	X	30.3	74	X	30.5	70	X
6	30.7	77	X	31.3	84	X	30.1	74	X	30.0	71	X	30.7	77	X	31.2	84	X	30.0	74	X	29.9	71	X
7	26.6	86	1.0m/s	27.7	81	1.5m/s	27.7	81	1.5m/s	27.1	83	1.0m/s	26.6	86	1.0m/s	27.6	81	1.5m/s	27.7	81	1.5m/s	27.1	83	1.0m/s
8	27.3	89	1.5m/s	27.6	87	1.5m/s	27.9	86	X	28.3	83	X	27.2	89	1.5m/s	27.6	87	1.5m/s	27.8	86	1.5m/s	28.3	83	X
9	29.7	88	X	29.8	88	X	30.5	85	X	30.1	86	X	29.7	89	X	29.8	88	X	30.5	85	X	30.0	86	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.1	87	X	31.0	89	X	31.0	88	X	31.7	85	X	31.0	88	X
11	32.3	88	X	32.2	88	X	32.8	85	X	32.7	85	X	32.3	88	X	32.1	88	X	32.8	85	X	32.6	86	X
12	33.3	84	X	33.1	84	X	33.9	81	X	32.8	86	X	33.2	84	X	33.0	85	X	33.8	81	X	32.7	86	X
13	34.1	84	X	33.8	85	X	34.5	82	X	33.4	87	X	34.0	84	X	33.7	85	X	34.3	82	X	33.3	87	X
14	33.8	76	X	33.7	77	X	34.2	74	X	33.5	78	X	33.7	76	X	33.6	77	X	34.1	75	X	33.4	79	X
15	34.6	68	X	34.1	71	X	34.7	68	X	33.9	72	X	34.5	69	X	34.0	71	X	34.6	69	X	33.8	72	X
16	33.9	78	X	34.2	77	X	33.9	78	X	34.0	78	X	33.9	78	X	34.1	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.3	81	X	33.7	79	X	33.8	79	X	32.8	83	X	33.2	82	X	33.6	80	X	33.7	79	X
18	29.9	75	X	30.2	74	X	30.3	73	X	31.2	71	X	29.8	75	X	30.2	74	X	30.2	74	X	31.1	71	X
19	29.3	83	X	29.2	83	X	29.3	83	X	30.4	78	X	29.2	83	X	29.2	83	X	29.2	83	X	30.3	78	X
20	29.8	81	X	30.4	78	X	30.4	78	X	30.8	76	X	29.7	81	X	30.4	79	X	30.3	79	X	30.8	76	X
21	28.2	85	X	28.5	83	X	28.5	83	X	32.4	69	X	28.2	85	X	28.4	84	X	28.5	84	X	32.3	70	X
22	28.7	82	X	29.4	79	X	29.4	79	X	30.6	74	X	28.6	82	X	29.4	79	X	29.3	79	X	30.6	74	X
23	32.8	68	X	31.9	73	X	31.1	72	X	30.9	71	X	32.7	68	X	31.8	74	X	31.0	73	X	30.8	71	X
24	31.7	73	X	32.0	76	X	31.0	73	X	31.0	70	X	31.6	73	X	31.9	76	X	30.9	73	X	30.9	70	X
Max	34.6	89		34.2	88		34.7	86		34.0	87		34.5	89		34.1	88		34.6	86		34.0	88	
Min	26.6	68		27.6	71		27.7	68		27.1	69		26.6	68		27.6	71		27.7	69		27.1	70	
Mean	31.2	80		31.4	81		31.3	78		31.4	77		31.1	80		31.4	81		31.2	78		31.3	77	
TC hours			2			2			1			1			2			2			2			1
CL (kWh)			1847			1312			1294			3626			1804			1269			1242			3527

	C2	C1
Total annual CL (kWh)	8079	7841
CL Index(kWh/m2))	135	131

Table C1.1

Expt 1A: Air Space - Thermal Performance, Thermal Comfort and Cooling Loads

	AS1											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.5	75	X	32.9	80	X	31.8	73	X	31.8	72	X
2	32.2	76	X	32.6	81	X	31.6	73	X	31.5	71	X
3	31.8	76	X	32.3	82	X	31.2	73	X	31.3	71	X
4	31.5	76	X	32.0	82	X	30.8	73	X	31.0	70	X
5	31.1	76	X	31.7	83	X	30.5	73	X	30.7	70	X
6	30.8	76	X	31.4	83	X	30.2	73	X	30.1	71	X
7	26.7	85	1.0m/s	27.7	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.5m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X
9	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X
10	31.0	89	X	31.2	88	X	31.9	84	X	31.3	86	X
11	32.3	88	X	32.4	87	X	33.0	84	X	32.9	84	X
12	33.4	83	X	33.3	83	X	34.1	80	X	33.1	85	X
13	34.2	84	X	34.1	84	X	34.7	81	X	33.7	85	X
14	33.8	75	X	34.2	75	X	34.4	73	X	33.9	77	X
15	34.8	68	X	34.6	69	X	34.9	67	X	34.3	70	X
16	34.0	78	X	34.4	76	X	34.0	78	X	34.2	77	X
17	32.9	83	X	33.5	80	X	33.9	79	X	34.0	78	X
18	30.0	74	X	30.4	73	X	30.5	72	X	31.4	70	X
19	29.4	82	X	29.4	82	X	29.5	82	X	30.6	77	X
20	29.9	81	X	30.6	78	X	30.6	78	X	31.0	75	X
21	28.3	84	X	28.6	83	X	28.7	83	X	32.6	68	X
22	28.8	81	X	29.6	78	X	29.6	78	X	30.8	73	X
23	33.0	67	X	32.1	72	X	31.4	71	X	31.1	70	X
24	31.9	72	X	32.2	75	X	31.3	71	X	31.3	69	X
Max	34.8	89		34.6	88		34.9	85		34.3	86	
Min	26.7	67		27.7	69		27.8	67		27.2	68	
Mean	31.3	79		31.6	80		31.5	77		31.6	76	
TC hours			2			2			2			1
CL (kWh)			1947			1415			1420			3894

	AS2 (BASE)											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	
1	32.5	75	X	32.9	80	X	31.8	73	X	31.7	72	X
2	32.2	76	X	32.6	81	X	31.6	74	X	31.5	71	X
3	31.8	76	X	32.4	82	X	31.2	73	X	31.3	71	X
4	31.5	76	X	32.0	82	X	30.8	73	X	31.0	70	X
5	31.1	76	X	31.7	83	X	30.5	73	X	30.7	70	X
6	30.8	76	X	31.5	83	X	30.2	73	X	30.1	71	X
7	26.7	85	1.0m/s	27.7	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.5m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X
9	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X
10	31.0	89	X	31.2	88	X	31.9	84	X	31.3	87	X
11	32.3	88	X	32.3	88	X	32.9	85	X	32.9	85	X
12	33.4	83	X	33.3	84	X	34.0	80	X	33.0	85	X
13	34.1	84	X	34.0	84	X	34.6	81	X	33.6	86	X
14	33.8	75	X	34.0	76	X	34.4	73	X	33.8	77	X
15	34.8	68	X	34.5	70	X	34.9	67	X	34.2	71	X
16	33.9	78	X	34.3	76	X	33.9	78	X	34.1	77	X
17	32.9	83	X	33.4	81	X	33.8	79	X	33.9	78	X
18	29.9	74	X	30.4	73	X	30.4	73	X	31.3	70	X
19	29.3	83	X	29.3	82	X	29.4	82	X	30.5	77	X
20	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X
21	28.3	85	X	28.6	83	X	28.6	83	X	32.6	69	X
22	28.7	82	X	29.6	78	X	29.5	78	X	30.7	73	X
23	33.0	67	X	32.1	72	X	31.4	71	X	31.0	70	X
24	31.9	72	X	32.2	75	X	31.3	72	X	31.2	69	X
Max	34.8	89		34.5	88		34.9	85		34.2	87	
Min	26.7	67		27.7	70		27.8	67		27.2	69	
Mean	31.3	79		31.6	80		31.4	77		31.6	76	
TC hours			2			2			2			1
CL (kWh)			1933			1398			1399			3827

	AS1	AS2 (BASE)
Total annual CL (kWh)	8676	8556
CLI (kWh/m2)	145	143

Table C1.1 – continue

Hour	AS3 Bed1 T	AS3 Bed1 RH	AS3 Bed1 TC	AS3 Bed2 T	AS3 Bed2 RH	AS3 Bed2 TC	AS3 Bed3 T	AS3 Bed3 RH	AS3 Bed3 TC	AS3 Family T	AS3 Family RH	AS3 Family TC	AS4 Bed1 T	AS4 Bed1 RH	AS4 Bed1 TC	AS4 Bed2 T	AS4 Bed2 RH	AS4 Bed2 TC	AS4 Bed3 T	AS4 Bed3 RH	AS4 Bed3 TC	AS4 Family T	AS4 Family RH	AS4 Family TC
1	32.5	75	X	32.9	80	X	31.8	74	X	31.7	72	X	32.5	75	X	32.9	80	X	31.8	74	X	31.7	72	X
2	32.2	76	X	32.6	81	X	31.6	74	X	31.5	71	X	32.2	76	X	32.6	81	X	31.6	74	X	31.5	71	X
3	31.8	76	X	32.4	82	X	31.2	73	X	31.3	71	X	31.9	76	X	32.4	82	X	31.2	73	X	31.3	71	X
4	31.5	76	X	32.1	82	X	30.8	73	X	31.0	70	X	31.5	76	X	32.1	82	X	30.8	73	X	31.0	70	X
5	31.1	76	X	31.7	83	X	30.5	73	X	30.7	70	X	31.1	76	X	31.7	83	X	30.5	73	X	30.7	70	X
6	30.8	76	X	31.5	83	X	30.2	73	X	30.1	71	X	30.8	76	X	31.5	83	X	30.2	73	X	30.1	71	X
7	26.7	85	1.0m/s	27.7	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.5m/s	26.7	85	1.0m/s	27.7	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.5m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X
9	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X
10	31.0	89	X	31.2	88	X	31.9	84	X	31.2	87	X	31.0	89	X	31.2	88	X	31.9	85	X	31.2	87	X
11	32.3	88	X	32.3	88	X	32.9	85	X	32.9	85	X	32.3	88	X	32.3	88	X	32.9	85	X	32.8	85	X
12	33.4	83	X	33.2	84	X	34.0	80	X	33.0	85	X	33.4	83	X	33.2	84	X	34.0	80	X	32.9	85	X
13	34.1	84	X	34.0	84	X	34.6	81	X	33.6	86	X	34.1	84	X	33.9	84	X	34.6	81	X	33.5	86	X
14	33.8	75	X	33.9	76	X	34.4	74	X	33.7	77	X	33.8	75	X	33.9	76	X	34.3	74	X	33.7	77	X
15	34.8	68	X	34.4	70	X	34.8	68	X	34.2	71	X	34.7	68	X	34.4	70	X	34.8	68	X	34.1	71	X
16	33.9	78	X	34.3	76	X	33.9	78	X	34.1	77	X	33.9	78	X	34.3	76	X	33.9	78	X	34.1	77	X
17	32.9	83	X	33.4	81	X	33.8	79	X	33.9	78	X	32.9	83	X	33.4	81	X	33.8	79	X	33.9	79	X
18	29.9	74	X	30.3	73	X	30.4	73	X	31.3	70	X	29.9	74	X	30.3	73	X	30.4	73	X	31.3	70	X
19	29.3	83	X	29.3	82	X	29.4	82	X	30.5	77	X	29.3	83	X	29.3	82	X	29.4	82	X	30.5	77	X
20	29.9	81	X	30.5	78	X	30.5	78	X	30.9	76	X	29.8	81	X	30.5	78	X	30.5	78	X	30.9	76	X
21	28.2	85	X	28.6	83	X	28.6	83	X	32.5	69	X	28.2	85	X	28.6	83	X	28.6	83	X	32.5	69	X
22	28.7	82	X	29.5	78	X	29.5	78	X	30.7	73	X	28.7	82	X	29.5	78	X	29.5	78	X	30.7	73	X
23	33.0	67	X	32.1	72	X	31.3	71	X	31.0	70	X	33.0	67	X	32.1	72	X	31.3	71	X	31.0	70	X
24	31.9	72	X	32.2	75	X	31.2	72	X	31.2	69	X	31.9	72	X	32.2	75	X	31.2	72	X	31.2	69	X
Max	34.8	89		34.4	88		34.8	85		34.2	87		34.7	89		34.4	88		34.8	85		34.1	87	
Min	26.7	67		27.7	70		27.8	68		27.2	69		26.7	67		27.7	70		27.8	68		27.2	69	
Mean	31.3	79		31.6	81		31.4	77		31.5	76		31.3	79		31.6	81		31.4	77		31.5	76	
TC hours			2			2			2			1			2			2			2			1
CL (kWh)			1926			1390			1389			3797			1922			1385			1383			3779

	AS3	AS4
Total annual CL (kWh)	8501	8469
CLI (kWh/m2)	142	141

Table C1.2

RIn00 (BASE)

	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.5	75	X	32.9	80	X	31.8	73	X	31.7	72	X
2	32.2	76	X	32.6	81	X	31.6	74	X	31.5	71	X
3	31.8	76	X	32.4	82	X	31.2	73	X	31.3	71	X
4	31.5	76	X	32.0	82	X	30.8	73	X	31.0	70	X
5	31.1	76	X	31.7	83	X	30.5	73	X	30.7	70	X
6	30.8	76	X	31.5	83	X	30.2	73	X	30.1	71	X
7	26.7	85	1.0m/s	27.7	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.5m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X
9	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X
10	31.0	89	X	31.2	88	X	31.9	84	X	31.3	87	X
11	32.3	88	X	32.3	88	X	32.9	85	X	32.9	85	X
12	33.4	83	X	33.3	84	X	34.0	80	X	33.0	85	X
13	34.1	84	X	34.0	84	X	34.6	81	X	33.6	86	X
14	33.8	75	X	34.0	76	X	34.4	73	X	33.8	77	X
15	34.8	68	X	34.5	70	X	34.9	67	X	34.2	71	X
16	33.9	78	X	34.3	76	X	33.9	78	X	34.1	77	X
17	32.9	83	X	33.4	81	X	33.8	79	X	33.9	78	X
18	29.9	74	X	30.4	73	X	30.4	73	X	31.3	70	X
19	29.3	83	X	29.3	82	X	29.4	82	X	30.5	77	X
20	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X
21	28.3	85	X	28.6	83	X	28.6	83	X	32.6	69	X
22	28.7	82	X	29.6	78	X	29.5	78	X	30.7	73	X
23	33.0	67	X	32.1	72	X	31.4	71	X	31.0	70	X
24	31.9	72	X	32.2	75	X	31.3	72	X	31.2	69	X
Max	34.8	89		34.5	88		34.9	85		34.2	87	
Min	26.7	67		27.7	70		27.8	67		27.2	69	
Mean	31.3	79		31.6	80		31.4	77		31.6	76	
TC hours			2			2			2			1
Annual CL (kWh)			1933			1398			1399			3827

RIn01

	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.5	75	X	32.9	80	X	31.8	74	X	31.7	72	X
2	32.2	76	X	32.7	81	X	31.6	74	X	31.5	71	X
3	31.9	76	X	32.4	82	X	31.2	73	X	31.3	71	X
4	31.5	76	X	32.1	82	X	30.8	73	X	31.0	70	X
5	31.1	76	X	31.8	83	X	30.5	73	X	30.7	70	X
6	30.8	76	X	31.5	83	X	30.2	73	X	30.1	71	X
7	26.7	85	1.0m/s	27.7	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.5m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X
9	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X
10	31.0	89	X	31.2	88	X	31.9	85	X	31.2	87	X
11	32.3	88	X	32.3	88	X	32.9	85	X	32.8	85	X
12	33.4	83	X	33.2	84	X	34.0	80	X	32.9	85	X
13	34.1	84	X	33.9	84	X	34.6	81	X	33.5	86	X
14	33.8	75	X	33.9	76	X	34.3	74	X	33.7	77	X
15	34.7	68	X	34.4	70	X	34.8	68	X	34.1	71	X
16	33.9	78	X	34.3	76	X	33.9	78	X	34.1	77	X
17	32.8	83	X	33.4	81	X	33.8	79	X	33.9	79	X
18	29.9	74	X	30.3	73	X	30.4	73	X	31.3	70	X
19	29.3	83	X	29.3	82	X	29.4	82	X	30.5	77	X
20	29.8	81	X	30.5	78	X	30.5	78	X	30.9	76	X
21	28.2	85	X	28.6	83	X	28.6	83	X	32.5	69	X
22	28.7	82	X	29.5	78	X	29.5	78	X	30.7	74	X
23	33.0	67	X	32.1	72	X	31.3	71	X	31.0	70	X
24	31.9	72	X	32.2	75		31.2	72	X	31.2	69	X
Max	34.7	89		34.4	88		34.8	85		34.1	87	
Min	26.7	67		27.7	70		27.8	68		27.2	69	
Mean	31.3	79		31.6	81		31.4	77		31.5	76	
TC hours			2			2			2			1
Annual CL (kWh)			1923			1386			1383			3768

	RIn00 (BASE)	RIn01
Total annual CL (kWh)	8556	8459
CLI(kWh/m2)	143	141

Table C1.2 – continue

RIn02

Hour	Bed1 T	Bed1 RH	Bed1 TC	Bed2 T	Bed2 RH	Bed2 TC	Bed3 T	Bed3 RH	Bed3 TC	Family T	Family RH	Family TC
1	32.5	75	X	32.9	80	X	31.8	74	X	31.7	72	X
2	32.2	76	X	32.7	81	X	31.5	74	X	31.5	71	X
3	31.9	76	X	32.4	82	X	31.2	73	X	31.2	71	X
4	31.5	76	X	32.1	82	X	30.8	73	X	31.0	70	X
5	31.2	76	X	31.8	83	X	30.5	73	X	30.7	70	X
6	30.9	76	X	31.5	83	X	30.3	73	X	30.1	71	X
7	26.7	85	1.0m/s	27.7	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.5m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X
9	29.7	88	X	29.9	87	X	30.6	84	X	30.1	85	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.2	87	X
11	32.3	88	X	32.3	88	X	32.9	85	X	32.8	85	X
12	33.3	83	X	33.2	84	X	34.0	80	X	32.9	85	X
13	34.1	84	X	33.9	85	X	34.5	82	X	33.5	86	X
14	33.8	75	X	33.8	76	X	34.3	74	X	33.6	78	X
15	34.7	68	X	34.3	70	X	34.8	68	X	34.1	71	X
16	33.9	78	X	34.3	77	X	33.9	78	X	34.1	77	X
17	32.8	83	X	33.3	81	X	33.7	79	X	33.8	79	X
18	29.9	75	X	30.3	74	X	30.3	73	X	31.2	71	X
19	29.3	83	X	29.3	83	X	29.3	82	X	30.5	77	X
20	29.8	81	X	30.5	78	X	30.5	78	X	30.9	76	X
21	28.2	85	X	28.5	83	X	28.6	83	X	32.5	69	X
22	28.7	82	X	29.5	78	X	29.5	78	X	30.7	74	X
23	33.0	67	X	32.1	72	X	31.3	72	X	31.0	71	X
24	31.9	72	X	32.2	75	X	31.2	72	X	31.2	69	X
Max	34.7	89		34.3	88		34.8	85		34.1	87	
Min	26.7	67		27.7	70		27.8	68		27.2	69	
Mean	31.3	80		31.6	81		31.4	77		31.5	76	
TC hours			2			2			2			1
Annual CL (kWh)			1912			1374			1369			3726

RIn03

Hour	Bed1 T	Bed1 RH	Bed1 TC	Bed2 T	Bed2 RH	Bed2 TC	Bed3 T	Bed3 RH	Bed3 TC	Family T	Family RH	Family TC
1	32.5	75	X	32.9	80	X	31.7	74	X	31.7	72	X
2	32.2	76	X	32.7	81	X	31.5	74	X	31.5	71	X
3	31.9	76	X	32.4	82	X	31.2	73	X	31.2	71	X
4	31.5	76	X	32.1	82	X	30.8	73	X	31.0	70	X
5	31.2	76	X	31.8	83	X	30.5	73	X	30.7	70	X
6	30.9	76	X	31.5	83	X	30.3	73	X	30.1	71	X
7	26.7	85	1.0m/s	27.7	81	1.5m/s	27.7	80	1.5m/s	27.2	83	1.0m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X
9	29.7	88	X	29.9	87	X	30.6	84	X	30.1	85	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.2	87	X
11	32.3	88	X	32.2	88	X	32.9	85	X	32.8	85	X
12	33.3	83	X	33.2	84	X	33.9	81	X	32.9	86	X
13	34.1	84	X	33.9	85	X	34.5	82	X	33.4	87	X
14	33.8	75	X	33.8	76	X	34.3	74	X	33.6	78	X
15	34.7	68	X	34.2	70	X	34.7	68	X	34.0	72	X
16	33.9	78	X	34.2	77	X	33.9	78	X	34.1	77	X
17	32.8	83	X	33.3	81	X	33.7	79	X	33.8	79	X
18	29.9	75	X	30.3	74	X	30.3	73	X	31.2	71	X
19	29.3	83	X	29.3	83	X	29.3	82	X	30.4	77	X
20	29.8	81	X	30.5	78	X	30.4	78	X	30.9	76	X
21	28.2	85	X	28.5	83	X	28.6	83	X	32.5	69	X
22	28.7	82	X	29.5	78	X	29.5	78	X	30.7	74	X
23	33.0	67	X	32.1	72	X	31.3	72	X	30.9	71	X
24	31.9	72	X	32.2	75	X	31.2	72	X	31.2	69	X
Max	34.7	89		34.2	88		34.7	85		34.1	87	
Min	26.7	67		27.7	70		27.7	68		27.2	69	
Mean	31.3	80		31.5	81		31.4	77		31.5	76	
TC hours			2			2			2			1
Annual CL (kWh)			1905			1365			1358			3695

	RIn02	RIn03
Total annual CL (kWh)	8382	8322
CLI(kWh/m2)	140	139

Table C1.2 – continue

RIn04	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.5	75	X	32.9	80	X	31.7	74	X	31.7	72	X
2	32.2	76	X	32.7	81	X	31.5	74	X	31.5	71	X
3	31.9	76	X	32.4	82	X	31.2	73	X	31.2	71	X
4	31.5	76	X	32.1	82	X	30.8	73	X	31.0	70	X
5	31.2	76	X	31.8	83	X	30.5	73	X	30.7	70	X
6	30.9	76	X	31.5	83	X	30.3	73	X	30.1	71	X
7	26.7	85	1.0m/s	27.7	81	1.5m/s	27.7	80	1.5m/s	27.2	83	1.0m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X
9	29.7	88	X	29.9	87	X	30.6	84	X	30.1	85	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.2	87	X
11	32.3	88	X	32.2	88	X	32.9	85	X	32.8	85	X
12	33.3	84	X	33.1	84	X	33.9	81	X	32.8	86	X
13	34.1	84	X	33.8	85	X	34.5	82	X	33.4	87	X
14	33.8	76	X	33.8	76	X	34.2	74	X	33.6	78	X
15	34.6	68	X	34.2	71	X	34.7	68	X	34.0	72	X
16	33.9	78	X	34.2	77	X	33.9	78	X	34.0	77	X
17	32.8	83	X	33.3	81	X	33.7	79	X	33.8	79	X
18	29.9	75	X	30.3	74	X	30.3	73	X	31.2	71	X
19	29.3	83	X	29.3	83	X	29.3	82	X	30.4	77	X
20	29.8	81	X	30.5	78	X	30.4	78	X	30.9	76	X
21	28.2	85	X	28.5	83	X	28.5	83	X	32.5	69	X
22	28.7	82	X	29.5	78	X	29.4	79	X	30.7	74	X
23	33.0	67	X	32.0	73	X	31.3	72	X	30.9	71	X
24	31.9	72	X	32.2	75	X	31.2	72	X	31.1	69	X
Max	34.6	89		34.2	88		34.7	85		34.0	87	
Min	26.7	67		27.7	71		27.7	68		27.2	69	
Mean	31.3	80		31.5	81		31.3	78		31.5	76	
TC hours			2			2			2			1
Annual CL (kWh)			1898			1358			1349			3671

RIn05	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.5	75	X	32.9	80	X	31.7	74	X	31.7	72	X
2	32.2	76	X	32.7	81	X	31.5	74	X	31.5	71	X
3	31.9	76	X	32.4	82	X	31.2	73	X	31.2	71	X
4	31.5	76	X	32.1	82	X	30.8	73	X	31.0	70	X
5	31.2	76	X	31.8	83	X	30.5	73	X	30.7	70	X
6	30.9	76	X	31.5	83	X	30.3	73	X	30.1	71	X
7	26.7	85	1.0m/s	27.7	81	1.5m/s	27.7	80	1.5m/s	27.2	83	1.0m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X
9	29.7	88	X	29.9	87	X	30.5	85	X	30.1	85	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.1	87	X
11	32.3	88	X	32.2	88	X	32.9	85	X	32.7	85	X
12	33.3	84	X	33.1	84	X	33.9	81	X	32.8	86	X
13	34.1	84	X	33.8	85	X	34.5	82	X	33.4	87	X
14	33.8	76	X	33.7	77	X	34.2	74	X	33.5	78	X
15	34.6	68	X	34.1	71	X	34.7	68	X	33.9	72	X
16	33.9	78	X	34.2	77	X	33.9	78	X	34.0	77	X
17	32.8	83	X	33.3	81	X	33.7	79	X	33.8	79	X
18	29.9	75	X	30.2	74	X	30.3	73	X	31.2	71	X
19	29.3	83	X	29.2	83	X	29.3	83	X	30.4	78	X
20	29.8	81	X	30.4	78	X	30.4	78	X	30.9	76	X
21	28.2	85	X	28.5	83	X	28.5	83	X	32.4	69	X
22	28.7	82	X	29.5	78	X	29.4	79	X	30.7	74	X
23	33.0	67	X	32.0	73	X	31.2	72	X	30.9	71	X
24	31.9	72	X	32.2	75	X	31.2	72	X	31.1	69	X
Max	34.6	89		34.2	88		34.7	85		34.0	87	
Min	26.7	67		27.7	71		27.7	68		27.2	69	
Mean	31.3	80		31.5	81		31.3	78		31.4	76	
TC hours			2			2			2			1
Annual CL (kWh)			1893			1353			1342			3650

	RIn04	RIn05
Total annual CL (kWh)	8276	8239
CLI(kWh/m2)	138	137

Table C1.2 – continue

	RIn06												RIn07											
	Bed1			Bed2			Bed3			Family			Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.5	75	X	32.8	80	X	31.7	74	X	31.7	72	X	32.5	75	X	32.8	80	X	31.7	74	X	31.7	72	X
2	32.2	76	X	32.7	81	X	31.5	74	X	31.5	71	X	32.2	76	X	32.7	81	X	31.5	74	X	31.5	71	X
3	31.9	76	X	32.4	82	X	31.2	73	X	31.2	71	X	31.9	76	X	32.4	82	X	31.2	73	X	31.2	71	X
4	31.5	76	X	32.1	82	X	30.8	73	X	31.0	70	X	31.5	75	X	32.1	82	X	30.8	73	X	31.0	70	X
5	31.2	76	X	31.8	82	X	30.5	73	X	30.7	70	X	31.2	76	X	31.8	82	X	30.5	73	X	30.7	70	X
6	30.9	76	X	31.5	83	X	30.3	73	X	30.1	71	X	30.9	76	X	31.6	83	X	30.3	73	X	30.1	71	X
7	26.7	86	1.0m/s	27.7	81	1.5m/s	27.7	80	1.5m/s	27.2	83	1.0m/s	26.7	86	1.0m/s	27.7	81	1.5m/s	27.7	80	1.5m/s	27.2	83	1.0m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	86	X	28.4	83	X	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	86	X	28.4	83	X
9	29.7	88	X	29.9	87	X	30.5	85	X	30.1	85	X	29.7	88	X	29.9	87	X	30.5	85	X	30.1	85	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.1	87	X	31.0	89	X	31.1	88	X	31.8	85	X	31.1	87	X
11	32.3	88	X	32.2	88	X	32.9	85	X	32.7	85	X	32.3	88	X	32.2	88	X	32.8	85	X	32.7	85	X
12	33.3	84	X	33.1	84	X	33.9	81	X	32.8	86	X	33.3	84	X	33.1	84	X	33.9	81	X	32.8	86	X
13	34.1	84	X	33.8	85	X	34.4	82	X	33.4	87	X	34.1	84	X	33.8	85	X	34.4	82	X	33.4	87	X
14	33.8	76	X	33.7	77	X	34.2	74	X	33.5	78	X	33.8	76	X	33.7	77	X	34.2	74	X	33.5	78	X
15	34.6	68	X	34.1	71	X	34.7	68	X	33.9	72	X	34.6	68	X	34.1	71	X	34.6	68	X	33.9	72	X
16	33.9	78	X	34.2	77	X	33.9	78	X	34.0	78	X	33.9	78	X	34.2	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.3	81	X	33.7	79	X	33.8	79	X	32.8	83	X	33.2	81	X	33.7	80	X	33.7	79	X
18	29.9	75	X	30.2	74	X	30.3	73	X	31.2	71	X	29.9	75	X	30.2	74	X	30.3	73	X	31.2	71	X
19	29.3	83	X	29.2	83	X	29.3	83	X	30.4	78	X	29.3	83	X	29.2	83	X	29.3	83	X	30.4	78	X
20	29.8	81	X	30.4	78	X	30.4	78	X	30.9	76	X	29.8	81	X	30.4	78	X	30.4	78	X	30.8	76	X
21	28.2	85	X	28.5	83	X	28.5	83	X	32.4	69	X	28.2	85	X	28.5	83	X	28.5	83	X	32.4	69	X
22	28.7	82	X	29.5	78	X	29.4	79	X	30.7	74	X	28.7	82	X	29.5	79	X	29.4	79	X	30.7	74	X
23	33.0	67	X	32.0	73	X	31.2	72	X	30.9	71	X	32.9	67	X	32.0	73	X	31.2	72	X	30.9	71	X
24	31.9	72	X	32.2	75	X	31.1	72	X	31.1	69	X	31.9	72	X	32.2	75	X	31.1	72	X	31.1	69	X
Max	34.6	89		34.2	88		34.7	86		34.0	87		34.6	89		34.2	88		34.6	86		34.0	87	
Min	26.7	67		27.7	71		27.7	68		27.2	69		26.7	67		27.7	71		27.7	68		27.2	69	
Mean	31.3	80		31.5	81		31.3	78		31.4	76		31.3	80		31.5	81		31.3	78		31.4	76	
TC hours			2			2			1			1			2			2			1			1
Annual CL (kWh)			1889			1348			1337			3634			1886			1345			1332			3620

	RIn06	RIn07
Total annual CL (kWh)	8208	8183
CLI(kWh/m2)	137	136

Table C1.2 – continue

Rin08

Hour	Bed1 T	Bed1 RH	Bed1 TC	Bed2 T	Bed2 RH	Bed2 TC	Bed3 T	Bed3 RH	Bed3 TC	Family T	Family RH	Family TC
1	32.5	75	X	32.8	80	X	31.7	74	X	31.6	72	X
2	32.2	76	X	32.7	81	X	31.5	74	X	31.5	71	X
3	31.9	76	X	32.4	82	X	31.2	74	X	31.2	71	X
4	31.5	75	X	32.1	82	X	30.8	73	X	31.0	70	X
5	31.2	76	X	31.8	82	X	30.5	73	X	30.7	70	X
6	30.9	76	X	31.6	83	X	30.3	73	X	30.1	71	X
7	26.7	86	1.0m/s	27.7	81	1.5m/s	27.7	80	1.5m/s	27.2	83	1.0m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	86	X	28.4	83	X
9	29.7	88	X	29.9	87	X	30.5	85	X	30.1	85	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.1	87	X
11	32.3	88	X	32.2	88	X	32.8	85	X	32.7	85	X
12	33.3	84	X	33.1	84	X	33.9	81	X	32.8	86	X
13	34.1	84	X	33.8	85	X	34.4	82	X	33.3	87	X
14	33.8	76	X	33.7	77	X	34.2	74	X	33.5	78	X
15	34.6	68	X	34.1	71	X	34.6	68	X	33.9	72	X
16	33.9	78	X	34.2	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	81	X	33.6	80	X	33.7	79	X
18	29.8	75	X	30.2	74	X	30.3	73	X	31.2	71	X
19	29.3	83	X	29.2	83	X	29.3	83	X	30.4	78	X
20	29.8	81	X	30.4	78	X	30.4	78	X	30.8	76	X
21	28.2	85	X	28.5	83	X	28.5	83	X	32.4	69	X
22	28.7	82	X	29.5	79	X	29.4	79	X	30.6	74	X
23	32.9	67	X	32.0	73	X	31.2	72	X	30.9	71	X
24	31.9	72	X	32.2	75	X	31.1	72	X	31.1	69	X
Max	34.6	89		34.2	88		34.6	86		34.0	87	
Min	26.7	67		27.7	71		27.7	68		27.2	69	
Mean	31.3	80		31.5	81		31.3	78		31.4	76	
TC hours			2			2			1			1
Annual CL (kWh)			1883			1341			1328			3609

Rin09

Hour	Bed1 T	Bed1 RH	Bed1 TC	Bed2 T	Bed2 RH	Bed2 TC	Bed3 T	Bed3 RH	Bed3 TC	Family T	Family RH	Family TC
1	32.5	75	X	32.8	80	X	31.7	74	X	31.6	72	X
2	32.2	76	X	32.7	81	X	31.5	74	X	31.5	71	X
3	31.9	76	X	32.4	82	X	31.2	74	X	31.2	71	X
4	31.5	75	X	32.1	82	X	30.8	73	X	31.0	70	X
5	31.2	76	X	31.8	82	X	30.5	73	X	30.7	70	X
6	30.9	76	X	31.6	83	X	30.3	73	X	30.1	71	X
7	26.7	86	1.0m/s	27.7	81	1.5m/s	27.7	80	1.5m/s	27.2	83	1.0m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	86	X	28.3	83	X
9	29.7	88	X	29.9	87	X	30.5	85	X	30.1	85	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.1	87	X
11	32.3	88	X	32.2	88	X	32.8	85	X	32.7	85	X
12	33.3	84	X	33.1	84	X	33.9	81	X	32.8	86	X
13	34.1	84	X	33.8	85	X	34.4	82	X	33.3	87	X
14	33.8	76	X	33.7	77	X	34.2	74	X	33.5	78	X
15	34.6	69	X	34.1	71	X	34.6	68	X	33.9	72	X
16	33.9	78	X	34.1	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	81	X	33.6	80	X	33.7	79	X
18	29.8	75	X	30.2	74	X	30.3	73	X	31.1	71	X
19	29.3	83	X	29.2	83	X	29.3	83	X	30.4	78	X
20	29.8	81	X	30.4	78	X	30.4	78	X	30.8	76	X
21	28.2	85	X	28.5	83	X	28.5	83	X	32.4	69	X
22	28.7	82	X	29.5	79	X	29.4	79	X	30.6	74	X
23	32.9	67	X	32.0	73	X	31.2	72	X	30.9	71	X
24	31.9	72	X	32.2	75	X	31.1	72	X	31.1	69	X
Max	34.6	89		34.1	88		34.6	86		34.0	87	
Min	26.7	67		27.7	71		27.7	68		27.2	69	
Mean	31.3	80		31.5	81		31.3	78		31.4	77	
TC hours			2			2			1			1
Annual CL (kWh)			1881			1339			1325			3599

	Rin08	Rin09
Total annual CL (kWh)	8162	8144
CLI(kWh/m2)	136	136

Table C1.2 – continue

Rin10												
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.5	75	X	32.8	80	X	31.7	74	X	31.6	72	X
2	32.2	76	X	32.7	81	X	31.5	74	X	31.5	71	X
3	31.9	76	X	32.4	82	X	31.2	74	X	31.2	71	X
4	31.6	75	X	32.1	82	X	30.8	73	X	31.0	70	X
5	31.2	76	X	31.8	82	X	30.5	73	X	30.7	70	X
6	30.9	76	X	31.6	83	X	30.3	73	X	30.1	71	X
7	26.7	86	1.0m/s	27.7	81	1.5m/s	27.7	80	1.5m/s	27.2	83	1.0m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	86	X	28.3	83	X
9	29.7	88	X	29.9	87	X	30.5	85	X	30.1	85	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.1	87	X
11	32.3	88	X	32.2	88	X	32.8	85	X	32.7	85	X
12	33.3	84	X	33.1	85	X	33.8	81	X	32.8	86	X
13	34.1	84	X	33.8	85	X	34.4	82	X	33.3	87	X
14	33.8	76	X	33.7	77	X	34.2	74	X	33.5	78	X
15	34.6	69	X	34.0	71	X	34.6	69	X	33.9	72	X
16	33.9	78	X	34.1	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	81	X	33.6	80	X	33.7	79	X
18	29.8	75	X	30.2	74	X	30.2	73	X	31.1	71	X
19	29.3	83	X	29.2	83	X	29.3	83	X	30.4	78	X
20	29.8	81	X	30.4	78	X	30.4	78	X	30.8	76	X
21	28.2	85	X	28.5	83	X	28.5	83	X	32.4	69	X
22	28.7	82	X	29.5	79	X	29.4	79	X	30.6	74	X
23	32.9	67	X	32.0	73	X	31.2	72	X	30.9	71	X
24	31.9	72	X	32.2	75	X	31.1	72	X	31.1	69	X
Max	34.6	89		34.1	88		34.6	86		34.0	87	
Min	26.7	67		27.7	71		27.7	69		27.2	69	
Mean	31.3	80		31.5	81		31.3	78		31.4	77	
TC hours			2			2			1			1
Annual CL (kWh)			1879			1337			1322			3591

Total annual CL (kWh)	8128
CLI(kWh/m2)	135

Table C1.3

	ComboC1											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.4	76	X	32.7	81	X	31.6	75	X	31.5	73	X
2	32.1	76	X	32.5	82	X	31.4	74	X	31.3	72	X
3	31.8	76	X	32.2	82	X	31.0	74	X	31.1	71	X
4	31.4	76	X	32.0	83	X	30.7	74	X	30.8	70	X
5	31.1	76	X	31.7	83	X	30.4	74	X	30.6	70	X
6	30.8	76	X	31.4	84	X	30.1	74	X	30.0	71	X
7	26.6	86	1.0m/s	27.7	81	1.5m/s	27.7	81	1.5m/s	27.1	83	1.0m/s
8	27.3	89	1.5m/s	27.6	87	1.5m/s	27.9	86	X	28.3	83	X
9	29.7	89	X	29.8	88	X	30.5	85	X	30.0	86	X
10	31.0	89	X	31.0	88	X	31.7	85	X	31.0	88	X
11	32.3	88	X	32.1	88	X	32.8	85	X	32.6	86	X
12	33.2	84	X	33.0	85	X	33.8	81	X	32.7	86	X
13	34.0	84	X	33.7	86	X	34.3	83	X	33.3	88	X
14	33.7	76	X	33.6	77	X	34.1	75	X	33.4	79	X
15	34.5	69	X	34.0	71	X	34.5	69	X	33.7	73	X
16	33.9	78	X	34.1	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	82	X	33.6	80	X	33.7	80	X
18	29.8	75	X	30.1	74	X	30.2	74	X	31.1	71	X
19	29.2	83	X	29.2	83	X	29.2	83	X	30.3	78	X
20	29.7	81	X	30.3	79	X	30.3	79	X	30.8	76	X
21	28.2	85	X	28.4	84	X	28.4	84	X	32.3	70	X
22	28.6	82	X	29.4	79	X	29.3	79	X	30.6	74	X
23	32.8	68	X	31.8	73	X	31.0	73	X	30.8	71	X
24	31.7	73	X	32.0	76	X	31.0	73	X	31.0	70	X
Max	34.5	89		34.1	88		34.5	86		34.0	88	
Min	26.6	68		27.6	71		27.7	69		27.1	70	
Mean	31.2	80		31.4	81		31.2	78		31.3	77	
TC hours			2			2			1			1
Annual CL (kWh)			1822.0			1283.0			1258.0			3504.0

	ComboC2											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.4	76	X	32.7	80	X	31.6	74	X	31.6	72	X
2	32.1	76	X	32.5	81	X	31.4	74	X	31.4	72	X
3	31.8	76	X	32.3	82	X	31.1	74	X	31.1	71	X
4	31.5	76	X	32.0	82	X	30.7	73	X	30.9	70	X
5	31.1	76	X	31.7	83	X	30.4	74	X	30.6	70	X
6	30.8	76	X	31.4	83	X	30.2	74	X	30.0	71	X
7	26.6	86	1.0m/s	27.7	81	1.5m/s	27.7	80	1.5m/s	27.1	83	1.0m/s
8	27.3	89	1.5m/s	27.6	87	1.5m/s	27.9	86	X	28.3	83	X
9	29.7	89	X	29.8	88	X	30.5	85	X	30.1	86	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.1	88	X
11	32.3	88	X	32.2	88	X	32.8	85	X	32.7	86	X
12	33.2	84	X	33.1	85	X	33.8	81	X	32.7	86	X
13	34.0	84	X	33.8	85	X	34.4	82	X	33.3	87	X
14	33.7	76	X	33.6	77	X	34.1	74	X	33.4	79	X
15	34.5	69	X	34.0	71	X	34.6	69	X	33.8	72	X
16	33.9	78	X	34.1	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	81	X	33.6	80	X	33.7	79	X
18	29.8	75	X	30.2	74	X	30.2	74	X	31.1	71	X
19	29.2	83	X	29.2	83	X	29.2	83	X	30.3	78	X
20	29.8	81	X	30.4	78	X	30.4	79	X	30.8	76	X
21	28.2	85	X	28.5	84	X	28.5	83	X	32.3	69	X
22	28.7	82	X	29.4	79	X	29.4	79	X	30.6	74	X
23	32.8	68	X	31.9	73	X	31.1	72	X	30.8	71	X
24	31.8	73	X	32.1	75	X	31.0	73	X	31.0	70	X
Max	34.5	89		34.1	88		34.6	86		34.0	88	
Min	26.6	68		27.6	71		27.7	69		27.1	69	
Mean	31.2	80		31.4	81		31.3	78		31.4	77	
TC hours			2			2			1			1
Annual CL (kWh)			1847.0			1308.0			1288.0			3559.0

	ComboC1	ComboC2
Total annual CL (kWh)	7876	8002
CLI (kWh/m2year)	131	133

Table C1.3 – continue

ComboC3	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.4	76	X	32.8	80	X	31.7	74	X	31.6	72	X
2	32.2	76	X	32.6	81	X	31.5	74	X	31.4	72	X
3	31.8	76	X	32.3	82	X	31.1	74	X	31.2	71	X
4	31.5	76	X	32.1	82	X	30.8	73	X	30.9	70	X
5	31.1	76	X	31.7	83	X	30.4	73	X	30.7	70	X
6	30.9	76	X	31.5	83	X	30.2	73	X	30.1	71	X
7	26.6	86	1.0m/s	27.7	81	1.5m/s	27.7	80	1.5m/s	27.2	83	1.0m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	86	X	28.3	83	X
9	29.7	88	X	29.9	87	X	30.5	85	X	30.1	85	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.1	87	X
11	32.3	88	X	32.2	88	X	32.8	85	X	32.7	85	X
12	33.3	84	X	33.1	84	X	33.9	81	X	32.8	86	X
13	34.1	84	X	33.8	85	X	34.4	82	X	33.4	87	X
14	33.8	76	X	33.7	77	X	34.2	74	X	33.5	78	X
15	34.6	68	X	34.1	71	X	34.6	68	X	33.9	72	X
16	33.9	78	X	34.2	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	81	X	33.7	80	X	33.7	79	X
18	29.8	75	X	30.2	74	X	30.3	73	X	31.2	71	X
19	29.3	83	X	29.2	83	X	29.3	83	X	30.4	78	X
20	29.8	81	X	30.4	78	X	30.4	78	X	30.8	76	X
21	28.2	85	X	28.5	83	X	28.5	83	X	32.4	69	X
22	28.7	82	X	29.5	79	X	29.4	79	X	30.6	74	X
23	32.9	68	X	32.0	73	X	31.2	72	X	30.9	71	X
24	31.8	72	X	32.1	75	X	31.1	72	X	31.1	69	X
Max	34.6	89		34.2	88		34.6	86		34.0	87	
Min	26.6	68		27.7	71		27.7	68		27.2	69	
Mean	31.2	80		31.5	81		31.3	78		31.4	77	
TC hours			2			2			1			1
Annual CL (kWh)			1873.0			1333.0			1319.0			3614

Total annual CL (kWh) 8139
CLI (kWh/m2year) 136

ComboC4	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.5	75	X	32.9	80	X	31.7	74	X	31.7	72	X
2	32.2	76	X	32.7	81	X	31.5	74	X	31.5	71	X
3	31.9	76	X	32.4	82	X	31.2	73	X	31.2	71	X
4	31.5	76	X	32.1	82	X	30.8	73	X	31.0	70	X
5	31.2	76	X	31.8	83	X	30.5	73	X	30.7	70	X
6	30.9	76	X	31.5	83	X	30.3	73	X	30.1	71	X
7	26.7	85	1.0m/s	27.7	81	1.0m/s	27.7	80	1.0m/s	27.2	83	1.0m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X
9	29.7	88	X	29.9	87	X	30.6	84	X	30.1	85	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.2	87	X
11	32.3	88	X	32.2	88	X	32.9	85	X	32.8	85	X
12	33.3	84	X	33.1	84	X	33.9	81	X	32.8	86	X
13	34.1	84	X	33.8	85	X	34.5	82	X	33.4	87	X
14	33.8	76	X	33.8	76	X	34.2	74	X	33.6	78	X
15	34.6	68	X	34.2	71	X	34.7	68	X	34.0	72	X
16	33.9	78	X	34.2	77	X	33.9	78	X	34.0	77	X
17	32.8	83	X	33.3	81	X	33.7	79	X	33.8	79	X
18	29.9	75	X	30.3	74	X	30.3	73	X	31.2	71	X
19	29.3	83	X	29.3	83	X	29.3	82	X	30.4	77	X
20	29.8	81	X	30.5	78	X	30.4	78	X	30.9	76	X
21	28.2	85	X	28.5	83	X	28.5	83	X	32.5	69	X
22	28.7	82	X	29.5	78	X	29.4	79	X	30.7	74	X
23	33.0	67	X	32.0	73	X	31.3	72	X	30.9	71	X
24	31.9	72	X	32.2	75	X	31.2	72	X	31.1	69	X
Max	34.6	89		34.2	88		34.7	85		34.0	87	
Min	26.7	67		27.7	71		27.7	68		27.2	69	
Mean	31.3	80		31.5	81		31.3	78		31.5	76	
TC hours			2			2			2			1
Annual CL (kWh)			1898.0			1358.0			1349.0			3671

Total annual CL (kWh) 8276
CLI (kWh/m2year) 138

Table C1.4

RV00 (BASE)

	Zone 7			Zone 8			Zone 9			Zone 10		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.5	75	X	32.9	80	X	31.8	73	X	31.7	72	X
2	32.2	76	X	32.6	81	X	31.6	74	X	31.5	71	X
3	31.8	76	X	32.4	82	X	31.2	73	X	31.3	71	X
4	31.5	76	X	32.0	82	X	30.8	73	X	31.0	70	X
5	31.1	76	X	31.7	83	X	30.5	73	X	30.7	70	X
6	30.8	76	X	31.5	83	X	30.2	73	X	30.1	71	X
7	26.7	85	1.0m/s	27.7	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.5m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X
9	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X
10	31.0	89	X	31.2	88	X	31.9	84	X	31.3	87	X
11	32.3	88	X	32.3	88	X	32.9	85	X	32.9	85	X
12	33.4	83	X	33.3	84	X	34.0	80	X	33.0	85	X
13	34.1	84	X	34.0	84	X	34.6	81	X	33.6	86	X
14	33.8	75	X	34.0	76	X	34.4	73	X	33.8	77	X
15	34.8	68	X	34.5	70	X	34.9	67	X	34.2	71	X
16	33.9	78	X	34.3	76	X	33.9	78	X	34.1	77	X
17	32.9	83	X	33.4	81	X	33.8	79	X	33.9	78	X
18	29.9	74	X	30.4	73	X	30.4	73	X	31.3	70	X
19	29.3	83	X	29.3	82	X	29.4	82	X	30.5	77	X
20	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X
21	28.3	85	X	28.6	83	X	28.6	83	X	32.6	69	X
22	28.7	82	X	29.6	78	X	29.5	78	X	30.7	73	X
23	33.0	67	X	32.1	72	X	31.4	71	X	31.0	70	X
24	31.9	72	X	32.2	75	X	31.3	72	X	31.2	69	X
Max	34.8	89		34.5	88		34.9	85		34.2	87	
Min	26.7	67		27.7	70		27.8	67		27.2	69	
Mean	31.3	79		31.6	80		31.4	77		31.6	76	
TC hours			2			2			2			1
Annual CL (kWh)			1933			1398			1399			3827

RV05

	Zone 7			Zone 8			Zone 9			Zone 10		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.2	76	X	32.6	81	X	31.6	74	X	31.5	73	X
2	31.9	77	X	32.4	82	X	31.4	75	X	31.3	72	X
3	31.6	77	X	32.1	83	X	31.0	74	X	31.1	71	X
4	31.2	77	X	31.7	84	X	30.6	74	X	30.8	71	X
5	30.9	77	X	31.4	84	X	30.3	74	X	30.5	70	X
6	30.6	77	X	31.2	85	X	30.0	74	X	29.9	71	X
7	26.6	86	1.0m/s	27.7	81	1.5m/s	27.7	81	1.5m/s	27.1	83	1.0m/s
8	27.2	89	1.5m/s	27.6	87	1.5m/s	27.9	86	X	28.3	83	X
9	29.7	88	X	29.8	88	X	30.5	85	X	30.1	85	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.1	87	X
11	32.3	88	X	32.2	88	X	32.9	85	X	32.8	85	X
12	33.3	83	X	33.2	84	X	33.9	80	X	32.9	85	X
13	34.1	84	X	33.9	85	X	34.5	82	X	33.5	86	X
14	33.8	75	X	33.8	76	X	34.3	74	X	33.6	78	X
15	34.7	68	X	34.3	70	X	34.8	68	X	34.1	71	X
16	33.9	78	X	34.3	77	X	33.9	78	X	34.1	77	X
17	32.8	83	X	33.3	81	X	33.7	79	X	33.8	79	X
18	29.9	75	X	30.3	74	X	30.3	73	X	31.2	71	X
19	29.3	83	X	29.3	83	X	29.3	82	X	30.4	77	X
20	29.8	81	X	30.4	78	X	30.4	78	X	30.9	76	X
21	28.2	85	X	28.5	83	X	28.5	83	X	32.4	69	X
22	28.7	82	X	29.5	79	X	29.4	79	X	30.7	74	X
23	32.7	68	X	31.8	74	X	31.1	72	X	30.9	71	X
24	31.6	73	X	31.9	76	X	31.0	73	X	31.0	70	X
Max	34.7	89		34.3	88		34.8	86		34.1	87	
Min	26.6	68		27.6	70		27.7	68		27.1	69	
Mean	31.2	80		31.4	81		31.3	78		31.4	77	
TC hours			2			2			1			1
Annual CL (kWh)			1851			1324			1312			3712

	RV00 (BASE)	RV05
Total annual CL (kWh)	8556	8199
CLI (kWh/m2year)	143	137

Table C1.4 – continue

	RV10											
	Zone 7			Zone 8			Zone 9			Zone 10		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.1	77	X	32.4	82	X	31.5	75	X	31.4	73	X
2	31.8	77	X	32.2	83	X	31.2	75	X	31.2	73	X
3	31.5	77	X	31.9	84	X	30.9	75	X	30.9	72	X
4	31.1	77	X	31.6	84	X	30.5	74	X	30.6	71	X
5	30.7	78	X	31.3	85	X	30.1	75	X	30.4	71	X
6	30.4	78	X	31.0	85	X	29.9	75	X	29.8	72	X
7	26.6	86	1.0m/s	27.6	82	1.5m/s	27.6	81	1.5m/s	27.1	83	1.0m/s
8	27.2	89	1.5m/s	27.6	87	1.5m/s	27.8	86	1.5m/s	28.2	84	X
9	29.7	89	X	29.8	88	X	30.5	85	X	30.0	86	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.1	87	X
11	32.3	88	X	32.2	88	X	32.8	85	X	32.7	85	X
12	33.3	84	X	33.1	84	X	33.9	81	X	32.8	86	X
13	34.1	84	X	33.8	85	X	34.5	82	X	33.4	87	X
14	33.8	76	X	33.8	76	X	34.2	74	X	33.6	78	X
15	34.7	68	X	34.2	70	X	34.7	68	X	34.0	72	X
16	33.9	78	X	34.2	77	X	33.9	78	X	34.0	77	X
17	32.8	83	X	33.3	81	X	33.7	79	X	33.8	79	X
18	29.8	75	X	30.2	74	X	30.3	73	X	31.2	71	X
19	29.3	83	X	29.2	83	X	29.3	83	X	30.4	78	X
20	29.8	81	X	30.4	78	X	30.4	78	X	30.8	76	X
21	28.2	85	X	28.5	84	X	28.5	83	X	32.3	70	X
22	28.6	82	X	29.4	79	X	29.4	79	X	30.6	74	X
23	32.6	69	X	31.6	74	X	31.0	73	X	30.8	71	X
24	31.5	74	X	31.7	77	X	30.9	73	X	30.9	70	X
Max	34.7	89		34.2	88		34.7	86		34.0	87	
Min	26.6	68		27.6	70		27.6	68		27.1	70	
Mean	31.1	80		31.3	82		31.2	78		31.3	77	
TC hours			2			2			2			1
Annual CL (kWh)			1806			1283			1263			3649

	RV15											
	Zone 7			Zone 8			Zone 9			Zone 10		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.0	77	X	32.3	82	X	31.4	75	X	31.3	73	X
2	31.7	78	X	32.1	83	X	31.2	75	X	31.1	73	X
3	31.4	78	X	31.8	84	X	30.8	75	X	30.9	72	X
4	31.0	78	X	31.5	85	X	30.4	75	X	30.6	72	X
5	30.7	78	X	31.2	85	X	30.1	75	X	30.3	71	X
6	30.4	78	X	30.9	86	X	29.8	75	X	29.8	72	X
7	26.5	86	1.0m/s	27.6	82	1.5m/s	27.6	81	1.5m/s	27.1	83	1.0m/s
8	27.2	89	1.5m/s	27.5	87	1.5m/s	27.8	86	1.5m/s	28.2	84	X
9	29.7	89	X	29.8	88	X	30.4	85	X	30.0	86	X
10	31.0	89	X	31.1	88	X	31.7	85	X	31.0	88	X
11	32.3	88	X	32.2	88	X	32.8	85	X	32.7	86	X
12	33.3	84	X	33.1	84	X	33.9	81	X	32.8	86	X
13	34.1	84	X	33.8	85	X	34.4	82	X	33.4	87	X
14	33.8	76	X	33.7	77	X	34.2	74	X	33.5	78	X
15	34.6	68	X	34.1	71	X	34.7	68	X	33.9	72	X
16	33.9	78	X	34.2	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	81	X	33.7	79	X	33.7	79	X
18	29.8	75	X	30.2	74	X	30.3	73	X	31.1	71	X
19	29.2	83	X	29.2	83	X	29.3	83	X	30.3	78	X
20	29.7	81	X	30.4	79	X	30.4	79	X	30.8	76	X
21	28.2	85	X	28.4	84	X	28.5	84	X	32.2	70	X
22	28.6	82	X	29.4	79	X	29.3	79	X	30.6	74	X
23	32.5	69	X	31.6	75	X	30.9	73	X	30.7	72	X
24	31.4	74	X	31.6	77	X	30.8	74	X	30.8	71	X
Max	34.6	89		34.2	88		34.7	86		34.0	88	
Min	26.5	68		27.5	71		27.6	68		27.1	70	
Mean	31.1	80		31.3	82		31.2	78		31.3	77	
TC hours			2			2			2			1
Annual CL (kWh)			1778			1257			1232			3609

	RV10	RV15
Total annual CL (kWh)	8000	7875
CLI (kWh/m2year)	133	131

Table C1.4 – continue

	RV20											
	Zone 7			Zone 8			Zone 9			Zone 10		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.0	78	X	32.3	82	X	31.3	76	X	31.3	74	X
2	31.7	78	X	32.0	84	X	31.1	76	X	31.1	73	X
3	31.3	78	X	31.7	85	X	30.7	75	X	30.8	73	X
4	31.0	78	X	31.4	85	X	30.4	75	X	30.5	72	X
5	30.6	78	X	31.1	86	X	30.0	75	X	30.2	72	X
6	30.3	79	X	30.9	86	X	29.8	76	X	29.7	72	X
7	26.5	86	1.0m/s	27.6	82	1.5m/s	27.6	81	1.5m/s	27.0	83	1.0m/s
8	27.2	89	1.5m/s	27.5	87	1.5m/s	27.8	86	1.5m/s	28.2	84	X
9	29.6	89	X	29.7	88	X	30.4	85	X	30.0	86	X
10	31.0	89	X	31.0	88	X	31.7	85	X	31.0	88	X
11	32.3	88	X	32.1	88	X	32.8	85	X	32.6	86	X
12	33.3	84	X	33.1	85	X	33.8	81	X	32.7	86	X
13	34.1	84	X	33.8	85	X	34.4	82	X	33.3	87	X
14	33.8	76	X	33.7	77	X	34.2	74	X	33.5	78	X
15	34.6	68	X	34.1	71	X	34.6	68	X	33.9	72	X
16	33.9	78	X	34.2	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	81	X	33.6	80	X	33.7	79	X
18	29.8	75	X	30.2	74	X	30.2	73	X	31.1	71	X
19	29.2	83	X	29.2	83	X	29.2	83	X	30.3	78	X
20	29.7	81	X	30.3	79	X	30.3	79	X	30.8	77	X
21	28.1	85	X	28.4	84	X	28.4	84	X	32.2	70	X
22	28.6	82	X	29.4	79	X	29.3	79	X	30.5	74	X
23	32.4	69	X	31.5	75	X	30.9	74	X	30.7	72	X
24	31.3	74	X	31.5	78	X	30.7	74	X	30.7	71	X
Max	34.6	89		34.2	88		34.6	86		34.0	88	
Min	26.5	68		27.5	71		27.6	68		27.0	70	
Mean	31.0	80		31.2	82		31.1	78		31.2	77	
TC hours			2			2			2			1
Annual CL (kWh)			1758			1239			1210			3581

Total annual CL (kWh) 7788
CLI (kWh/m2year) 130

	RV25											
	Zone 7			Zone 8			Zone 9			Zone 10		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	31.9	78	X	32.2	83	X	31.3	76	X	31.2	74	X
2	31.6	78	X	32.0	84	X	31.1	76	X	31.0	73	X
3	31.3	78	X	31.7	85	X	30.7	76	X	30.8	73	X
4	30.9	78	X	31.4	86	X	30.3	75	X	30.5	72	X
5	30.6	78	X	31.1	86	X	30.0	76	X	30.2	72	X
6	30.3	79	X	30.8	86	X	29.7	76	X	29.7	73	X
7	26.5	86	1.0m/s	27.6	82	1.5m/s	27.6	81	1.5m/s	27.0	83	1.0m/s
8	27.2	89	1.5m/s	27.5	87	1.5m/s	27.8	86	1.5m/s	28.2	84	X
9	29.6	89	X	29.7	88	X	30.4	85	X	30.0	86	X
10	31.0	89	X	31.0	89	X	31.7	85	X	31.0	88	X
11	32.3	88	X	32.1	88	X	32.8	85	X	32.6	86	X
12	33.3	84	X	33.1	85	X	33.8	81	X	32.7	86	X
13	34.1	84	X	33.8	85	X	34.4	82	X	33.3	87	X
14	33.8	76	X	33.7	77	X	34.2	74	X	33.5	78	X
15	34.6	69	X	34.1	71	X	34.6	68	X	33.9	72	X
16	33.9	78	X	34.1	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	81	X	33.6	80	X	33.7	79	X
18	29.8	75	X	30.2	74	X	30.2	74	X	31.1	71	X
19	29.2	83	X	29.2	83	X	29.2	83	X	30.3	78	X
20	29.7	81	X	30.3	79	X	30.3	79	X	30.7	77	X
21	28.1	85	X	28.4	84	X	28.4	84	X	32.1	70	X
22	28.6	82	X	29.3	79	X	29.3	79	X	30.5	74	X
23	32.4	70	X	31.4	75	X	30.8	74	X	30.6	72	X
24	31.3	75	X	31.5	78	X	30.7	74	X	30.7	71	X
Max	34.6	89		34.1	89		34.6	86		34.0	88	
Min	26.5	69		27.5	71		27.6	68		27.0	70	
Mean	31.0	81		31.2	82		31.1	79		31.2	77	
TC hours			2			2			2			1
Annual CL (kWh)			1744			1225			1194			3560

7723
129

Table C1.4 – continue

	RV30											
	Zone 7			Zone 8			Zone 9			Zone 10		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	31.9	78	X	32.2	83	X	31.3	76	X	31.2	74	X
2	31.6	78	X	31.9	84	X	31.0	76	X	31.0	73	X
3	31.3	78	X	31.6	85	X	30.7	76	X	30.7	73	X
4	30.9	78	X	31.3	86	X	30.3	75	X	30.4	72	X
5	30.5	79	X	31.0	86	X	29.9	76	X	30.2	72	X
6	30.2	79	X	30.8	87	X	29.7	76	X	29.6	73	X
7	26.5	86	1.0m/s	27.5	82	1.5m/s	27.6	81	1.5m/s	27.0	84	1.0m/s
8	27.2	89	1.5m/s	27.5	88	1.5m/s	27.8	86	1.5m/s	28.2	84	X
9	29.6	89	X	29.7	88	X	30.4	85	X	29.9	86	X
10	31.0	89	X	31.0	89	X	31.7	85	X	31.0	88	X
11	32.3	88	X	32.1	89	X	32.8	85	X	32.6	86	X
12	33.2	84	X	33.0	85	X	33.8	81	X	32.7	86	X
13	34.1	84	X	33.8	85	X	34.4	82	X	33.3	87	X
14	33.8	76	X	33.7	77	X	34.1	74	X	33.4	79	X
15	34.6	69	X	34.1	71	X	34.6	69	X	33.8	72	X
16	33.9	78	X	34.1	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	81	X	33.6	80	X	33.7	79	X
18	29.8	75	X	30.2	74	X	30.2	74	X	31.1	71	X
19	29.2	83	X	29.1	83	X	29.2	83	X	30.3	78	X
20	29.7	81	X	30.3	79	X	30.3	79	X	30.7	77	X
21	28.1	85	X	28.4	84	X	28.4	84	X	32.1	70	X
22	28.6	82	X	29.3	79	X	29.3	79	X	30.5	74	X
23	32.4	70	X	31.4	75	X	30.8	74	X	30.6	72	X
24	31.3	75	X	31.5	78	X	30.6	74	X	30.6	71	X
Max	34.6	89		34.1	89		34.6	86		34.0	88	
Min	26.5	69		27.5	71		27.6	69		27.0	70	
Mean	31.0	81		31.2	82		31.1	79		31.2	77	
TC hours			2			2			2			1
Annual CL (kWh)			1733			1215			1182			3543

	RV35											
	Zone 7			Zone 8			Zone 9			Zone 10		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	31.9	78	X	32.1	83	X	31.2	76	X	31.2	74	X
2	31.6	78	X	31.9	84	X	31.0	76	X	31.0	73	X
3	31.2	79	X	31.6	85	X	30.7	76	X	30.7	73	X
4	30.9	78	X	31.3	86	X	30.3	76	X	30.4	72	X
5	30.5	79	X	31.0	86	X	29.9	76	X	30.1	72	X
6	30.2	79	X	30.7	87	X	29.7	76	X	29.6	73	X
7	26.5	86	1.0m/s	27.5	82	1.5m/s	27.6	81	1.5m/s	27.0	84	1.0m/s
8	27.2	89	1.5m/s	27.5	88	1.5m/s	27.8	86	1.5m/s	28.2	84	X
9	29.6	89	X	29.7	88	X	30.4	85	X	29.9	86	X
10	31.0	89	X	31.0	89	X	31.7	85	X	31.0	88	X
11	32.3	88	X	32.1	89	X	32.8	85	X	32.6	86	X
12	33.2	84	X	33.0	85	X	33.8	81	X	32.7	86	X
13	34.0	84	X	33.8	85	X	34.4	82	X	33.3	87	X
14	33.7	76	X	33.6	77	X	34.1	75	X	33.4	79	X
15	34.6	69	X	34.0	71	X	34.6	69	X	33.8	72	X
16	33.9	78	X	34.1	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	82	X	33.6	80	X	33.7	79	X
18	29.8	75	X	30.1	74	X	30.2	74	X	31.1	71	X
19	29.2	83	X	29.1	83	X	29.2	83	X	30.3	78	X
20	29.7	81	X	30.3	79	X	30.3	79	X	30.7	77	X
21	28.1	85	X	28.4	84	X	28.4	84	X	32.1	71	X
22	28.6	82	X	29.3	79	X	29.3	79	X	30.5	74	X
23	32.3	70	X	31.4	75	X	30.8	74	X	30.6	72	X
24	31.2	75	X	31.4	78	X	30.6	75	X	30.6	71	X
Max	34.6	89		34.1	89		34.6	86		34.0	88	
Min	26.5	69		27.5	71		27.6	69		27.0	71	
Mean	31.0	81		31.2	82		31.1	79		31.2	78	
TC hours			2			2			2			1
Annual CL (kWh)			1724			1207			1172			3530

	RV30	RV35
Total annual CL (kWh)	7674	7634
CLI (kWh/m2year)	128	127

Table C1.4 – continue

	RV40											
	Zone 7			Zone 8			Zone 9			Zone 10		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	31.9	78	X	32.1	83	X	31.2	76	X	31.2	74	X
2	31.6	78	X	31.9	85	X	31.0	76	X	31.0	74	X
3	31.2	79	X	31.6	85	X	30.6	76	X	30.7	73	X
4	30.8	79	X	31.3	86	X	30.3	76	X	30.4	72	X
5	30.5	79	X	31.0	86	X	29.9	76	X	30.1	72	X
6	30.2	79	X	30.7	87	X	29.7	76	X	29.6	73	X
7	26.5	86	1.0m/s	27.5	82	1.5m/s	27.5	81	1.5m/s	27.0	84	1.0m/s
8	27.2	89	1.5m/s	27.5	88	1.5m/s	27.7	86	1.5m/s	28.1	84	X
9	29.6	89	X	29.7	88	X	30.4	85	X	29.9	86	X
10	31.0	89	X	31.0	89	X	31.7	85	X	31.0	88	X
11	32.3	88	X	32.1	89	X	32.7	86	X	32.6	86	X
12	33.2	84	X	33.0	85	X	33.8	81	X	32.7	86	X
13	34.0	84	X	33.7	85	X	34.3	82	X	33.3	87	X
14	33.7	76	X	33.6	77	X	34.1	75	X	33.4	79	X
15	34.5	69	X	34.0	71	X	34.6	69	X	33.8	72	X
16	33.9	78	X	34.1	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	82	X	33.6	80	X	33.7	79	X
18	29.8	75	X	30.1	74	X	30.2	74	X	31.1	71	X
19	29.2	83	X	29.1	83	X	29.2	83	X	30.3	78	X
20	29.7	81	X	30.3	79	X	30.3	79	X	30.7	77	X
21	28.1	85	X	28.4	84	X	28.4	84	X	32.1	71	X
22	28.6	82	X	29.3	79	X	29.3	79	X	30.5	75	X
23	32.3	70	X	31.3	75	X	30.7	74	X	30.6	72	X
24	31.2	75	X	31.4	78	X	30.6	75	X	30.6	71	X
Max	34.5	89		34.1	89		34.6	86		34.0	88	
Min	26.5	69		27.5	71		27.5	69		27.0	71	
Mean	31.0	81		31.2	82		31.1	79		31.2	78	
TC hours			2			2			2			1
Annual CL (kWh)			1717			1200			1164			3519

	RV45											
	Zone 7			Zone 8			Zone 9			Zone 10		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	31.8	78	X	32.1	83	X	31.2	76	X	31.2	74	X
2	31.5	79	X	31.9	85	X	31.0	76	X	30.9	74	X
3	31.2	79	X	31.6	86	X	30.6	76	X	30.7	73	X
4	30.8	79	X	31.3	86	X	30.2	76	X	30.4	72	X
5	30.5	79	X	31.0	87	X	29.9	76	X	30.1	72	X
6	30.2	79	X	30.7	87	X	29.6	76	X	29.6	73	X
7	26.5	86	1.0m/s	27.5	82	1.5m/s	27.5	81	1.5m/s	27.0	84	1.0m/s
8	27.2	89	1.5m/s	27.5	88	1.5m/s	27.7	86	1.5m/s	28.1	84	X
9	29.6	89	X	29.7	88	X	30.4	85	X	29.9	86	X
10	31.0	89	X	31.0	89	X	31.7	85	X	31.0	88	X
11	32.3	88	X	32.1	89	X	32.7	86	X	32.6	86	X
12	33.2	84	X	33.0	85	X	33.8	81	X	32.7	86	X
13	34.0	84	X	33.7	85	X	34.3	82	X	33.3	87	X
14	33.7	76	X	33.6	77	X	34.1	75	X	33.4	79	X
15	34.5	69	X	34.0	71	X	34.6	69	X	33.8	72	X
16	33.9	78	X	34.1	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	82	X	33.6	80	X	33.7	80	X
18	29.8	75	X	30.1	74	X	30.2	74	X	31.0	71	X
19	29.2	83	X	29.1	83	X	29.2	83	X	30.3	78	X
20	29.7	82	X	30.3	79	X	30.3	79	X	30.7	77	X
21	28.1	85	X	28.4	84	X	28.4	84	X	32.0	71	X
22	28.6	82	X	29.3	79	X	29.3	79	X	30.5	75	X
23	32.3	70	X	31.3	76	X	30.7	74	X	30.5	72	X
24	31.2	75	X	31.4	78	X	30.6	75	X	30.6	71	X
Max	34.5	89		34.1	89		34.6	86		34.0	88	
Min	26.5	69		27.5	71		27.5	69		27.0	71	
Mean	31.0	81		31.2	82		31.1	79		31.2	78	
TC hours			2			2			2			1
Annual CL (kWh)			1712			1195			1158			3511

	RV40	RV45
Total annual CL (kWh)	7601	7575
CLI (kWh/m2year)	127	126

Table C1.4 – continue

Hour	RV50 Zone 7 T	RH	TC	Zone 8 T	RH	TC	Zone 9 T	RH	TC	Zone 10 T	RH	TC
1	31.8	78	X	32.1	83	X	31.2	76	X	31.1	74	X
2	31.5	79	X	31.8	85	X	31.0	76	X	30.9	74	X
3	31.2	79	X	31.5	86	X	30.6	76	X	30.7	73	X
4	30.8	79	X	31.2	86	X	30.2	76	X	30.4	72	X
5	30.4	79	X	30.9	87	X	29.9	76	X	30.1	72	X
6	30.2	79	X	30.7	87	X	29.6	76	X	29.6	73	X
7	26.5	86	1.0m/s	27.5	82	1.5m/s	27.5	81	1.5m/s	27.0	84	1.0m/s
8	27.2	89	1.5m/s	27.5	88	1.5m/s	27.7	86	1.5m/s	28.1	84	X
9	29.6	89	X	29.7	88	X	30.4	85	X	29.9	86	X
10	31.0	89	X	31.0	89	X	31.7	85	X	30.9	88	X
11	32.3	88	X	32.1	89	X	32.7	86	X	32.6	86	X
12	33.2	84	X	33.0	85	X	33.7	81	X	32.7	86	X
13	34.0	84	X	33.7	85	X	34.3	83	X	33.3	88	X
14	33.7	76	X	33.6	77	X	34.1	75	X	33.4	79	X
15	34.5	69	X	34.0	71	X	34.6	69	X	33.8	72	X
16	33.9	78	X	34.1	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	82	X	33.6	80	X	33.7	80	X
18	29.8	75	X	30.1	74	X	30.2	74	X	31.0	71	X
19	29.2	83	X	29.1	83	X	29.2	83	X	30.3	78	X
20	29.7	82	X	30.3	79	X	30.3	79	X	30.7	77	X
21	28.1	85	X	28.4	84	X	28.4	84	X	32.0	71	X
22	28.6	82	X	29.3	79	X	29.3	79	X	30.5	75	X
23	32.3	70	X	31.3	76	X	30.7	74	X	30.5	72	X
24	31.2	75	X	31.4	79	X	30.6	75	X	30.6	71	X
Max	34.5	89		34.1	89		34.6	86		34.0	88	
Min	26.5	69		27.5	71		27.5	69		27.0	71	
Mean	31.0	81		31.1	82		31.1	79		31.2	78	
TC hours			2			2			2			1
Annual CL (kWh)			1707			1190			1152			3503

Total annual CL (kWh) 7552
CLI (kWh/m2year) 126

Table C1.5

	ComboRVC1												ComboRVC2											
	Zone 7			Zone 8			Zone 9			Zone 10			Zone 7			Zone 8			Zone 9			Zone 10		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	
1	32.0	77	X	32.3	82	X	31.3	76	X	31.2	74	X	32.0	77	X	32.3	82	X	31.3	76	X	31.3	74	X
2	31.7	78	X	32.1	84	X	31.1	76	X	31.0	73	X	31.7	78	X	32.1	84	X	31.1	76	X	31.1	73	X
3	31.4	78	X	31.8	85	X	30.7	76	X	30.8	73	X	31.4	78	X	31.8	84	X	30.8	75	X	30.8	72	X
4	31.0	78	X	31.5	85	X	30.4	75	X	30.5	72	X	31.1	78	X	31.5	85	X	30.4	75	X	30.5	72	X
5	30.7	78	X	31.2	85	X	30.0	75	X	30.2	71	X	30.7	78	X	31.2	85	X	30.1	75	X	30.3	71	X
6	30.4	78	X	30.9	86	X	29.8	75	X	29.7	72	X	30.4	78	X	31.0	86	X	29.8	75	X	29.7	72	X
7	26.5	86	1.0m/s	27.6	82	1.5m/s	27.6	81	1.5m/s	27.0	83	1.0m/s	26.5	86	1.0m/s	27.6	82	1.5m/s	27.6	81	1.5m/s	27.1	83	1.0m/s
8	27.2	89	1.5m/s	27.5	88	1.5m/s	27.8	86	1.5m/s	28.2	84	X	27.2	89	1.5m/s	27.5	87	1.5m/s	27.8	86	1.5m/s	28.2	84	X
9	29.6	89	X	29.7	88	X	30.4	85	X	29.9	86	X	29.6	89	X	29.7	88	X	30.4	85	X	29.9	86	X
10	31.0	89	X	31.0	89	X	31.7	85	X	30.9	88	X	31.0	89	X	31.0	89	X	31.7	85	X	30.9	88	X
11	32.2	88	X	32.1	89	X	32.7	86	X	32.5	87	X	32.3	88	X	32.1	89	X	32.7	86	X	32.5	86	X
12	33.2	84	X	32.9	85	X	33.7	82	X	32.6	87	X	33.2	84	X	33.0	85	X	33.7	82	X	32.6	87	X
13	34.0	84	X	33.6	86	X	34.2	83	X	33.2	88	X	34.0	84	X	33.7	86	X	34.2	83	X	33.2	88	X
14	33.7	76	X	33.5	77	X	34.0	75	X	33.2	79	X	33.7	76	X	33.5	77	X	34.0	75	X	33.3	79	X
15	34.4	69	X	33.9	71	X	34.4	69	X	33.6	73	X	34.5	69	X	33.9	71	X	34.5	69	X	33.7	73	X
16	33.8	78	X	34.0	78	X	33.8	78	X	33.9	78	X	33.9	78	X	34.0	77	X	33.9	78	X	33.9	78	X
17	32.8	83	X	33.1	82	X	33.5	80	X	33.6	80	X	32.8	83	X	33.1	82	X	33.5	80	X	33.6	80	X
18	29.7	75	X	30.1	75	X	30.1	74	X	31.0	72	X	29.8	75	X	30.1	74	X	30.1	74	X	31.0	72	X
19	29.2	83	X	29.1	84	X	29.1	83	X	30.2	78	X	29.2	83	X	29.1	83	X	29.1	83	X	30.2	78	X
20	29.7	82	X	30.3	79	X	30.2	79	X	30.7	77	X	29.7	82	X	30.3	79	X	30.3	79	X	30.7	77	X
21	28.1	85	X	28.4	84	X	28.4	84	X	32.1	71	X	28.1	85	X	28.4	84	X	28.4	84	X	32.1	70	X
22	28.6	82	X	29.3	79	X	29.2	79	X	30.5	75	X	28.6	82	X	29.3	79	X	29.3	79	X	30.5	74	X
23	32.4	69	X	31.4	75	X	30.8	74	X	30.6	72	X	32.5	69	X	31.5	75	X	30.8	74	X	30.6	72	X
24	31.4	74	X	31.5	78	X	30.6	74	X	30.7	71	X	31.4	74	X	31.6	78	X	30.7	74	X	30.7	71	X
Max	34.4	89		34.0	89		34.4	86		33.9	88		34.5	89		34.0	89		34.5	86		33.9	88	
Min	26.5	69		27.5	71		27.6	69		27.0	71		26.5	69		27.5	71		27.6	69		27.1	70	
Mean	31.0	81		31.2	82		31.1	79		31.2	78		31.1	81		31.2	82		31.1	79		31.2	78	
TC hours			2			2			2			1			2			2			2			1
CL (kWh)			1722			1196			1156			3409			1737			1211			1175			3447

	ComboRVC1	ComboRVC2
Total annual CL (kWh)	7482	7570
CLI (kWh/m2year)	125	126

Table C1.5 – continue

	ComboRVC3											
	Zone 7			Zone 8			Zone 9			Zone 10		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.1	77	X	32.3	82	X	31.3	76	X	31.3	73	X
2	31.8	78	X	32.1	83	X	31.1	76	X	31.1	73	X
3	31.4	78	X	31.8	84	X	30.8	75	X	30.8	72	X
4	31.1	78	X	31.5	85	X	30.4	75	X	30.6	72	X
5	30.7	78	X	31.2	85	X	30.1	75	X	30.3	71	X
6	30.4	78	X	31.0	86	X	29.9	75	X	29.8	72	X
7	26.5	86	1.0m/s	27.6	82	1.5m/s	27.6	81	1.5m/s	27.1	83	1.0m/s
8	27.2	89	1.5m/s	27.5	87	1.5m/s	27.8	86	1.5m/s	28.2	84	X
9	29.6	89	X	29.7	88	X	30.4	85	X	29.9	86	X
10	31.0	89	X	31.0	89	X	31.7	85	X	31.0	88	X
11	32.3	88	X	32.1	89	X	32.7	86	X	32.6	86	X
12	33.2	84	X	33.0	85	X	33.7	81	X	32.6	87	X
13	34.0	84	X	33.7	86	X	34.3	83	X	33.2	88	X
14	33.7	76	X	33.6	77	X	34.1	75	X	33.3	79	X
15	34.5	69	X	34.0	71	X	34.5	69	X	33.7	73	X
16	33.9	78	X	34.1	77	X	33.9	78	X	33.9	78	X
17	32.8	83	X	33.2	82	X	33.6	80	X	33.6	80	X
18	29.8	75	X	30.1	74	X	30.2	74	X	31.0	71	X
19	29.2	83	X	29.1	83	X	29.2	83	X	30.3	78	X
20	29.7	81	X	30.3	79	X	30.3	79	X	30.7	77	X
21	28.1	85	X	28.4	84	X	28.4	84	X	32.1	70	X
22	28.6	82	X	29.3	79	X	29.3	79	X	30.5	74	X
23	32.5	69	X	31.5	75	X	30.8	74	X	30.6	72	X
24	31.4	74	X	31.6	77	X	30.7	74	X	30.7	71	X
Max	34.5	89		34.1	89		34.5	86		33.9	88	
Min	26.5	69		27.5	71		27.6	69		27.1	70	
Mean	31.1	80		31.2	82		31.1	79		31.2	77	
TC hours			2			2			2			1
CL (kWh)			1753			1227			1194			3482

	ComboRVC4											
	Zone 7			Zone 8			Zone 9			Zone 10		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.1	77	X	32.4	82	X	31.4	75	X	31.3	73	X
2	31.8	77	X	32.2	83	X	31.2	75	X	31.1	73	X
3	31.4	78	X	31.9	84	X	30.8	75	X	30.9	72	X
4	31.1	77	X	31.6	85	X	30.5	75	X	30.6	71	X
5	30.7	78	X	31.3	85	X	30.1	75	X	30.3	71	X
6	30.4	78	X	31.0	85	X	29.9	75	X	29.8	72	X
7	26.5	86	1.0m/s	27.6	82	1.5m/s	27.6	81	1.5m/s	27.1	83	1.0m/s
8	27.2	89	1.5m/s	27.5	87	1.5m/s	27.8	86	1.5m/s	28.2	84	X
9	29.6	89	X	29.7	88	X	30.4	85	X	30.0	86	X
10	31.0	89	X	31.0	89	X	31.7	85	X	31.0	88	X
11	32.3	88	X	32.1	89	X	32.8	85	X	32.6	86	X
12	33.2	84	X	33.0	85	X	33.8	81	X	32.7	86	X
13	34.0	84	X	33.7	85	X	34.3	82	X	33.3	88	X
14	33.7	76	X	33.6	77	X	34.1	75	X	33.4	79	X
15	34.5	69	X	34.0	71	X	34.6	69	X	33.8	73	X
16	33.9	78	X	34.1	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	82	X	33.6	80	X	33.7	80	X
18	29.8	75	X	30.1	74	X	30.2	74	X	31.1	71	X
19	29.2	83	X	29.1	83	X	29.2	83	X	30.3	78	X
20	29.7	81	X	30.3	79	X	30.3	79	X	30.7	77	X
21	28.1	85	X	28.4	84	X	28.4	84	X	32.2	70	X
22	28.6	82	X	29.4	79	X	29.3	79	X	30.5	74	X
23	32.5	69	X	31.6	75	X	30.9	73	X	30.7	72	X
24	31.5	74	X	31.7	77	X	30.8	74	X	30.8	71	X
Max	34.5	89		34.1	89		34.6	86		34.0	88	
Min	26.5	69		27.5	71		27.6	69		27.1	70	
Mean	31.1	80		31.3	82		31.2	78.5		31.3	77	
TC hours			2			2			2			1
CL (kWh)			1768			1242			1212			3518

	ComboRVC3	ComboRVC4
Total annual CL (kWh)	7655	7739
CLI (kWh/m2year)	128	129

Table C1.6

ComboC1nc

Hour	Bed1 T	Bed1 RH	Bed1 TC	Bed2 T	Bed2 RH	Bed2 TC	Bed3 T	Bed3 RH	Bed3 TC	Family T	Family RH	Family TC
1	31.2	75	X	31.3	75	X	30.6	77	X	31.0	75	X
2	31.0	75	X	31.1	74	X	30.4	77	X	30.8	75	X
3	30.7	74	X	30.8	74	X	30.0	76	X	30.5	74	X
4	30.4	73	X	30.5	73	X	29.7	76	X	30.2	74	X
5	30.1	73	X	30.2	73	X	29.3	76	X	29.9	74	X
6	29.3	74	X	29.4	74	X	29.4	74	X	28.4	78	1.5m/s
7	26.6	86	1.0m/s	26.3	87	1.0m/s	27.3	82	1.5m/s	26.6	86	1.0m/s
8	27.6	87	1.5m/s	27.7	86	1.5m/s	27.9	86	X	27.4	88	1.5m/s
9	29.9	87	X	29.9	87	X	30.2	86	X	29.6	88	X
10	31.0	89	X	31.0	89	X	31.3	87	X	31.0	89	X
11	32.2	88	X	32.2	88	X	32.5	87	X	32.4	87	X
12	33.3	83	X	33.3	84	X	33.5	83	X	33.1	84	X
13	34.0	84	X	34.0	85	X	34.2	84	X	33.8	85	X
14	33.7	76	X	33.6	76	X	34.0	75	X	33.5	77	X
15	34.2	70	X	34.0	71	X	34.4	69	X	34.0	71	X
16	33.9	78	X	33.9	78	X	33.8	79	X	33.9	78	X
17	32.7	83	X	32.7	84	X	32.9	83	X	33.2	82	X
18	30.0	74	X	30.0	75	X	28.5	80	X	30.0	74	X
19	29.5	82	X	29.2	83	X	29.6	81	X	29.1	84	X
20	29.7	82	X	29.7	82	X	29.8	81	X	30.2	79	X
21	29.1	81	X	29.1	81	X	29.2	81	X	30.2	77	X
22	28.7	82	X	28.8	81	X	28.9	81	X	29.6	78	X
23	30.4	73	X	30.2	74	X	30.2	74	X	29.2	78	X
24	30.4	73	X	30.4	73	X	29.9	76	X	30.1	74	X
Max	34.2	89		34.0	89		34.4	87		34.0	89	
Min	26.6	70		26.3	71		27.3	69		26.6	71	
Mean	30.8	79		30.8	79		30.7	79		30.7	79	
TC hours			2			2			1			3
CL (kWh)			2237			1206			1472			9442

ComboC2nc

Hour	Bed1 T	Bed1 RH	Bed1 TC	Bed2 T	Bed2 RH	Bed2 TC	Bed3 T	Bed3 RH	Bed3 TC	Family T	Family RH	
1	31.2	75	X	31.3	75	X	30.6	76	X	31.0	75	X
2	31.0	74	X	31.1	74	X	30.4	77	X	30.8	75	X
3	30.7	74	X	30.8	74	X	30.1	76	X	30.5	74	X
4	30.4	73	X	30.5	73	X	29.7	76	X	30.2	74	X
5	30.1	73	X	30.2	73	X	29.3	76	X	30.0	73	X
6	29.3	74	X	29.4	74	X	29.4	74	X	28.4	78	1.5m/s
7	26.6	86	1.0m/s	26.3	87	1.0m/s	27.3	82	1.5m/s	26.6	85	1.0m/s
8	27.7	87	1.5m/s	27.8	86	1.5m/s	27.9	86	X	27.4	88	1.5m/s
9	30.0	87	X	29.9	87	X	30.3	86	X	29.7	88	X
10	31.0	89	X	31.0	89	X	31.3	87	X	31.0	88	X
11	32.2	88	X	32.3	88	X	32.6	87	X	32.5	87	X
12	33.3	83	X	33.3	84	X	33.6	82	X	33.2	84	X
13	34.0	84	X	34.0	84	X	34.3	83	X	33.8	85	X
14	33.7	76	X	33.6	76	X	34.1	74	X	33.6	77	X
15	34.2	70	X	34.0	71	X	34.6	68	X	34.1	71	X
16	33.9	78	X	34.0	78	X	33.8	79	X	33.9	78	X
17	32.7	83	X	32.7	84	X	33.0	83	X	33.2	81	X
18	30.1	74	X	30.1	74	X	28.5	80	X	30.1	74	X
19	29.6	81	X	29.2	83	X	29.6	81	X	29.1	83	X
20	29.7	81	X	29.7	81	X	29.8	81	X	30.2	79	X
21	29.1	81	X	29.1	81	X	29.2	81	X	30.2	77	X
22	28.7	82	X	28.8	81	X	28.9	81	X	29.6	78	X
23	30.4	73	X	30.2	74	X	30.3	74	X	29.2	78	X
24	30.4	73	X	30.5	73	X	30.0	75	X	30.2	74	X
Max	34.2	89		34.0	89		34.6	87		34.1	88	
Min	26.6	70		26.3	71		27.3	68		26.6	71	
Mean	30.8	79		30.8	79		30.8	79		30.8	79	
TC hours			2			2			1			3
CL (kWh)			2258			1225			1505			9586

	ComboC1nc	ComboC2nc
Total annual CL (kWh)	14357	14575
CLI (kWh/m2year)	239	243

Table C1.6 – continue

	ComboC3nc											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	31.3	74	X	31.3	74	X	30.7	76	X	31.0	75	X
2	31.1	74	X	31.1	74	X	30.5	77	X	30.8	75	X
3	30.8	74	X	30.8	74	X	30.1	76	X	30.6	74	X
4	30.5	73	X	30.5	73	X	29.7	76	X	30.3	73	X
5	30.1	73	X	30.2	73	X	29.4	76	X	30.0	73	X
6	29.3	74	X	29.4	74	X	29.4	74	X	28.4	78	1.5m/s
7	26.6	86	1.0m/s	26.4	87	1.0m/s	27.4	82	1.0m/s	26.6	85	1.0m/s
8	27.7	86	1.5m/s	27.8	86	1.5m/s	27.9	85	1.5m/s	27.4	88	1.0m/s
9	30.1	86	X	30.0	86	X	30.3	85	X	29.7	88	X
10	31.0	89	X	31.0	89	X	31.4	87	X	31.1	88	X
11	32.3	88	X	32.3	88	X	32.6	86	X	32.6	86	X
12	33.3	83	X	33.3	84	X	33.8	81	X	33.3	84	X
13	34.0	84	X	34.0	84	X	34.4	82	X	33.9	85	X
14	33.7	76	X	33.6	76	X	34.3	74	X	33.7	77	X
15	34.2	70	X	34.0	71	X	34.9	67	X	34.2	71	X
16	34.0	78	X	34.0	77	X	33.8	79	X	34.0	78	X
17	32.7	83	X	32.7	84	X	33.0	82	X	33.2	81	X
18	30.1	74	X	30.1	74	X	28.6	80	X	30.1	74	X
19	29.6	81	X	29.3	83	X	29.7	81	X	29.1	83	X
20	29.7	81	X	29.8	81	X	29.9	81	X	30.2	79	X
21	29.1	81	X	29.1	81	X	29.2	81	X	30.2	77	X
22	28.8	81	X	28.8	81	X	28.9	81	X	29.6	78	X
23	30.4	73	X	30.3	74	X	30.3	74	X	29.2	77	X
24	30.5	73	X	30.5	73	X	30.0	75	X	30.2	73	X
Max	34.2	89		34.0	89		34.9	87		34.2	88	
Min	26.6	70		26.4	71		27.4	67		26.6	71	
Mean	30.9	79		30.8	79		30.8	79		30.8	79	
TC hours			2			2			2			3
CL (kWh)			2279			1244			1537			9733

	ComboC4nc											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	31.3	74	X	31.4	74	X	30.7	76	X	31.1	75	X
2	31.1	74	X	31.2	74	X	30.5	76	X	30.9	75	X
3	30.8	74	X	30.9	73	X	30.1	76	X	30.6	74	X
4	30.5	73	X	30.6	73	X	29.8	76	X	30.3	73	X
5	30.2	73	X	30.3	73	X	29.4	76	X	30.0	73	X
6	29.4	74	X	29.4	74	X	29.4	74	X	28.4	78	1.5m/s
7	26.6	86	1.0m/s	26.4	87	1.0m/s	27.4	82	1.5m/s	26.6	85	1.0m/s
8	27.7	86	1.5m/s	27.8	86	1.5m/s	27.9	85	1.5m/s	27.4	88	1.0m/s
9	30.2	86	X	30.1	86	X	30.4	85	X	29.7	83	X
10	31.0	89	X	31.0	89	X	31.5	86	X	31.1	88	X
11	32.3	88	X	32.3	88	X	32.7	86	X	32.6	86	X
12	33.3	83	X	33.3	84	X	33.9	81	X	33.4	83	X
13	34.0	84	X	34.0	84	X	34.5	82	X	34.0	84	X
14	33.7	76	X	33.6	76	X	34.5	73	X	33.7	77	X
15	34.2	70	X	34.0	71	X	35.2	66	X	34.2	71	X
16	34.0	78	X	34.1	77	X	33.8	79	X	34.0	78	X
17	32.8	83	X	32.7	84	X	33.0	82	X	33.3	81	X
18	30.1	74	X	30.1	74	X	28.6	80	X	30.1	74	X
19	29.6	81	X	29.3	82	X	29.7	80	X	29.2	83	X
20	29.7	81	X	29.8	81	X	29.9	81	X	30.3	79	X
21	29.1	81	X	29.2	81	X	29.3	80	X	30.3	76	X
22	28.8	81	X	28.8	81	X	28.9	81	X	29.6	78	X
23	30.4	73	X	30.3	74	X	30.3	73	X	29.3	77	X
24	30.5	73	X	30.5	73	X	30.0	75	X	30.3	73	X
Max	34.2	89		34.1	89		35.2	86		34.2	88	
Min	26.6	70		26.4	71		27.4	66		26.6	71	
Mean	30.9	79		30.9	79		30.9	79		30.9	79	
TC hours			2			2			2			3
CL (kWh)			2300			1263			1569			9879

	ComboC3nc	ComboC4nc
Total annual CL (kWh)	14793	15011
CLI (kWh/m2year)	247	250

Table C1.7

	COMBORVC1nc											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	30.1	78	X	30.2	78	X	30.0	78	X	30.0	78	X
2	29.9	78	X	30.0	78	X	29.8	78	X	29.8	78	X
3	29.6	77	X	29.6	77	X	29.4	78	X	29.5	77	X
4	29.2	77	X	29.3	76	X	29.1	77	X	29.1	77	X
5	28.9	77	X	29.0	77	X	28.7	78	X	28.8	77	X
6	28.4	78	1.5m/s	28.5	77	1.5m/s	28.5	77	1.5m/s	28.1	79	1.5m/s
7	26.3	87	1.0m/s	26.1	88	1.0m/s	27.0	84	1.0m/s	26.5	86	1.0m/s
8	27.4	88	1.5m/s	27.5	87	1.5m/s	27.6	87	1.5m/s	27.3	89	1.5m/s
9	29.7	88	X	29.7	88	X	30.0	87	X	29.5	89	X
10	31.0	89	X	31.0	89	X	31.2	88	X	30.9	89	X
11	32.2	88	X	32.2	88	X	32.4	87	X	32.4	87	X
12	33.3	83	X	33.2	84	X	33.4	83	X	33.0	85	X
13	34.0	84	X	34.0	85	X	34.1	84	X	33.7	86	X
14	33.6	76	X	33.6	76	X	33.9	75	X	33.5	77	X
15	34.2	70	X	34.0	71	X	34.3	69	X	33.9	71	X
16	33.9	78	X	33.9	78	X	33.8	79	X	33.9	78	X
17	32.7	83	X	32.7	84	X	32.9	83	X	33.1	82	X
18	29.9	75	X	29.9	75	X	28.5	80	X	29.9	75	X
19	29.3	82	X	29.1	84	X	29.4	82	X	29.0	84	X
20	29.4	83	X	29.5	83	X	29.6	82	X	30.0	80	X
21	28.8	82	X	28.8	82	X	28.9	82	X	30.0	77	X
22	28.4	83	X	28.5	83	X	28.6	82	X	29.4	79	X
23	29.7	76	X	29.5	77	X	29.6	77	X	29.0	78	X
24	29.4	77	X	29.4	77	X	29.2	77	X	29.2	77	X
Max	34.2	89.0		34.0	89.1		34.3	87.8		33.9	89.0	
Min	26.3	69.8		26.1	70.5		27.0	69.3		26.5	71.0	
Mean	30.4	80.7		30.4	80.8		30.4	80.6		30.4	80.6	
TC hours			3			3			3			3
CL (kWh)			2026			1028			1160			9285

	COMBORVC2nc											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	
1	30.1	77	X	30.2	77	X	30.0	78	X	30.0	78	X
2	29.9	78	X	30.0	77	X	29.8	78	X	29.8	78	X
3	29.6	77	X	29.7	77	X	29.5	78	X	29.5	77	X
4	29.2	77	X	29.3	76	X	29.1	77	X	29.2	77	X
5	28.9	77	X	29.0	77	X	28.7	78	X	28.8	77	X
6	28.4	78	1.5m/s	28.5	77	1.5m/s	28.5	77	1.5m/s	28.1	79	1.5m/s
7	26.3	87	1.0m/s	26.1	88	1.0m/s	27.0	84	1.0m/s	26.5	86	1.0m/s
8	27.5	88	1.5m/s	27.5	87	1.5m/s	27.6	87	1.5m/s	27.3	89	1.5m/s
9	29.8	88	X	29.7	88	X	30.1	86	X	29.6	89	X
10	31.0	89	X	31.0	89	X	31.3	87	X	30.9	89	X
11	32.2	88	X	32.2	88	X	32.5	87	X	32.4	87	X
12	33.3	83	X	33.2	84	X	33.6	82	X	33.1	84	X
13	34.0	84	X	34.0	85	X	34.2	83	X	33.8	85	X
14	33.6	76	X	33.6	76	X	34.0	75	X	33.5	77	X
15	34.2	70	X	34.0	71	X	34.5	69	X	34.0	71	X
16	33.9	78	X	33.9	78	X	33.8	79	X	33.9	78	X
17	32.7	83	X	32.7	84	X	32.9	83	X	33.1	82	X
18	29.9	75	X	29.9	75	X	28.5	80	X	30.0	75	X
19	29.4	82	X	29.1	83	X	29.4	82	X	29.1	84	X
20	29.4	83	X	29.5	83	X	29.6	82	X	30.0	80	X
21	28.8	82	X	28.9	82	X	29.0	82	X	30.0	77	X
22	28.5	83	X	28.5	82	X	28.6	82	X	29.4	79	X
23	29.7	76	X	29.6	77	X	29.6	76	X	29.1	78	X
24	29.4	77	X	29.4	77	X	29.3	77	X	29.3	77	X
Max	34.2	89.0		34.0	89.0		34.5	87.4		34.0	88.7	
Min	26.3	69.8		26.1	70.5		27.0	68.7		26.5	70.8	
Mean	30.4	80.6		30.4	80.7		30.5	80.4		30.4	80.4	
TC hours			3			3			3			3
CL (kWh)			2045			1044			1182			9412

	COMBORVC1nc	COMBORVC2nc
Total annual CL (kWh)	13499	13683
CLI (kWh/m2year)	225	228

Table C1.7 – continue

COMBORVC3nc

Hour	Bed1 T	Bed1 RH	Bed1 TC	Bed2 T	Bed2 RH	Bed2 TC	Bed3 T	Bed3 RH	Bed3 TC	Family T	Family RH	Family TC
1	30.2	77	X	30.2	77	X	30.0	78	X	30.1	78	X
2	30.0	77	X	30.0	77	X	29.8	78	X	29.9	78	X
3	29.6	77	X	29.7	77	X	29.5	78	X	29.5	77	X
4	29.3	77	X	29.3	76	X	29.1	77	X	29.2	77	X
5	28.9	77	X	29.0	76	X	28.8	77	X	28.8	77	X
6	28.5	78	1.5m/s	28.5	77	1.5m/s	28.6	77	1.5m/s	28.2	79	1.5m/s
7	26.3	87	1.0m/s	26.1	88	1.0m/s	27.0	84	1.0m/s	26.5	86	1.0m/s
8	27.5	88	1.5m/s	27.6	87	1.5m/s	27.7	87	1.5m/s	27.3	89	1.5m/s
9	29.9	87	X	29.8	87	X	30.2	86	X	29.6	89	X
10	31.0	89	X	31.0	89	X	31.3	87	X	31.0	88	X
11	32.2	88	X	32.2	88	X	32.6	87	X	32.5	87	X
12	33.3	83	X	33.2	84	X	33.7	82	X	33.2	84	X
13	34.0	84	X	34.0	85	X	34.3	83	X	33.9	85	X
14	33.7	76	X	33.6	76	X	34.2	74	X	33.6	77	X
15	34.2	70	X	34.0	71	X	34.7	68	X	34.1	71	X
16	33.9	78	X	34.0	78	X	33.8	79	X	33.9	78	X
17	32.7	83	X	32.7	84	X	32.9	83	X	33.2	82	X
18	30.0	75	X	30.0	75	X	28.5	80	X	30.0	75	X
19	29.4	82	X	29.1	83	X	29.4	82	X	29.1	84	X
20	29.4	83	X	29.5	82	X	29.6	82	X	30.1	80	X
21	28.8	82	X	28.9	82	X	29.0	82	X	30.1	77	X
22	28.5	83	X	28.6	82	X	28.6	82	X	29.4	79	X
23	29.7	76	X	29.6	76	X	29.6	76	X	29.1	78	X
24	29.4	77	X	29.4	76	X	29.3	77	X	29.3	77	X
Max	34.2	89.0		34.0	89.0		34.7	87.1		34.1	88.6	
Min	26.3	69.7		26.1	70.5		27.0	68.1		26.5	70.5	
Mean	30.4	80.5		30.4	80.6		30.5	80.2		30.5	80.3	
TC hours			3			3			3			3
CL (kWh)			2063			1060			1204			9540

COMBORVC4nc

Hour	Bed1 T	Bed1 RH	Bed1 TC	Bed2 T	Bed2 RH	Bed2 TC	Bed3 T	Bed3 RH	Bed3 TC	Family T	Family RH	Family TC
1	30.2	77	X	30.2	77	X	30.1	78	X	30.1	78	X
2	30.0	77	X	30.0	77	X	29.9	78	X	29.9	78	X
3	29.6	77	X	29.7	77	X	29.5	78	X	29.6	77	X
4	29.3	76	X	29.4	76	X	29.1	77	X	29.2	77	X
5	28.9	77	X	29.0	76	X	28.8	77	X	28.9	77	X
6	28.5	78	1.5m/s	28.6	77	1.5m/s	28.6	77	1.5m/s	28.2	79	1.5m/s
7	26.4	87	1.0m/s	26.2	88	1.0m/s	27.0	84	1.0m/s	26.5	86	1.0m/s
8	27.5	87	1.5m/s	27.6	87	1.5m/s	27.7	86	1.5m/s	27.3	89	1.5m/s
9	29.9	87	X	29.9	87	X	30.2	86	X	29.6	89	X
10	31.0	89	X	31.0	89	X	31.4	87	X	31.0	88	X
11	32.2	88	X	32.2	88	X	32.6	86	X	32.5	87	X
12	33.3	83	X	33.2	84	X	33.8	81	X	33.2	84	X
13	34.0	84	X	34.0	85	X	34.4	82	X	33.9	85	X
14	33.7	76	X	33.6	76	X	34.3	74	X	33.6	77	X
15	34.2	70	X	34.0	71	X	34.9	67	X	34.1	71	X
16	34.0	78	X	34.0	77	X	33.8	79	X	33.9	78	X
17	32.7	83	X	32.7	84	X	33.0	82	X	33.2	81	X
18	30.0	75	X	30.0	75	X	28.5	80	X	30.0	74	X
19	29.4	82	X	29.1	83	X	29.5	82	X	29.1	84	X
20	29.5	83	X	29.5	82	X	29.6	82	X	30.1	80	X
21	28.9	82	X	28.9	82	X	29.0	82	X	30.1	77	X
22	28.5	83	X	28.6	82	X	28.6	82	X	29.4	79	X
23	29.8	76	X	29.6	76	X	29.7	76	X	29.1	78	X
24	29.4	76	X	29.5	76	X	29.3	77	X	29.3	77	X
Max	34.2	89.0		34.0	89.0		34.9	86.8		34.1	88.5	
Min	26.4	69.7		26.2	70.5		27.0	67.4		26.5	70.7	
Mean	30.5	80.4		30.4	80.5		30.6	80.0		30.5	80.2	
TC hours			3			3			3			3
CL (kWh)			2081			1075			1226			9665

	COMBORVC3nc	COMBORVC4nc
Total annual CL (kWh)	13867	14047
CLI (kWh/m2year)	231	234

Table C1.8

	Cln00 (BASE)												Cln01											
	Bed1			Bed2			Bed3			Family			Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.5	75	X	32.9	80	X	31.8	73	X	31.7	72	X	32.6	75	X	33.0	79	X	31.8	73	X	31.8	71	X
2	32.2	76	X	32.6	81	X	31.6	74	X	31.5	71	X	32.3	75	X	32.7	80	X	31.6	73	X	31.6	71	X
3	31.8	76	X	32.4	82	X	31.2	73	X	31.3	71	X	31.9	75	X	32.5	81	X	31.3	73	X	31.3	70	X
4	31.5	76	X	32.0	82	X	30.8	73	X	31.0	70	X	31.6	75	X	32.2	82	X	30.9	73	X	31.0	70	X
5	31.1	76	X	31.7	83	X	30.5	73	X	30.7	70	X	31.2	76	X	31.9	82	X	30.5	73	X	30.8	69	X
6	30.8	76	X	31.5	83	X	30.2	73	X	30.1	71	X	30.9	76	X	31.6	83	X	30.3	73	X	30.2	71	X
7	26.7	85	1.0m/s	27.7	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.5m/s	26.7	85	1.0m/s	27.8	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.5m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X
9	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X
10	31.0	89	X	31.2	88	X	31.9	84	X	31.3	87	X	31.0	89	X	31.2	88	X	31.9	84	X	31.3	87	X
11	32.3	88	X	32.3	88	X	32.9	85	X	32.9	85	X	32.3	88	X	32.3	88	X	32.9	85	X	32.9	85	X
12	33.4	83	X	33.3	84	X	34.0	80	X	33.0	85	X	33.4	83	X	33.3	84	X	34.0	80	X	33.0	85	X
13	34.1	84	X	34.0	84	X	34.6	81	X	33.6	86	X	34.1	84	X	34.0	84	X	34.6	81	X	33.6	86	X
14	33.8	75	X	34.0	76	X	34.4	73	X	33.8	77	X	33.8	75	X	34.0	76	X	34.4	73	X	33.8	77	X
15	34.8	68	X	34.5	70	X	34.9	67	X	34.2	71	X	34.8	68	X	34.5	70	X	34.9	68	X	34.2	71	X
16	33.9	78	X	34.3	76	X	33.9	78	X	34.1	77	X	33.9	78	X	34.3	76	X	33.9	78	X	34.1	77	X
17	32.9	83	X	33.4	81	X	33.8	79	X	33.9	78	X	32.9	83	X	33.4	81	X	33.8	79	X	33.9	78	X
18	29.9	74	X	30.4	73	X	30.4	73	X	31.3	70	X	29.9	74	X	30.3	73	X	30.4	73	X	31.3	70	X
19	29.3	83	X	29.3	82	X	29.4	82	X	30.5	77	X	29.3	83	X	29.3	82	X	29.4	82	X	30.5	77	X
20	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X
21	28.3	85	X	28.6	83	X	28.6	83	X	32.6	69	X	28.3	85	X	28.6	83	X	28.6	83	X	32.6	68	X
22	28.7	82	X	29.6	78	X	29.5	78	X	30.7	73	X	28.8	81	X	29.6	78	X	29.5	78	X	30.8	73	X
23	33.0	67	X	32.1	72	X	31.4	71	X	31.0	70	X	33.1	67	X	32.2	72	X	31.4	71	X	31.0	70	X
24	31.9	72	X	32.2	75	X	31.3	72	X	31.2	69	X	32.0	72	X	32.3	74		31.3	71	X	31.3	69	X
Max	34.8	89		34.5	88		34.9	85		34.2	87		34.8	89		34.5	88		34.9	85		34.2	87	
Min	26.7	67		27.7	70		27.8	67		27.2	69		26.7	67		27.7	70		27.8	68		27.2	68	
Mean	31.3	79		31.6	80		31.4	77		31.6	76		31.3	79		31.6	80		31.4	77		31.6	76	
TC hours			2			2			2			1			2			2			2			1
Annual CL (kWh)			1933			1398			1399			3827			1941			1400			1402			3821

	Cln00 (BASE)	Cln01
Total annual CL (kWh)	8556	8565
CLI(kWh/m2year)	143	143

Table C1.8 – continue

	ClIn02												ClIn03											
	Bed1			Bed2			Bed3			Family			Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.7	75	X	33.0	79	X	31.9	73	X	31.8	71	X	32.7	74	X	33.1	79	X	31.9	73	X	31.8	71	X
2	32.4	75	X	32.8	80	X	31.7	73	X	31.6	71	X	32.4	75	X	32.9	80	X	31.7	73	X	31.6	71	X
3	32.0	75	X	32.6	81	X	31.3	73	X	31.4	70	X	32.1	75	X	32.6	80	X	31.3	73	X	31.4	70	X
4	31.7	75	X	32.3	81	X	30.9	72	X	31.1	69	X	31.7	75	X	32.4	81	X	31.0	72	X	31.1	69	X
5	31.3	75	X	32.0	82	X	30.6	73	X	30.8	69	X	31.4	75	X	32.1	81	X	30.6	73	X	30.9	69	X
6	31.0	75	X	31.7	82	X	30.3	73	X	30.2	70	X	31.1	75	X	31.8	82	X	30.4	73	X	30.2	70	X
7	26.7	85	1.0m/s	27.8	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.5m/s	26.7	85	1.0m/s	27.8	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.0m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	28.0	85	X	28.4	83	X	27.3	89	1.5m/s	27.7	87	1.5m/s	28.0	85	X	28.4	83	X
9	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X
10	31.0	89	X	31.2	88	X	31.9	84	X	31.2	87	X	31.0	89	X	31.2	88	X	31.9	84	X	31.2	87	X
11	32.3	88	X	32.3	88	X	32.9	85	X	32.8	85	X	32.3	88	X	32.3	88	X	32.9	85	X	32.8	85	X
12	33.4	83	X	33.2	84	X	34.0	80	X	32.9	85	X	33.3	83	X	33.2	84	X	34.0	80	X	32.9	85	X
13	34.1	84	X	33.9	84	X	34.6	81	X	33.5	86	X	34.1	84	X	33.9	85	X	34.6	81	X	33.5	86	X
14	33.8	75	X	33.9	76	X	34.4	74	X	33.7	77	X	33.8	75	X	33.9	76	X	34.3	74	X	33.7	78	X
15	34.8	68	X	34.4	70	X	34.8	68	X	34.1	71	X	34.7	68	X	34.4	71	X	34.8	68	X	34.1	71	X
16	33.9	78	X	34.3	76	X	33.9	78	X	34.1	77	X	33.9	78	X	34.3	76	X	33.9	78	X	34.1	77	X
17	32.9	83	X	33.4	81	X	33.8	79	X	33.9	78	X	32.9	83	X	33.4	81	X	33.8	79	X	33.9	79	X
18	29.9	74	X	30.3	73	X	30.4	73	X	31.3	70	X	29.9	74	X	30.3	73	X	30.4	73	X	31.3	70	X
19	29.3	83	X	29.3	82	X	29.4	82	X	30.5	77	X	29.3	83	X	29.3	82	X	29.4	82	X	30.5	77	X
20	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X
21	28.3	85	X	28.6	83	X	28.6	83	X	32.6	68	X	28.3	84	X	28.6	83	X	28.6	83	X	32.6	68	X
22	28.8	81	X	29.6	78	X	29.5	78	X	30.8	73	X	28.8	81	X	29.6	78	X	29.5	78	X	30.8	73	X
23	33.1	67	X	32.2	72	X	31.4	71	X	31.1	70	X	33.2	67	X	32.3	72	X	31.4	71	X	31.1	70	X
24	32.1	71	X	32.4	74	X	31.3	71	X	31.3	69	X	32.1	71	X	32.4	74	X	31.4	71	X	31.3	68	X
Max	34.8	89		34.4	88		34.8	85		34.1	87		34.7	89		34.4	88		34.8	85		34.1	87	
Min	26.7	67		27.7	70		27.8	68		27.2	68		26.7	67		27.7	71		27.8	68		27.2	68	
Mean	31.4	79		31.6	80		31.4	77		31.6	76		31.4	79		31.7	80		31.4	77		31.6	76	
TC hours			2			2			1			1			2			2			1			1
Annual CL (kWh)			1951			1401			1405			3791			1957			1401			1408			3772

	ClIn02	ClIn03
Total annual CL (kWh)	8548	8538
CLI(kWh/m2year)	142	142

Table C1.8 – continue

	Cln04											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.8	74	X	33.1	79	X	31.9	73	X	31.8	71	X
2	32.5	75	X	32.9	80	X	31.7	73	X	31.7	71	X
3	32.1	75	X	32.7	80	X	31.4	73	X	31.4	70	X
4	31.8	74	X	32.4	81	X	31.0	72	X	31.1	69	X
5	31.4	75	X	32.1	81	X	30.6	73	X	30.9	69	X
6	31.1	75	X	31.9	81	X	30.4	73	X	30.2	70	X
7	26.7	85	1.0m/s	27.8	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.0m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	28.0	85	X	28.4	83	X
9	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X
10	31.0	89	X	31.1	88	X	31.9	84	X	31.2	87	X
11	32.3	88	X	32.3	88	X	32.9	85	X	32.8	85	X
12	33.3	83	X	33.2	84	X	34.0	80	X	32.9	85	X
13	34.1	84	X	33.9	85	X	34.6	81	X	33.5	86	X
14	33.8	75	X	33.8	76	X	34.3	74	X	33.6	78	X
15	34.7	68	X	34.3	70	X	34.8	68	X	34.1	71	X
16	33.9	78	X	34.3	76	X	33.9	78	X	34.1	77	X
17	32.9	83	X	33.4	81	X	33.8	79	X	33.9	79	X
18	29.9	74	X	30.3	73	X	30.4	73	X	31.3	70	X
19	29.3	83	X	29.3	82	X	29.4	82	X	30.5	77	X
20	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X
21	28.3	84	X	28.6	83	X	28.6	83	X	32.6	68	X
22	28.8	81	X	29.6	78	X	29.5	78	X	30.8	73	X
23	33.2	66	X	32.3	72	X	31.5	71	X	31.1	70	X
24	32.2	71	X	32.5	74	X	31.4	71	X	31.3	68	X
Max	34.7	89		34.3	88		34.8	85		34.1	87	
Min	26.7	66		27.7	70		27.8	68		27.2	68	
Mean	31.4	79		31.7	80		31.5	77		31.6	76	
TC hours			2			2			1			1
Annual CL (kWh)			1962			1402			1409			3758

	Cln05											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.8	74	X	33.1	78	X	31.9	73	X	31.8	71	X
2	32.5	74	X	33.0	79	X	31.7	73	X	31.7	71	X
3	32.2	74	X	32.7	80	X	31.4	73	X	31.4	70	X
4	31.8	74	X	32.5	80	X	31.0	72	X	31.2	69	X
5	31.5	74	X	32.2	81	X	30.6	72	X	30.9	69	X
6	31.2	75	X	31.9	81	X	30.4	73	X	30.2	70	X
7	26.7	85	1.0m/s	27.8	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.0m/s
8	27.3	88	1.5m/s	27.7	87	1.5m/s	28.0	85	X	28.4	83	X
9	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X
10	31.0	89	X	31.1	88	X	31.9	84	X	31.2	87	X
11	32.3	88	X	32.3	88	X	32.9	85	X	32.8	85	X
12	33.3	83	X	33.2	84	X	34.0	80	X	32.9	86	X
13	34.1	84	X	33.9	85	X	34.6	81	X	33.4	87	X
14	33.8	75	X	33.8	76	X	34.3	74	X	33.6	78	X
15	34.7	68	X	34.3	70	X	34.8	68	X	34.0	71	X
16	33.9	78	X	34.3	76	X	33.9	78	X	34.1	77	X
17	32.9	83	X	33.4	81	X	33.8	79	X	33.9	79	X
18	29.9	74	X	30.3	73	X	30.4	73	X	31.3	70	X
19	29.3	83	X	29.3	82	X	29.4	82	X	30.5	77	X
20	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X
21	28.3	84	X	28.6	83	X	28.6	83	X	32.6	68	X
22	28.8	81	X	29.6	78	X	29.5	78	X	30.8	73	X
23	33.2	66	X	32.3	72	X	31.5	71	X	31.1	70	X
24	32.2	71	X	32.5	74	X	31.4	71	X	31.3	68	X
Max	34.7	89		34.3	88		34.8	85		34.1	87	
Min	26.7	66		27.7	70		27.8	68		27.2	68	
Mean	31.4	79		31.7	80		31.5	77		31.6	76	
TC hours			2			2			1			1
Annual CL (kWh)			1965			1402			1411			3747

	Cln04	Cln05
Total annual CL (kWh)	8531	8525
CLI(kWh/m2year)	142	142

Table C1.8 – continue

	Cln06												Cln07											
	Bed1			Bed2			Bed3			Family			Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.8	74	X	33.2	78	X	31.9	73	X	31.8	71	X	32.8	74	X	33.2	78	X	31.9	73	X	31.8	71	X
2	32.5	74	X	33.0	79	X	31.7	73	X	31.7	71	X	32.5	74	X	33.0	79	X	31.7	73	X	31.7	71	X
3	32.2	74	X	32.7	80	X	31.4	73	X	31.4	70	X	32.2	74	X	32.8	80	X	31.4	73	X	31.4	70	X
4	31.8	74	X	32.5	80	X	31.0	72	X	31.2	69	X	31.9	74	X	32.5	80	X	31.0	72	X	31.2	69	X
5	31.5	74	X	32.2	81	X	30.6	72	X	30.9	69	X	31.5	74	X	32.2	81	X	30.7	72	X	30.9	69	X
6	31.2	75	X	31.9	81	X	30.4	73	X	30.2	70	X	31.2	74	X	32.0	81	X	30.4	73	X	30.3	70	X
7	26.7	85	1.0m/s	27.8	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.0m/s	26.7	85	1.0m/s	27.8	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.0m/s
8	27.3	88	1.5m/s	27.7	86	1.5m/s	28.0	85	X	28.4	83	X	27.3	88	1.5m/s	27.7	86	1.5m/s	28.0	85	X	28.4	83	X
9	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X
10	31.0	89	X	31.1	88	X	31.9	84	X	31.2	87	X	31.0	89	X	31.1	88	X	31.9	84	X	31.2	87	X
11	32.3	88	X	32.3	88	X	32.9	85	X	32.8	85	X	32.3	88	X	32.2	88	X	32.9	85	X	32.8	85	X
12	33.3	83	X	33.2	84	X	34.0	80	X	32.8	86	X	33.3	83	X	33.2	84	X	34.0	80	X	32.8	86	X
13	34.1	84	X	33.9	85	X	34.6	82	X	33.4	87	X	34.1	84	X	33.9	85	X	34.6	82	X	33.4	87	X
14	33.8	75	X	33.8	76	X	34.3	74	X	33.6	78	X	33.8	75	X	33.8	76	X	34.3	74	X	33.6	78	X
15	34.7	68	X	34.2	70	X	34.8	68	X	34.0	72	X	34.7	68	X	34.2	70	X	34.8	68	X	34.0	72	X
16	33.9	78	X	34.3	76	X	33.9	78	X	34.1	77	X	33.9	78	X	34.3	77	X	33.9	78	X	34.1	77	X
17	32.9	83	X	33.3	81	X	33.8	79	X	33.8	79	X	32.9	83	X	33.3	81	X	33.8	79	X	33.8	79	X
18	29.9	74	X	30.3	73	X	30.4	73	X	31.3	70	X	29.9	74	X	30.3	73	X	30.4	73	X	31.3	70	X
19	29.3	83	X	29.3	82	X	29.4	82	X	30.5	77	X	29.3	82	X	29.3	82	X	29.4	82	X	30.5	77	X
20	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X
21	28.3	84	X	28.6	83	X	28.6	83	X	32.6	68	X	28.3	84	X	28.6	83	X	28.6	83	X	32.6	68	X
22	28.8	81	X	29.6	78	X	29.5	78	X	30.8	73	X	28.8	81	X	29.6	78	X	29.5	78	X	30.8	73	X
23	33.3	66	X	32.3	71	X	31.5	71	X	31.1	70	X	33.3	66	X	32.3	71	X	31.5	71	X	31.1	70	X
24	32.2	71	X	32.5	74	X	31.4	71	X	31.3	68	X	32.2	71	X	32.5	73	X	31.4	71	X	31.3	68	X
Max	34.7	89		34.3	88		34.8	85		34.1	87		34.7	89		34.3	88		34.8	85		34.1	87	
Min	26.7	66		27.7	70		27.8	68		27.2	68		26.7	66		27.7	70		27.8	68		27.2	68	
Mean	31.4	79		31.7	80		31.5	77		31.6	76		31.4	79		31.7	80		31.5	77		31.6	76	
TC hours			2			2			1			1			2			2			1			1
Annual CL (kWh)			1968			1402			1412			3739			1970			1403			1413			3732

	Cln06	Cln07
Total annual CL (kWh)	8522	8519
CLI(kWh/m2year)	142	142

Table C1.8 – continue

	Cln08												Cln09											
	Bed1			Bed2			Bed3			Family			Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.8	74	X	33.2	78	X	31.9	73	X	31.8	71	X	32.9	74	X	33.2	78	X	31.9	73	X	31.9	71	X
2	32.6	74	X	33.0	79	X	31.7	73	X	31.7	71	X	32.6	74	X	33.0	79	X	31.7	73	X	31.7	71	X
3	32.2	74	X	32.8	80	X	31.4	73	X	31.4	70	X	32.2	74	X	32.8	80	X	31.4	73	X	31.4	70	X
4	31.9	74	X	32.5	80	X	31.0	72	X	31.2	69	X	31.9	74	X	32.5	80	X	31.0	72	X	31.2	69	X
5	31.5	74	X	32.2	80	X	30.7	72	X	30.9	69	X	31.5	74	X	32.3	80	X	30.7	72	X	30.9	69	X
6	31.2	74	X	32.0	81	X	30.4	73	X	30.3	70	X	31.3	74	X	32.0	81	X	30.4	73	X	30.3	70	X
7	26.7	85	1.0m/s	27.8	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.0m/s	26.7	85	1.0m/s	27.8	81	1.5m/s	27.8	80	1.5m/s	27.2	82	1.0m/s
8	27.3	88	1.5m/s	27.7	86	1.5m/s	28.0	85	X	28.4	83	X	27.3	88	1.5m/s	27.7	86	1.5m/s	28.0	85	X	28.4	83	X
9	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X
10	31.0	89	X	31.1	88	X	31.9	84	X	31.2	87	X	31.0	89	X	31.1	88	X	31.9	84	X	31.2	87	X
11	32.3	88	X	32.2	88	X	32.9	85	X	32.8	85	X	32.3	88	X	32.2	88	X	32.9	85	X	32.8	85	X
12	33.3	83	X	33.1	84	X	34.0	80	X	32.8	86	X	33.3	83	X	33.1	84	X	34.0	80	X	32.8	86	X
13	34.1	84	X	33.9	85	X	34.6	82	X	33.4	87	X	34.1	84	X	33.9	85	X	34.6	82	X	33.4	87	X
14	33.8	75	X	33.8	76	X	34.3	74	X	33.6	78	X	33.8	75	X	33.8	76	X	34.3	74	X	33.6	78	X
15	34.7	68	X	34.2	70	X	34.8	68	X	34.0	72	X	34.7	68	X	34.2	70	X	34.8	68	X	34.0	72	X
16	33.9	78	X	34.2	77	X	33.9	78	X	34.1	77	X	33.9	78	X	34.2	77	X	33.9	78	X	34.1	77	X
17	32.9	83	X	33.3	81	X	33.8	79	X	33.8	79	X	32.9	83	X	33.3	81	X	33.8	79	X	33.8	79	X
18	29.9	74	X	30.3	73	X	30.4	73	X	31.3	70	X	29.9	74	X	30.3	73	X	30.4	73	X	31.3	70	X
19	29.3	82	X	29.3	82	X	29.4	82	X	30.5	77	X	29.3	82	X	29.3	82	X	29.4	82	X	30.5	77	X
20	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X
21	28.3	84	X	28.6	83	X	28.6	83	X	32.6	68	X	28.3	84	X	28.6	83	X	28.6	83	X	32.6	68	X
22	28.8	81	X	29.6	78	X	29.5	78	X	30.8	73	X	28.8	81	X	29.6	78	X	29.5	78	X	30.8	73	X
23	33.3	66	X	32.3	71	X	31.5	71	X	31.1	70	X	33.3	66	X	32.3	71	X	31.5	71	X	31.1	70	X
24	32.2	71	X	32.5	73	X	31.4	71	X	31.3	68	X	32.3	71	X	32.6	73	X	31.4	71	X	31.3	68	X
Max	34.7	89		34.2	88		34.8	85		34.1	87		34.7	89		34.2	88		34.8	85		34.1	87	
Min	26.7	66		27.7	70		27.8	68		27.2	68		26.7	66		27.7	70		27.8	68		27.2	68	
Mean	31.4	79		31.7	80		31.5	77		31.6	76		31.4	79		31.7	80		31.5	77		31.6	76	
TC hours			2			2			1			1			2			2			1			1
Annual CL (kWh)			1972			1403			1414			3727			1974			1403			1415			3722

	Cln08	Cln09
Total annual CL (kWh)	8516	8514
CLI(kWh/m2year)	142	142

Table C1.8 – continue

	Cln10											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.9	74	X	33.2	78	X	31.9	73	X	31.9	71	X
2	32.6	74	X	33.0	79	X	31.7	73	X	31.7	71	X
3	32.2	74	X	32.8	80	X	31.4	73	X	31.4	70	X
4	31.9	74	X	32.5	80	X	31.0	72	X	31.2	69	X
5	31.6	74	X	32.3	80	X	30.7	72	X	30.9	69	X
6	31.3	74	X	32.0	81	X	30.4	73	X	30.3	70	X
7	26.7	85	1.0m/s	27.8	81	1.5m/s	27.8	80	1.5m/s	27.2	82	1.0m/s
8	27.3	88	1.5m/s	27.7	86	1.5m/s	28.0	85	X	28.4	83	X
9	29.8	88	X	29.9	87	X	30.6	84	X	30.2	85	X
10	31.0	89	X	31.1	88	X	31.9	84	X	31.2	87	X
11	32.3	88	X	32.2	88	X	32.9	85	X	32.8	85	X
12	33.3	83	X	33.1	84	X	34.0	80	X	32.8	86	X
13	34.1	84	X	33.8	85	X	34.6	82	X	33.4	87	X
14	33.8	75	X	33.8	76	X	34.3	74	X	33.6	78	X
15	34.7	68	X	34.2	70	X	34.8	68	X	34.0	72	X
16	33.9	78	X	34.2	77	X	33.9	78	X	34.1	77	X
17	32.9	83	X	33.3	81	X	33.8	79	X	33.8	79	X
18	29.9	74	X	30.3	73	X	30.4	73	X	31.3	70	X
19	29.3	82	X	29.3	82	X	29.4	82	X	30.5	77	X
20	29.9	81	X	30.5	78	X	30.5	78	X	31.0	76	X
21	28.3	84	X	28.6	83	X	28.6	83	X	32.6	68	X
22	28.8	81	X	29.6	78	X	29.5	78	X	30.8	73	X
23	33.3	66	X	32.3	71	X	31.5	71	X	31.1	70	X
24	32.3	71	X	32.6	73	X	31.4	71	X	31.3	68	X
Max	34.7	89		34.2	88		34.8	85		34.1	87	
Min	26.7	66		27.7	70		27.8	68		27.2	68	
Mean	31.4	79		31.7	80		31.5	77		31.6	76	
TC hours			2			2			1			1
Annual CL (kWh)			1976			1404			1416			3717

Total annual CL (kWh)	8512
CLI(kWh/m2year)	142

Table C1.9

COMBOCln: Thermal performance, thermal comfort hours and cooling loads

	ComboC1Cln											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.5	75	X	32.8	80	X	31.6	74	X	31.6	72	X
2	32.2	75	X	32.6	81	X	31.4	74	X	31.4	72	X
3	31.9	76	X	32.4	82	X	31.1	74	X	31.2	71	X
4	31.6	75	X	32.1	82	X	30.8	73	X	30.9	70	X
5	31.2	75	X	31.9	82	X	30.4	73	X	30.7	70	X
6	31.0	76	X	31.6	83	X	30.2	74	X	30.1	71	X
7	26.7	86	1.0m/s	27.7	81	1.5m/s	27.7	80	1.5m/s	27.2	83	1.0m/s
8	27.3	89	1.5m/s	27.6	87	1.5m/s	27.9	86	X	28.3	83	X
9	29.7	89	X	29.8	88	X	30.5	85	X	30.1	86	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.0	88	X
11	32.3	88	X	32.1	88	X	32.8	85	X	32.6	86	X
12	33.2	84	X	33.0	85	X	33.8	81	X	32.7	86	X
13	34.0	84	X	33.7	86	X	34.3	82	X	33.2	88	X
14	33.7	76	X	33.6	77	X	34.1	75	X	33.4	79	X
15	34.5	69	X	34.0	71	X	34.6	69	X	33.7	73	X
16	33.9	78	X	34.1	77	X	33.9	78	X	33.9	78	X
17	32.8	83	X	33.2	82	X	33.6	80	X	33.7	80	X
18	29.8	75	X	30.1	74	X	30.2	74	X	31.1	71	X
19	29.2	83	X	29.2	83	X	29.2	83	X	30.3	78	X
20	29.8	81	X	30.4	79	X	30.3	79	X	30.8	76	X
21	28.2	85	X	28.4	84	X	28.5	84	X	32.4	69	X
22	28.7	82	X	29.4	79	X	29.4	79	X	30.6	74	X
23	32.9	68	X	31.9	73	X	31.1	72	X	30.8	71	X
24	31.9	72	X	32.1	75	X	31.0	73	X	31.0	70	X
Max	34.5	89		34.1	88		34.6	86		33.9	88	
Min	26.7	68		27.6	71		27.7	69		27.2	69	
Mean	31.3	80		31.5	81		31.3	78		31.4	77	
TC hours			2			2			1			1
Annual CL (kWh)			1846			1289			1261			3509

	ComboC2Cln											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.6	75	X	32.9	80	X	31.7	74	X	31.6	72	X
2	32.3	75	X	32.7	81	X	31.5	74	X	31.5	71	X
3	32.0	75	X	32.4	81	X	31.2	74	X	31.2	71	X
4	31.6	75	X	32.2	82	X	30.8	73	X	31.0	70	X
5	31.3	75	X	31.9	82	X	30.5	73	X	30.7	70	X
6	31.0	76	X	31.6	82	X	30.2	73	X	30.1	71	X
7	26.7	85	1.0m/s	27.7	81	1.5m/s	27.7	80	1.5m/s	27.2	83	1.0m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	86	X	28.3	83	X
9	29.7	88	X	29.8	88	X	30.5	85	X	30.1	85	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.1	88	X
11	32.3	88	X	32.2	88	X	32.8	85	X	32.7	86	X
12	33.2	84	X	33.1	85	X	33.8	81	X	32.7	86	X
13	34.0	84	X	33.8	85	X	34.4	82	X	33.3	87	X
14	33.7	76	X	33.6	77	X	34.2	74	X	33.4	79	X
15	34.6	69	X	34.0	71	X	34.6	69	X	33.8	72	X
16	33.9	78	X	34.1	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	82	X	33.6	80	X	33.7	79	X
18	29.8	75	X	30.2	74	X	30.2	73	X	31.1	71	X
19	29.3	83	X	29.2	83	X	29.2	83	X	30.3	78	X
20	29.8	81	X	30.4	78	X	30.4	79	X	30.8	76	X
21	28.2	85	X	28.5	84	X	28.5	83	X	32.4	69	X
22	28.7	82	X	29.4	79	X	29.4	79	X	30.6	74	X
23	33.0	67	X	32.0	73	X	31.2	72	X	30.9	71	X
24	31.9	72	X	32.2	75	X	31.1	72	X	31.1	69	X
Max	34.6	89		34.1	88		34.6	86		34.0	88	
Min	26.7	67		27.7	71		27.7	69		27.2	69	
Mean	31.3	80		31.5	81		31.3	78		31.4	77	
TC hours			2			2			1			1
Annual CL (kWh)			1869			1313			1291			3557

	ComboC1Cln	ComboC2Cln
Total annual CL (kWh)	7906	8030
CL Index(kWh/m2year)	132	134

Table C1.9 – continue

Hour	ComboC3Cln Bed1 T	RH	TC	Bed2 T	RH	TC	Bed3 T	RH	TC	Family T	RH	TC
1	32.6	75	X	32.9	79	X	31.7	74	X	31.7	72	X
2	32.3	75	X	32.7	80	X	31.5	74	X	31.5	71	X
3	32.0	75	X	32.5	81	X	31.2	73	X	31.3	71	X
4	31.6	75	X	32.2	81	X	30.8	73	X	31.0	70	X
5	31.3	75	X	32.0	82	X	30.5	73	X	30.8	69	X
6	31.0	75	X	31.7	82	X	30.3	73	X	30.1	71	X
7	26.7	85	1.0m/s	27.7	81	1.5m/s	27.7	80	1.5m/s	27.2	83	1.0m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X
9	29.7	88	X	29.9	87	X	30.5	85	X	30.1	85	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.1	87	X
11	32.3	88	X	32.2	88	X	32.9	85	X	32.7	85	X
12	33.3	84	X	33.1	84	X	33.9	81	X	32.8	86	X
13	34.1	84	X	33.8	85	X	34.4	82	X	33.3	87	X
14	33.8	76	X	33.7	77	X	34.2	74	X	33.5	78	X
15	34.6	68	X	34.1	71	X	34.6	68	X	33.9	72	X
16	33.9	78	X	34.1	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	81	X	33.7	80	X	33.7	79	X
18	29.9	75	X	30.2	74	X	30.3	73	X	31.2	71	X
19	29.3	83	X	29.2	83	X	29.3	83	X	30.4	78	X
20	29.8	81	X	30.4	78	X	30.4	78	X	30.8	76	X
21	28.2	85	X	28.5	83	X	28.5	83	X	32.4	69	X
22	28.7	82	X	29.5	78	X	29.4	79	X	30.7	74	X
23	33.0	67	X	32.1	72	X	31.2	72	X	30.9	71	X
24	32.0	72	X	32.3	75	X	31.1	72	X	31.1	69	X
Max	34.6	89		34.1	88		34.6	85		34.0	87	
Min	26.7	67		27.7	71		27.7	68		27.2	69	
Mean	31.3	79		31.5	81		31.3	78		31.4	76	
TC hours			2			2			2			1
Annual CL (kWh)			1893			1337			1321			3695

Hour	ComboC4Cln Bed1 T	RH	TC	Bed2 T	RH	TC	Bed3 T	RH	TC	Family T	RH	TC
1	32.6	75	X	33.0	79	X	31.8	74	X	31.7	72	X
2	32.4	75	X	32.8	80	X	31.6	74	X	31.5	71	X
3	32.0	75	X	32.6	81	X	31.2	73	X	31.3	70	X
4	31.7	75	X	32.3	81	X	30.9	73	X	31.0	70	X
5	31.3	75	X	32.0	82	X	30.5	73	X	30.8	69	X
6	31.0	75	X	31.7	82	X	30.3	73	X	30.2	71	X
7	26.7	85	1.0m/s	27.8	81	1.5m/s	27.8	80	1.5m/s	27.2	83	1.0m/s
8	27.3	89	1.5m/s	27.7	87	1.5m/s	27.9	85	1.5m/s	28.4	83	X
9	29.7	88	X	29.9	87	X	30.6	84	X	30.1	85	X
10	31.0	89	X	31.1	88	X	31.8	85	X	31.1	87	X
11	32.3	88	X	32.2	88	X	32.9	85	X	32.7	85	X
12	33.3	84	X	33.1	84	X	33.9	81	X	32.8	86	X
13	34.1	84	X	33.8	85	X	34.5	82	X	33.4	87	X
14	33.8	76	X	33.7	77	X	34.2	74	X	33.5	78	X
15	34.6	68	X	34.1	71	X	34.7	68	X	33.9	72	X
16	33.9	78	X	34.2	77	X	33.9	78	X	34.0	77	X
17	32.8	83	X	33.3	81	X	33.7	79	X	33.8	79	X
18	29.9	75	X	30.2	74	X	30.3	73	X	31.2	71	X
19	29.3	83	X	29.3	83	X	29.3	82	X	30.4	77	X
20	29.8	81	X	30.5	78	X	30.4	78	X	30.9	76	X
21	28.2	85	X	28.5	83	X	28.6	83	X	32.5	69	X
22	28.7	82	X	29.5	78	X	29.5	78	X	30.7	74	X
23	33.1	67	X	32.1	72	X	31.3	72	X	31.0	71	X
24	32.0	72	X	32.3	74	X	31.2	72	X	31.2	69	X
Max	34.6	89		34.2	88		34.7	85		34.0	87	
Min	26.7	67		27.7	71		27.8	68		27.2	69	
Mean	31.3	79		31.6	81		31.4	77		31.5	76	
TC hours			2			2			2			1
Annual CL (kWh)			1916			1360			1352			3655

	ComboC3Cln	ComboC4Cln
Total annual CL (kWh)	8156	8283
CL Index(kWh/m2year)	136	138

Table C2.0

COMBORVCIn: Thermal performance, thermal comfort hours and cooling loads

	ComboRVC1CIn											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.3	76	X	32.6	81	X	31.4	75	X	31.4	73	X
2	32.1	76	X	32.4	82	X	31.2	75	X	31.3	72	X
3	31.7	76	X	32.1	83	X	30.9	75	X	31.0	72	X
4	31.4	76	X	31.9	83	X	30.6	74	X	30.7	71	X
5	31.0	76	X	31.6	84	X	30.2	74	X	30.5	70	X
6	30.7	77	X	31.3	84	X	30.0	75	X	29.9	72	X
7	26.6	86	1.0m/s	27.6	82	1.5m/s	27.6	81	1.5m/s	27.1	83	1.0m/s
8	27.2	89	1.5m/s	27.6	87	1.5m/s	27.8	86	1.5m/s	28.2	84	X
9	29.6	89	X	29.7	88	X	30.4	85	X	30.0	86	X
10	31.0	89	X	31.0	89	X	31.7	85	X	31.0	88	X
11	32.3	88	X	32.1	89	X	32.7	86	X	32.5	86	X
12	33.2	84	X	33.0	85	X	33.7	82	X	32.6	87	X
13	34.0	84	X	33.7	86	X	34.2	83	X	33.2	88	X
14	33.7	76	X	33.5	77	X	34.0	75	X	33.3	79	X
15	34.5	69	X	33.9	71	X	34.5	69	X	33.6	73	X
16	33.9	78	X	34.0	78	X	33.8	78	X	33.9	78	X
17	32.8	83	X	33.1	82	X	33.5	80	X	33.6	80	X
18	29.8	75	X	30.1	74	X	30.1	74	X	31.0	72	X
19	29.2	83	X	29.1	83	X	29.1	83	X	30.2	78	X
20	29.7	81	X	30.3	79	X	30.3	79	X	30.7	77	X
21	28.1	85	X	28.4	84	X	28.4	84	X	32.2	70	X
22	28.6	82	X	29.3	79	X	29.3	79	X	30.5	74	X
23	32.7	68	X	31.7	74	X	30.9	73	X	30.7	72	X
24	31.7	73	X	31.9	76	X	30.8	74	X	30.9	70	X
Max	34.5	89		34.0	89		34.5	86		33.9	88	
Min	26.6	68		27.6	71		27.6	69		27.1	70	
Mean	31.2	80		31.3	82		31.1	78		31.3	77	
TC hours			2			2			2			1
Annual CL (kWh)			1781			1227			1181			3440

	ComboRVC2CIn											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.4	76	X	32.6	81	X	31.5	75	X	31.5	73	X
2	32.1	76	X	32.4	82	X	31.3	75	X	31.3	72	X
3	31.7	76	X	32.2	83	X	30.9	75	X	31.0	72	X
4	31.4	76	X	31.9	83	X	30.6	74	X	30.8	71	X
5	31.1	76	X	31.6	83	X	30.2	74	X	30.5	70	X
6	30.8	76	X	31.4	84	X	30.0	74	X	29.9	71	X
7	26.6	86	1.0m/s	27.6	82	1.5m/s	27.6	81	1.5m/s	27.1	83	1.0m/s
8	27.2	89	1.5m/s	27.6	87	1.5m/s	27.8	86	1.5m/s	28.2	83	X
9	29.7	89	X	29.8	88	X	30.5	85	X	30.0	86	X
10	31.0	89	X	31.0	89	X	31.7	85	X	31.0	88	X
11	32.3	88	X	32.1	89	X	32.8	85	X	32.6	86	X
12	33.2	84	X	33.0	85	X	33.7	81	X	32.6	87	X
13	34.0	84	X	33.7	86	X	34.3	83	X	33.2	88	X
14	33.7	76	X	33.5	77	X	34.1	75	X	33.3	79	X
15	34.5	69	X	33.9	71	X	34.5	69	X	32.7	73	X
16	33.9	78	X	34.0	77	X	33.9	78	X	33.9	78	X
17	32.8	83	X	33.2	82	X	33.6	80	X	33.6	80	X
18	29.8	75	X	30.1	74	X	30.2	74	X	31.0	71	X
19	29.2	83	X	29.1	83	X	29.2	83	X	30.3	78	X
20	29.7	81	X	30.3	79	X	30.3	79	X	30.7	77	X
21	28.2	85	X	28.4	84	X	28.4	84	X	32.3	70	X
22	28.6	82	X	29.4	79	X	29.3	79	X	30.6	74	X
23	32.8	68	X	31.7	74	X	30.9	73	X	30.7	72	X
24	31.7	73	X	31.9	76	X	30.8	73	X	30.9	70	X
Max	34.5	89		34.0	89		34.5	86		33.9	88	
Min	26.6	68		27.6	71		27.6	69		27.1	70	
Mean	31.2	80		31.4	81		31.2	78		31.3	77	
TC hours			2			2			2			1
Annual CL (kWh)			1794			1241			1199			3473

	ComboRVC1CIn	ComboRVC2CIn
Total annual CL (kWh)	7629	7708
CL Index(kWh/m2year)	127	128

Table C2.0 – continue

	ComboRVC3Cln											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.4	76	X	32.6	81	X	31.5	75	X	31.5	73	X
2	32.1	76	X	32.5	82	X	31.3	75	X	31.3	72	X
3	31.8	76	X	32.2	83	X	31.0	74	X	31.1	71	X
4	31.4	76	X	31.9	83	X	30.6	74	X	30.8	71	X
5	31.1	76	X	31.6	83	X	30.3	74	X	30.5	70	X
6	30.8	76	X	31.4	84	X	30.0	74	X	30.0	71	X
7	26.6	86	1.0m/s	27.7	81	1.5m/s	27.7	81	1.5m/s	27.1	83	1.0m/s
8	27.2	89	1.5m/s	27.6	87	1.5m/s	27.8	86	1.5m/s	28.3	83	X
9	29.7	89	X	29.8	88	X	30.5	85	X	30.0	86	X
10	31.0	89	X	31.0	89	X	31.7	85	X	31.0	88	X
11	32.3	88	X	32.1	89	X	32.8	85	X	32.6	86	X
12	33.2	84	X	33.0	85	X	33.8	81	X	32.7	87	X
13	34.0	84	X	33.7	86	X	34.3	83	X	33.2	88	X
14	33.7	76	X	33.6	77	X	34.1	75	X	33.3	79	X
15	34.5	69	X	34.0	71	X	34.5	69	X	33.7	73	X
16	33.9	78	X	34.1	77	X	33.9	78	X	33.9	78	X
17	32.8	83	X	33.2	82	X	33.6	80	X	33.6	80	X
18	29.8	75	X	30.1	74	X	30.2	74	X	31.1	71	X
19	29.2	83	X	29.1	83	X	29.2	83	X	30.3	78	X
20	29.7	81	X	30.3	79	X	30.3	79	X	30.8	77	X
21	28.2	85	X	28.4	84	X	28.4	84	X	32.3	70	X
22	28.6	82	X	29.4	79	X	29.3	79	X	30.6	74	X
23	32.8	68	X	31.8	74	X	31.0	73	X	30.8	71	X
24	31.7	73	X	31.9	76	X	30.9	73	X	30.9	70	X
Max	34.5	89		34.1	89		34.5	86		33.9	88	
Min	26.6	68		27.6	71		27.7	69		27.1	70	
Mean	31.2	80		31.4	81		31.2	78		31.3	77	
TC hours			2			2			2			1
Annual CL (kWh)			1808			1255			1217			3504

	ComboRVC4Cln											
	Bed1			Bed2			Bed3			Family		
Hour	T	RH	TC	T	RH	TC	T	RH	TC	T	RH	TC
1	32.4	76	X	32.7	81	X	31.5	75	X	31.5	73	X
2	32.1	76	X	32.5	82	X	31.3	75	X	31.3	72	X
3	31.8	76	X	32.2	82	X	31.0	74	X	31.1	71	X
4	31.4	76	X	32.0	83	X	30.6	74	X	30.8	71	X
5	31.1	76	X	31.7	83	X	30.3	74	X	30.6	70	X
6	30.8	76	X	31.4	84	X	30.1	74	X	30.0	71	X
7	26.6	86	1.0m/s	27.7	81	1.5m/s	27.7	81	1.5m/s	27.1	83	1.0m/s
8	27.2	89	1.5m/s	27.6	87	1.5m/s	27.8	86	1.5m/s	28.3	83	X
9	29.7	89	X	29.8	88	X	30.5	85	X	30.0	86	X
10	31.0	89	X	31.0	88	X	31.7	85	X	31.0	88	X
11	32.3	88	X	32.1	88	X	32.8	85	X	32.6	86	X
12	33.2	84	X	33.0	85	X	33.8	81	X	32.7	86	X
13	34.0	84	X	33.7	85	X	34.4	82	X	33.3	88	X
14	33.7	76	X	33.6	77	X	34.1	75	X	33.4	79	X
15	34.5	69	X	34.0	71	X	34.6	69	X	33.8	73	X
16	33.9	78	X	34.1	77	X	33.9	78	X	34.0	78	X
17	32.8	83	X	33.2	82	X	33.6	80	X	33.7	79	X
18	29.8	75	X	30.2	74	X	30.2	74	X	31.1	71	X
19	29.2	83	X	29.2	83	X	29.2	83	X	30.3	78	X
20	29.7	81	X	30.4	79	X	30.3	79	X	30.8	76	X
21	28.2	85	X	28.4	84	X	28.5	84	X	32.3	70	X
22	28.6	82	X	29.4	79	X	29.3	79	X	30.6	74	X
23	32.8	68	X	31.8	74	X	31.0	73	X	30.8	71	X
24	31.8	73	X	32.0	76	X	30.9	73	X	31.0	70	X
Max	34.5	89		34.1	88		34.6	86		34.0	88	
Min	26.6	68		27.6	71		27.7	69		27.1	70	
Mean	31.2	80		31.4	81		31.2	78		31.3	77	
TC hours			2			2			2			1
Annual CL (kWh)			1821			1269			1235			3533

	ComboRVC3Cln	ComboRVC4Cln
Total annual CL (kWh)	7784	7858
CL Index(kWh/m2year)	130	131

Table C2.1

Summary of thermal and energy performances for RV models

Model		Bed1	Bed2	Bed3	Family	RSpace	Annual CL (kWh)	CL Index ($kWhm^{-2}year^{-1}$)
RV00 (BASE; RV=0 ach)	T_{max} (°C)	34.8	34.5	34.9	34.2	43.4		
	T_{min} (°C)	26.7	27.7	27.8	27.2	28.0		
	T_{mean} (°C)	31.3	31.6	31.4	31.6			
	TC hrs	2	2	2	1			
	CL (kWh)	1933	1398	1399	3827		8556	143
RV05 (RV=5 ach)	T_{max} (°C)	34.7	34.3	34.8	34.1	40.6		
	T_{min} (°C)	26.6	27.6	27.7	27.1	26.9		
	T_{mean} (°C)	31.2	31.4	31.3	31.4			
	TC hrs	2	2	2	1			
	CL (kWh)	1851	1324	1312	3712		8199	137
RV10 (RV=10 ach)	T_{max} (°C)	34.7	34.2	34.7	34.0	39.1		
	T_{min} (°C)	26.6	27.6	27.6	27.1	26.3		
	T_{mean} (°C)	31.1	31.3	31.2	31.3			
	TC hrs	2	2	2	1			
	CL (kWh)	1806	1283	1263	3649		8000	133
RV15 (RV=15 ach)	T_{max} (°C)	34.6	34.2	34.7	34.0	38.2		
	T_{min} (°C)	26.5	27.5	27.6	27.1	26.0		
	T_{mean} (°C)	31.1	31.3	31.2	31.3			
	TC hrs	2	2	2	1			
	CL (kWh)	1778	1257	1232	3609		7875	131
RV20 (RV = 20 ach)	T_{max} (°C)	34.6	34.2	34.6	34.0	37.5		
	T_{min} (°C)	26.5	27.5	27.6	27.0	25.8		
	T_{mean} (°C)	31.0	31.2	31.1	31.2			
	TC hrs	2	2	2	2			
	CL (kWh)	1758	1239	1210	3581		7788	130
RV25 (RV = 25 ach)	T_{max} (°C)	34.6	34.1	34.6	34.0	37.1		
	T_{min} (°C)	26.5	27.5	27.6	27.0	25.6		
	T_{mean} (°C)	31.0	31.2	31.1	31.2			
	TC hrs	2	2	2	1			
	CL (kWh)	1744	1225	1194	3560		7723	129
RV30 (RV = 30 ach)	T_{max} (°C)	34.6	34.1	34.6	34.0	36.7		
	T_{min} (°C)	26.5	27.5	27.6	27.0	25.5		
	T_{mean} (°C)	31.0	31.2	31.1	31.2			
	TC hrs	2	2	2	1			
	CL (kWh)	1733	1215	1182	3543		7674	128
RV35 (RV = 35 ach)	T_{max} (°C)	34.6	34.1	34.6	34.0	36.5		
	T_{min} (°C)	26.5	27.5	27.6	27.0	25.4		
	T_{mean} (°C)	31.0	31.2	31.1	31.2			
	TC hrs	2	2	2	1			
	CL (kWh)	1724	1207	1172	3530		7634	127
RV40 (RV = 40 ach)	T_{max} (°C)	34.5	34.1	34.6	34.0	36.2		
	T_{min} (°C)	26.5	27.5	27.5	27.0	25.3		
	T_{mean} (°C)	31.0	31.2	31.1	31.2			
	TC hrs	2	2	2	1			
	CL (kWh)	1717	1200	1164	3519		7601	127
RV45 (RV = 45 ach)	T_{max} (°C)	34.5	34.1	34.6	34.0	36.1		
	T_{min} (°C)	26.5	27.5	27.5	27.0	25.2		
	T_{mean} (°C)	31.0	31.2	31.1	31.2			
	TC hrs	2	2	2	1			
	CL (kWh)	1712	1195	1158	3511		7575	126
RV50 (RV = 50 ach)	T_{max} (°C)	34.5	34.1	34.6	34.0	35.9		
	T_{min} (°C)	26.5	27.5	27.5	27.0	25.2		
	T_{mean} (°C)	31.0	31.1	31.1	31.2			
	TC hrs	2	2	2	1			
	CL (kWh)	1707	1190	1152	3503		7552	126

Table C2.2

Summary of thermal and energy performance for CIn models

Model		Bed1	Bed2	Bed3	Family	RSpace	Annual CL (kWh)	CLI ($kWhm^{-2}year^{-1}$)
CIn00 (BASE; t=0 mm)	T_{max} (°C)	34.8	34.5	34.9	34.2	43.4		
	T_{min} (°C)	26.7	27.7	27.8	27.2	28.0		
	T_{mean} (°C)	31.3	31.6	31.4	31.6			
	TC hrs	2	2	2	1			
	CL (kWh)	1933	1398	1399	3827		8556	143
CIn01 (t=10 mm)	T_{max} (°C)	34.8	34.5	34.9	34.2	43.8		
	T_{min} (°C)	26.7	27.7	27.8	27.2	27.6		
	T_{mean} (°C)	31.3	31.6	31.4	31.6			
	TC hrs	2	2	2	1			
	CL (kWh)	1941	1400	1402	3821		8565	143
CIn02 (t=20 mm)	T_{max} (°C)	34.8	34.4	34.8	34.1	44.3		
	T_{min} (°C)	26.7	27.7	27.8	27.2	27.3		
	T_{mean} (°C)	31.4	31.6	31.4	31.6			
	TC hrs	2	2	1	1			
	CL (kWh)	1951	1401	1405	3791		8548	142
CIn03 (t=30 mm)	T_{max} (°C)	34.7	34.4	34.8	34.1	44.5		
	T_{min} (°C)	26.7	27.7	27.8	27.2	27.2		
	T_{mean} (°C)	31.4	31.7	31.4	31.6			
	TC hrs	2	2	1	1			
	CL (kWh)	1957	1401	1408	3772		8538	142
CIn04 (t=40 mm)	T_{max} (°C)	34.7	34.3	34.8	34.`	44.7		
	T_{min} (°C)	26.7	27.7	27.8	27.2	27.1		
	T_{mean} (°C)	31.4	31.7	31.5	31.6			
	TC hrs	2	2	1	1			
	CL (kWh)	1962	1402	1409	3758		8531	142
CIn05 (t=50 mm)	T_{max} (°C)	34.7	34.3	34.8	34.1	44.8		
	T_{min} (°C)	26.7	27.7	27.8	27.2	27.0		
	T_{mean} (°C)	31.4	31.7	31.5	31.6			
	TC hrs	2	2	1	1			
	CL (kWh)	1965	1402	1411	3747		8525	142
CIn06 (t=60 mm)	T_{max} (°C)	34.7	34.3	34.8	34.1	44.9		
	T_{min} (°C)	26.7	27.7	27.8	27.2	27.0		
	T_{mean} (°C)	31.4	31.7	31.5	31.6			
	TC hrs	2	2	1	1			
	CL (kWh)	1968	1402	1412	3739		8522	142
CIn07 (t=70 mm)	T_{max} (°C)	34.7	34.3	34.8	34.1	45.0		
	T_{min} (°C)	26.7	27.7	27.8	27.2	26.9		
	T_{mean} (°C)	31.4	31.7	31.5	31.6			
	TC hrs	2	2	1	1			
	CL (kWh)	1970	1403	1413	3732		8519	142
CIn08 (t=80 mm)	T_{max} (°C)	34.7	34.2	34.8	34.1	45.1		
	T_{min} (°C)	26.7	27.7	27.8	27.2	26.9		
	T_{mean} (°C)	31.4	31.7	31.5	31.6			
	TC hrs	2	2	1	1			
	CL (kWh)	1972	1403	1414	3727		8516	142
CIn09 (t=90 mm)	T_{max} (°C)	34.7	34.2	34.8	34.1	45.1		
	T_{min} (°C)	26.7	27.7	27.8	27.2	26.9		
	T_{mean} (°C)	31.4	31.7	31.5	31.6			
	TC hrs	2	2	1	1			
	CL (kWh)	1974	1403	1415	3722		8514	142
CIn10 (t=100 mm)	T_{max} (°C)	34.7	34.2	34.8	34.1	45.2		
	T_{min} (°C)	26.7	27.7	27.8	27.2	26.8		
	T_{mean} (°C)	31.4	31.7	31.5	31.6			
	TC hrs	2	2	1	1			
	CL (kWh)	1976	1404	1416	3717		8512	142