Chapter 1

Outline of thesis

1.1 Introduction

During the mid to late 1970s the energy crisis, the increase in greenhouse gas emissions and global warming concerns became important international issues. The importance of these issues for the future of humanity has led to international efforts in sustainable development. The “Brundtland Report” (1987) entitled “Our Common Future” showed that economic growth at the world’s current rate was not sustainable on ecological grounds. The report saw potential climate change as an issue that threatened sustainable development, and recommended urgent action to increase energy efficiency. International concern about greenhouse gas emissions resulted in the Kyoto Protocol, which shares the 1992 United Nation’s Convention’s objective for reducing green house gas emissions of at least 5% from 1990 levels in the commitment period 2008–2012, with 168 countries, having ratified the protocol to date (United Nation, 1998).

However, according to the IEA (International Energy Agency, 2006), world energy consumption and carbon dioxide emissions have been increasing significantly. At the same time the International Energy Outlook report (Energy Information Administration, 2006) predicts “strong growth” for world-wide energy demand until 2030. This is shown in Figure 1-1.

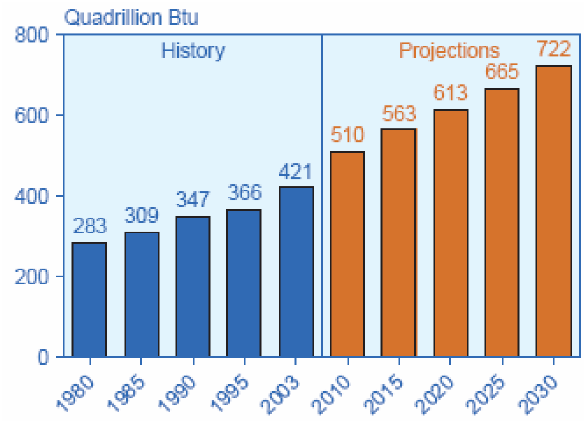


Figure 1- 1 World market energy consumption, 1980- 2030

Source History: Energy Information Administration (EIA), International Energy Annual 2003 (May-July 2005), World Energy and Economic Outlook (2006)

The impact of buildings on the environment is an important component in the consideration of sustainability. Buildings not only consume natural resources such as energy and raw materials, but also produce harmful atmospheric emissions. It is said that buildings consume one third of the world's resources (Atkinson, 2006), which includes approximately one third of primary energy supply (Hong, Chou and Bong, 2000). That means that buildings are an important contributor to global warming as well.

The residential building sector is seen to be a significant contributor to energy consumption and subsequently to greenhouse gas emissions. Residential buildings have been found to be responsible for emitting about 15% of greenhouse gas emission in OECD[1] countries such as Australia (Harrington, Foster, Wilkendfeld et al., 1999), US (United Nations, 2004) and UK (Office of the UK Deputy Prime Minister, 2004). Meanwhile the IEA (2006) has projected that residential energy end-use will rise by an average of 1.7% per year. Thus in most International Energy Agency countries, the residential sector has been the focus of more energy related policies than any other sector.

In response to the call for reducing energy demand in the building sector, House Energy Rating Schemes (HERS) have been developed in order to promote energy efficient design.

[1] Organization for Economic Co-operation and Development (OECD), consisting of 30 countries

These schemes offer a means for comparing the energy efficiency of different homes by generally providing a standardized evaluation of a home's existing energy efficiency, expected energy use cost and its potential for improvement. They differ in the range of energy end use categories covered, but commonly the basis of most programs has been the normalized energy requirement for space heating and cooling and sometimes water heating. However, relying on the control of energy consumption is not the only way to achieve energy efficiency in architectural design.

The main objective of HERS is to reduce energy consumption and greenhouse gas emissions. They mainly operate through the calculation of predicted energy requirements of buildings in order to enable energy conservation and energy efficient building design. HERS have been created to make it possible for energy efficiency to become an explicit component in home evaluation and thermal performance assessment and thus in the purchasing decision process. Vine *et. al* (1988), Turrent and Mainwaring (1990) and Ballinger and Cassell (1994) have all argued that HERS are one of the most successful methods for improving residential energy efficiency in developed countries. This claim is supported in many nations which have created a link between financing (through mortgages) and HERS to support energy efficiency design (Farhar, Collins and Walsh, 1996). Clearly the most effective way of achieving efficient architecture, and thus the main objective of HERS, would be the promotion of passive architectural design, with value placed on the efficiency of house design in 'free running operation'[2]. However, as it stands, HERS are limited in their effectiveness, since they generally ignore the significance of passive architectural design as a means of ensuring energy efficiency (Soebarto, 2000; Williamson, 2000).

---

[2] In this study the definition of *free running* that is used is: The state of a building that is naturally ventilated and does not use any mechanical equipment to maintain or improve its indoor thermal condition. In contrast, those buildings that are provided with an energy supply applied to heat/cool air or surfaces to maintain indoor conditions within a defined comfort zone are referred to in this dissertation as operating in *conditioned mode*.

1.2 Definition of problem

As it stands, the current House Energy Rating Schemes discriminate against free running houses[3]; and, therefore may be said to discourage architects and designers in the promotion of passive architecture buildings. This is the result of the fact that a systematic method for the evaluation of the free running performance of houses is missing in these house rating schemes. While the main objective of these schemes has been a reduction of energy consumption and greenhouse gas emissions in the building industry, they have been developed on the basis of predicted energy requirements, and the use of active heating and cooling. They do not deal at all with free running buildings designed to largely *avoid* heating and cooling. A building obtains a higher score through such a scheme if the predicted active energy use is low compared to the defined standard reference for the system. Logically, however, the highest score should actually be attached to a passive architectural design with no need for artificial energy for space heating and cooling. In fact, the result is that under the current house rating schemes the passive climate control features of houses may be sacrificed to pay for air conditioners. This becomes a significant issue in the moderate climates of some regions, such as in Australia, in which passive architectural design could be said to be the most suitable response for achieving the objectives of HRS, and could therefore be considered in building regulatory frameworks.

Another important phenomenon is that there is a growing demand for space heating and cooling (EIA, 2006, 2007), as people demand a higher level of indoor comfort in modern society, using air conditioning[4], and this is a problem which is unlikely to be solved under present conditions because of the dependency of current house rating schemes on calculating energy consumption. This is exacerbated by the fact that while authorities have been trying to encourage the application of efficient building design with higher ratings reflecting decreased energy demand, people tend to think that the higher score means a higher level of comfort. This tendency results in a "take back effect", which occurs when people with more efficient homes actually use more energy than expected because they are

---

[3] This issue is discussed in detail in the next chapter (See section 2.5)

[4] See EIA web site ,*comparison with other projection,* on: http://www.eia.doe.gov/oiaf/aeo/pdf/forecast.pdf

less cautious about basic efficiency measures such as thermostat settings (Stein, 1997b). It has been noted that despite efforts to improve energy performance, currently "houses do not perform optimally" (Wray, Piette, Sherman et al., 2000); in other words, the thermal performance of houses when occupied is not as has been expected or intended.

Research has demonstrated a number of shortcomings in the current rating schemes, which mean that they have been unable to reach the desired objectives of sustainability (Stein, 1997a; Soebarto, 2000; Stein and Meier, 2000; Williamson, 2000). These shortcomings, namely the inaccuracy of ratings, unrealistic standardised occupancy scenarios and the unreliability of a normalized index for evaluating the thermal performance of buildings, will be discussed in more detail in Chapter 2.

1.3 Research hypothesis

The hypothesis of this study is that an efficient design for a house in free running operation differs from that for the same house in the conditioned operation mode, and that this is a primary reason for the inability of current energy based rating schemes to adequately assess the performance of passive architectural design, in the form of free running houses.

It follows that to produce a reliable rating, therefore, it should be possible to develop a new house rating framework, based on existing computational tools, to overcome this problem, as well as to address other shortcomings in the current rating schemes which affect the accuracy of HERS.

1.4 Research objective

In view of the shortcomings described above, the main objective of this study is to develop a new framework for a House Rating Scheme by which the efficiency of the architectural design of all houses can be evaluated without unrealistically compromising the value of any particular design.

In order to achieve this, certain preliminary objectives must be met. The first of these is to establish a definition of an indicator for the evaluation of the free running performance of a house as a prerequisite for the new HRS. In other words, it requires an investigation of how the thermal performance of free running houses can be evaluated in relation to thermal comfort.

It is assumed that a cause of some of the shortcomings in current rating schemes is the lack of multiple occupancy scenarios (Boland, 2004). To address this issue, there is a need for a realistic assessment of such scenarios. This involves a consideration of the time of occupation, because if a dwelling is not occupied, it does not matter what the indoor climate is. Predicting the occupied time within dwellings exactly is impossible, but in order to achieve more accurate results it is necessary to define a multiple occupancy scenario to create an appropriate simulation algorithm for rating scheme. The aim is, therefore, to accommodate the variations in occupancy within standardised ratings.

Since the aim is to increase the efficacy of house rating schemes in evaluating all house types fairly, a comparative examination of the thermal performance of different house types is required. This includes an investigation into the way ratings appear to discriminate against different house sizes, namely single storey as against double storey houses.

1.5 Research framework and overall methodology

The methodology applied as the framework for this project is presented in Figure 1-2. The process is categorized under the three main steps: literature review, methodology and analysis. This involves the following tasks, which form the structure of this thesis.

1) To define an indicator of thermal comfort to be used as a basis for evaluating free running houses
2) To establish manageable multiple occupancy scenarios and examine the effect of these on the evaluation of a house thermal performance
3) To develop an algorithm (or a process) for assessing houses in the free running operation mode
4) To test the reliability of a free running evaluation system on the basis of the proposed indicator against a current energy based rating system

5) To investigate the response of conditioned performance and free running performance of similar houses to changing design features in order to test the hypothesis
6) To develop a new framework for a House Rating Scheme
7) To examine the likely reliability of the developed framework in achieving its objective

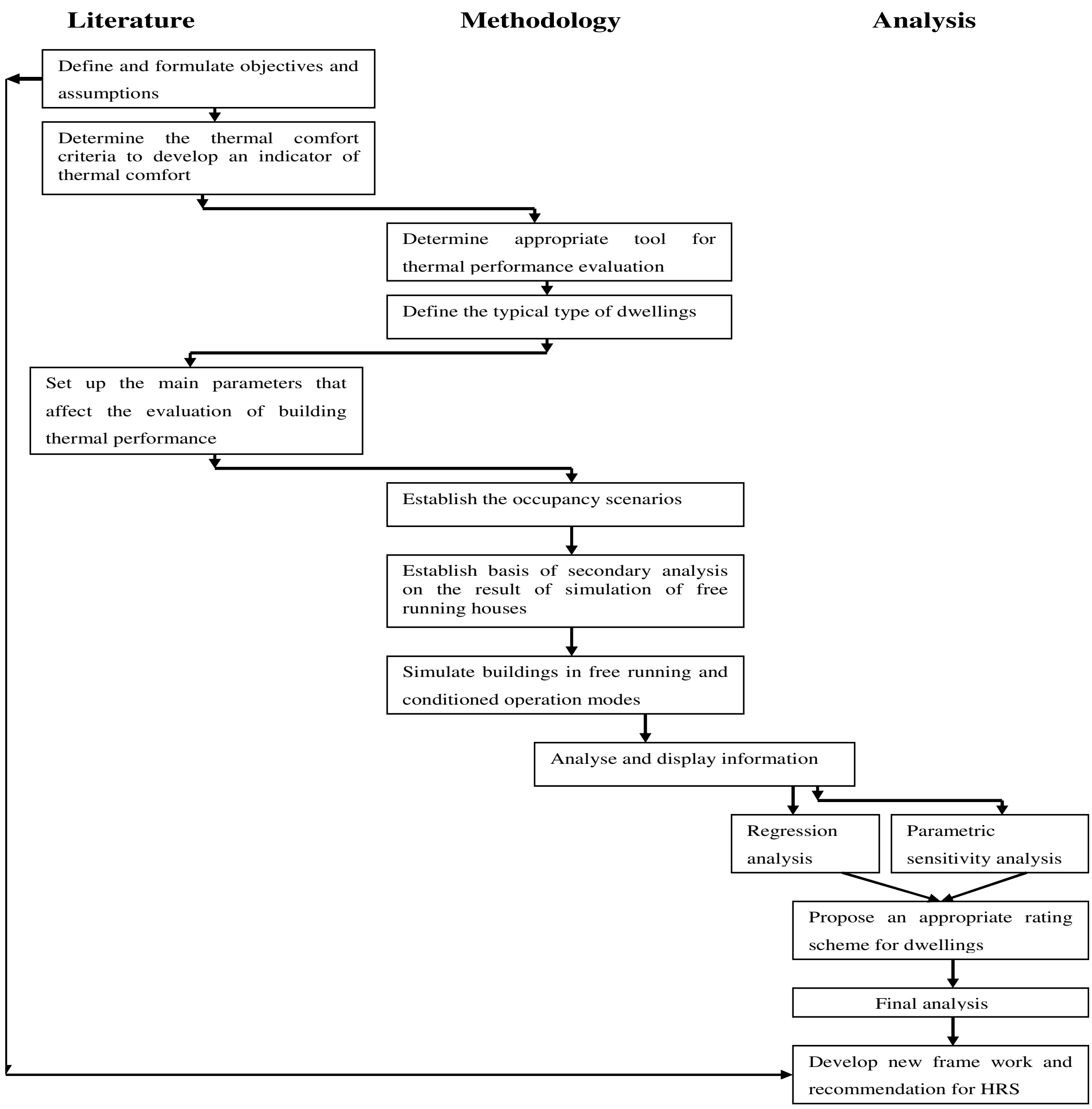


Figure 1- 2 Research framework in this study

This project focuses on typical residential houses in New South Wales with the moderate climates of Sydney and Canberra (See Section 3.1.4). The method and approach, however, need not be limited to these specified houses and locations but should be applicable to other housing types and other moderate locations.

1.6 Structure of the thesis

Chapter 2 presents a review of the literature relating to current House Energy Rating Schemes, to specifically identify shortcomings in the current HERS. This background is used to present a proposal for a new rating scheme for free running houses on the basis of thermal comfort.

In response to Task 1, Chapter 3 investigates the theoretical aspects of thermal comfort in buildings, based on a literature review. The result of this investigation is then used to propose how thermal comfort or its measurable parameters can become the basis for a rating scheme for free running houses. A specific indicator of thermal comfort is defined for free running performance measurement.

Chapter 4 then focuses on the methodology applied in this thesis to test the basic hypothesis, and to respond to the objectives outlined in Section 1.4. It determines the scope of this study through establishing a definition of typical houses and climates. In response to Task 2 it proposes a method for dealing with multiple occupancy scenarios and in response to Task 3 it establishes a process for evaluating the thermal performance of free running houses.

Chapter 5 has two parts. The first part reports the results of the test, identified as Task 4, to establish the reliability of a free running rating compared to an energy based rating, in terms of addressing aspects of efficiency in an architectural design. The second part presents a preliminary comparative analysis of typical houses as base cases for this study, in both the climates of Sydney and Canberra.

In response to Task 5, Chapters 6 and 7 report the results of two different analyses for testing the hypothesis. Chapter 6 describes the result of a parametric sensitivity analysis of typical houses. Its aim is to compare the thermal performance of simulated samples in different operation modes. Chapter 7 reports the results of a statistical analysis to examine the correlation between the thermal performance of houses in free running mode and those in the conditioned operation mode. The significant outcome is a comparison of the relative effects of design features on the performance of simulated houses in different operation modes.

Chapter 8, dealing with Task 6, develops a simplified framework for a free running rating scheme for dwellings, and then proposes a new framework for HRS. The general utility of the proposed rating framework is then tested and reported.

Chapter 9 presents a summary of the conclusions of all chapters to offer recommendations regarding the implications of the rating framework, and a program delivery mechanism. It recapitulates the limitations of this research and recommends further work.

Chapter 2

House Rating Schemes

This chapter reviews selected House Energy Rating Systems in diverse contexts. The review aims to explore the different aspects of a House Energy Rating Scheme (HERS). It will be shown that there are inadequacies in the current rating schemes which this research study attempts to address.

2.1 House Energy Rating Schemes (HERS)

The *energy* rating of a house is a standard measure that allows the energy efficiency of new or existing houses to be evaluated, such that dwellings may be compared. The comparison is commonly performed on the basis of the energy requirements for the heating and cooling of indoor spaces. Some of the HERS includes all energy requirements such as energy for water heating, washing machines and cooking.

Energy is not the only criterion for house evaluation in all rating schemes. Criteria are determined on the basis of the purpose of rating. Other criteria that have been used as important parameters in building evaluation systems are the production of greenhouse gas (GHG) emissions, indoor environment quality, cost efficiency and thermal comfort.

The energy rating of a residential building can provide detailed information on the energy consumption and the relative energy efficiency of the building. It is performed through standard measurements carried out under specific regulations and experimental procedures by specialists (Santamouris, 2005). Overall, HERS can facilitate informed decision-making for all stakeholders, as well as home-buyers considering mortgages (Ballinger, 1998a). The main impetus behind most of the rating systems has been to inform consumers about the relative energy efficiency of homes in order to encourage home-owners to use this information in making their purchasing decisions (SRC, 1991).

HERS is found in a variety of forms,

- prescriptive
- calculation-based
- performance based

All of those evaluate a building performance within the scope of a program which has been developed by the authorities of a country to promote efficiency in building design. *Prescriptive* schemes provide minimum standards for the materials, equipment and methods of efficient design and construction that must be met to qualify for an energy efficient rating. *Calculation* based ratings employ computer based models to predict a building's performance relative to that required in order to qualify for a rating under the program. *Performance* based ratings utilize actual building energy consumption data to evaluate building energy efficiency that is then compared with the required standards of the program.

Prescriptive and calculation schemes are predominant, whereas performance based rating schemes are very rare because of the time-consuming nature of the system, which requires an extensive effort. Performance based schemes are not applicable to new buildings because of their limited value as a tool for predicting performance and encouraging improvements prior to construction.

Rating schemes are generally associated with either *certification* or *labelling*. The former refers to the evaluation of building performance at the design stage, while labelling assesses in-use performance of the building when it is compared with other similar buildings.

The schemes vary in practice, from simply a paper-based check-list to full thermal simulations. A good example of a paper-based check-list is the Model Energy Code (MEC) (Andersen, Jorgensen, Lading et al., 2004) which was developed for the Department of Energy Building Standards and Guidelines Program in the United States. MEC focuses on the insulation of the envelope and windows of a building, the cooling and heating system, the water heating system, and air leakage. Most of these rating schemes use a grading scale to score buildings. One hundred point scales and star rating systems are common, while some use either a pass/fail system, or simply classify by terms such as bronze, silver, or gold. MEC is a simple pass or fail scheme (US Department of Energy, 1995).

Generally, all developed rating schemes around the world appear to be similar in their objective but different in programming and details. A general review of developed

HERS, based on an internet search and on the final report of a review of thirty different HERS programs by SRC Inc (SRC, 1991) has shown that these schemes are widely implemented in the US. The following section reviews HERS programs that have been actively implemented in United State, Europe, Canada and Australia.

2.1.1 The United States of America

Energy rating schemes have been used in the USA since the 1980s (Santamouris, 2005). Over the past years a range of rating schemes have been implemented by the different states, cities, utilities and vendors. There are a variety of efficiency certification programs and numerous tools for analysing building performance.

Among the various schemes, the Energy Rated Homes of America is predominant, as it is currently operating in more than 18 states with other schemes in continuous development in the other states. This scheme uses a 100-point scale of efficiency, divided into ten categories of stars (from one star, one star plus, to five stars plus). A higher star represents a house with better energy efficiency. The energy efficiency rating in this system expresses the predicted energy consumption, which is represented in the form of normalised annual energy consumption. The dependency of this rating system on a calculation of the amount of energy consumed makes the use of efficient appliances result in a more favourable rating than that of an efficient architect designed house, were arguably a free running house should have priority for reducing energy consumption.

Numerous software programs have been developed to foster increased energy efficiency in the building sector. In North America alone there exist about a hundred building energy tools serving a diversity of users (Mills, 2004). Many of these are applied to rate buildings, such as LEED, CHEERS, RECA 2000, Kansas, HOT2000, Ohio, REM/Rate, TRET, Energy Gauge USA, T. A. P, BESTTEST, HEED, Colorado and E-Star[5].

---

[5] More details about software programs can be found in the web-based references given by the US Department of Energy US Department of Energy, 2006, *Building energy software tools directory,* <http://www.eren.doe.gov/buildings/tools-directory/>, US Department of Energy.

The main objectives of the Home Energy Rating Schemes implemented in the USA are: affordability (a higher quality and more comfortable home for less money), qualifying for a more favourable mortgage loan, and environmental protection (through optimizing residential and commercial energy and indoor environmental performance).The association of home energy rating systems with a scheme called Energy Efficiency Mortgages brought about the penetration of this rating system into the residential market (Santamouris, 2005). The mortgage industry uses existing energy audits to make loans for energy improvements (Barbara, 2000).

2.1.2 Europe

Following the energy crisis in the 1970s, preliminary steps for energy saving measurement in Europe occurred in Sweden. Since 1993 a 'Specific Actions for Vigorous Energy Efficiency Directive' has been employed throughout the countries in the European Union (Cook G. D., 1997). The aim has been to "certify" the energy efficiency of homes. Since the directive neither specifies the certification procedure nor identifies the kind of energy that should be assessed, the states were requested to prepare their own national methodologies (Santamouris, 2005) and each member country has produced a different interpretation of the term "certification"(Richalet and Henderson, 1999) The European Energy Commission has now put forward a proposal for a new specific directive on the energy rating of buildings (based on "Energy performance of Building Directive 2002/91/EC 16" as mentioned in Miguez et al. (2006). The aim of this proposal is to identify a set of unified criteria and the application of a common method to calculate the energy performance of buildings in the EU.

A review of energy ratings of dwellings in the European Unions by Miguez et al. (2006) describes the various rating systems in EU countries. Current rating systems, based on several regulations, all aim to save energy and reduce greenhouse gas emissions. These rating systems assess a building as to whether it complies with regulations. A range of techniques has been developed for the building assessment, and all are based on an experimental protocol for collecting energy data and theoretical algorithms to *normalize total energy consumption* for classifying buildings. Total energy consumption results from heating, hot water and lighting. Due to a high heating energy requirement, all the member states in the EU have introduced compulsory maximum levels for coefficients of heat transmission in new buildings. The cold climate in these countries demands more insulation generally, meaning lower energy losses and GHG emissions.

Although the preliminary steps for energy saving and efficient energy use in the building sector were taken in Sweden, this nation still has no official energy rating system for buildings. However they do have stringent regulations. Among different rating systems in the EU, Denmark's is known as the only system which provides full energy rating in the sense of awarding a graded score to buildings. The ratings developed in the UK and Denmark are discussed in more detail as they are the two pioneering rating systems in the EU.

2.1.2.1 United Kingdom

The oldest HERS exists in the United Kingdom. It mainly aims to decrease energy consumption and GHG emissions. Two house energy-rating schemes are currently operating in the UK. The National Home Energy Rating scheme (Hasson, Keeney and McKenna, 2000) was developed and implemented by the National Energy Foundation, an independent charitable trust (Turrent and Mainwaring, 1990). This scheme measures the thermal efficiency of dwellings in terms of energy running costs on a scale of 0 to 10. The rating procedure is carried out through the use of a computer program based on the Building Research Establishment Domestic Energy Model (BREDEM). This is used in different ways as the basis of the Standard Assessment Procedure (SAP), National Home Energy Rating (NHER) and $C0^2$ Dwelling Emission Rate (DER) (Energy Efficiency Partnership for Homes, 2006). It was expected that the latter would have been implemented in the new building regulations due to come into effect in April 2006. In BREDEM the energy usage of a house is calculated on the basis of a description of its dimensions, insulation and heating system.

The Standard Assessment Procedure (SAP) has been developed by British planning authorities as the principal basis for labelling and house rating. It was drawn up to define the method of energy rating of residential buildings (Richalet and Henderson, 1999; Miguez et al., 2006). Energy rating is based on energy balance and cost for space and water heating per square meter of floor area assuming average occupancy patterns. It includes details of the house as factors affecting energy efficiency such as heating system, thermal insulation, ventilation characteristics of dwellings and the type of fuel used for heating. Fuel costs and gas emissions are assessed, and based on this, individual suggestions for improvements are given. This rating does not consider lighting and domestic appliances in the process of calculating energy consumption; and it ignores the location of the building for the rating purpose. These omissions would appear to have a significant effect on the accuracy of the rating system and to discriminate against the value of a building design which might be suitable for a particular location and climate.

As there were doubts about its ability to achieve the target of energy saving and reduction of GHG emissions in the building sector, the SAP regulations were revised in 2001 (DEFRA, 2005). Nevertheless, as the basis of the methodology for improving the energy efficiency of buildings continues to be the calculation of energy consumption, it may well not be accurate in providing passive energy measurements as demanded by Association for Environment Conscious Buildings (AECB, 2006) and is unlikely to grade passive architecture designs accurately.

NHER measures the energy efficiency of houses as a function of energy running costs per square meter. It calculates energy usage by taking into account the house details, including house location, design, construction, water heating system, cooking, lighting, ventilation and appliances. To calculate the rating a standard occupancy scenario is assumed in which the number of occupants is estimated from the house floor area and standard heating patterns. Thermostat settings and the period of occupation are also included as standard. The actual occupancy data can be used to estimate the running cost, fuel use and emissions, but this will not alter the rating.

2.1.2.2 Denmark

As a pioneer of energy rating in the EU, Denmark started energy saving measurement in 1981. This country established a different type of energy audit known as the “Act on the Promotion of Energy and Water Conservation in Buildings” (Energie- Cites, 2003; International Energy Agency, 2003). It comprises energy certificates for large and small buildings as well as for industrial buildings and CO_2 emissions in industry (Miguez et al., 2006).

The rating system is based on an energy inventory recorded by a qualified specialist. It includes three parts. The first part reports on water and energy consumption and CO_2 emissions per annum compared with other similar buildings, on a rating scale from A1 to C5 (maximum to minimum efficiency). An energy plan is the second part of the system, through which ways for saving energy and water in buildings are proposed, with an estimation of costs involved and annual savings for each one. The final part of the rating provides information on the current state of the building in terms of its size, heating system, and energy usage, and the cost of energy and heating.

The rating system appears to be sufficiently comprehensive for conditioned buildings but it does not seem to be able to deal with rating free running houses, owing to its dependency on the energy base.

2.1.3 Canada

The Office of Energy Efficiency (OEE) has developed and promoted a wide range of programs in Canada. These are aimed at improving energy efficiency in the energy sector of the Canadian economy, at conserving energy resources, aiding financial savings and reducing greenhouse gas emissions.

Home energy rating systems for houses in Canada was based on the report "Efficiency of Natural Resources Canada" (NRCan) which began in 1997[6]. There are two national energy rating programs for residential buildings, named Ener-Guide for Houses (EGH) and Ener-Guide for New Houses (EGNH). These governmental programs use HOT2XP and HOT2000 as their rating tools. The tools are programmed to make a comparison of each house with reference to houses of a similar size in a similar climatic region for rating purposes. To factor out the influence of occupants on energy consumption, standard operating conditions are used in calculating the rating. The energy rating assessment begins with a site evaluation, using a blower door test to measure the rate of air leakage in homes. The space heating and cooling systems and domestic hot water, appliance usage, and mechanical systems are analysed to produce an energy efficiency

---

[6] Based on information from a media release, retrieved September 20, 2005, from http://www.oag-bvg.gc.ca/domino/reports.nsf/html/ch9710e.html

rating based on the home's annual energy consumption on a rating ranging from 0 to 100 (Allen, 1999). The lower rating on the scale indicates high leakage, no insulation, high-energy consumption and therefore an uncomfortable home to live in.

Two standard bases for evaluating buildings are R-2000 standards[7] and the Model National Energy Code of Canada (MNECH)[8]. To meet Canada's specifications Code, a house needs to be rated within the 80-85 range to comply with R-2000, or in the 70-75 range to comply with MNECH (Allen, 1999). The softwares used for analysing a building's performance are: HOT 2000, HOT 3000, HOT2XP, HOT2EC, EE4, GBtool and BILDTRAD. All can evaluate the energy performance of a building but are unlikely to be applicable for a free running house evaluation.

2.1.4 Australia

House Energy Rating Schemes have also been introduced in Australia with the same objectives as those in the other mentioned countries. The main objectives are to decrease residential energy consumption and greenhouse gas emissions, and to increase thermal comfort by encouraging improved building envelope design (Ballinger, 1998a).

Where the Australian climates differ from those of Europe and Canada, differences in the programming of HERS in Australia were expected. "It has been shown in many studies that passive solar design and energy conservation techniques are very cost-effective in Australia. Our [Australian] climates allow us to enjoy the outdoor generally throughout the year except on days of temperature extremes" (Ballinger, 1988, P 67). The moderate climate of some regions in Australia makes passive architectural designs

---

[7] "The R-2000 Standard is based on an energy consumption target for each house and a series of technical requirements for ventilation, air tightness, insulation, choice of materials, water use and other factors" retrieved on 13th Oct. 2006, from http://oee.nrcan.gc.ca/residential/personal/new-homes/r-2000/About-r-2000.cfm?attr=4

[8] "[MNECB]is intended to help you design energy-efficient buildings. It sets out minimum requirements for features of buildings that determine their energy efficiency, taking into account regional construction costs, regional heating fuel types and costs and regional climatic differences. The MNECB has, in addition to sections on the building envelope and water heating, detailed information on lighting, HVAC systems and electrical power, which can offer major energy savings". Retrieved on 13th Oct. 2006 from http://irc.nrc-cnrc.gc.ca/pubs/codes/nrcc38731_e.html

such as free running houses a good option, and most suitable for achieving the objectives of HERS. However, house ratings in Australia, as in other countries, are based on prediction of energy requirements and have not been modified to give more value to free running houses.

The Five Star Design Rating was the first energy-rating scheme developed in Australia in the 1980s, by the GMI Council of Australia. It was adopted for use in Victoria, New South Wales and South Australia. "Five Star Design Rating" (FSDR) is a form of certification available for dwelling buildings which comply with a number of requirements for energy efficient design. The design principles of a five star home under this system are based on the three basic elements of glass, mass and insulation (Ballinger, 1988). However, this system was not widely accepted by the building industry due to its restrictive guidelines and its limitation to a single pass/fail rating.

During the 1990s individual states in Australia attempted to develop their own House Energy Rating Scheme (HERS) to meet particular needs (Ballinger, 1991; Gellender, 1992; Wathen, 1992). Among different schemes, the Victorian scheme, based on a computer program, was found to be the most effective; however, it was not flexible enough for all climates, particularly for warm humid climates such as in Queensland. It was therefore thought appropriate to develop a nationwide HERS.

The development of a nationwide House Energy Rating Scheme (HERS) was started in 1993 on behalf of the Australian and New Zealand Minerals and Energy Council (Szokolay, 1992b; Ballinger and Cassell, 1994). The aim was to create a simple rating for energy efficiency for each dwelling throughout different climate zones and conditions in Australia. A graded five-star rating system has been used to categorize the relative energy efficiency of dwellings, using a computer program based on the CHEETAH (engine) which was developed for the rating assessment (Ballinger and Cassell, 1994).

HERS predict the demand for heating and cooling energy required to maintain conditions of thermal comfort inside a building and rates the building's average energy consumption per square meter (MJ/m^2). Predictions are based on the extensive research and development embodied in CHEENATH, the core energy software model developed by CSIRO suitable for Australian climates (Ballinger, 1998a). This engine, which is a significantly enhanced version of the CHEETAH engine, is the current basis of most modelling systems, such as NatHERS, FirstRate and Quick Rate, BERS, Q Rate and ACTHERS, which have been developed in different states. NatHERS and BERS simulate the operational energy usage in a home by running CHEENATH directly (with different user interfaces) while FirstRate, QRate, ACTHERS and Quick Rate are correlation programs, which do not carry out simulations.

AccuRate is the latest tool developed for HERS (Isaacs, 2005). It addresses some of the limitations in the NatHERS software and is now a replacement for NatHERS. More details regarding this are presented in Section 4.2.

At the time when NatHERS was developed it was assumed that this software would be developed in the future on the basis of comfort achieved without the use of heating and cooling (Ballinger, 1998b). However this project still remains incomplete, even in the latest developed tool for HERS. It is this issue which has led to the main research objective for this project (see Section1.4).

2.2 Rating methodologies for buildings

Buildings present many qualities that need to be taken into account for an appropriate evaluation (Roulet C-A., 1999) and rating scheme. To evaluate buildings a wide range of rating methods has been developed[9]. Each method considers a number of parameters and criteria to assess buildings on a particular basis. The parameters and criteria include perceived health, the provision of thermal, visual and acoustic comfort, indoor air quality, cost effectiveness, environmental impact and energy efficiency. However, energy efficiency is seen as the main parameter in almost all developed building rating schemes, even in those which aggregate and evaluate buildings based on a multi-criteria method.

---

[9] Some of these methods appear in a review by.Kotsaki, K. and G. Sourys, 2000. *Critical Review and State of the Art of the Existing rating and Classification Techniques* .Group Building Environmental Studies, University of Athens, Greece.

A review of the various methodologies developed to evaluate the energy efficiency of buildings has shown that they are principally based on predicting energy consumption to assess a building in order to certify the level of a building's performance (Santamouris M., 1995; Zmeureanu, Fazio, DePani et al., 1999; Richalet, Neirac, Tellez et al., 2001; Santamouris and Dascalaki, 2002; Boland, Kravchuk, Saman et al., 2003; Santamouris, 2005; Santamouris, Mihalakakou, Patargias et al., 2006, 2007). The method is the same whether the building is residential or office space.

A historical review by Fairey et.al (2000) of the national HERS methods used in the US describes the following four proposed methods for rating the energy efficiency of homes :

1) the original method
2) the equipment adjustment factor method
3) the modified loads method
4) the normalized modified loads method.

Each method was developed to overcome shortcomings in the previous method. In the *original method* the score of a home depended on the fraction that the total estimated purchased energy consumption of a house represented of that for a reference home[10]. The dependence of this method on the fuel type involved represents a 'flaw' in the method. This 'flaw' is due to the 'floating' value of the reference house whose value could change as the function of a selected fuel type and consequently the score of a home could simply change. This problem was solved through the second method by adding an *equipment adjustment factor.* However, the main issue with the second method was that "rating directly by energy consumption misrepresents the relative value of envelope efficiency measures with respect to equipment efficiency measures" (Fairey, 200, P4). *The modified loads method* was then developed to avoid the above

---

[10] A home score in the original method was calculated from 100 – 20*(ER/EC), in which ER is the total purchased energy consumption for heating, cooling and hot water for the rated home; and, EC is that for the reference home

problem. In this method building loads[11] were used instead of energy consumption to establish the rating fraction used in the original method. Since the load on building end uses does not change as a function of fuel, the 'floating' problem was also solved. However the presence of a 'fuel neutrality flaw' was a problem with this method due to the fact that different fuel types may be discriminated against in the marketing. A 'normalized modified load method' was then proposed that reflects differences in potential equipment improvements[12].

The first two methods rely on the calculation of energy consumption while the last two refer to the amount of energy load. Although the second basis is more reliable, both bases have the shortcoming that they are unable to exactly predict actual energy consumption and energy load, because certain variables such as occupancy and the behaviour of occupants could change the results of the calculation

Botsaris and Prebezanos (2004) introduced a method for the certification of the energy consumption of a building by recording its 'energy behaviour'. In this method energy indices such as Index of Thermal Charge (ITC) or Index of Energy Disposition (Andersen et al., 2004) are employed to simulate the heat losses of the building and the heat flow due to temperature difference from the indoor to the outdoor space. This work is based on an interpretation of the energy sources behaviour, such as the operation and cessation time of the sources. Cessation times can be predicted relatively reliably for office buildings with a clear occupation time. However, this method for residential buildings may not be accurate, owing to the variability of its occupants' activities. The method can, however, help to accurately predict the energy consumption of residential buildings if it is adapted to include *multiple occupancy scenarios*.

A review of the latest developments in the field of energy rating of dwellings, mainly in Europe, describes the theoretical and experimental techniques for energy characterization of buildings that have been employed (Santamouris, 2005; Miguez et

---

[11] Load in this method is defined as the amount of heating energy that must be added or removed from a building to satisfy a specified level of comfort in the building; and. Energy Use is the amount of energy required by the equipment that satisfies the load.

[12] The mathematical process is described in Fairey (2000) and is not the main concern of this section.

al., 2006) and shows that all of the systems have been developed basically to predict the total energy demand of a building.

EUROCLASS is a recent method developed for the energy rating of buildings through the European SAVE program. It suggests a theoretical technique that comprises all specific energy uses and treats energy normalization in a new manner. It proposes a new framework based on the use of "the relative frequency distribution curves for the different end users of the energy" (Santamouris, 2005, P71). The variables which are determined to grade a building are "total supplied energy" (kWh/m^2) and "total delivered energy" (kWh/m^3). These variables can be obtained from two protocols: the Billed Energy Protocol (BEP) and the Monitored Energy Protocol (MEP). Each of these protocols provides useful information for carrying out a rating test of a building in a specific comparison scenario. EUROTARGET is the software developed within the frame of the EUROCLASS project to apply this proposed rating methodology for dwellings.

There are a number of studies that propose multi-criteria for a building assessment and rating scheme. These studies include a number of parameters to rank buildings, such as energy use for heating and cooling, indoor environment quality, cost, impact on external environment and the life-cycle of the embodied energy of construction (Soebarto and Williamson, 2001; Roulet, Flourentzou, Labben et al., 2002; Roulet, Johner, Oostra et al., 2005).

In the study by Soebarto et.al (2001) a methodology based on a weighting method was developed to assist the building design process and assess a building's environmental performance in accordance with multi-criteria assessment. This methodology converts the criteria into a two criteria problem by creating a weighted sum of benefits and costs for each solution. These two functions are normalized to reflect the average weighting value. Based on this method an environmental performance assessment tool, ENE-RATE, was developed to perform environmental ratings. Although this study accepts that thermal comfort in an unconditioned building would be considered as a criterion for building evaluation, it does not clarify any method of incorporating that criterion for that purpose.

Roulet et al.(2002) produced a multicriteria ranking methodology to rate office buildings. The method employs fuzzy logic on a set of indices, each of which addresses a particular aspect of building performance in the two categories of energy and comfort. Based on a principal components analysis the energy and comfort parameters are combined in a single indicator that globally characterizes the performance of the building. Annual energy use for heating, cooling and lighting (kwh/m^2) and discomfort hours during winter and summer (h) are the criteria used to define this single indicator. The proposed criteria for indoor environment quality are: predicted percentage of dissatisfaction based on the Fanger comfort model[13], outdoor airflow rate per person and noise level in the working place. Each parameter is given a weight depending on the scale of values of the user of the method. This method would not appear to be successful in evaluating thermal comfort conditions in a naturally ventilated building because the employed criteria are only applicable for conditioned buildings[14]. The method can be adapted for use in any multicriteria rating scheme.

Regardless of the function of a building, *normalised energy use* is seen as the most common method to evaluate the efficiency of a building in the conditioned operation mode (Chung, Hui and Lam, 2006).This method regards the building's size and annual energy use, divided by the conditioned floor area or by volume. There are shortcomings in this method which make it unrealistic in addressing the efficiency of an architectural design. These will be discussed later in Sections 2.5.3 and 5.3.

2.3 Bases for residential building rating schemes

Almost all of the rating schemes address the features of the building's envelope and the efficiency of equipment for cooling, heating indoor space, and hot water. Some of them include energy related fixed components such as washing machines, dishwashers, refrigerators, freezers and dryers. Current tools employed for rating systems have the capability of calculating heating, cooling, hot water, lighting, and appliance energy loads. Some of them also predict the energy cost of new and existing single and multifamily homes based on the prediction of total energy requirement, the type of fuel

---

[13] The Fanger thermal comfort model will be discussed in chapter 3

[14] In a personal conversation with the author (2005), Roulet agreed that this method needs to be modified if it is to be used for naturally ventilated buildings

and the efficiency of appliances. Occupancy factors have usually been considered as a default or are standardized; however a limited number of ratings tools are flexible enough to change the occupancy variables such as the number of occupants and the hours of occupation.

There are many similarities between the systems studied. They all use some combination of data collection and calculation to present information to building users about energy consumption. Their reliance on calculation is almost inevitable because of the highly disparate nature of buildings. This utility metric method is, however, limited in its accuracy because the amount of energy consumption is so dependent on occupants' preferences and occupation time.

2.4 Why an energy rating base

Energy efficiency is a critical issue for high quality housing. Energy as a measurable variable not only represents a high percentage of the running cost of a building but also has a major effect on the thermal and optical comfort of the occupants.

In some climates it is difficult to have a comfortable indoor condition without an energy load. As the energy rating of a building can provide specific information on the energy consumption and the relative energy efficiency of the building, it is then possible for a potential buyer to have information on the energy bills that are likely to arise. Through this information the owner of a house may also be able to identify and pinpoint specific cost-effective improvements. However, in a moderate climate a successful passive architectural design could provide thermally comfortable conditions in which occupants do not need heating and cooling devices. In this case the current rating scheme may fail in its assessment of a building's performance.

Whilst environmental issues were the main reason for developing HERS, financing and marketing have become the major motivations for promoting it. A highly rated building on the market may be eligible for special recognition through a series of voluntary or compulsory programs, which increases its value for sale or rental income. Through HERS, energy-efficient financing is achievable because energy-efficient houses cost less to operate. For the promotion of HERS the market needs a measurable basis for HERS which is attractive enough for the public to apply for it. Energy and comfort are two parametric options for this purpose that are related to each other. Energy as an expensive parameter would appear to be the more appropriate basis for HERS for marketing purposes, although the provision of comfort may actually be more expensive. However in modern society in which the public are increasingly dependent on energy for the provision of thermal comfort, energy appears to be a preferable parameter as the basis for HERS.

Connecting the HERS and mortgage incentives for energy efficient development has affected the rating systems in the US (National Renewable Energy Laboratory Washington, 1992). HERS provides standardized information on the energy performance of homes, and energy-efficient mortgages (EEM) provide a financing mechanism for energy efficiency. The estimation of energy costs generated by a reliable HERS is a valuable source of information for facilitating EEM. This objective leads to the combining of cost- effectiveness and energy efficiency and so great attention has been paid to house ratings based on energy usage and its cost.

In addition, predicting ratings on an energy basis helps to choose appropriate HVAC equipment where heating and cooling plants are a part of building construction. This creates an opportunity to optimize heating and cooling plants and also allows for competition in the market to refine the rated capacity of the size of plant(Hunt, 2003).

The Australian marketing of rating systems is different from that in the US, the EU and Canada. In these countries rating schemes have been employed to support different financial arrangements, while in Australia sustainability and environmental impact are the main policy drivers of the building rating schemes. Moreover HERS in Australia, with most of its population living in its moderate climate zones, is more amenable to independence from energy in the provision of thermal comfort as a basis for HERS.

2.5 Shortcomings in the current rating schemes

2.5.1 Rating and achievement of sustainability

Current rating schemes have not been sufficiently complex to address the main issues of sustainability. It has been argued in the “design paradigm” that buildings can reverse their environmental impact, and can even have positive impacts over their whole life cycle. This requires integrating conditions for ecosystem preservation in the building fabric. General ecological criteria must then be added to any assessment system for sustainable development. However, current building assessment tools provide only limited support for this issue (Chau, Lee, Yik et al., 2000). Sustainability is a design problem rather than a technical problem, but the current rating systems are not based on design criteria. Instead, the emphasis is on predicting the negative impacts of a proposed design such as the level of energy consumption, energy cost and GHG emissions. To move toward sustainable development, Birkeland (2002) proposed that a building must be designed to interact with its context beyond the exterior envelope of the building. It appears that no rating system based on an assessment of energy usage includes all ecologically relevant parameters; even multi indicator ratings such as those explained earlier in Section 2.2. However, a few include embodied energy, which is a technical aspect that can affect the ecosystem. This is one of the reasons for light-weight buildings to be undervalued in the current rating system, while such buildings could contribute to improving sustainability.

2.5.2 Rating free running buildings

Free running buildings cannot be accurately evaluated by the current rating scheme. Because all rating systems assume buildings to be artificially heated and cooled, they do not deal at all with free running buildings.

When comparing the actual performance of an occupied free running house with the predicted performance by a rating scheme, Soebarto (Soebarto, 2000) demonstrates a low score from the rating, although her study shows the house performed reasonably well in terms of its indoor comfort condition, energy use and environmental impact. This reflects the inability of the rating system to assess free running buildings adequately. The benefits of passive architecture design, therefore, may not be properly evaluated in this case because of its independence from energy use. Another study on thermal performance of three award winning houses in Australia (Soebarto, Williamson, Radford et al., 2006) illustrated that the houses did not conform to comfort standards and national regulations, in addition to achieving an unacceptable score in the mandated regulatory rating scheme, while the occupants of all the houses were largely satisfied with the houses' thermal performances.

These two studies imply a probable difference between an efficient design for a free running house and that for a conditioned house. This subject needs to be investigated further and becomes a key part of the hypothesis of this study. If the reliability of this hypothesis is proved, then the development of a free running rating scheme, under regulations for free running buildings, would appear to be essential.

2.5.3 Rating Index

Regardless of which method is applied for HERS, an adjusted energy indicator is employed as an indicator of efficient building design. The chosen indicator plays an important role in the reliability of the rating designed to assess the thermal performance of buildings.

Although energy minimization is promoted as an energy efficient building strategy (Boland et al., 2003), low energy usage does not necessarily indicate design efficiency (Sjosten, 2003; Olofsson, Meier and Lamberts, 2004). Energy consumption can be relatively low because the building is not occupied most of the time, or the building amenities are low. Low energy consumption can also be due to efficient appliances. Since appliances use a significant portion of the energy used in a home[15] (Environmental Protection Agency, 2000; Office of Energy Efficiency, 2005), highly efficient equipment can reduce the total energy requirement. That means that the energy demand of a building can be reduced by using more efficient appliances rather than by improving building design.

Further more, a *normalized* energy based rating is not sufficient to convey the credibility of an energy efficient design. This point has been argued in many studies (Soebarto, 2000; Williamson, 2000; Meier, 2002; Kordjamshidi, King and Prasad, 2005) The concept underlying the definition of energy efficient indicators for policy purposes is discussed in (Patterson, 1996; Haas, 1997). They show that normalized energy use is typically derived as annual energy used divided by the conditioned floor area or volume. Based on this index a smaller house achieves a poorer value than a similarly constructed larger house (Thomas and Thomas, 2000) where in reality

---

[15] Appliances in a home account for 35% of total energy use on average and up to 50% in a moderate climate

reducing house size is an effective way of reducing total energy consumption (Gray, 1998). One of the reasons for this regressive tendency is a real physical phenomenon. Smaller houses have a higher proportion of envelope for a given volume; therefore the fabric heat flux per unit of floor area or volume is greater in smaller houses. A study of project houses in NSW (SOLARCH, 2000) also found that double storey houses ordinarily could achieve acceptable scores (3.5 stars) with moderate levels of insulation, while single storey houses, especially smaller houses, could not easily achieve this rating. Yet according to one study (Luxmoore, Jayasinghe and Mahendran, 2005) the cooling requirements of larger houses with a high energy rating (5 star or more) were found to be significantly higher than those of houses with a low (3.5) rating, which becomes particularly relevant in the context of predicted global warming (AGO, 2002).

It is most likely that an appropriate indicator for evaluating the efficiency of building design could address the issue of the performance of a building independent of artificial energy load. In that situation, an improvement in the thermal performance of a building should reduce the energy requirements for providing a thermally comfortable space. To fulfil the main objective of HERS the indicator should be chosen so as to be *related* to the prediction of energy requirements, but not *exclusively based on* prediction of energy requirements.

If a building is operated in the conditioned mode, the provision of thermal comfort is related to energy consumption. Occupants use energy for space heating or cooling when the indoor climate does not coincide with thermal comfort. Where the indoor environment is naturally comfortable in terms of temperature and humidity, the need for an active energy load will decrease.

The question then arises whether thermal comfort can be used as a basis for assessing the efficiency of a house design. This is important for assessing the efficiency of a house in *entirely* free running operation mode, as opposed to assessing the efficiency of that house in conventional conditioned operation mode on the basis of energy usage.

The correlation between these two bases, comfort and energy, as indicators of the efficiency of a house in different operation modes needs to be investigated. A probabilistic correlation between thermal comfort and energy requirement does not necessarily mean that a house designed to be free running (comfort based) is an equally efficient conditioned house (energy based). This difference may be crucial with regard to the fundamental role of a house rating system which is to influence house performance improvement during the design of a house. This subject will be addressed in more detail in Chapter 7 of this dissertation.

2.5.4 Occupancy scenarios

Almost all reviewed rating systems, designed to evaluate the thermal performance of buildings in terms of energy efficiency, set a standard scenario for occupants at the design stage to estimate the annual energy requirements of a building and then evaluate the thermal performance of the building on the basis of that estimation. However, a standard set of behavioural assumptions for all possible occupancy scenarios cannot give an accurate evaluation.

Occupant behaviour is in fact the most significant determinant of actual energy use. One study suggests that 54% of the variation in energy consumption can be attributed to the building envelope and 46% to occupants' behaviour (Sonderegger, 1978). A similar study (Pettersen, 1994) concluded that where inhabitants' behaviour was unknown the total predicted energy consumption resulted in +15% -20% uncertainty and the range of error for estimated energy heating use was +35% - 40% in a mild winter climate. A number of studies have gone further and shown that actual energy performance depends on the way the occupants "use" the buildings and does not necessarily relate to the building design at all (Ballinger, Samuels, Coldicutt et al., 1991; Haberl, Bou-saada, Reddy et al., 1998). Indeed, "the predicted energy use or energy cost can be off by 50% or more due to occupant behaviour" (Stein and Meier, 2000).

In a standard occupancy scenario the parameters such as the number of occupants, period of occupation and thermostat settings for air-conditioners are assumed to be standard. A standard occupancy scenario seems to be essential in order to simplify the comparison of building performances in similar conditions. Some of the systems provide an option to set the actual number of occupants; but they cannot change the occupied time in a building when they are set for rating the building.

For instance AccuRate software, programmed for HERS in Australia, sets a standard scenario for 'occupied time'. Living zones are usually considered to be occupied for 17 hours a day between 8 a.m. and midnight, and bed zones to be occupied for 17 hours between 5 p.m. and 9 a.m. The "17 hours scenario" is extremely effective in predicting the thermal performance of a house under a conservative possible occupancy regime, especially when taken together with a completely deterministic estimate of activation of artificial heating and cooling, regardless of occupants' behaviour or climatic seasons.

However, although the occupants' behaviour is not entirely predictable, a more realistic estimation could be employed to evaluate a building's performance and to estimate energy requirements for space heating and cooling. It is not generally possible to predict exactly at which times a dwelling is occupied, but defining multiple occupancy scenarios for rating could result in greater accuracy of prediction.

Setting a single time for occupation can particularly underestimate the value of lightweight buildings. In response to then current concerns about occupied times and thermostat settings, Boland (2004) noted that "the lightweight dwelling may be disadvantaged unnecessarily". Depending on the time of occupation, a lightweight dwelling may give a better performance because it responds more quickly to temperature changes. This ability, in particular for short period occupation, and particularly in hot summer, is an advantage that cannot be addressed by a permanent "17 hours occupancy scenario". The ability of lightweight buildings to achieve a favourable thermal performance needs therefore to be tested for different durations of occupied time.

Occupant behaviours are not a predictable factor. Szokolay (1992a) argues that occupancy factors cannot be taken into account in a rating system because of their high variability; so that the house itself has to be rated. In contrast, Olofsson *et* al. (2004) argue that if the rating is to reflect the energy efficiency of the occupied building, the actual influence of the users has to be taken into account, for which an evaluation of users is required. In this study, the latter view is adopted, since this parameter, particularly in residential buildings, can considerably modify the assessment of total energy consumption.

2.5.5 Accuracy of HERS

The credibility of HERS depends on its accuracy. However several studies have demonstrated that the accuracy of energy based rating schemes is questionable. This situation is mainly due to the variability of occupancy behaviour and the rating index as is described above. While the accuracy of rating systems has not been considered by HERS experts to be the most important barrier to widespread use of HERS, all agree that accuracy is important for the long-term credibility and success of this system. A lack of accuracy may eventually impact on some HERS and cause “irreparable” damage to credibility (Stein, 1997a; Stein and Meier, 2000).

It is clear, therefore, that while HERS relies on an index of energy, the energy requirement cannot be estimated accurately. A comparison by Stein (1997a) between actual residential energy bills and energy estimation by four different HERS, namely CHEERS, HERO-Ohio, ERHC-Colorado and Midwest-Kansas demonstrated a significant overestimation (50%) of actual energy cost by CHEERS and smaller errors in estimating energy cost or energy use by the other methods. However, interestingly, no clear relationship was observed between rating scores and actual energy usage. Stein’s case study investigation showed that it is more difficult to accurately predict energy used in a mild climate than in a severe climate. Stein concluded that the main reason was the variation in occupants’ behaviour and suggested that “incorporating a few pieces of information” about occupants into a rating could improve its accuracy while elsewhere he pointed out that “actual usage may vary” (Stein, 1997 b).

A critical aspect of predicting energy consumption, and consequently of the accuracy of HERS, is determining thermostat settings. All of the current building rating systems consider standard defaults for thermostat settings, taken from thermally comfortable conditions of the building standards, based on a particular strategy. Employing an inappropriate strategy for thermostat settings can effectively reduce the accuracy of predicting energy requirements. This situation has been demonstrated to be more critical in a moderate climate, “where the balance between summer and winter energy consumption is a crucial factor and usually determines the nature of design advice” (Williamson and Riordan, 1997). Neglecting the effect of occupants’ behaviour appears to be an issue for thermostat settings in simulation methods for predicting the energy requirements of buildings.

Occupants expect a higher degree of comfort in higher scoring buildings. This tendency is likely to result in higher energy consumption than energy usage predicted by rating tools. The discrepancy occurs because the system depends on the active energy load, which is variable for different occupants. One way to deal with this problem could be to make house rating schemes independent of energy. Changing the basis of rating from energy to thermal comfort and evaluating buildings in free running mode could encourage the occupants to reduce the energy load for space heating and cooling, and to adapt themselves to natural conditions as far as possible.

2.5.5.1 The effect of seasons on occupant behaviour and the accuracy of HERS

Ignoring seasonal occupant behaviours responding to the psychological effect of cold and hot months also diminishes the accuracy of HERS. To predict the annual energy requirements in HERS it is assumed that occupants use energy to maintain indoor temperature in the comfort range whenever the temperature is outside the comfort zone. However, in real life, reasonably, there is no tendency for occupants to mechanically heat a space during summer (hot months) even if the indoor temperature goes down for a few hours. Analogously, the opposite happens for over heating periods during winter.

In a parallel simulation study (Kordjamshidi et al., 2005b) it was shown that the simulation software correctly predicts that during summer the temperature may come down below the comfort range just between midnight to sunrise, and in winter it may rise above it around midday for just 2 or 3 hours. These two particular conditions not only are not critical, but psychologically occupants may accept them as desirable. However this issue has been ignored in the procedure of calculating or simulating annual energy demand in dwellings in most software developed for HERS, such as NatHERS. (See Appendix C.2, Section 6)

2.6 The necessity of a new basis for assessing building energy efficiency

Rating as ranking

A rating system requires a simplified method of recognition of the complicated parameters of a building and its occupants. Although estimating energy requirements particularly through simulation programs seems a simplified method, this method depends on an active system design for dwellings. Any attempt to achieve an energy efficient design and to reduce energy consumption and GHG emission relying only on the active energy load to evaluate a dwelling is not going to produce satisfactory results since it encourages the public to acquire conditioned houses rather than efficient free running ones

A reliable rating system would be able to rank buildings in order of the efficiency of their design. This is recognised by Soebarto and Williamson (1999) who claim that "for a HERS mechanism to be sufficient for compliance testing it is only necessary that the scoring system be relatively correct" and Stein (1997a, p.17) who argues that "the actual numerical scores are not important as long as the houses are ranked in the correct order". On the other hand, as the above literature review shows, it is realized that buildings which are designed for energy conservation in their free running performance cannot achieve a suitable score in the current rating system. Therefore, when free running and conditioned buildings are ranked in the current rating system, free running buildings are given inappropriate placement. This occurs when scoring is dependent on energy consumption ratings. There is, therefore, a need for a new index to be introduced, by which the thermal performance of buildings of any design type can be accurately scored and ranked.

To recapitulate, HERS have not been developed to predict the energy requirements of a house; the estimation of energy requirements is only a basis on which to make a comparison between the designs of houses for scoring them in relation to energy consumption. Where energy requirements cannot be predicted accurately, the scoring will not be a reliable reflection of the rate of efficiency of houses. If, on the other hand, the efficiency of a house design is to be evaluated on the basis of its free running performance, a new index would need to be proposed as the basis for a House Free running Rating Scheme (HFRS)[16]. Where both types of performance of a house, conditioned and free running, are important at the policy level for the development of energy efficiency, then HERS and HFRS should be aggregated within one framework.

Metrics, norms and diagnostics

Three elements, namely *metrics*, *norms* and *diagnostics* are used to evaluate the thermal performance of buildings. Metrics provides a quantification of the performance of the relevant components or systems without indicating the quality of performance, while they form the basis for developing the norms against which components or system performance are compared. Diagnostics is a procedure involving measurements and analyses to evaluate performance metrics for a system or component under functional testing or actual building site conditions.

Metrics used for the evaluation of the free running performance of buildings can be derived from the indexes of “thermal comfort” (See Section 2.6.3). The next chapter reviews thermal comfort criteria to investigate how they can be a reliable basis for a house rating scheme.

2.7 Summary

HERS are used to evaluate and promote efficient architectural building design. The most efficient buildings involve architecture design which can provide thermally comfortable indoor conditions for occupants without a mechanical thermal energy load. This means that the efficiency of a building design should be investigated in relation to the thermal performance of the building in free running operation. However, as described above, energy based ratings cannot at present deal with free running houses. The development of a House Free running Rating Scheme, therefore, (HFRS) appears necessary in order to promote efficient architecture design and effectively reduce energy requirements in residential buildings.

---

[16] House Free Running Rating Scheme (HFRS) is a clumsy term in English, however it has been used in this study to make it consistent with the previous term, ‘House Energy Rating Scheme (HERS)’ for house ratings

With regard to the shortcomings in the current rating schemes (see Section 2.6) the following aspects need to be investigated because of the lack of current knowledge in these areas:

- Multiple occupancy scenarios, which should probably be added to the HERS. This will help to identify the probably better performance of lightweight houses.
- A new index on the basis of thermal comfort should be established, as an indicator for evaluating the thermal performance of free running buildings, to form a basis for HFRS.
- The psychological effect of seasons on occupants in computing annual energy requirements should be considered in order to increase the accuracy of energy based rating systems.
- Comparisons between the thermal performance of houses in conditioned and free running operation mode should be studied to see whether designs for free running houses differ from those for conditioned houses.
- A new framework should be developed for HFRS
- Since large and double storey houses compared to single storey houses achieve better scores in current HERS, this comparison needs to be tested for free running houses

These subjects will be addressed in this study by considering typical residential houses and appropriate tools for evaluating the thermal performance of these houses in different operation modes (more detail in Chapter 4). A moderate climate zone in Australia is the context for this study, employing its climatic data for the purpose of simulation, as further explained in Section 3.1.4.

Chapter 3

Climate and Thermal comfort

The question of establishing thermal comfort as a basis for HRS is a broad subject. The extent to which a dwelling can provide thermally comfortable conditions for its occupants can be determined from the differences between prevailing weather conditions and the desired comfort condition. The desired comfort condition is therefore determined in the context of climate.

This chapter is divided into two sections relating to climate and thermal comfort. The climate section reviews general descriptions of the main climatic parameters and, having reviewed climatic classifications in Australia, limits this study to a moderate climate. This section also describes how the climatic data were chosen for thermal performance simulation in this study.

The next section reviews general aspects of thermal comfort and approaches to thermal comfort for the assessment of naturally ventilated buildings. It proposes an appropriate indicator as a basis for building performance assessment in the free running operation mode, and then establishes thermal comfort boundaries in the specified moderate climates to be used in the evaluation of the free running performance of houses in this study.

3.1 Climate

The interaction between the outdoor climate and the indoor environment is a major concern in the context of the thermal performance of buildings. Climate has a great impact both on the energy and environmental performance of buildings and also on the comfort sensation of a building's occupants. Obviously, the characteristics and also the impact of climate on the occupants and building behaviour depend on the climatic parameters and therefore a general review of these parameters is necessary when human comfort and building performance are the subjects of a study.

3.1.1 Climatic parameters

The main climatic parameters which have to be taken into account when designing a building are: air temperature, humidity, wind, solar radiation, and microclimate (Olgyay, 1963; Givoni, 1976; Markus and Morris, 1980).

Air temperature which is determined by the rate of heating and cooling of the surface of the earth is affected by solar radiation. The extent of its effect on the thermal performance of a building depends on humidity and wind.

Humidity affects the behaviour of building materials and their rate of deterioration, as well as people's thermal sensation (which is more important in warm conditions) and this influences the evaluation of the thermal performance of a building. High and low humidity can cause discomfort either by reducing the evaporation of sweat to provide a cooling effect or by making the skin dry. The effect of humidity on the thermal performance of a building is always modified by interaction with the effect of wind.

Wind is the most important factor in improving the thermal performance of free running buildings as it can significantly turn a discomfort condition into a thermally comfortable one by accelerating convective heat exchange and evaporation. However the occasionally unfavourable effect of wind on the thermal performance of conditioned houses should not be ignored. Cold winds in winter make it difficult to warm a building. On the other hand hot winds in summer make it difficult to maintain cool conditions.

Although energy ***radiation*** from the sun is an advantage for heating during the cold months it causes over-heating in nearly all climates during summer, unless it is controlled by appropriate measures such as light colours, insulation and shading. "The most effective way the designer can control the amount of heat reaching the interior of a building is to give careful consideration to the way the external envelope either absorbs or reflects solar radiation" (Milne, 1976; p. 182).

The effect of all these climatic parameters should be investigated in the context of ***microclimate***, which is the localised climate around a building. This may exist around a building or be created by neighbouring buildings and terrain features. The prevailing climate may be considerably modified by local factors such as altitude and shading by trees or other buildings (Szokolay, 1980). Improving the microclimate around a building can be achieved by providing windbreaks, solar shading, and solar access in winter, etc.

3.1.2 Climate classification

There are different systems of climate classification, depending on their purpose. Kopper's system of classification (1918), which was based on temperature, established the major climate groups in the world. This classification is regarded as standard for any other climate classification.

Many national and international climatic classifications have been developed to deal with building design issues and thermal comfort. The majority have been briefly reviewed in a study by Briggs (Briggs, Lucas and Taylor, 2002), which proposes a new climate classification for energy codes and standards to be used for characterizing the performance of energy efficiency measures for buildings. This study considers the efficiency aspect of building design in addition to climatic parameters. Because of this it is particularly appropriate for the purpose of energy efficiency development in the building sector. The unique approach in Briggs' study that makes it especially relevant for this research is its ability to identify the appropriate design type (free running or conditioned design) for a particular climate. However, it needs to be adjusted, based on national strategies for energy efficiency design and on geographic climatic variables, in order to make it applicable for such a study.

Currently, a simple basic classification of climate is used in many nations to apply to building design. It is based on the nature of human thermal requirements in each particular location (Szokolay, 2004). The four main climates are: cold, temperate, hot-dry and warm humid. The major problem in a cold climate is the lack of heat or excessive heat dissipation for most of the year. Temperate climates have seasonal variations between under- and overheating, but these are not severe. Overheating is the main problem in a hot-dry climate. It has large diurnal temperature variations. The diurnal fluctuation of temperatures is less in hot humid climates. Overheating also is not as great as in hot–dry regions, but high humidity aggravates the sensation of temperature because of restricting the evaporation potential. From this classification, it would appear that a moderate climate is most likely to have potential for the design of free running houses.

3.1.3 Australian Climate

This continent covers a wide range of latitudes from 9° S to 43° S and so there is a significant range of climates within the continent. Only the "very cold climate" is not present in the broad climate classifications. The alpine region of Australia has a climate close to this classification, but its population is very small.

Three major climate types, namely hot – humid, hot – arid and temperate (Drysdale, 1975) have been identified for the purpose of building design in Australia. This classification, which was originally based on max/min temperature, humidity and precipitation, was later expanded into several sub-zones. Figure 3-1 shows the distribution of six regions on the basis of temperature and humidity in Australia. However, the detail of all climate zones is not an issue in this study. As described in the following section, this study is limited to of temperate climate.

The characteristics of the temperate zone in Australia have been described as follows by Drysdale (1975):

Summer: High daytime, dry bulb temperature (30° C - 35° C)
Moderate dry bulb temperature at night (13° C – 18° C)
Moderate humidity (30% - 40%)

Winter: Cool to cold days (10° C – 15° C)
Cold night (2° C - 7° C)

General: Rainfall throughout the year, with winter maximum except in northern N.S.W. Considerable diurnal temperature range (11° C –16° C) and a seasonal range of about 16° C.

Both underheating and overheating, depending on the season, can be a problem but neither is severe.

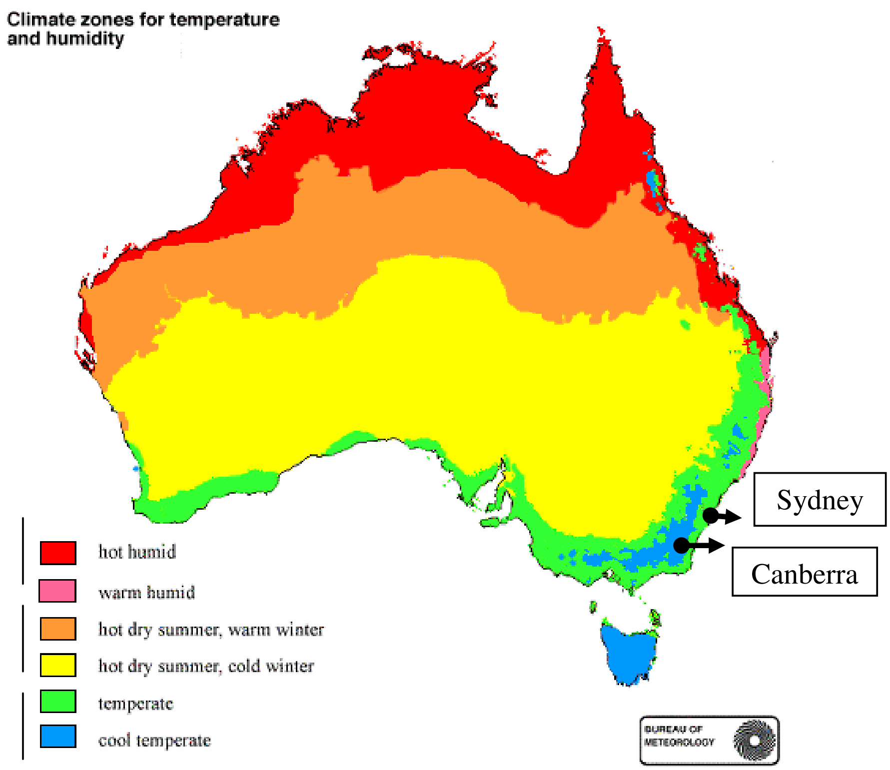


Figure 3 - 1 A broad classification of Australian climates based on Australian Bureau of Meteorology data

3.1.4 Climatic zone and data in this study

The temperate climate zone in Australia is the focus of this study for the following reasons.

As described in Chapter 2, a moderate climate may be described as a critical climate, as energy requirements cannot be accurately predicted with uncertainty in this regard being greater than in severe climates. Moreover, moderate climate zones are potentially more amenable to the design and employment of free running houses, which is the core concern in this study. Therefore a House Free running Rating Scheme (HFRS) is likely to be most appropriate for this type of climate in promoting efficient architectural design and reducing energy requirements, particularly as the population in this zone is greater than in other regions. This climatic condition has therefore been chosen to as the context of analysis for the development of HFRS.

The moderate climate of Sydney is the context for this evaluation of the thermal performance of houses in different operation modes. As the uncertainty in predicting heating energy requirements in mild climates has been found to be quite critical (Pettersen, 1994), this study undertook to compare the thermal performance of houses in another moderate climate with a colder winter. The Canberra climate was therefore chosen. A hot humid climate would appear to be equally critical for comparing the thermal performance of houses in both operation modes, but this requires further research.

For the purpose of evaluating the thermal performance of buildings, hourly climatic data are required. The Nationwide House Energy Rating Scheme defined 28 climatic zones based on hourly data throughout Australia, which are used for simulations in computer programs. Although this climatic classification seems to be enough for the purpose of building efficiency design, the Australian Greenhouse Office has reviewed the weather data from more local weather stations in order to expand the selection of climatic zones and improve the statistical correlation with average data (Lee and Snow, 2006). Recently climate zones have been divided into 69 categories (Lee and Snow, 2006) which can be employed for simulation in any relevant software. However at the time of running this project this climatic file was not available and the hourly data for both Sydney (Climate 17) and Canberra (Climate 24) were taken from the previously available climatic data files (Delsante and Mason, 1990). The parameters which are included in the hourly data file are: dry bulb temperature (^{o}C), absolute humidity (g/kg), wind speed (m/s), cloud cover (oktas), diffuse irradiance on horizontal (W/m^2) and direct irradiance normal to sun (W/m^2).

3.2 Thermal Comfort

The main objective of any effort to develop energy efficient buildings is the provision of thermal comfort with minimum energy consumption, by employing climatic building design. One of the key points is to ensure that occupants' thermal comfort is not sacrificed in order to reduce energy requirements. Therefore any assessment system to evaluate the efficiency of a particular building needs to consider the criterion of thermal comfort as the context for its evaluation of building performance.

The objective of this section is to establish the criterion of thermal comfort for evaluating the thermal performance of buildings. It first reviews many definitions of thermal comfort in the building sector to find the most appropriate one for this study. Secondly it reviews the main variables which impact on the provision, and affect the sensation of thermal comfort, in order to specify the main parameters that should be considered in evaluating the performance of a building on the basis of thermal comfort. The third and more important section is a review of the current standards in order to select an appropriate indicator of thermal comfort on which building performance will be evaluated.

3.2.1 Definition of thermal comfort

Numerous definitions of thermal comfort have been proposed by various researchers (Watt, 1963; Fanger, 1970; Givoni, 1976; O`Callaghan, 1978; Benzinger, 1979; Hensen, 1990; Ihab, 2002; Chappells Heather, 2004). Generally thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment” (ASHRAE, 2001). Owing to biological variance, it is not possible that everyone will be satisfied at the same time and in the same climate. Therefore some subjective criteria need to be applied to establish optimal comfort. Fanger (1970) suggests an optimal thermal condition as being one in which the highest possible percentage of a group is in thermal comfort. Optimal thermal condition is defined as a state in which there is no driving impulse to correct the environment by behaviour. Thermal comfort is interpreted by Givoni (1976) as the absence of irritation and discomfort due to heat or cold, and the state of pleasantness. Hensen (1990) detailed the causes of dissatisfaction in terms of the whole body’s being too warm or cold as well as unwanted heating or cooling in a part of the body (local body). Benzinger (1979) examined thermal comfort in terms of “ideal” thermal comfort and relative or “mixed” comfort.

A universal definition of comfort is almost impossible because of people’s variable preferences and the particular characteristics of different climates which affect the sensation of thermal comfort. A condition in which 80% - 90% of occupants feel thermally comfortable is accepted as a standard universal term. The specification of that condition depends on the parameters or variables which impact on thermal comfort. Theses parameters are reviewed in the following section

3.2.2 Human comfort and variables affecting thermal comfort

Human life requires a deep - body temperature of between 35^{o} C and 40^{o} C, for which 37^{o} C is the proxy mean. Skin temperature is normally between 31^{o} C and 34^{o} C. If heat is to be lost then the temperature of the surrounding environment must be less than skin temperature.

The most important variable to determine human comfort is air temperature. However this is not the only indicator. A number of factors influence the various heat exchange processes on the body surface which affect the sensation of comfort or discomfort (Szokolay, 1980). These factors are divided into two groups: environmental "climatic" and "non-climate" factors. The main environmental parameters have been identified as:

- Air temperature
- Humidity
- Air velocity
- Radiation (Parsons, 2003; Szokolay, 2004)

In addition there are other factors involved, such as draught, a high vertical temperature difference between head and ankles, or too high radiant temperature asymmetry. Increasing temperature always causes a corresponding change in the thermal sensation.

The impact of **humidity** on the human thermal comfort balance is complex. It has no significant effect on thermal comfort unless temperatures are very high or low. It has been demonstrated that up to about 27^{o} C a sedentary subject could not experience any difference between relative humidities of 30% and 80% in their subjective sensations (Givoni, 1998). At a comfortable temperature perspiration is not important, but the heat dissipation mechanism is important at high temperatures.

The rate of evaporation of perspiration depends on the absolute humidity. High proportions of humidity (above 12g/ kg) can cause unpleasant sensations because of restricting evaporation and consequently its cooling effect. Low humidity (generally less than 4g/kg) can cause drying out of mucous membranes. Thus the effect of humidity in the sensation of thermal comfort cannot be ignored in a climate such as that of Sydney in which the relative humidity (RH) is higher much of the time than the acceptable range.

Air movement around the body convectively transfers heat and causes cooling. Still air surrounding the body produces a thin insulation layer around the body. Air movement reduces the thickness of this insulation and so provides a cooling effect. It is an important mechanism for removing heat generated by the body, particularly when the level of humidity is high. Increasing air velocity decreases the amount of moisture held in the air around the body and results in increasing evaporation (ASHRAE, 1981).

The beneficial effect of air velocity therefore should not be ignored in an efficient design, particularly in a humid climate, as it can significantly reduce cooling energy requirements. This is a key point in designing for free running buildings. The employment of a specific strategy to provide maximum air circulation in indoor spaces should be one of the design priorities for free running buildings in a moderate climate with relative high humidity, such as Sydney's.

The thermal sensation experienced by a subject in an environment is significantly affected by the **radiative** heat exchange between the human body and the surrounding surfaces. This contributes as much as 30% of the whole thermal exchanges of the subject (La Gennusa, Nucara, Rizzo et al., 2005).

Mean Radiant Temperature (MRT) is applied to define the average temperature of all surfaces in a given space to which the body is exposed. The MRT is twice as important as the dry bulb temperature for lightly clothed people, while in cooler climates these two temperatures are equally important. Olgyay (1963) in his bioclimatic chart showed the interaction of the four main environmental factors for thermal comfort and used 0.8^{o} C increase in the mean radiant temperature to adjust 1 ^{o} C decrease in the dry bulb temperature. This chart has been revised and has become more complicated in later more sophisticated studies. The most well-known is found in the ASHRAE standard.

The interaction between the above four climatic variables is what makes an indoor environment thermally comfortable or uncomfortable. Givoni (1998) notes that heat discomfort inside buildings is correlated generally with 'environmental temperature' and air speed over the body. Environmental temperature is the combined effect of the air temperature and mean radiant temperature of the enclosure. If the air and mean radiant temperature are not the same, the globe temperature is a convincing measure of the resulting environmental temperature. Environmental temperature would appear to be a more appropriate indicator than only air temperature as one of the factors for evaluating the degree of comfort of indoor conditions.

There are some other, 'non-climate', factors which can affect how comfortable a person feels in a given situation, such as: age (Young, 1991; Mayer, 1993; Young and Lee, 1997) clothing, acclimatisation, sex (Chung and Tong, 1990; Parsons, 2001; Nakano, Tanabe and Kimura, 2002; Lee and Choi, 2004), health and activity (Yoshida, Nomura, Mikami et al., 2000; Parsons, 2003) and subcutaneous fat.

While the geographic location would seem to have an influence on thermal sensation, Parsons (2003) argues that this has not been shown to be the case in some research. He refers to the observation of various studies (Nevins et al, 1996; Fanger 1970; Ellis, 1953) that found no significant difference between conditions preferred by subjects in different geographical locations. However, it should be noted that the results of those studies were obtained for occupants in conditioned buildings and not free running, naturally ventilated ones, and, as will be explained later, in the case of the latter geographical location is relevant.

The sensation of comfort depends on the activity, physiology and thermoregulatory system of the body (Yaglou, 1927; Gagge, Herrington and Winslow, 1937; Winslow, Herrington and Gagge, 1937; Fanger, 1967; Gagge, Stolwijk and Hardy, 1967; McNall, 1967; Gagge, 1973). The level of an occupant's activity can be roughly predicted by noting the building's function. For instance, in office buildings occupants can be considered to be sedentary with a low level of activity (1 - 1.2 met). However, the variation of activity in residential buildings is not predictable. Because of the unpredictability of occupants' activities and the type clothing they wear in the residential sector, the criteria for comfort conditions for this type of building may differ from those in buildings such as offices. It was observed by de Dear (1997) that although there were distinct differences in the degree of behavioural thermoregulatory adjustment made by residential building occupants compared to those in office buildings, there were no discernibly sharp differences in occupants' evaluations of the building's indoor climatic quality. Thus in at least some situations the criteria of thermal comfort for residential buildings may be considered to be similar to those in office buildings.

3.2.3 Thermal comfort models and standards

Over the past 100 years many research efforts have been devoted to developing indices and models predicting the thermal sensation of people. Thermal comfort prediction models generally are mathematical models of the relationship between one or more environmental factors and certain occupant factors. The main aim of comfort models is to provide a single index that encompasses all relevant parameters.

Thermal models of the human body and its interaction with the surrounding thermal environment are often proposed and used as the basis of thermal comfort standards. Comfort standards rely on such models of human thermal comfort to establish the interior environmental conditions they prescribe and to provide a single index that encompasses all the relevant physical parameters. The two basic types are empirical and theoretical. A review of the development of these two types and their details for measuring thermal comfort has appeared in "Thermal Comfort" (Auliciems and Szokolay, 1997) and Proceedings of "Moving Thermal Comfort Standards into the 21st Century" (2001). The models that have been developed vary from a simple linear equation relative to an indoor comfort temperature, to the outdoor dry bulb temperature, to complex algorithms. Both simple and complex models have limitations for use in establishing standards. These limitations affect the accuracy of any system, such as a simulation that employs such models and the accuracy of the inputs to the model (Jones, 2001). The point is that the most complex models are not always the most accurate and the simplest are not always the easiest to use. However, the simpler index is most likely to find widespread practical application (Holm and Engelbrecht, 2005). The accuracy of the model depends to what purpose it has been used for.

The most notable models have been developed by Fanger (1967, 1970), the Pierce Foundation (the Pierce two-node mode) originally developed by Gagg (1971) and researchers at Kansas State University (The KSU two-node model) (Azer and Hsu, 1977). The theory behind these three models is described by Berglund (1978). All three models employ an energy balance in a person and use the mechanism of energy exchange along with physiological parameters which were derived experimentally to predict the thermal sensation and physiological response of a person to their environment. The models differ in the criteria which are used to predict thermal sensation, physiological models for heat transfer from the body and the human control system. Among these three models, Fanger's model appears to be the most commonly used model in academic research, the development of software and the establishment of standards.

ASHRAE standard 55 (ASHRAE, 2004) and ISO 7730 (ISO 7730, 1995) have been widely adopted as international thermal comfort standards. These standards are based on a human energy balance obtained by assuming steady-state conditions. Those are deduced from the experiments conducted by Fanger (1970) in climatic chambers; using the predicted mean vote (PMV) and Predicted Percentage Dissatisfied (PPD) to estimate the human mean response to the thermal environment from six thermal variables. These related indices are based on a combination and interaction between environmental and personal parameters as follows:

- Environmental parameters include:
  - air temperature
  - radiant temperature or globe temperature
  - air velocity
  - air relative humidity (RH) or vapour pressure
- Personal parameters that are related to occupant adaptability to the local climate include:
  - metabolic rate
  - clothing insulation

However, it has been demonstrated that ISO 7730 and PMV/PPD overestimate warm discomfort (Humphreys and Nicol, 1995; Williamson, Coldicutt and Riordan, 1995; Karynono, 1996; de Dear et al., 1997).

ASHRAE provides the recognized world standard for thermal comfort in interior environments. This standard sets a narrow temperature zone in which 80% - 90% of slightly active people would find the environment thermally acceptable. However thermal discomfort is often reported by a large percentage of occupants in offices when the thermal environment complies with the recommendations in the standards (Melikov, 2004). This is related to the variability of occupants' preferences. Personality differences in preferred air temperature may be as great as 10^{o} C (Grivel and Candas, 1991). Occupants' preferences for air movement may differ more than four times (Melikov, 1996).

A thermal comfort zone is typically determined on a psychometric chart which is related to the air temperature and humidity. A combination of humidity and air temperature to determine the breadth of the comfort zone appears in (ET*) index (ASHRAE, 2003).

3.2.4 Applicability of the thermal comfort index for naturally ventilated buildings

Arguably the most widely accepted index of thermal sensation is Fanger`s "predicted mean vote" (PMV) (1970), which is the main index of comfort in ASHRAE Standard 55. This comfort index was developed on the basis of the physics of heat transfer combined with an empirical fit to sensation and based on the steady state. It is known to be a complicated equation because of the need to consider the main factors (personal and environmental) affecting thermal comfort. Although it is the most appropriate thermal index for buildings with an environmental control system, there are some features which limit its application. The PMV model does not include the effect of solar radiation through the windows on the occupant. It only includes the mean radiant temperature of a space in its computation. Thus discomfort caused by window radiation cannot be predicted by this model. This problem is addressed by Lyons (1999; 2006), who proposed a solar correction factor when calculating PPD.

The steady state condition, on the basis of which the PMV model was developed, makes it inapplicable to free running houses. This has been demonstrated by many studies, particularly by de Dear (Humphreys, 1975; Nicol and Aulicien, 1994; Forwood, 1995; Baker and Standeven, 1996; de Dear et al., 1997; Brager and de Dear, 1998; de Dear, 1998; Brager and de Dear, 2000; Brager, 2001; de Dear, 2001; de Dear and Brager, 2002; Humphreys and Fergus Nicol, 2002; de Dear, 2004). This study shares many of their concerns about the inapplicability of a laboratory based index to free running buildings.

Because of the strict application of steady state conditions, the index exaggerates the percentage of dissatisfied people if it is used for naturally ventilated buildings and where indoor temperature is controlled manually by the occupants according to their feelings. People in real situations show a wider range of preferences than they do in laboratory experience. A review of thermal comfort standards by Lovins (1992) showed that the comfort model developed from chamber research is “seriously flawed”, basically because it overlooked factors such as acclimatization, dependence and physiological variables among individuals. It has also been argued that strict reliance on laboratory-based comfort standards ignores important contextual influences that can decrease sensitivity to a given set of thermal conditions (Brager and de Dear, 1998). A number of case studies (Wong, Feriadi, Lim et al., 2002; Feriadi and Wong, 2004; Bouden and Ghrab, 2005) have also shown a significant deviation between thermal comfort sensation in naturally ventilated buildings and what PMV predicts. From an exhaustive analysis of all reported research from both naturally ventilated and HVAC controlled buildings, de Dear et al. (1997) concluded that while a mechanistic model of heat transfer may well describe the responses of people within a controlled indoor thermal environment, it is "inapplicable to naturally ventilated premises because it only partially accounts for processes of thermal adaptation to indoor climate".

The heat balance model ignores the psychological adaptation of occupants to a natural climate, and the fact that the tolerance of occupants in free running building is wider than in conditioned buildings. Thermal sensation, satisfaction, and acceptability are all influenced by the match between one’s expectations about the indoor climate in a special context and what the actual outdoor environment is (Fountain, Brager and de Dear, 1996). De Dear (2002, p.1) sums this up by stating that this model “…ignores the psychological dimension of adaptation which may be particularly important in contexts where people’s interactions with the environmental (i.e. personal thermal comfort), or diverse thermal experiences, may alter their expectations, and thus their thermal sensation and satisfaction. One context where these factors play a particularly important role is in naturally ventilated buildings.”

De Dear (2002) also points out that the environmental inputs to conventional heat balance thermal comfort models, such as PMV, have been taken from the indoor environment surrounding the building occupants. These models also need the user to have information on the occupants’ clothing insulation (clo) and metabolic rates. These last parameters are often difficult to estimate in the field, particularly in the use of free running house rating, in which we need to consider identical conditions for occupants in order to obtain a reliable comparison between dwelling buildings.

A study by Brager (2000) clearly showed that thermal sensation based on PMV does not correspond with that for naturally ventilated buildings. This study developed the following model, which shows how people felt too warm or too cool in conditioned buildings compared to naturally ventilated buildings. It was found that the occupants of centralized HVAC buildings were twice as sensitive to deviations in temperature as were occupants of naturally ventilated buildings.

$TS = 0.51\ T_{op} - 11.96$ (Centralized HAVC buildings) (Eq 3.1)

$TS = 0.27\ T_{op} - 6.65$ (Naturally ventilated buildings) (Eq 3.2)

In which: TS = mean thermal sensation which represents a vote on the seven point thermal sensation (PMV).

T_{op} = mean indoor operative temperature

Figure 3-2 illustrates a comparison between the thermal sensation of occupants of a naturally ventilated building and a building with centralized HAVC, based on the Brager models. It reveals a greater difference between the thermal sensations in the discomfort temperature range. It would appear from her comparison that any model developed for evaluation of the thermal performance of a conditioned building cannot be applied for the evaluation of a free running building.

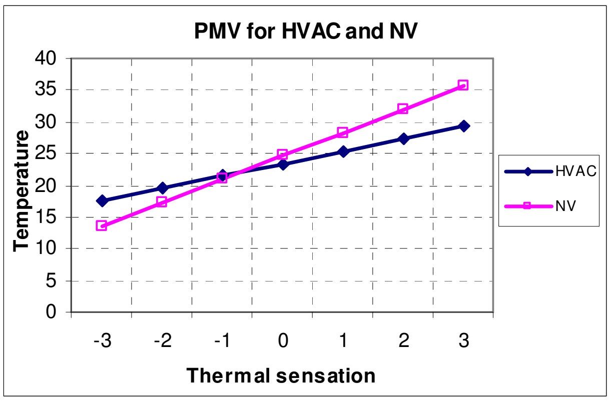


Figure 3 - 2 Comparison of PMV for conditioned and free running buildings based on de Dear study

An extension of the PMV model that includes an "expectancy" factor was added by Fanger (2002) to the PMV index, to make it applicable for use in non-air-conditioned buildings in warm climates. This model accorded well with some field studies in warm climates but its applicability for other climates needs to be examined in further study. To extend such a PMV model for naturally ventilated buildings, more research needs to be done before any practical implications can be drawn.

3.2.5 Adaptive thermal comfort models for naturally ventilated/free running buildings

The adaptive thermal comfort index has been developed through several investigations using "real" people engaged in "real" tasks in "real" built environments rather than in laboratory experiments. A number of studies have shown a correlation between outdoor temperature and thermally comfortable indoor condition for naturally ventilated buildings. "Meta-studies" of thermal comfort field studies have shown that indoor comfort temperature, as felt by the occupants, is a function of the mean outdoor temperature (Auliciems, A. and de Dear, R., 1986; de Dear, Fountain, Popovic et al., 1993; Nicol and Aulicien, 1994; Nicol and Roaf, 1996; Brager and de Dear, 1998; de Dear, 1998). This means that we can relate indoor comfort temperature to climate, region and seasons. For free running buildings and according to different surveys conducted under different climatic conditions, Humphreys (1976), reviewing the available field data, found a strong statistical dependence of thermal neutrality on the mean level of air or globe temperature. He found (1978) that the comfort temperature can be obtained from the mean outdoor temperature with Eq.3.3

$$Tn = 0.534T + 11.9 \qquad \text{(Eq 3.3)}$$

Auliciems (1981; 1983) revised Humphrey's equation by deleting some field studies such those with children as the subjects, and adding more information from other studies not included by Humphreys. These revisions increased the database to 53 separate field studies in various climatic zones covering more countries and more climates. After combining the data for naturally ventilated and air-conditioned buildings, the analysis led to an equation involving both the outdoors air temperature (T_o) and the indoor air temperature (T_i). The resulting equation is (Eq. 3.4):

T_c=0.48T_i+0.14T_o+9.22 (Eq 3.4)

Auliciems and de Dear (1986) have also proposed a single line for all buildings, covering naturally ventilated buildings and air-conditioned buildings. This relation is given by Eq.3.5

T_c=0.31T_o+17.6 (Eq 3.5)

Nicol (1996) has conducted several surveys under different climatic conditions. In a first survey in Pakistan he established a relation between comfort temperature and outdoor temperature given by Eq. 3.6.

T_c=0.38T_o+17.0 (Eq 3.6)

In a second survey in Pakistan (Nicol, Raja, Allaudin et al., 1999), he developed a second regression given by Eq. 3.7.

T_c=0.36T_o+18.5 (Eq 3.7)

These relations show clearly that the comfort temperature is related to the outdoor temperature and so to the climate. A regression has been developed in the function of outdoor ET*(Effective Temperature) (de Dear et al., 1997). The equation for all buildings is:

T_n = 20.9 + 0.16 ET* (Eq 3.8)

And for free running buildings is:

T_n = 18.9 + 0.255 ET* (Eq 3.9)

According to de Dear (2002) the adaptive comfort model which was formulated in terms of mean monthly outdoor air temperature is more applicable and familiar than ET* to engineers.

"….*It was agreed by every one on SSPC 55*[17] *that ET* is primarily an index used by researchers, and that practitioners would be more likely to use ACS*[18] *if the meteorological input data was a more familiar and accessible index. The ACS was therefore reformulated in terms of mean monthly outdoor air temperature, defined simply as the arithmetic average of the mean daily minimum and main daily maximum outdoor (dry bulb) temperatures for the month in question. This climate data is readily available and familiar to engineers*." (de Dear, 2002, P 557).

$T_{comf} = 0.31T_{a,out} + 17.8$ (Eq 3.10)

The above studies have demonstrated a line of best fit through data analyses. Figure 3- 3 collects these lines together. Variations can be seen between these studies, particularly between the first study by Humphrey and the last work, done by de Dear. The two lines intersect at a thermal neutrality of 25° C. These measures of temperature are only the same when the relative humidity is 50%, but a discrepancy exists at other levels of humidity. The reasons for this could lie in the type of buildings and the characteristics of occupants, such as their physiological, psychological and cultural features. Although the field investigations seem to cover different countries, this particular issue needs more study to show the probability of the effect of culture on thermal sensation and energy consumption.

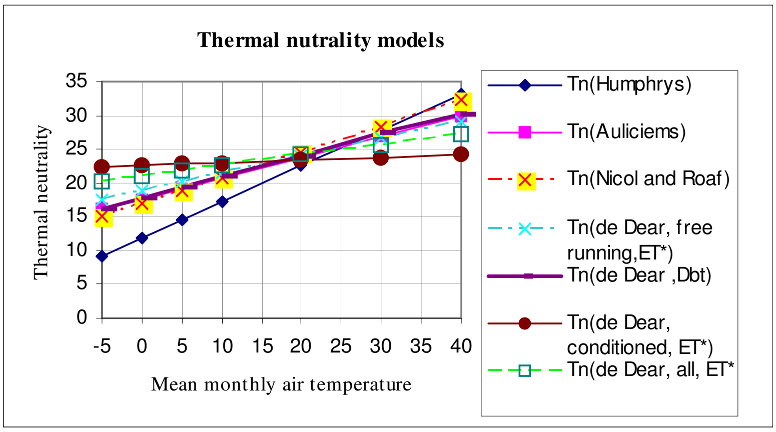


Figure 3 - 3 Thermal neutrality models, which show the correlation between thermal neutrality and mean monthly outdoor temperature (DBT)

---

[17] SSPC 55 is the ASHRAE committee in charge of revising thermal comfort standards

[18] ACT Adoptive Comfort Standard

Although the best correlation is shown between the adaptive comfort models and thermal sensation in naturally ventilated buildings, a more complex index in which all effective environmental and personal factors would be included, needs to be developed for free running houses. This model does not include human clothing or activity, nor the four classical thermal parameters that have a significant impact on the human heat balance and therefore on thermal sensation. However, the model is applicable where there is no other completed model developed for free running buildings.

3.2.6 Acceptable thermal conditions in free running buildings based on the ASHRAE standard

ASHRAE (2004) introduced an acceptable operative temperature range for naturally conditioned buildings, based on de Dear's adaptive model. It is applicable for spaces with operable windows that can be opened to the outdoors and adjusted by the occupants. In this model, metabolic rates range from 1.0 met to 1.3 met. Although "no humidity or air limits are required" in the application for this model, one cannot ignore the effect of humidity and air ventilation on the sensation of thermal comfort, particularly in warm and high humid climates.

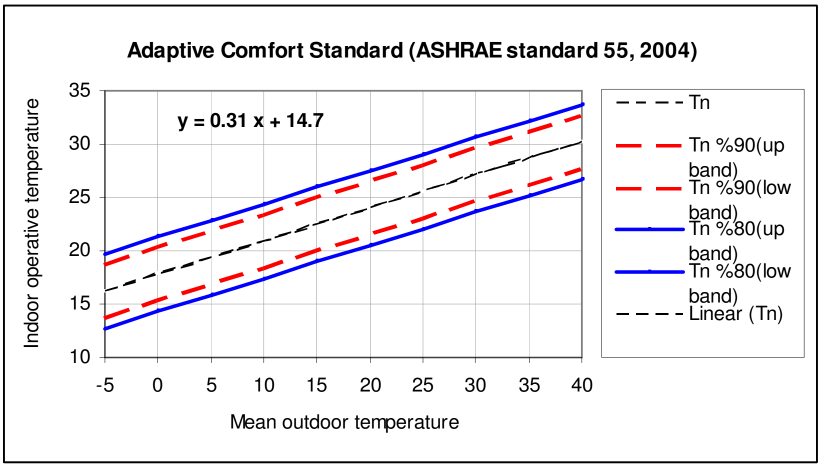


Figure 3 - 4 Adaptive Thermal Comfort standard (ACS), applied for naturally ventilated buildings in ASHRAE 55-2004

3.2.7 Applicability of the adaptive comfort model for free running residential buildings

The applicability of the adaptive comfort standard in residential buildings is a challenge since defining the criteria of thermal comfort in such buildings is problematic owing to the substantial variability of occupants' behaviour. The adaptive comfort standard has emerged from many studies done basically on office buildings in which the scenario of occupancy in terms of occupation time, where occupants sit, the level of activity and clothes are predictable. However, due no doubt to the wide variety of occupant behaviour in residential buildings, no comfort model has been developed specifically for residential buildings.

A study by the Davis Energy Group (2004) presents the reasons for which the thermal performance of a residential building are most likely to differ from the developed standards, including adaptive models. The differences are said to be owing to the following factors:

- Activity
- Size of population
- Steady -state assumption
- Assumption of natural ventilation or HVAC but not a combination of both
- Minimisation of "circumstantial restraints"

The report highlights, that "finding some agreement on input conditions to generate a comfort zone for more than one conditioned zone and for all occupants is a challenge" (David Energy Group, 2004, p.7). While a comfort model is developed for the sedentary activity of office work it does not apply to bed zones or to children, the elderly and disabled people who would be considered as among the occupants. Furthermore, the number of occupants varies for different families, which may influence the thermal conditions of how a house performs. Individuals for many different reasons vary in their comfort preferences and all variations cannot be predicted for residential buildings. A thermal condition of a house "tends to cycle though great flux in internal gains and external gains". However a standard cannot address the effect of this cycle on thermal comfort in adaptive models. An adaptive model is only suitable for buildings with no mechanical condition at all; it is not applicable for houses with combined systems.

Occupants in residential buildings have a wide flexibility in choice for clothing, activity and location to adjust themselves to indoor conditions in order to become comfortable. The concept "circumstantial restriction", which is described by Humphrey and Nicol (1998), and considered by them to develop comfort models predominantly non domestic settings, may not be observed in houses.

In spite of the above argument, the adaptive comfort model would appear to be more applicable for free running houses than other thermal comfort models since there is no established model developed for residential buildings. The main advantage of the adaptive model which makes it applicable for free running houses in this study is that it respects the effect of acclimatization. Acclimatization is the main parameter that influences the evaluation of thermal performance of a house through its effect on the behaviour of occupants. This might be a reason for differences between evaluations of thermal performance of a house in different operation modes.

3.3 Evaluation of a residential building's thermal performance on the basis of thermal comfort

The evaluation of the thermal indoor climate of a building in terms of human comfort response can be classified by the percentage of satisfied or dissatisfied occupants. This method has been employed in ISSO (2004) and two other studies (Olesen, Seppanen and Boerstra, 2006; van der Linden, Boerstra, Raue et al., 2006) that categorise buildings into three different groups : A, B and C. Level A corresponds to 90% thermal acceptability and is applied to buildings with high performance for thermal comfort. Level B is defined as corresponding to 80% thermal acceptability, meaning good indoor thermal comfort and finally 65% thermal acceptability is labelled level C and can be applied in temporary situations to existing buildings.

As the scope of thermal comfort for a conditioned house differs from that for a free running house, methods and criteria to determine thermal acceptability should be determined in relation to the house operation mode. ISSO 2004 relies on the Fanger model (PMV) and other studies based on the indoor operative temperature as a function of mean monthly outdoor air temperature.

However, this method is limited to only three categories, and does not differentiate between buildings with thermal performance below 65% thermal acceptance. Moreover it has been developed for office buildings and its applicability to residential buildings needs to be examined further. These restrictions make it inapplicable for the purpose of evaluating house performance for a house rating scheme.

The thermal performance of buildings can also be evaluated by employing the "degree hour" method. A degree hour is the amount of time spent above or below a standard reference thermal comfort zone during an hour. This method is used to express the length of time and how far the indoor temperature falls below or above the comfort temperature. It has been used in a variety of studies to evaluate or predict a building's performance (Willrath, 1998) and to estimate the annual energy requirement of buildings (Buyukalaca, Bulut and Yilmaz, 2001; de Dear, 2002; Christenson, Manz and Gyalistras, 2005).

An important issue in employing this method for thermal performance evaluation of buildings is the method of summing up the length of time that the comfort range is exceeded, because the value of different degree hours may not be the same. For this purpose weighting factors are proposed by some sources (ISSO, 1990; International Standards Organisation, 2003; Olesen, 2004) and in GBA (Government Buildings Agency) in the Netherlands as described in van der Linden (van der Linden, Boerstra, Raue et al., 2002). But these are only applicable for conditioned buildings because they propose a weighting factor which depends on Fanger's (PMV) model[19], the inapplicability of which to free running houses has already been discussed.

---

[19] Based on ISO 2003, the time during which the PMV exceeds the comfort boundaries is weighted with a factor which is a function of the PPD on a yearly basis and is expressed as follows:

$$Wf = PPD_{\text{actual PMV}} / PPD_{\text{PMV limit}} \quad \text{(Eq 3.11)}$$

Where $PPD_{\text{actual PMV}}$ is the instantaneous value in which the PPD exceeds the limit PPD_{PMVlimit} which depends on the class of comfort. The warm period is calculated from $\sum Wf$ * time hours, where $PMV > PMV_{\text{limit}}$ and the cold period is obtained from it when $PMV < PMV_{\text{limit.}}$.

The entirety of the resulting "weighting factor * time" is named "weighting time" in hours, which is applicable for the assessment of long term conditions but not for free running buildings.

3.3.1 Computing degree hours for free running houses

The weighting factor for computing "degree hours" in free running houses can be determined on the basis of the percentage of dissatisfied people in naturally ventilated houses for each discomfort hour. However, extensive research has still not produced a framework or model to determine the PPD for naturally ventilated buildings.

A study in South Brazil (Xavier, 2001) showed the probit regression of dissatisfied people in a number of naturally ventilated schools. It showed the percentage of dissatisfied occupants when the temperature changed from the comfort temperature range. This method can be applied for office buildings as well as schools, but not for residential buildings because there are inflexible conditions for occupants in both, unlike in dwellings. As mentioned above, the behaviour of residents and their use of clothing is not predictable in residential buildings.

In a study to assess the thermal performance of free running houses Willarah (1998) used an equivalence between degree hours of discomfort, in which ten degree hours of discomfort were equivalent to one hour at ten degrees of discomfort or ten hours at one degree over or under the comfort limit. For different occupied zones, a weighting in proportion to its area as a fraction of the total was given to the total degree hours of each zone.

The above equivalence between degree hours is a simple concept that can be applied to evaluate the free running performance of a house on the basis of thermal comfort. Although there is no linear relationship between the percentage of dissatisfied people

---

A similar method has been introduced in ISSO for the sum of weighted temperature exceeding hours (Wf), as explained by Breesch and Janssens (2004). Wf is considered directly as a proportion of PPD, in which an hour with 20% dissatisfied occupancy counts twice as much as an hour with 10% dissatisfaction.

Based on van der Linden et al. (2002) the GBA (Government Buildings Agency) in the Netherlands also applied Fanger's PPD as a criterion for calculating the extent of excess temperatures. Over the period in which it exceeded a PMV= 0.5 (PPD= 10%), a weighting directly proportional to the PPD was applied, which means 1h with 20% dissatisfied people was weighted twice as much as 1 h with 10% dissatisfied occupants.

and the degree range, as there is no framework or model developed for discomfort beyond the comfort zone, the above simplified method of degree hours appeared to be suitable for the purpose of this study. This method has also been accepted by other experts (de Dear, 2005).

The two main criteria for evaluating free running buildings as a basis for a comfort based rating scheme in this study are:

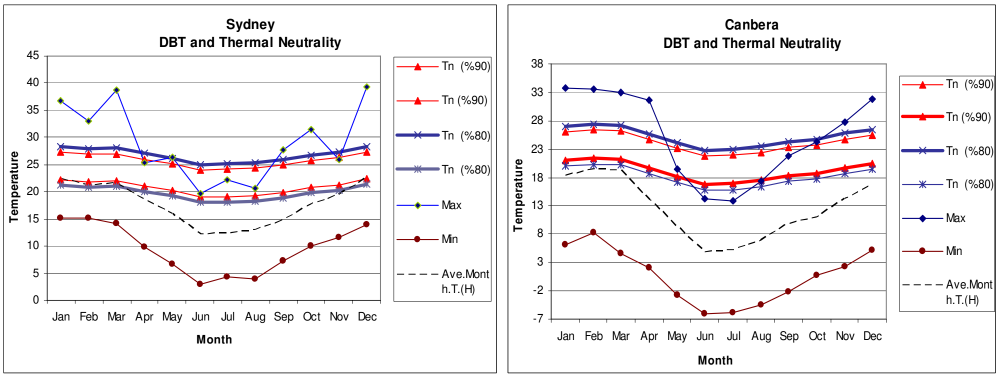
- the boundaries of the comfort zone for defining thermal neutrality.
- the temperature exceedance degree hour method

3.4 Thermal neutrality as applied in this study

3.4.1 For free running houses

Adaptive comfort models are arguably more relevant for determining thermal neutrality in houses in the free running operation mode. No significant difference (approximately 1^{o} C) was observed, as shown in Figure 3-3, between the ranges of temperature and the range used for thermal neutrality proposed by different scholars; thus for the purpose of a *comparative study* on the thermal performance of houses all proposed equations are applicable.

The boundaries of thermal neutrality in this study have been defined on the basis of ASHRAE 55(2004), as proposed by de Dear (ACS) [Figure 3-4]. The thermal neutrality limits have been set as 90% of occupant acceptability, for which the range of the comfort zone has been set at 2.5^{o} C on either side of the optimum comfort temperature. It has been defined separately for each month, based on hourly climatic data (Fig. 3 -5). These ranges have been used as the comfort conditions in the living zone of houses occupied during the day-time. The limits for the bedroom zone, during sleeping time (between 12 – 6 am), have been defined as being five degrees less than these bands. The logic is that occupants can easily use a blanket during this time without any complaints about indoor temperature. Other studies have also applied a wider range of thermal neutrality for sleeping areas. For example, the AHRC project (Walsh, 1982) calculated a lower band of comfort temperature for the sleeping zone, at 5^{o} C less than its range for the living zone.



a) Sydney **b) Canberra**

Figure 3 - 5 DBT, Max and Min temperature for each month, and thermal neutrality comfort band for Sydney and Canberra

Table 1 shows the average monthly climate data for Sydney and Canberra, taken from the climate data file of AccuRate software. Average mean monthly temperature is calculated on the basis of hourly and max/min monthly temperatures. In a parallel study it was shown that for more accuracy in calculating thermal neutrality and the thermostat setting the mean monthly temperature should be computed for hourly temperatures rather than max/min temperatures (See Appendix A).

The range of optimum thermal neutrality over a typical year was observed to be:

- for Sydney 20.7≤ Tn ≤25.7
- for Canberra 19.1≤ Tn ≤ 24.1

Table 3- 1 Average monthly temperatures based on hourly temperature and max. min. monthly temperature, and thermal neutrality for 90% occupant acceptability in the Sydney and Canberra climates

Sydney	Based on hourly data			Based on max& min data				
Month	Average T(H)	Tn(H)	Tn(90%)	Max	Min	Ave. Tem	Tn(optimum)	Tn(90%)
Jan	22.4	24.7	22.6-27.2	36.8	15.1	25.9	25.8	23.3- 28.3
Feb	21.2	24.3	21.8- 26.8	33.1	15.2	24.1	25.2	22.7- 27.7
March	21.6	24.5	22.0- 27.0	38.7	14.1	26.4	25.9	23.4- 28.4
April	18.5	23.5	21.0- 26.0	25.4	9.8	17.6	23.2	20.7- 25.7
May	15.8	22.7	20.2- 25.2	26.4	6.7	16.5	22.9	20.4- 25.4
Jun	12.0	21.5	19.0- 24.0	19.7	3	11.3	21.3	18.8- 23.8
July	12.3	21.6	19.1- 24.1	22.2	4.4	13.3	21.9	19.4- 24.4
Aug	12.9	21.8	19.3- 24.3	20.6	4	12.3	21.6	19.1- 24.1
Sep	14.8	22.3	19.8- 24.8	27.7	7.2	17.45	23.2	20.7- 25.7
Oct	17.6	23.2	20.7- 25.7	31.5	10	20.75	24.2	21.7- 26.7

Sydney	Based on hourly data			Based on max& min data				
Month	Average T(H)	Tn(H)	Tn(90%)	Max	Min	Ave. Tem	Tn(optimum)	Tn(90%)
Nov	19.3	23.8	21.3- 26.3	26	11.5	18.75	23.6	21.1- 26.1
Dec	22.6	24.8	22.3- 27.3	39.3	14	26.0	28.5	29.5- 23.5

Sydney

Canberra	Based on hourly data				Based on max& min Data			
Month	Average T(H)	Tn(H)	Tn(90%)	Max	Min	Ave. Tem	Tn(optimum)	Tn(90%)
Jan	18.2	23.4	20.9- 25.9	33.8	6.1	19.9	23.9	21.4- 26.4
Feb	19.4	23.8	21.3- 26.3	33.6	8.2	20.9	24.2	21.7- 26.7
March	19.2	23.7	21.2- 26.2	32.9	4.6	18.75	23.6	21.1- 26.1
April	14.1	22.1	19.6- 24.6	31.7	2	16.85	23.0	20.5- 25.5
May	9.2	20.6	18.1- 23.1	19.4	-2.8	8.3	20.3	17.8- 22.8
Jun	4.7	19.2	16.7- 21.7	14.3	-6	4.15	19.0	16.5- 21.5
July	5.1	19.3	16.8- 21.8	13.8	-5.9	3.95	19.0	16.5- 21.5
Aug	6.8	19.9	17.4- 22.4	17.4	-4.4	6.5	19.8	17.3- 22.3
Sep	9.7	20.8	18.3- 23.3	21.8	-2.2	9.8	20.8	18.3- 23.3
Oct	11.0	21.2	18.7- 23.7	24.2	0.7	12.45	21.6	19.1- 24.1
Nov	14.3	22.2	19.7- 24.7	27.7	2.3	15	22.45	19.9- 24.9
Dec	16.7	23.0	20.5- 25.5	31.9	5.1	18.5	23.5	21.0- 26.0

Canberra

This study used environmental temperature rather than air temperature in evaluating the thermal performance of houses because the AccuRate software[20] which was used in this study computes environmental temperature rather than dry bulb temperature. According to Delsante (1995a) as mentioned in Willrath (1998), during the summer months environmental temperature is 1K higher than dry bulb temperature, but during the cold months the two temperatures are approximately the same. It is worth noting that environmental temperature is more reliable than dry bulb temperature in the evaluation of thermal comfort conditions (see Section 3.2.2) because the actual thermal sensation of occupants is affected by environmental temperature.

3.4.1.1 The effect of humidity and airspeed on the sensation of indoor temperature

Although the adaptive model proposed in ASHRAE 55-2004 does not require the inclusion of humidity and air speed, one cannot ignore the effects of humidity on temperature sensation in a humid climate. While humidity is not a major factor in a

[20] More details about the AccuRate software and the reasons for using it will be described in Chapter 4

moderate climate, it cannot be ignored in the Sydney climate in which humidity reaches 80% at times (Australian Bureau of Meteorology, 2006).

The limit boundaries of thermal neutrality in this study were changed on an hourly basis in response to relative humidity. Certain methods have been proposed to include the effect of *humidity* on the limits of comfort temperatures in the sensation of air temperature (Sutherland, 1971; Auliciems and Szokolay, 1997). This study has taken account of the effect of humidity in accordance with ASHRAE standard effective temperature line and by employing the following (Eq 12) simplified equation proposed by Szokolay (1991).

$$T_{intercept} = T + 23*(T - 14)\ 8\ HR_T \quad (^{o}C) \qquad \text{(Eq 3.12)}$$

Where HR_T is the humidity ratio at temperature T and 50 percent RH

Indoor humidity is considered approximately similar to outdoor humidity in free running houses. However, in reality indoor relative humidity can be lower or higher than outside humidity (Hyde, 1996), depending on the climate. Since there was not an appropriate tool available to simulate and compute hourly humidity, it was agreed to assume indoor humidity to be similar to outdoor humidity for houses in free running mode. This assumption is accepted by other experts in this field (de Dear, 2005).

The effect of *natural air ventilation* is accounted for by the AccuRate software which has been employed in this study. This will be described in more detail in the next chapter.

3.4.2 For conditioned houses

The notion of thermal comfort in conditioned buildings is implied in the thermostat settings. The thermostat settings indicate when heating and cooling is switched on in the computer simulations. It plays an important role in predicting energy requirements for space heating and cooling. There are several methods to determine the thermostat settings for conditioned houses (Williamson and Riordan, 1997). Different strategies for discretionary heating and cooling of houses result in different predictions of energy requirements; this issue is particularly critical in temperate climates.

This study kept the thermostat settings which were set in the AccuRate software. In this software, thermal neutrality as a reference for thermostat setting was calculated on the basis of mean January temperature, rounded to the nearest 0.5 degrees (Delsante, 2006). The thermostat setting for heating living space was set to 20^{o} C everywhere in Australia. For bedrooms the heating thermostat setting was 18 ^{o} C, and over sleeping time (0-7am) it was 15^{o} C.

The settings were left unchanged in order to maintain a controlled study, and to enable a comparison between the evaluations of house thermal performances on the basis of the current HERS and of the HFRS to be proposed in this study.

3.5 Indicators to measure thermal performance of houses

3.5.1 Conditioned mode

In this study, conditioned houses have had their thermal performance evaluated in terms of energy, which is an aggregation of the heating and cooling energy (sensible + latent) required to maintain comfort temperatures within particular zones for specifically nominated time periods. This is similar to the method applied in all energy based rating systems. Annual energy required is expressed in ***MJ/m^2.annum*** as an indicator of house thermal performance in the conditioned operation mode.

Despite, the unreliability of this indicator for the purpose of a rating scheme, as previously discussed, this study has employed it in order to make a comparison between the current rating scheme and a rating scheme that is proposed in this project.

3.5.2 Free running mode

Houses in the free running operation mode have had their thermal performance evaluated in terms of annual Degree Discomfort Hours (DDH). This is calculated from a combination of ‘heating and cooling discomfort hours’. Heating energy requirements for a conditioned building and ‘heating’ discomfort hours for the building in free running mode are indicators of a winter building performance in this study. Likewise cooling energy requirements and ‘cooling’ discomfort hours have been determined to investigate summer performance. Figure 3-6 shows the state of these two categories associated with the boundaries of the comfort zone.

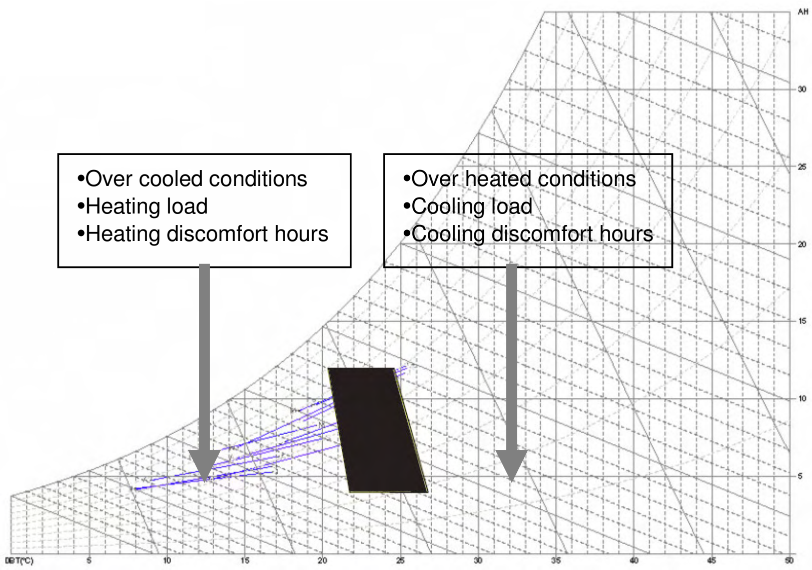


Figure 3 - 6 The state of discomfort hours relative to the comfort zone

3.5.3 Discussion

It appears that the two indicators mentioned above to evaluate the thermal performance of houses are strongly related to each other, particularly when DDHs are adjusted with area weighting. Occupants are basically more willing to turn on air conditioning or to load energy for space heating and cooling when the indoor environment is not thermally comfortable. Thus there may not be a significant difference between evaluating the thermal performance of houses in different operation modes. However, even if there is a strong correlation between those two indicators, it does not mean that an efficient architectural design for a free running house would be similar to an efficient architectural design for that house in conditioned mode. Therefore the value of an efficient free running house may be diminished if it is to be evaluated on the basis of its thermal performance in conditioned operation mode. This supposition, which has already been described as the hypothesis of this study will be tested and discussed further in the next chapters.

3.6 Summary

The principal work on comfort by Fanger, which was based on the heat balance between the surrounding environment and subjects in steady state conditions, has been replaced by recent studies, and adaptive thermal models, such as those produced by Humphries, Auliciems and de Dear. These take into account the effect of acclimatization. This particular consideration makes the adaptive comfort model applicable for naturally ventilated buildings. The de Dear comfort equation, which is expressed in ASHRAE 55 (2004), has been used in this study as a basis for calculating *degree discomfort hours* in free running dwellings.

Thermal neutrality for free running buildings has been determined in this study on the basis of hourly temperature. The comfort zone has been defined by a 5 ^{o}C band centred on the optimum thermal neutrality calculated for each month. The upper and lower limit of this band has been modified for relative humidity based on ASHRAE standard ET lines.

Since the humidity inside the building is not known and calculating the hourly indoor humidity manually is extremely time consuming, it was assumed that absolute humidity inside the building was the same as outside humidity for free running buildings.

Annual Degree Discomfort Hours (DDH) has been taken as an indicator to evaluate the thermal performance of a free running house and a normalized energy load (MJ/m^2.annum) has been accepted in this study as an indicator for the evaluation of thermal performance of houses in the conditioned operation mode. Although this is not an ideal indicator for the evaluation of the energy performance of houses, this study has employed it as a common indicator which is used in the majority of energy based rating systems in order to examine its applicability for addressing aspects of efficiency in architectural design and to compare the current energy based rating schemes with ones based on thermal comfort.

It should be noted that the concept of free running houses in this study refers to naturally ventilated houses without any mechanical equipment to improve their indoor thermal condition. This definition, as Aynsley (2007) has noted, is not applicable in warm humid climates in which the benefits of using fans for improving summer performance would not be ignored. However the definition used in this study is appropriate for a moderate climate, such as that of Sydney, in which the effect of the "intelligent management of buildings" by occupants should not be ignored. The means for this includes controlling shutters and blinds to take advantage of outside weather, particularly with regard to directing natural ventilation into the inside environment.

Chapter 4

Research method and modelling

This chapter describes the framework of this research, and the methods applied. It explains the tools and criteria which were employed to evaluate the thermal performance of houses in conditioned and free running operation modes; then describes the house variations which were modelled in order to establish a building performance evaluation. A brief summary of the method for analysing data and testing the hypothesis is given as well.

4.1 Research framework

There are two main sections in this study. The first; based on the literature and reported in Chapters 2 and 3, highlighted the value of using HFRS and then considers how thermal comfort can be used as a basis for thermal performance assessment of free running buildings. The main criteria for thermal comfort and the main parameters to be included in the HRS have been determined on the basis of the literature. In the next step, simulation is employed to evaluate building performance to identify probabilistic differences between the thermal performances of buildings in different operation modes; and to determine the extent to which the range of numerical indicators of building performance may vary. Finally, parametric sensitivity analysis and statistical methods are applied to the simulation data to test the hypothesis and develop a new framework for HRS.

4.2. Building performance evaluation

Building performance assessment is an approach to the design and construction of a building, which systematically compares the actual or expected performance of buildings to explicitly documented criteria for their expected performance (Preiser, 2005; Preiser and Vischer, 2005). It deals with post-occupancy performance evaluation for further building construction or renovation (Bordass and Leaman, 2005) often by using simulation programs. This method is employed in order to ensure the quality of a building during the design process, making improvements where possible. The assessment is usually expressed in terms of annual energy requirements, thermal comfort, embodied energy, cost effectiveness, environmental impact and other parameters, depending on the purpose of the evaluation. In this study, for the purpose of developing house rating schemes, the first two parameters are involved.

The methods used for building performance evaluation are:

- Calculation
- Experimentation
- Simulations

The first of these methods, calculation, was done manually in earlier times by architects and building services engineers using pre-selected design conditions, and they often resorted to the ‘rule-of-thumb’ methods of estimation to extend beyond conventional design concepts. This approach frequently led to poor assessment of energy performance due to excessive part-load operations (Hong, Chou and Bong, 2000). The “bin method” as a simple hand-calculation procedure has also been used for calculating energy requirements in buildings based on the assumption of steady state conditions and simple building descriptions, but this method is also limited in its applicability; in addition to being unreliable (Klein, 1983; Hanby, 1995).

There are also problems with physical experiments in that they are often expensive and time consuming. Besides, it is difficult to modify parameters to determine the effect of modification on the thermal performance of a building. This method therefore is not suitable at the design stage, but could be appropriate for evaluating the reliability of any result from a study which employed the other two methods.

The third general approach, simulation, however, has been highly developed with the advancement in computer technology, and many simulation models now exist to predict the thermal behaviour of buildings. Simulation computer programs are flexible, accurate and reliable tools for designing and analysing the efficiency of a building design. These advantages have been confirmed by a number of reviews of simulation models (Littler, 1982; Sowell and Hittle, 1995; Al-Homoud, 2000; Hong et al., 2000; Clarke, 2001). An appropriate computer simulation can provide information on thermal performance that is as accurate as a physical experiment, while involving less time and expenditure. In the design stage for a building, computer tools such as full-scale mock-ups and simulations of interior and exterior spaces can provide further information for assessing all the different aspects of design. Such programs are thus the most appropriate for the evaluation of the thermal performance of houses at the design stage.

The simulation method is employed in this study for the purpose of evaluating the thermal performance of houses in different operation modes. In addition to the above-mentioned advantages there are two further important reasons for this. The first is that it helps to evaluate the thermal performance of a large number of houses within a limited time, and the second is that it is the most common method used to evaluate the thermal performance of buildings in HERS. Since the development of HERS is the core of this study; any improvements based on this method would be equally applicable to these rating systems.

4.2.1 Building simulation programs

Simulation programs are undergoing continuous development. Most building simulations perform hour-by-hour calculations for analysis and all use algorithms and models which provide approximate representations of the heat transfer mechanism of the physical elements to the environment, to other buildings and to internal energy resources. For this research a number of developed programs were investigated through the Building Energy Software Tools Directory[21], which categorises tools on the basis of subject, platform and country. The subject category is classified as follows:

- Whole Building Analysis
    - Energy Simulation
    - Load Calculation
    - Renewable Energy
    - Retrofit Analysis
    - Sustainability/ Green Building
- Code and Standards
- Materials, Components, Equipment, and system
- Other applications

[21] Retrieved September 10, 2004 and October 17, 2006, from : http://www.eere.energy.gov/buildings/tools_directory/

Under the energy simulation category there are about 100 software programs, mainly developed in the US, each of which has a particular weakness or limitation, depending on the purpose for which it is used. For the purpose of this study a close investigation was done into the software packages developed in Australia, particularly into those which have been used for the purpose of HERS.

4.2.1.1 Building simulation programs in Australia

The development of simulation programs for buildings started in Australia, in the 1970s with programs such as TEMPER, BUNYIP, Star performer, and CHEETAH. The latter is a development of the program ZSTEP3 (Delsante, 1987) and is well documented and validated (Delsante, 1995b). According to Clarke (2006) it "is considered by many to be equal to any in the world". This program is used to calculate hourly temperatures, and the heating and cooling energy requirements of small buildings, specially houses. It is based on the total–zone response factor method, which uses measured hourly weather data (temperature, solar irradiance and wind speed).

The first developed computer program for the establishment of house ratings was based on CHEETAH (Ballinger and Cassell, 1994), the core energy software model developed by the CSIRO for Australian climates (Ballinger, 1998a). Most modelling systems used in HERS, such as NatHERS, FirstRate and QuickRate, BERS, QRate and ACTHERS are based on this engine. NatHERS and BERS simulate the operational energy used in a home, while FirstRate, QRate, ACTHERS and QuickRate are correlation programs, which do not carry out simulations. A study by CSIRO has found that BERS and NatHERS software give similar results for a range of house variations. They produce the same result because they use the same engine, CHEENATH. The former, BERS, originally just contained star rating settings for 12 climate zones in Queensland but later came to cover all climate zones of Australia (Ballinger, 1998a).

NatHERS simulation software has been accepted nationally as the benchmark tool for assessing the thermal performance of houses and was known to be a tool unique to Australia in addressing the issue of energy efficiency. It allows houses to be rated on the basis of energy consumption and has been used for several years in both regulatory and voluntary rating schemes. However, NatHERS was found to have a number of shortcomings which led to criticism of the software as the foundation of a national regulatory rating scheme and as an appropriate tool for efficient design analysis. The main shortcomings which concern this study are:

- it ignores the physiological effect of natural ventilation in its computation for estimating energy requirements
- it is limited to only three conditioned zones in a house for simulation

A new rating tool, AccuRate, which is a development of NatHERS, was created in 2005 to address these shortcomings (Isaacs, 2005). Its engine is an enhanced version of the CHEENATH simulation engine. Its ventilation model was completely revised to include the physiological cooling effect of ventilation in computing the cooling energy requirement for conditioned houses. The process of this inclusion is described by Delsante (2005) and is briefly discussed in Section 4.5.2. The effect of that improvement has been demonstrated in a comparative study of NatHERS and AccuRate (Isaacs, 2004). This study demonstrated a substantial reduction in predicting the cooling energy requirement of a well-ventilated house for seven different climates. The other aspects which are improved in AccuRate and make it appropriate for the purpose of this study are:

- room by room zoning (up to 99 zones)
- flexibility in making a particular construction
- improvement in the modelling of reflective insulation
- user interface improvement
- detailed hourly outputs adjustment for floor area correction[22]

Although rating houses by AccuRate would appear to be more precise than using NatHERS, the shortcomings in AccuRate are still considerable, namely the lack of capability to rate free running buildings completely, and inflexibility in dealing with different occupancy scenarios.

AccuRate software is not flexible enough in simulating thermal performance of houses to deal with variations in occupant behaviour and in modelling occupant interactions.

[22] Small houses compared to large houses usually are penalised in the star rating scheme due to the basis of rating (MJ/m), which was discussed in Section 2.5.3. AccuRate has addressed this concern by developing an area correction factor (Isaacs, 2005)

Any condition in which doors, windows and blinds need to be opened and closed for specific purposes cannot be simulated by this software. A model has been set in the software, by which doors and windows would be opened when the indoor environmental temperature exceeds the boundaries of thermal comfort and outdoor temperature is less than indoor temperature. The software in this situation opens the windows of a simulated house in order to reduce indoor temperature by increasing heat transfer and natural ventilation, without considering whether the house is occupied or not. It is obvious that if a house is not occupied, windows cannot be opened automatically; however, this reality is ignored in the design of the AccuRate software. Another issue in the setting of the software program is that the state of occupation in relation to the operation of blinds and external shading is ignored. This simulation therefore does not mirror the actual performance of a house with real occupants. However the issue is not important enough to make the software inapplicable for the purpose of a rating scheme.

4.3 The validity of developed simulation programs

Validation is the key issue when attempting to instil confidence in a building simulation tool, which means that the credibility of any program for simulation has to be validated and that it is essential to continue improvement of the program (Clark, 1982). The main objective of validation is to establish the accuracy of numerical results and the range over which the model is applicable, and whether it is appropriate for a particular purpose. To validate a program a procedure needs to be adopted that can identify the magnitude of errors that the program produces in its simulation

In an attempt to validate programs in Australia, Deeble et al. (1988) reviewed several methods and proposed the following procedure to be followed:

- Check for consistency of results using simple models that can be easily checked manually or by other programs
- Compare predicted performance with the record of the monitored building
- Compare programs with each other to determine relative user friendliness
- Compare the output of the program with that desired by users

Internationally, many methodologies for the systematic validation of building energy simulation programs have been developed. Generally these are based on three main constructs developed by Judkoff and Neymark (1995). These are:

- Analytical verification: comparing the program or subroutine output for an analytical solution
- Empirical validation: comparing the program to monitored data; and
- Inter model comparison: comparing the program to other programs or itself.

Based on these techniques the IEA BESTTEST was developed in 1995 by the International Energy Agency Solar Heating and Cooling (IEA/SHC) and the Energy Conservation in Buildings and Community Systems as a test procedure for evaluating building energy simulation software. It involves comparing the results of simulations for a series of chosen test cases.

A validation study on AccuRate (Delsante, 2004) based on BESTTEST has given sufficient credit to the software to make it applicable in the study of building thermal performance. BESTTEST involved comparing the AccuRate program with the results from a set of eight reference programs from Europe and USA, namely BLAST, DOE2.1D, SUNCODE, SERI-RES, ESP, S3PAS, TRNSYS and TASE. Overall the comparisons were very satisfactory because no major discrepancies were found between the results of the reference programs and the AccuRate simulation engine in terms of computing annual total incident and transmitted solar radiation, hourly incident solar radiation on vertical surfaces, and in computing heating and cooling energy requirements for building variations, including changing the mass of a building, rotating the building and shading the windows.

4.3.1 Building simulation in this project

Because none of the above-mentioned shortcomings in the NatHERS and AccuRate interfere with the purpose of this study, these were applied for use as the research tool. At the time of running the simulations in the preliminary stages of this study, AccuRate was still under development and thus NatHERS was used for the pilot studies for this project (Kordjamshidi, King and Prasad, 2005a, 2005b).

For the purpose of this study, the shortcomings in the AccuRate and NatHERS software are not as important as they might appear. The main limitation in relation to this study is the inability of the softwares to deal with various occupancy scenarios. However, this problem also exists in all the other available software programs in Australia. The few software packages elsewhere which have attempted to deal with this problem, such as Energy Plus and Energy10 would appear to be difficult and complex in scheduling the opening of windows and doors in a manner compatible the Australian rating scheme. This issue was not, however, the main concern in this research, although it could be tested in further studies.

The other shortcoming, which is the inability of these softwares to properly deal with free running houses, is the main subject of this study and will be addressed.

There are other advantages in using AccuRate software in addition to those mentioned in Section 4.2.1.1. Both software programs, NatHERS and AccuRate, have been designed for the Australian climate and have the capability of analysing the energy consumption and hourly indoor temperature for non air-conditioned buildings and both engines have been validated by BESTTEST (Delsante, 1995a, 1995b, 2004). Moreover both softwares have been developed for HERS, which is the main concern of this study.

At the time of the simulations for this study being done, AccuRate was under Beta test to ensure that the software was working as intended. In this project the sensitivity of AccuRate was tested against NatHERS for two typical houses in a Sydney climate to find out the range of accuracy of each and to establish confidence in the reliability of AccuRate as compared to NatHERS.

The result of this comparison is reported in Appendix B. AccuRate software appeared to be more sensitive and accurate than NatHERS software in terms of accounting for the effect of natural ventilation and computing energy requirements. This observation, confirming the reports by Isaacs (2004), supported the use of AccuRate for this study.

A version of AccuRate software under development *(V 0.99.6.3)* was available at the time of running the simulation and so was employed in this study.

4.4 Typical houses

It is very difficult to precisely define all the various house types designed in Australia and thus it was necessary to use the concept of ‘typical houses’ for simulations. Typical houses are representative of popular practice in national architectural design; therefore the result of an examination of these samples reflects the performances of representative buildings of the entire nation and can then be generalized for a larger group of buildings which are subpopulations of interest and from which subpopulations of interest can be extrapolated.

For the purpose of this study, a sample of typical houses developed initially by SOLARCH (2000) was selected. This was mainly due to the similarity between the context of this study and that project.

In that study, to establish typical houses, 100 designed houses were collected from Project Home Display Villages throughout Sydney. Six typical houses were identified from these samples representing the following parameters:

- single and double storey dwellings
- large and small dwellings
- dwellings with potential for adaptation of plans for a range of ideal orientations

These six house designs are different in size and planning and cover a broad range of those available in Sydney. The floor plans of the samples are shown in Figures 4-2 to 4-7. General metric descriptions of the samples are presented in Table 4-1. Since window areas in different orientations differ among these six typical houses, Figure 4-1 represents this variation. It shows the percentage window-to-wall ratio for each orientation of each typical house. The ratio is computed from [window area / total wall area] in which total wall area means (window + wall) area.

Table 4- 1 Window, wall, ceiling, floor areas of typical houses

House	Number of floors	External wall area(m^2)	Window area(m^2)	Ceiling area (m^2)	Internal wall(m^2)	Floor area(m^2)
1A	1	137	32.4	138.2	96.6	138.2
1C	1	150	24.8	155.4	88.1	155.4
1D	1	196.5	45.9	244.9	160.4	244.9
2A	2	256.7	50	166	156.1	292.8
2C	2	260	56.5	136.3	182.3	315.7
2D	2	234	40	144.4	174.4	229

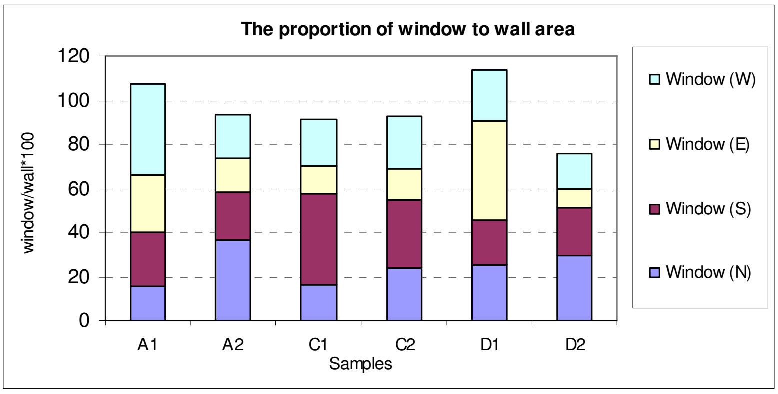


Figure 4- 1 The percentage of [window/ (window + wall)] for each orientation of typical houses

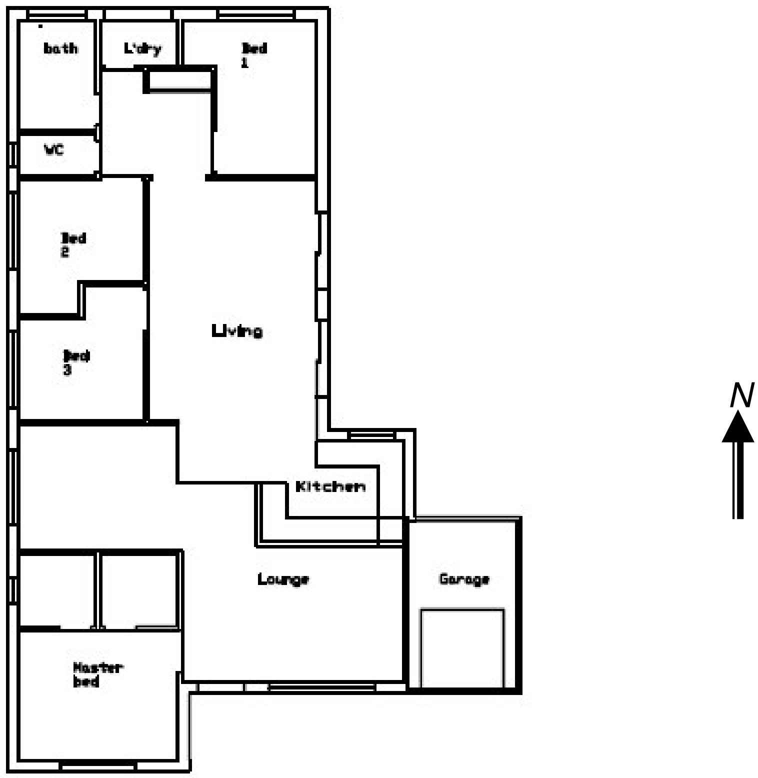


Figure 4- 2 Plan of typical house (House A1) (1/200)

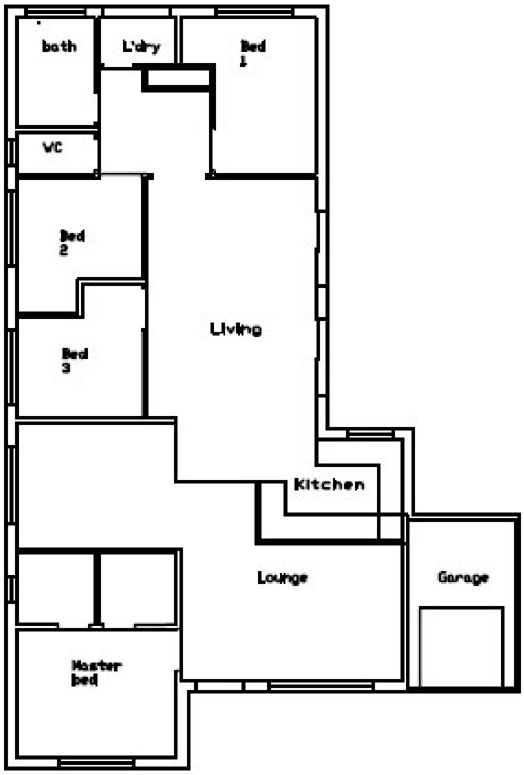


Figure 4- 3 Plan of typical house (House C1)

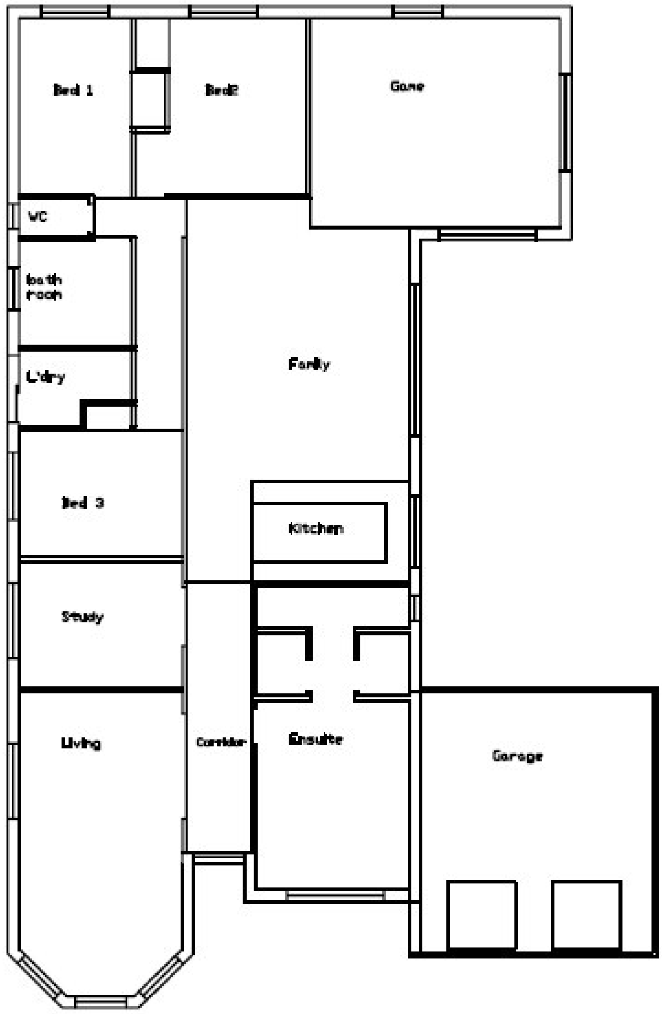


Figure 4- 4 Plan of typical house (House D1)

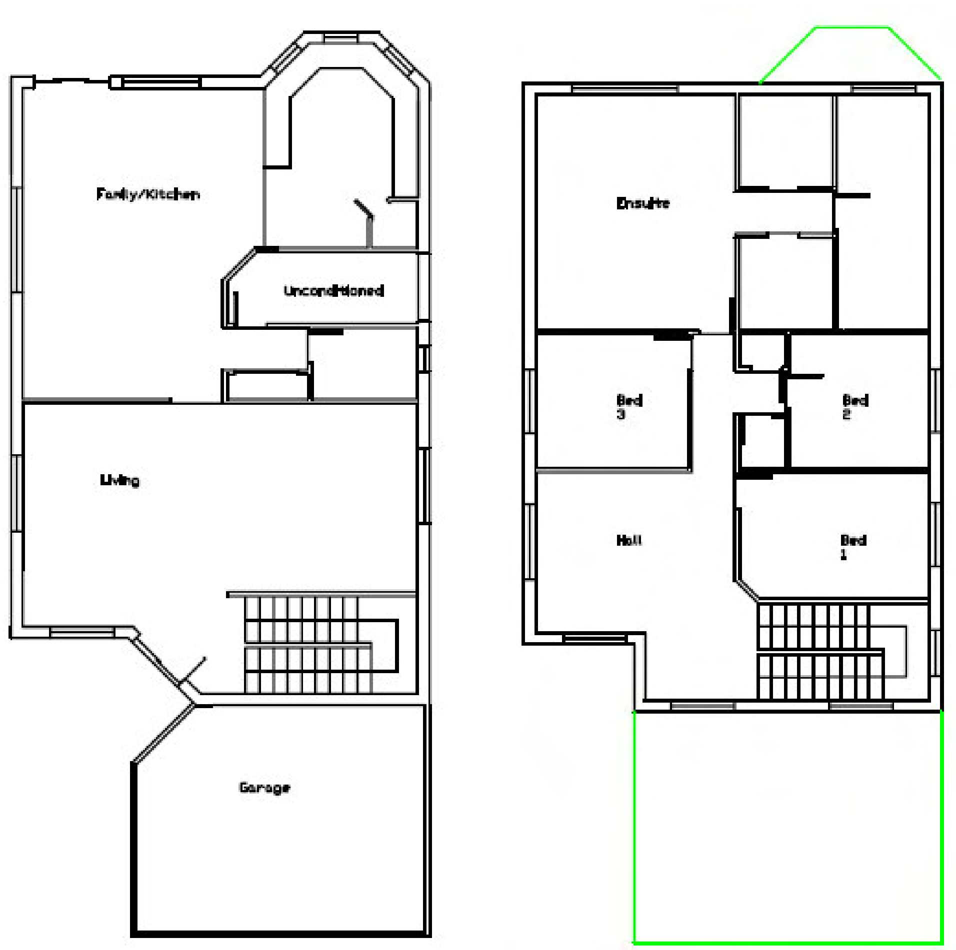


Figure 4- 5 Plan of typical house (House A2)

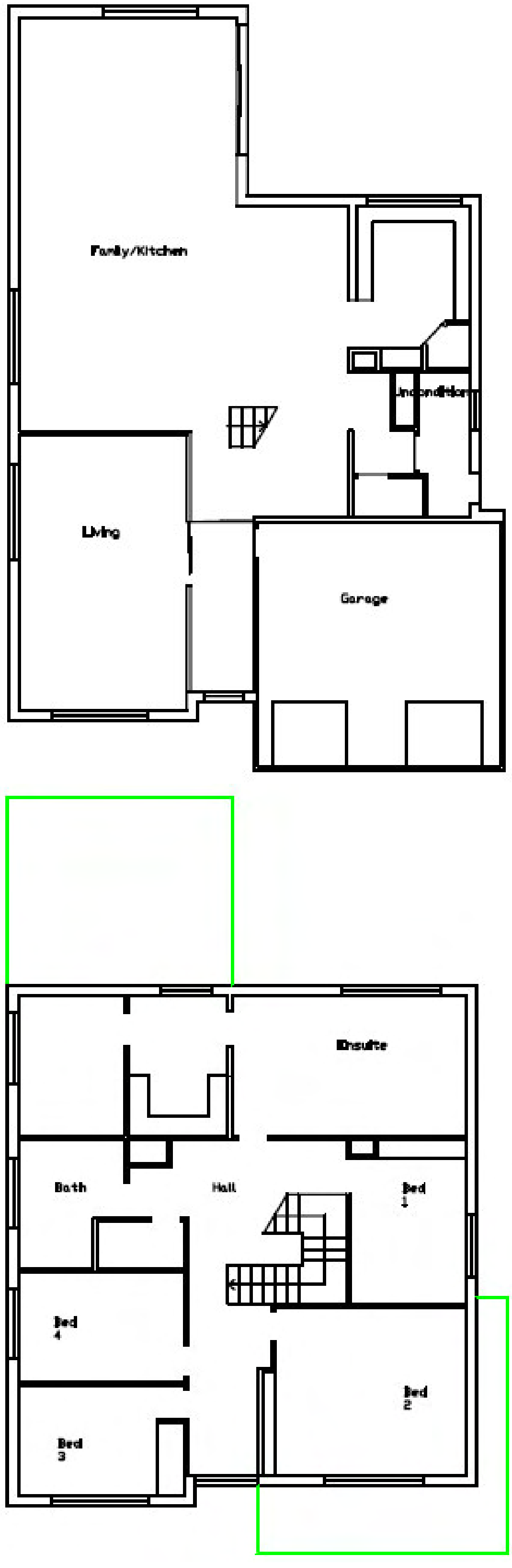


Figure 4- 6 Plan of typical house (House C2)

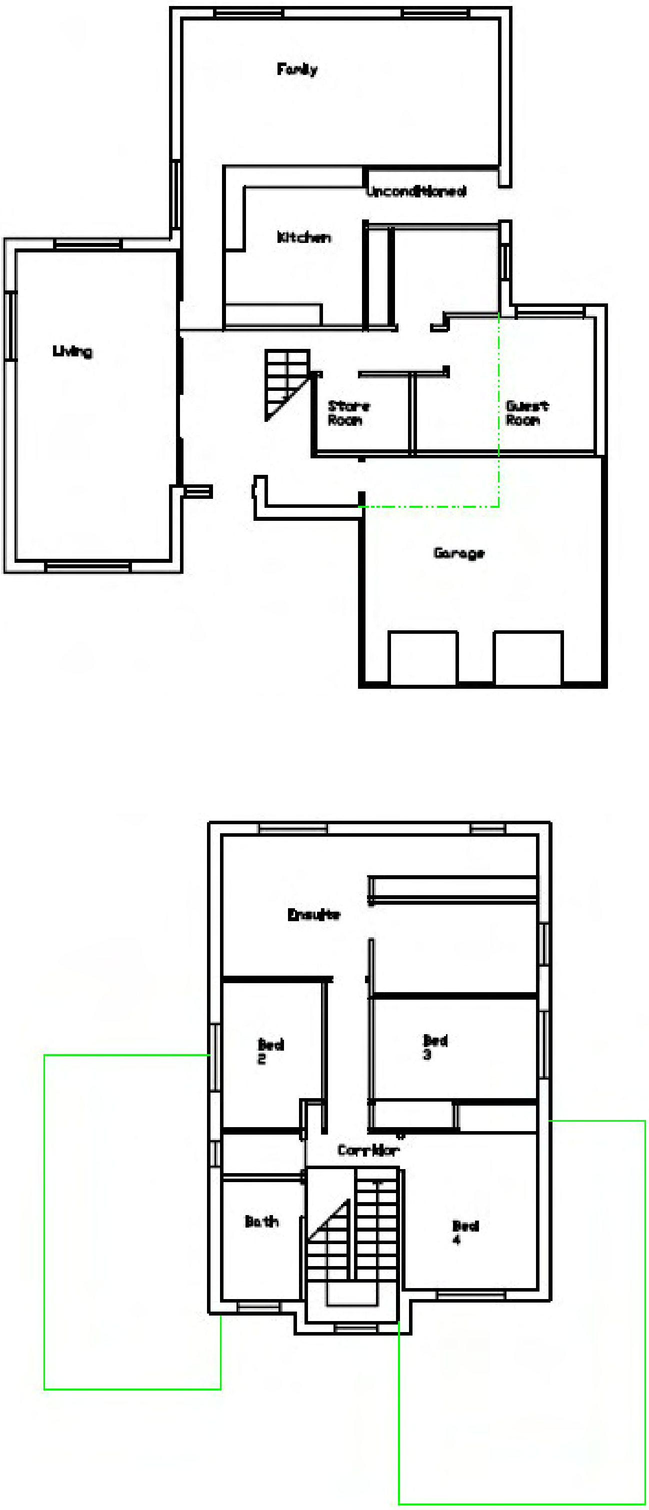


Figure 4- 7 Plan of typical house (House D2)

The main construction approaches to houses in Australia are usually referred to as heavyweight, lightweight and composite constructions (Walsh, 1982; Boland, 2004). The term Heavy Weight (HW) is used to describe building materials of high capacitance and is to be contrasted with Light Weight (LW) materials of low capacitance. HW material can be incorporated into any part of the building envelope, but most easily as a component of walls or floors.

As briefly discussed at Section 2.5.4, the issue of the rating of houses of different constructions is considered critical. In this study both Heavy Weight (HW) and Light Weight (LW) constructions were employed for the typical houses in order to compare the sensitivity in thermal performance of these two types in response to variations in occupancy scenarios and other design feature variations that will be described in Sections 4.5.1.1 and 4.6. Therefore the 6 typical house types were extended to 12 as base cases in this study. The main difference between HW and LW base houses is in the construction of their floors and external walls. The full description of the components of these two types of construction as used in this study is shown in Table 4-2.

Table 4- 2 General description of the materials used in the simulation for the 6 base houses

Construction	Heavy Weight (HW)	Light Weight (LW)
External wall	Brick veneer (uninsulated) External colour: light Internal colour: Medium	Weatherboard (uninsulated) External colour: light Internal colour: Medium
Internal wall	Plasterboard on studs Colour: (Medium)	Plasterboard on studs Colour: (Medium)
Window	Single glassed clear (4 mm)	Single glassed clear (4 mm)
Window internal cover	Closed weave	Closed weave
Window external cover	None	None
Window frame	Aluminium Colour: (Medium)	Timber Colour: (Medium)
Door	Timber (hollow) External (solid)	Timber (hollow) External (solid)
Roof	Roofing tiles Colour: (Medium)	Roofing tiles Colour: (Medium)
Ceiling	Plasterboard 13 mm	Plasterboard 13 mm

Construction	Heavy Weight (HW)	Light Weight (LW)
Floor Colour: (Medium)	Concrete Slab 100mm carpet/ bare Concrete Slab 100mm ceramic/ bare	Timber, bare Timber, ceramic tile/ bare The floor is suspended 60cm above the ground

4.5 Criteria for simulations in this study

This section describes the criteria applied for simulations in this study. These can be grouped into the five categories of:

- Occupancy scenario
- Comfort condition boundaries
- Thermostat settings
- Indicators for evaluating house performances
- Computation of annual performances

4.5.1 Occupancy scenarios

As discussed in Section 2.5.4, a house performance depends on how its occupants run the building. Occupant behaviour is not predictable; thus most house/home rating systems employ a typical one-occupancy scenario for evaluating thermal performance. However, establishing multiple occupancy scenarios for such a rating system could increase its accuracy.

For this purpose, occupancy scenarios should be defined as parameters that *affect the thermal performance of houses*, rather than how occupants evaluate the particular performance of a house. For example, the type of clothing of occupants should not be an important issue in this definition, since it involves personal evaluation. But the period of time when a house is occupied is a key parameter because over this time it is important for the thermal performance of a house to be acceptable for its occupants, since that is when occupants may turn on the air conditioner. The following parameters would therefore appear to be the simplest key parameters for establishing occupancy scenarios.

- Occupation time
- Occupied zones

Occupancy scenarios could be established on the basis of these two key parameters from:

- Surveys or
- Probabilistic scenario based analysis

Surveys are an appropriate way to correlate the time when a house may be occupied by different family types. However, social surveys are time-consuming and beyond the scope of this study. Since the occupation time depends on the family type, statistical information of households and family types, taken from the Australian Bureau of Statistics (ABS)[23] was investigated. This information shows the number and demographic characteristics of people living in families, the relationships between family members and the types of houses that families live in. It describes the usual resident population of Australia and how the Australian people use their time. However, this statistical information was not sufficient to establish a correlation between family types and house occupation times.

A more recent study however, by Foster (2006) using ABS information proposed an "occupants factor" to deal with the question of occupancy scenarios in response to criticism of the AccuRate software. By using a section from the ABS survey entitled "How Australians use their time"[24] he proposed multiple weightings to occupancy profiles by day of week. The weightings were determined with regard to the percentage of time that a house might be occupied over a weekday and weekends and would be applied in aggregating the results of multiple simulations based on these profiles.

Nevertheless, the proposed method, which is conceived as being based on a survey, does not design an appropriate occupancy scenario in relation to the aims for which multiple occupancy scenarios need to be established in this study. This is because it does not include differences between occupied zones of a house, which is an important parameter affecting the evaluation of a house thermal performance. Moreover, the proposed weightings cannot be accepted for other regions as standard since the numerical value of these factors may vary in different countries and in the future, as

---

[23] (ABS) http://www.abs.gov.au/

[24] Australia Bureau Statistic (ABS) 'Time Use Survey' Cat. No. 4153

family types are changing in modern society. The inapplicability of this method and the lack of more research in this regard have meant that a multiple occupancy scenario had to be developed for this study to fulfil its objectives.

A probabilistic method was considered to be a possible appropriate solution for determining multiple occupancy scenarios. The probabilistic occupancy scenarios could be established on the basis of the above two key parameters (time and zone). There could be at least 24! * 3! Scenarios, in which the first number refers to 24 hours per day and the second number refers the minimum number of conditioned zones in a house, namely the bed zone, living zone and one other conditioned zone[25]. However a more manageable number of scenarios would have to be established for application in a future building evaluation system.

In order to come up with a manageable number of synthesized probabilistic scenarios, it was necessary to classify a typical day and occupied conditioned rooms into certain categories. A typical day can be categorized into four categories of wakeup, daytime, evening and night time. In this study, therefore, the 24 hours of a day were grouped into four categories of 6 hours each. With regard to the typical activity of occupants at home (living and sleeping), all conditioned spaces in a residential house were classed into two conditioned zones: the living and the bed zone. With four groups of time and two main conditioned zones, 48 = (4!*2!) scenarios could be developed for HRS. Each scenario will show the probability of each zone being occupied at a particular time.

4.5.1.1 Occupancy Scenarios in this study

An investigation into the effect of different occupancy scenarios on the evaluation of thermal performance of houses appears to be a prerequisite for integrating multiple occupancy scenarios with such a HRS. For this purpose, a few scenarios were selected to examine how their different effects might be significant in evaluating and rating house performances, particularly in evaluating a lightweight house against heavyweight one. For this purpose, six scenarios of the 48 probabilistic occupancy scenarios were employed, as shown in Table 4-3.

---

[25] Note: The three conditioned zones are the minimum zones in a house in which the occupied time and occupant's activities differ. This is the condition considered in some HERS such as NatHERS.

Table 4- 3 Multiple occupancy scenarios in this study

Scenarios \ Zone	Living Zone				Bed Zone			
	0-6	6-12	12-18	18-24	0-6	6-12	12-18	18-24
Scenario 1		*	*	*	*			
Scenario 2		*	*	*	*			*
Scenario 3				*	*			
Scenario 4		*	*	*	*	*	*	*
Scenario 5		*		*	*	*		*
Scenario 6			*		*		*	

These six scenarios were selected on the basis of a small investigation of the family and householder types reported by the ABS. The first scenario involves families who use bedrooms only for sleeping. The second is similar to the standard scenario defined in the current rating scheme, namely NatHERS. The third scenario relates to families who are a couple, and are not at home during the day; however, it does not include the weekend and holiday occupation times. Through scenario four, the performance of a building is evaluated for full-time occupation. Scenarios five and six were considered, specifically, to investigate the performance of heavyweight and lightweight buildings over the times when lightweight buildings are likely to show better performance.

The importance of the above occupancy scenarios in HRS is described in (Kordjamshidi et al., 2005b) (See Appendix C.2, Section 7). It shows the importance of the occupied time and occupied zone in determining occupancy scenarios and demonstrates how different occupancy scenarios may affect the result of ranking in a house performance evaluation system.

4.5.2 Comfort boundaries for free running houses

As described in Section 3.4.1, the comfort band range was determined by setting the boundaries of monthly thermal neutrality and the humidity for each hour. Thermal neutrality was calculated for each month, using de Dears method (2002), in which average monthly temperatures were calculated from hourly climatic temperatures.
The comfort band was considered as being 90% acceptability by occupants. This was defined as:

- Thermal neutrality plus or minus 2.5^{o} C for the living area

- The lower band limit adjusted downward for sleeping time by 5° C
- The effect of humidity included to compensate for its effect on the sensation of temperature

The times of occupation determined on the basis of the multiple occupancy scenarios.

4.5.3 Thermostat settings for conditioned houses

As described in Section 3.4.2, the notion of thermal comfort is implied in the thermostat settings for conditioned houses. Thermostat settings indicate when heating and cooling is turned on in the computer simulations. The heating and cooling thermostat settings used in this study were similar to those in the AccuRate software and the settings for the Sydney and Canberra climate are shown in Table 4-4.

Table 4- 4 Thermostat setting in AccuRate software for Sydney and Canberra

Location	Heating for bed zone	Heating	Cooling
Sydney	18 C°	20 C°	24.5 C°
Canberra	18 C°	20 C°	24 C°

All conditioned zones were heated and cooled to maintain the indoor temperature in the comfort band over the occupied time. The occupied time was taken to be the same as that for the free running mode, as specified above in Section 4.5.1.1 Service areas, such as laundry, bathroom, store room and garage were not heated and cooled at all.

Heating and cooling are invoked in AccuRate[26] when they are required. Heating is applied for a conditioned zone if its environmental temperature at the end of an hour without heating is below the heating thermostat setting. Cooling is applied if the zone at the end of an hour without cooling or ventilation is outside (above or right side) the bounds of thermal comfort. The boundaries of the comfort region are determined as being between 12g/kg absolute humidity (AH) at the top of the range, 0g/kg AH at the bottom and ET* line based on cooling thermostat +2.5 degrees at the right. If the zone temperature is above the outdoor temperature, ventilation is turned on, and a new temperature and air speed are calculated. If the air speed is above 0.2m/s, the described

[26] This information is based on the AccuRate manual and the help option in the software (2005)

comfort region is extended in two ways: the 90% relative humidity (RH) line is considered for the top boundary and the right boundary is an ET* where:

$T = 6(V- 0.2) – 1.6 (V- 0.2)^2$ V is estimated indoor speed (m/s)

If the conditioned zone is still outside the comfort bounds, the zone openings are closed and cooling is invoked, and so the zone temperature at the end of the hour is the same as the cooling thermostat setting.

The samples are considered to be air conditioned when they are simulated in the conditioned operation mode, so during cooling dehumidification is invoked as well. The total annual energy consumption reported is therefore the total predicted energy requirement for cooling, heating and dehumidification.

4.5.4 Indicators for evaluating the thermal performance of houses

As described in Section 3.4, energy (*MJ/M²̲.annum*) and weighted exceedance hours (*DDH*) were determined as indicators to evaluate the thermal performance of houses in the conditioned and free running operation modes respectively. Energy requirements were predicted through simulation by AccuRate software with a house run in the conditioned mode. To calculate DDH, an algorithm was designed in order to convert hourly temperature data produced by AccuRate software into DDH.

Post processing was carried out to calculate the DDH. The process of calculating DDH is shown in Figure 4-8. The simplified algorithm was written in Excel to convert computed annual indoor temperatures (8760 hours) for all zones of a house into the respective DDH indicators.

As the typical houses differed in the number of their rooms and area (m^2), 6 typical files were required to be designed for the 6 base samples in order to compute DDH for each simulated model. Each Excel file contained a number of separate sheets matched with the number of conditioned zones. Hourly temperatures for each simulated house in the free running mode were imported into the related Excel file in order to calculate its annual DDHs. The outcome contained two indicators of DDH; one being *DDH with* *area weighting*, which is weighted by proportion of area, and the other being *DDH without area weighting*.

The purpose of considering an area weighted DDH was to investigate a better correlation between two identified indicators of house performances: MJ/m^2 and DDH with weighted area, in two different house operation modes. The DDH of each living area and bed zone (conditioned zones) was given a weighting in proportion to its area as a fraction of the total area. The sum of the area weighted DDHs of conditioned zones provided the 'DDH with area weighting'.

However, it was assumed that degree discomfort hours would be free of the effect of floor area, so as to avoid the same probabilistic problem which was observed in the energy based rating schemes discussed in Section 2.5.3.

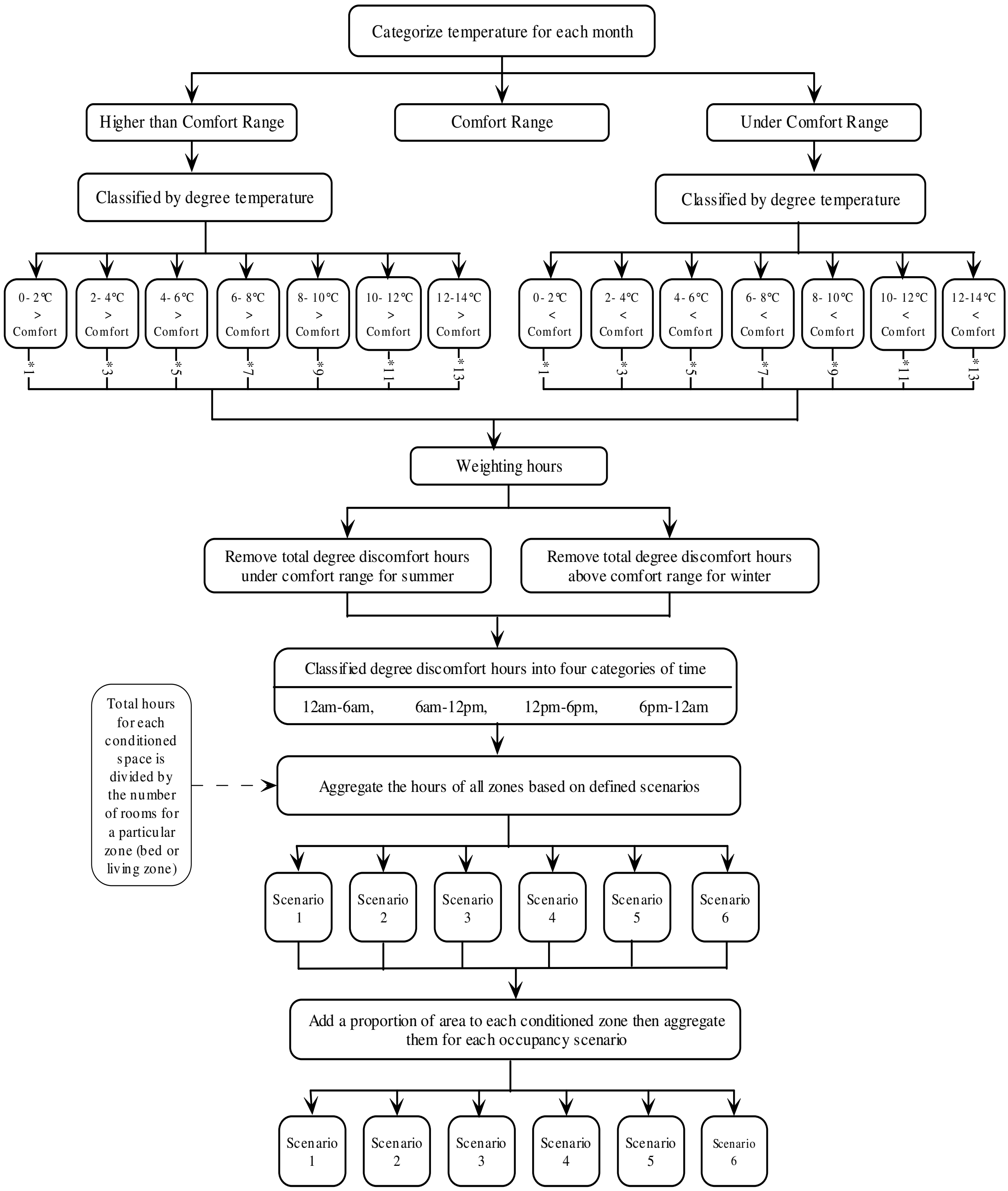


Figure 4- 8 Process of computing DDH

4.5.5 Correction in the computation of aggregate annual DDHs, to account for the psychological effect of seasons

As discussed before in Section 2.5.5.1, the psychological effect of seasons on the sensation of thermal comfort by occupants should be considered in order to correct the computation of energy requirements and DDH. This correction improves the accuracy of any system. This study therefore made such a correction and included it in the process of calculating DDH by removing 'heating degree hours' over summer and 'cooling degree hours' over winter. For this purpose it was necessary to define the 'cut off' dates for summer and winter.

Summer and winter in Australia, like other countries in the southern hemisphere, are the duration of time between December to February and June to August respectively. However the 'cut off' date for summer is defined as between 15th of December to 15th of March because, the maximum and average temperatures for the first 15 days of March were greater than for the first 15 days of December in both the climate of Sydney and Canberra based on the climatic data available which was used for simulations. The 'cut off' date for winter was defined to be between 1st of June to 31st of August.

4.6 Parameter variations

The effect of the following design parameters on the thermal performances of typical houses for both house operation modes was investigated for the moderate climate of Sydney and Canberra. These parameters were selected because they have been recognized by other studies as the main variables affecting the performance of a building (Krichkanok, 1997; Willrath, 1997; Willrath, 1998; Hyde, 2000; Planning, 2006; Tavares and Martins, 2007; Zhai and Chen, 2006). The effect of each of the parameters was tested separately to investigate whether their individual effect was similar in the performance of a house in both conditioned and free running operation modes.

4.6.1 Internal wall

Internal walls, which are a partition from which convective heat flows between zones, affect the indoor temperature of a conditioned zone. An interior wall between two zones with a large temperature differences behaves like an exterior wall (Akbari, Samano, Mertol et al., 1986). Thus the mass and construction of indoor walls can significantly affect the thermal sensation and also the heating and cooling energy requirements. The three different constructions which were considered for internal walls are shown in detail in Table 4-5.

Table 4- 5 Internal wall constructions in this study

Internal wall		Wall construction	
		Layer	Material
Base wall	Plaster board on studs	1	Plaster board
		2	Air gap, vertical 90mm, unventilated, non reflective (0.9/0.9, E=0.82)
		3	Plaster board
1	Concrete block	1	Plaster board
		2	Concrete block, 90 dense weigh, not core filled
		3	Plaster board
2	Brick plaster board	1	Plaster board
		2	Brick work: generic extruded clay brick (typical density)
		3	Plaster board
3	Cavity Brick	1	Plaster board
		2	Brick work
		3	Air gap, vertical 90mm
		4	Brick work
		5	Plaster board

4.6.2 Insulation

Heat conduction through building envelopes noticeably affects the fluctuation of indoor temperature and is a major component of the cooling and heating energy load, so that the indoor climate effectively depends on the resistance of a building's external surface. Three levels of insulation for floor and ceiling, and four levels for external walls were simulated. The level of insulation that was chosen was based on the Australian Standard (Australian Standard, 1993) for buildings, with values higher and lower than the required resistance in the AS. Wall insulation levels were: none, R1, R1.5, R2, R2.5; and, floor and ceiling insulation were: none, R1, R2 and R3.

4.6.3 External Colour

The colour of the outside surface of a building envelope influences the thermal performance of a building because it determines the amount of absorbed solar radiation and its inward transmission into a building. Dark external colours improve performance in the winter as they increase the absorbance of solar energy, and reduce summer performance.

Three levels of absorbance were investigated: light (S.A. =30%), medium (S.A. =50%) and dark (S.A. = 85%), for external walls and roofs. The internal colour was taken as medium for all samples.

4.6.4 Building orientation

Building orientation can also affect the indoor climate of a zone or room because of its effect on the ventilation and solar absorbance of external walls. Orientation is relatively more important with respect to wind than to the patterns of solar irradiation, as discussed by Givoni (1976). Since natural ventilation is a key parameter in improving the performance of buildings, particularly in free running operation, the magnitude of orientation as a factor cannot be ignored for an efficient architectural design.

The computer model simulated eight orientations, covering a complete 360 ^{o} rotation in 45 ^{o} increments.

4.6.5 Infiltration

Air infiltration through cracks results in heat gain and heat loss; therefore infiltration or an uncontrolled ventilation rate reduces the thermal performance of a building. Four levels of infiltration, varying from 0 to 5 air-changes per hour, were simulated for typical houses.

4.6.6 Glazing type

The effect of glazing type on the performance of a building has been well documented (Klainsek, 1991; Nielsen, Duer and Svendsen, 2001; Omar and Al-Ragom, 2002) particularly for air conditioned buildings. Glazing systems have a huge impact on the performance of a building, and glazing modification often presents an opportunity for indoor climate improvements in a building. Window glazing and frames are a major factor in determining the energy efficiency of the building envelope.

The three main types of glass are clear, reflective and tinted. Reflective windows diminish solar transmission without heating up the glass area. A large proportion of the radiation can be absorbed by tinted glass, where the glass surface is heated up. The heat is then radiated and conducted to the surrounding area so for summer the benefit of this type of glass, compared to reflective glass, is reduced.

Single glazed windows provide only a small amount of insulation to the passage of heat because of thin films of still air that exist next to the glass. Double glazing gives better insulation because there are two panes of glass with a sealed space between them. The performance of base houses was simulated for both glazing types as shown in Table 4-6.

Table 4- 6 Glazing types in this study

Window type	Abbreviation	Shading coefficient
Single glaze, clear	SG Clr	1
Single glaze, reflective	SG refl	0.52
Single glaze, toned	SG Tone	0.70
Double glaze clear	DG Clr	0.88
Double glaze, toned	DG Tone	0.60

4.6.7 Internal window covering

Window coverings present a different effect on the performance of a building depending on their placement, whether internal or external. An internal window covering limits the glare resulting from solar radiation. This device is effective in minimizing uncomfortable glare from direct beams, and in reducing the sun's heat from entering the space, depending on its material and colour. Moreover, it increases the heat resistance of glazed areas when closed.

Four different internal coverings for windows, of different levels of resistance, were selected for simulation to investigate their effect on total energy consumption and also on the thermal indoor environment (Table 4-7).

Table 4- 7 Internal window coverings in this study

Window covering	Abbreviation	Add resistance (m^2.K/W)	Transmittance	Absorbance
Open Wave	Open W	0.0	1	0.0
Closed weave	Closed W	0.03	0.25	0.35
Heavy drapes	Drape	0.055	0.10	0.40
Heavy Drapes+ Pelmets	D+ Pel	0.33	0.10	0.40

4.6.8 Sun shading devices

External shading devices affect the thermal performance of a house by reducing the incident solar intensity and therefore incident solar energy/or the amount of solar energy on windows and walls. Shading can be created by overhangs or eaves and vertical side fins but the former have been shown to be more effective in shading than the latter (Offiong and Ukpoho, 2004). However their effectiveness depends on their width.

Other studies have generally only investigated overhang sensitivity (Krichkanok, 1997; Willrath, 1998); therefore in this study the effect of overhangs on the thermal performance of typical houses was investigated. Three different overhang widths (450,600,1000mm) were applied for all windows without offset[27].

4.6.9 Ratio of openable windows

The presence of openable doors and windows affects air ventilation and improves the thermal performance of a naturally ventilated building when the outdoor temperature is less than the indoor temperature during summer. Depending on the climate, increasing its ratio to that of overall glazing can also significantly reduce the cooling load.

Three levels of *percentage of openable window*, 25%, 50% and 75%, without changes in the glazing area, were simulated.

---

[27] Offset refers to the distance between overhang and the top of the window

4.6.10 Window to wall ratio

Windows have been described as 'thermal holes" (Fisette, 2003). They are mostly 10 times less energy efficient than the wall area they replace. Thus, depending on the window area and its orientation, a house can lose 30% of its air-conditioning energy. However their effect on the indoor environment of a naturally ventilated building will differ from that of a conditioned building.

This study, by increasing the window glazing areas of base typical houses by 15% and 25%, compared the changes in the thermal behaviour of typical houses for free running and conditioned modes.

4.7 Data analysis

As described earlier, to test the hypothesis two data analysis process were adopted to investigate the effect of the identified design parameters in the thermal performance of houses in different operation modes in order. These were:

- Parametric sensitivity analysis
- Statistical analysis

4.7.1 Parametric sensitivity analysis

Sensitivity is a measure of the effect of change in one factor on another factor. Sensitivity analysis is potentially useful in all phases of the modelling process: model formulation, model calibration and model verification. Tarantola and Saltelli (2003) concluded that sensitivity analysis can produce useful information regarding the behaviour of the underlying simulated system. Sensitivity analysis is used to assess the relationship between variations in input parameters to variations in output parameters and has been used in many studies on buildings (Lomas and Eppel, 1992; Lam and Hui, 1996; Zhai and Chen, 2006), including for assessing their thermal performance and their energy load characteristics.

The aim of sensitivity analysis is to observe the system's response following modification in a given design parameter (Cammarata, Fichera and Marletta, 1993). However there are no formal rules or well-defined procedures for performing sensitivity analysis for building design because the objectives of each study will be different and building descriptions are quite complicated. In most cases, perturbation techniques and sensitivity methods are used to study the impact of input parameters on different simulation outputs as compared to a base case situation. The results are then interpreted and generalized so as to predict the likely responses of the system. The concept is simple and straightforward but a clear understanding of what sensitivity analysis can do for studies of building thermal performance and energy consumption and how the results should be interpreted is very important.

In this study the aim of sensitivity analysis has been to investigate the effects of house envelope variations on the annual and seasonal behaviour of the typical houses and also to investigate possible linkages between the thermal performances of a house in different operation modes in response to the variations described above in Section 4. 6.

4.7.2 Statistical analysis methods

In building energy research, statistical analysis has been used in the form of multivariate regression analysis and correlation coefficients, always in order to provide data description and prediction (Sullivan, Nozari, Johnson et al., 1985; Krichkanok, 1997; Thornton, Nair and Mistry, 1997; Poupard, Blondeau, Iordache et al., 2005)

A set of parametric statistical analyses, including correlation coefficient and multivariate regression analysis have been applied in this research to investigate the relationship, similarity and differences between the thermal performance of typical houses in conditioned and free running modes. The detailed discussion of each statistical analysis is included in Chapter 7.

The computer-based statistical package SPSS 14 for Windows was used to perform the statistical analysis. There are a number of other packages available for statistical analysis, but SPSS was found to be easier for use in this study because the software is user friendly and is flexible for importing data from Excel sheets.

Chapter 5

Reliability of HFRS and Base case analysis

This chapter reports two preliminary steps required before starting the bulk of the simulations and the main analysis for testing the research hypothesis. Thus it contains the following two sections.

The first section is designed to examine the reliability of DDH as a nominator for evaluating houses free running performance in a HFRS, compared to MJ/m^2, which is the current nominator for evaluating house conditioned performance in HERS.
The second section establishes the base case characteristics of the two indicators (MJ/m^2) for energy base and (DDH) for comfort base against:

- House construction (HW/LW)
- House type (SS/ DS)
- Seasonal performance
- Occupancy scenarios

in the two climates of Sydney and Canberra. Preliminary conclusions reported in this section are investigated more deeply in the next chapter.

5.1 A comparison of conditioned and free running building evaluation approaches

As suggested in Section 2.5.3, one of the shortcomings in the current rating scheme is the unreliability of a normalized energy index in addressing aspects of efficiency in architectural design. The issue concerned the inclusion of house size (m^2) in establishing the indicators for evaluating house energy performance. The house area is a major parameter in predicting energy requirements and cannot be ignored as a factor in determining the energy efficiency of a house, unless the evaluation involves a factor other than just energy consumption. In contrast, the evaluation of a house performance on the basis of thermal comfort (DDH) can be independent of area weighting[28]. Although the size of a room/house is a parameter which can significantly affect the

[28] DDH with and without area weighting were determined and described in Section 4.5.4 to be a basis for evaluating house free running performance on the basis of thermal comfort.

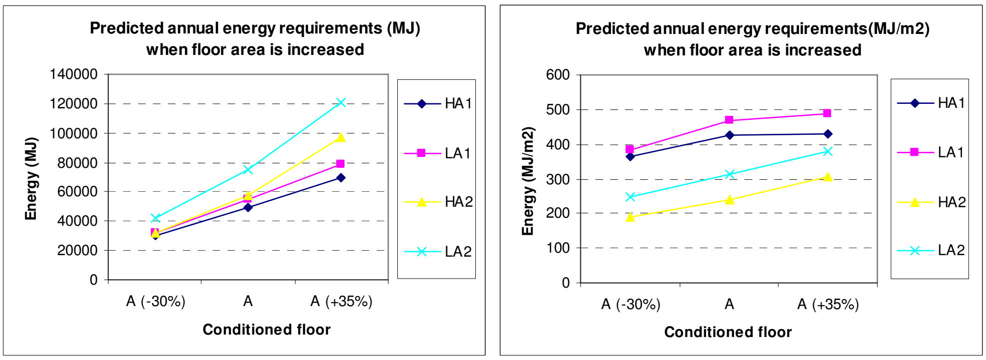
provision of thermal comfort for its occupants, this parameter should be considered as one of the design features, such as the parameters specified in Section 4.6, and not as an inclusive factor in determining an indicator of thermal comfort for performance evaluation. However, if the DDH indicator is to be used as a parameter for predicting energy requirement, the effect of the area of the house should be counted in.

This section makes a comparison between the reliability of the two different indicators employed in this study. Reliability in this context is used to describe the ability of the indicator to consistently rank relative efficiency of architect designed houses. This is examined by employing a simple parametric sensitivity investigation for a sample of each house types (DS and SS) and for the climate of Sydney as a representative moderate climate.

Two typical houses, one single storey (A1) and one double storey (A2) with two different constructions (light weight and heavy weight) were selected from the six typical houses introduced in Section 4.4 for this comparative analysis to evaluate their annual thermal performance when the size of their floor area is changed. First the total size of these base houses was reduced by 30%, and then it was expanded by 35%. No changes were made to their architectural form.

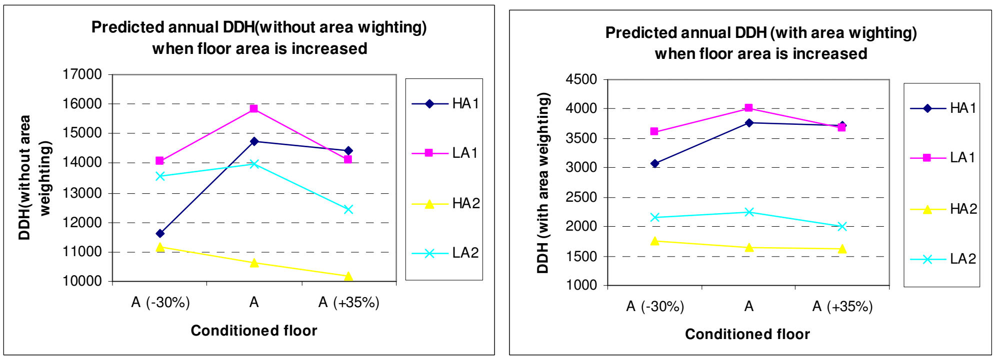
The thermal performance of houses in the conditioned operation mode was evaluated on the basis of energy as a function of MJ and MJ/m^2, and in free running operation mode on the basis of thermal comfort as a function of DDH (with area weighting) and DDH (without area weighting).

The effect of increasing house size on thermal performance on the basis of the two different indicators is shown in Figures 5-1 and 5-2. A comparison between the Figures 5-1 and 5-2 reveals a significant difference between the evaluations of their performance on the basis of energy and of thermal comfort.



a) Energy (MJ) **b) Energy (MJ/m^2)**

Figure 5- 1 The effect of house size on the evaluation of house thermal performance in conditioned mode on the basis of energy



a) DDH (without area weighting) **b) DDH (with area weighting)**

Figure 5- 2 The effect of house size on the evaluation of house thermal performance in free running mode on the basis of thermal comfort

Figure 5-1 shows an increase in the predicted annual energy requirements of both light weight and heavy weight houses when the floor area of houses was increased. This result is the same whether the energy indicator is MJ or MJ/m^2. This observation implies that smaller houses are more energy efficient in design. However, although smaller houses need less energy for space heating and cooling, it should not be concluded that the architectural design of any small house is more efficient. A previous similar study by NatHERS showed that houses with bigger floor areas achieved better results in a rating system than those with a floor area of less than 100m^2 on the basis of (MJ/m^2) (Thomas and Thomas, 2000; Kordjamshidi et al., 2005a). However, when the basis of the rating was changed to MJ, smaller houses performed better. It would appear therefore that the size of the floor area is a key factor in determining the level of efficiency of an architectural design in an energy based rating system. However, a reliable house rating system should be able to address the main aspects of efficiency in architectural design without being strongly dependent on the house size.

Figure 5-2 illustrates the result of an evaluation of the thermal performance of the same houses in free running operation mode on the basis of DDH. This clearly demonstrates that, when assessing comfort conditions, the size of the floor area is not a fundamental determinant of efficient architecture design in an evaluation system. Moreover, adjusting DDH with area weighting does not change that result. For instance, by reducing the floor area of HA2 by 30% it was found that its annual thermal performance in free running operation mode deteriorated only slightly. The deterioration was 5% on the basis of DDH without area weighting and 7.2% with area weighting. On the other hand, when the construction was changed from heavy weight to light weight, the same change to its floor area caused an improvement in annual thermal performance. This implies that the floor area is only one of the parameters affecting the efficiency of an architectural design. Thus it is better for the evaluation of the free running performance of a house to be free of area weighting in order to avoid any discrimination between the efficiency of bigger or smaller houses.

5.2 Base case analysis

In order to understand the components and building parameters of models, an analysis of the simulation results of the base case models is important (Lam and Li, 1999). Base Case Analysis here establishes broad performance characteristics - in this case of typical house types in two identified climates.

The software used for simulation was AccuRate. Some of the limitations of the software in relation to this study are discussed in the relevant sections. The comparative analysis of Sydney and Canberra base cases is described in terms of the following variables that were specified in the previous chapter:

- two different operation modes: conditioned and free running
- two different constructions: heavyweight (HW) and lightweight (LW)
- two seasonal performances: winter and summer. Winter performance refers to heating energy and ‘heating’ degree discomfort hours and summer performance

refers to the cooling energy and 'cooling' degree discomfort hours. The cooling energy load is the sum of sensible and latent cooling energy.

- two building types: single storey (SS) and double storey (DS)
- occupancy scenarios

A number of clear differences emerged in the responses of the typical houses. These are summarised below.

5.2.1 Base case analysis in the Sydney climate

As established in Section 3.4, in this study the range of annual thermal neutrality for the Sydney climate was set on the monthly basis of between 19^o C– 27.3^o C in the free running mode. The thermostat setting used for the simulations was between 20^o C – 24.5^o C for the living zone and 18^o C - 24.5^o C for the bed zone. The typical houses were simulated to predict annual degree discomfort hours and energy requirements on the basis of these settings.

a) Comparison of free running and conditioned modes

Figure 5-3 compares the result of ranking the typical houses in terms of their annual thermal performances in the two different operation modes. The numerical value of energy based thermal performance (MJ/m^2) is intrinsically smaller than that of DDH indicators of their performance in the free running mode; therefore the scale of Degree Discomfort Hours was reduced to 1/10 in this illustration in order to make the range of numerical values of these two indicators comparable at the same level.

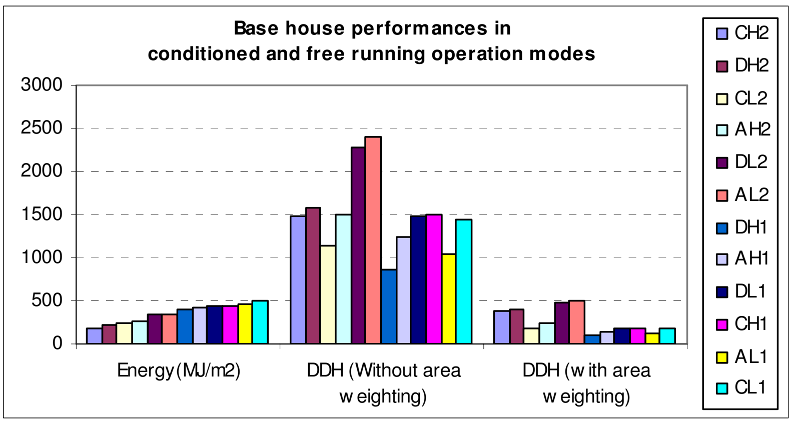


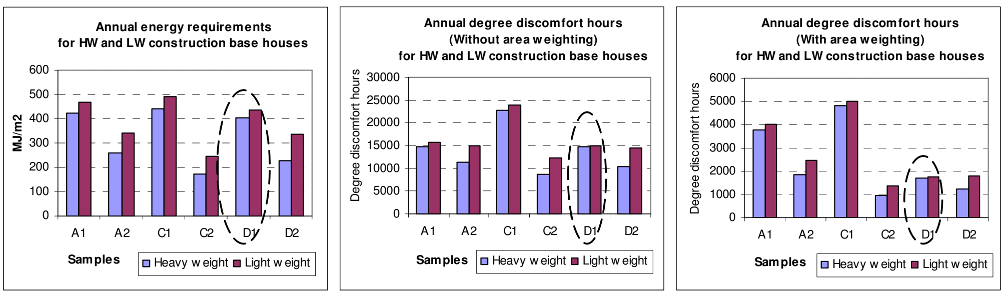
Figure 5- 3 Comparison between ranking typical house performances in conditioned and free running operation modes in the Sydney climate

It was observed that the typical houses in conditioned mode, when ranked in order of annual energy use, assumed the following order CH2, DH2, CL2, AH2, DL2, AL2, DH1, AH1, DL1, CH1, AL1 and CL1. The order differed for these same houses in the free running operation mode. The order for free running mode on the basis of DDH without area weighting was DH1, AL1, CL2, AH1, CL1, CH2, DL1, AH2, CH1, DH2, DL2, AL2. This order differed slightly when area weighting was added to the degree discomfort hours.

The ranking is intended to recognize the most and the least efficiently designed house. However, in the above ranking the most efficient house design for conditioned operation mode was not found to be the same as that for free running operation mode. This suggests there may be a significant difference between efficient architectural design for conditioned houses and that for free running houses and needs to be examined in more detail further in this study.

b) Comparison between heavyweight and lightweight construction

Figure 5 - 4 shows the comparison between the thermal performances of two different construction types for each typical house. It illustrates a superior performance for HW compared to LW construction, whether houses were in conditioned or free running operation mode. However in one case, (D1), which is circled in the figures, there was an insignificant difference (about 2%) in annual thermal performance in the two constructions in free running mode. As the base samples were completely different in their architectural plan design, the above observation implies that, depending on the architectural design, LW construction could be an appropriate response to the need to provide energy efficiency, particularly in free running operation mode.

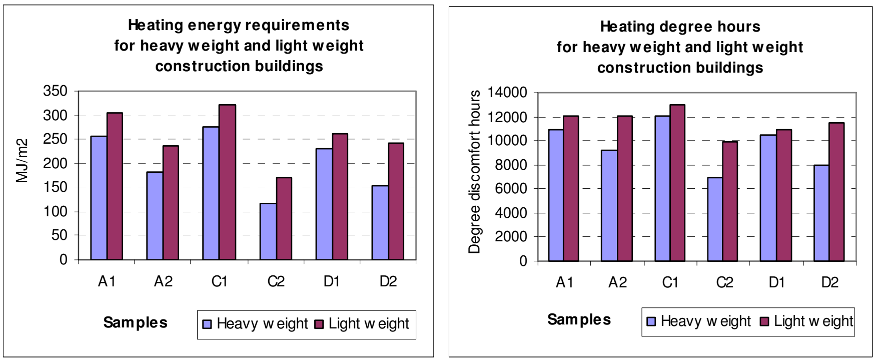


a) Energy(MJ/m^2)   b) DDH(without area weighting)   c) DDH(with area weighting)

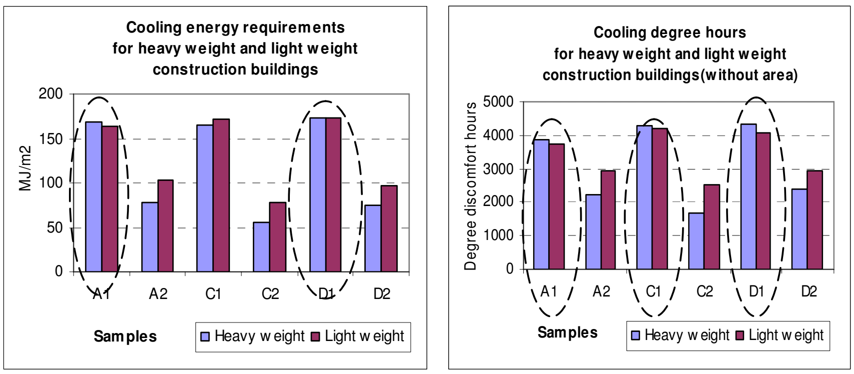
Figure 5- 4 Comparison between the performance of HW and LW constructions of typical base houses in the Sydney climate

c) A comparison of seasonal performance

An investigation of the seasonal performance of typical houses indicated that HW construction always achieved better thermal behaviour in cold months, whether for conditioned or free running operation use. This situation is depicted in Figure 5-5 (a), which illustrates comparisons between the winter performances of typical houses with different construction. On the other hand, in some cases LW houses achieved slightly better summer performance. These samples are circled in Figure 5-5(b). This result lends some qualified support to the claims that LW buildings are a more appropriate response to tropical climates such as in Darwin (Walsh, 1982).



a) Winter performance



b) Summer performance

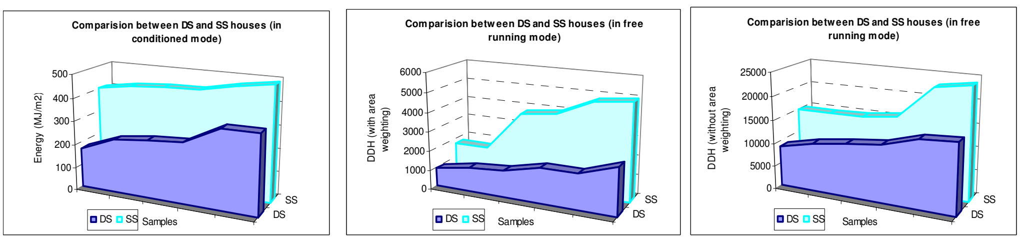
Figure 5- 5 Comparison of base houses seasonal performance for HW and LW construction in the Sydney climate

d) A comparison between house types

Comparisons between the predicted thermal performance of double storey and single storey houses are shown in Figure 5-6 (a, b & c) for both house operation modes. The figures compare the range of numerical values of the thermal performance of DS houses with those of SS houses. They demonstrate generally better annual performance for DS houses, as the range of predicted energy requirement and DDH for these houses is less than that for SS houses. Two main factors for this phenomenon are the external surface ratio and the design type.

The proportion of external area to plan area or volume of DS houses is smaller than in SS with a similar total area in plan. This results in lower heat transfer between the interior and exterior in a DS house than in a SS house. In conditioned houses this reduces the energy requirement for maintaining indoor thermal comfort. Figure 5-6 (a) gives supportive evidence, with the average predicted energy requirement for the six typical DS houses being 40% less than that for the six typical SS houses.

Another reason for DS houses performing better is a particular design feature of DS houses in this study, namely that the bedrooms are all located above the living spaces. This effectively increases the *isolation* of the living zones which are occupied over the day. Therefore there is no direct heat transference through the roof between living zones (LZ) and the outside environment during the time of occupation. This factor results in a slight reduction in the 'heating' degree hours and heating energy during cold months. Since living zones are not directly affected by the impact of solar radiation through the roof during the hot months, the 'cooling' degree hours and amount of cooling energy required are also considerably decreased. A DS building's potential to reduce both seasonal degree discomfort hours and energy requirements therefore makes it a suitable design for both hot and cold climates.

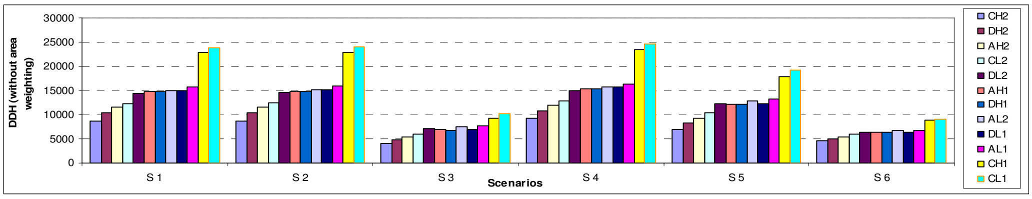


a) Conditioned mode (MJ/m^2), b) Free running (DDH with area weighting), c)Free running(DDH without area weighting)

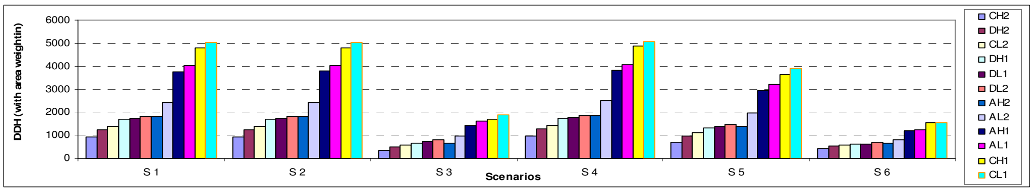
Figure 5- 6 The range of predicted annual energy requirements and degree discomfort hours among SS and DS in the Sydney climate

e) A comparison between multiple occupancy scenarios

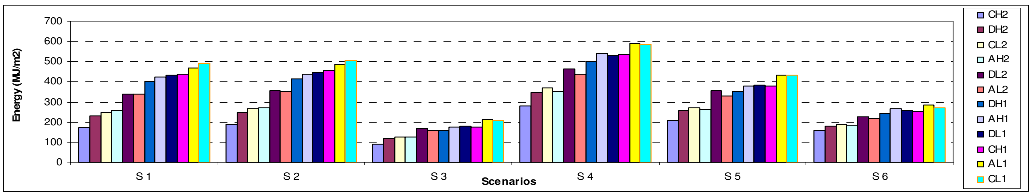
Figures 5 -7 (a & b & c) compare the order of typical houses as the function of three different indicators for the six different occupancy scenarios which were defined in Section 4.5.1.1. It illustrates that when houses were ranked in order on the basis of their performance for the first occupancy scenario, this ranking was not exactly the same as in other occupancy scenarios. This observation was similar, whether the indicator of free running performance was integrated with area weighting or not; and was also the same for both house operation modes. It is worth noting that these slight changes might be more significant, particularly for ranking free running performance, if the software were flexible in dealing with occupancy scenarios. As described in Section 4.2.1.1, AccuRate software does not permit for flexible change in opening and closing windows, blinds and curtains, thus ineffectively dealing with necessary variables corresponding to whether a house is occupied or not.



a) Free running performance (DDH without area weighting)



b) Free running performance (DDH with area weighting)



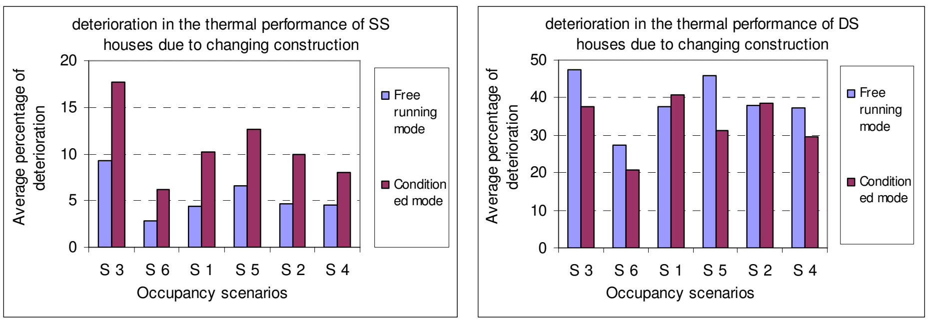
c) Conditioned performance on the basis of energy (MJ/m^2)

Figure 5- 7 Comparison between rankings of the free running performance of typical houses for six occupancy scenarios

It was assumed that, depending on the occupancy scenario, a house with LW construction could achieve a better thermal performance than that house with HW construction. However each typical house with HW construction showed superior performance for all occupancy scenarios. The difference between the predicted values depends on the occupancy scenario and house operation mode.

Figure 5-8 compares the average deterioration in the predicted thermal performance of houses in different operation modes in response to changes in their construction from HW to LW. It separates the SS houses from DS houses since the range of thermal performance of these two groups was significantly different and aggregating all of them could have masked some interesting findings. The figure shows that SS houses in conditioned mode were more sensitive to changes in construction than in free running operation mode. This phenomenon was expected because of greater heat transfer in LW houses than in HW houses, while reducing heat transfer in conditioned mode is an important factor in reducing energy requirements.

The projected deterioration in the thermal performance of DS houses in response to changing their construction from HW to LW was greater in free running operation mode than in conditioned operation mode. This phenomenon is likely to be due to the fact that there is less external surface in DS than SS houses, and because of the design type, as discussed in Section 5.2.1(d).



a) Single Storey houses **b) Double Storey houses**

Figure 5- 8 Comparison between average deterioration in the thermal performance of typical houses in response to changing their construction from HW to LW in different operation modes

From Figure 5-8 it can also be seen that for both house operation modes little deterioration occurred in the thermal performance of houses for 'Scenario 6' and significant deterioration occurred for 'Scenario 3'. The specification for the occupancy scenario (see Section 4.5.1.1) shows that 'Occupancy Scenario 3' is the one with *less* duration of occupation, during which the living zone is occupied in the evening between 6 pm to midnight and the bed zone is occupied for six hours during bed time. Comparing this scenario with 'Scenario 6', in which the living zone is not occupied as in Scenario 3, has implications for the importance of the thermal performance of a house during the evening. It suggests that the *duration* of occupation in a house is not the only important parameter in dealing with occupancy scenarios in an accurate rating scheme. It would appear that *the time of occupation* (not *length* of occupation) is the main variable contributing to the variation and consequently the evaluation of a house thermal performance. However this factor is not explicitly accounted for in the occupancy scenario of the National House Energy Rating Scheme (NatHERS) in Australia.

5.2.2 Base case analysis in the Canberra climate

The range of thermal neutrality for the Canberra climate was set on the monthly basis of between 16.7^{o} C – 26.3^{o} C for free running buildings. The range for thermostat settings in conditioned buildings was between 20^{o} C – 24^{o} C for the living zone. As stated before in Section 4.5.3, the lower band was 18^{o} C for heating during bedtime in the bed zone.

a) Comparison of free running and conditioned modes

The result of the simulations by which the annual thermal performance of the houses was predicted, is presented for the Canberra climate in Figure 5-9. It compares the rank order of typical houses when their annual thermal performances were evaluated in conditioned mode on the basis of energy use against their annual thermal performance in the free running mode on the basis of degree discomfort hours. The scale of the graphs for the free running measurements has been reduced to 1/10 as described in Section 5.2.1 (a).

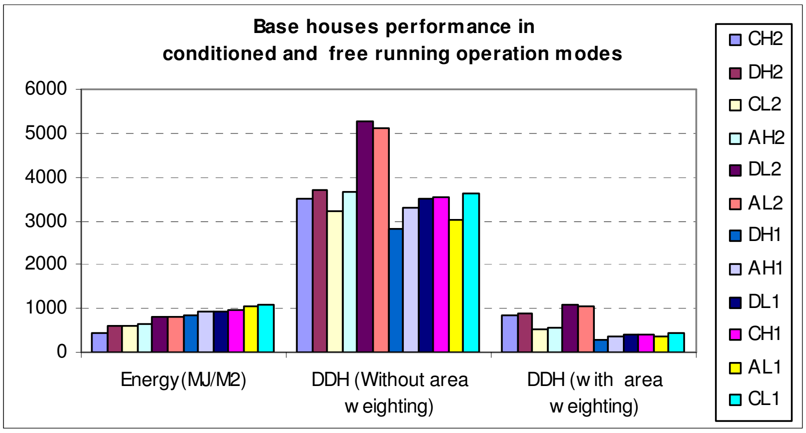


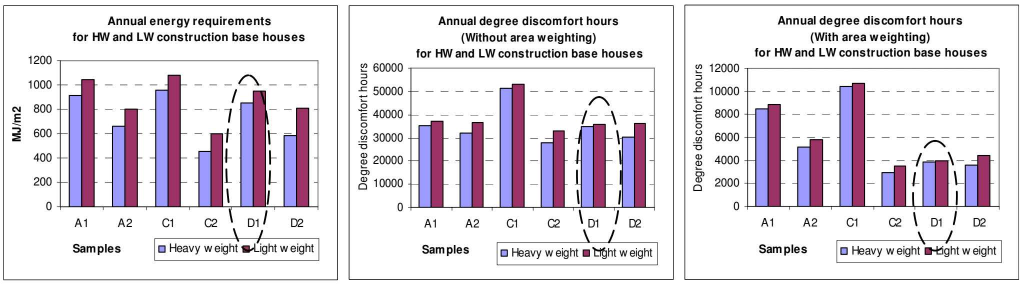
Figure 5- 9 A Comparison between base house performances in conditioned and free running operation modes in the Canberra climate

It was found that when the houses in conditioned mode were ranked in order, this ranking did not produce the same order as for free running houses.

This result, which was observed previously for the Sydney climate, reported in Section 5.2.1, supports the contention which was argued in Section 3.5, that the result of an evaluation of a building performance in the conditioned mode may differ from that in the free running mode. It suggests that there is no reliable reason for an efficient conditioned building to have a comparably good performance in its free running operation mode. A free running rating for dwellings may therefore be quite different from a rating in the conditioned mode. However more investigations are required to demonstrate differences between efficient designs for free running and conditioned houses; and this will be tested through parametric sensitivity analysis and multivariate regression analysis in Chapters 6 and 7.

b) Comparison between heavyweight and lightweight construction

Overall, typical houses presented better thermal behaviour when simulated in HW than in LW construction in the Canberra climate. However, as observed in the results of simulations for the Sydney climate, there is one case (D1) which showed less deterioration (about 3%) in its annual thermal performance when changed from HW to LW in the free running operation mode. This situation is illustrated in Figure 5-10. It implies that although Canberra has a more severe winter than Sydney, the thermal performance of a LW house can be improved in the free running operation mode in the former by employing appropriate architectural design. The result supports the case for architectural design for naturally ventilated LW buildings in moderate climates.

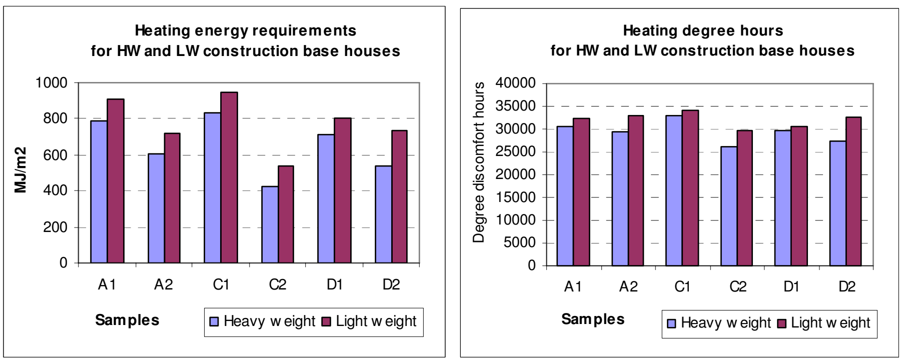


a) Energy(MJ/m^2) **b) DDH(without area weighting)** **c) DDH(with area weighting)**

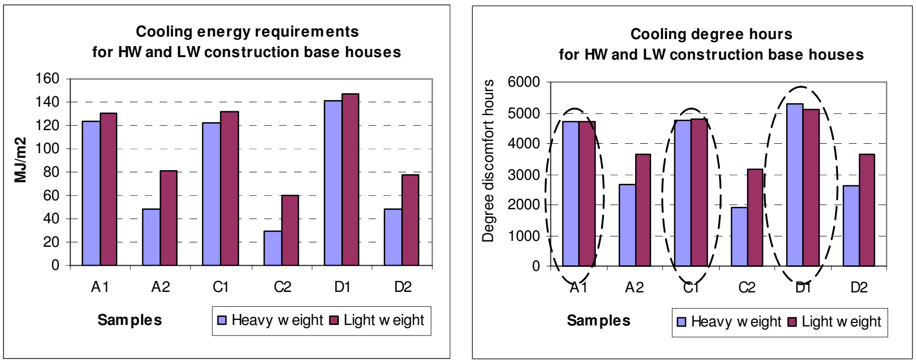
Figure 5- 10 Comparison between the performance of HW and LW constructions of typical base houses in the Canberra climate

c) A comparison of seasonal performance requirements

Comparisons of seasonal performances between the typical houses are depicted in Figure 5-11 for cold months (a) and warm months (b). The figure shows that HW houses achieved better thermal performance in both seasons and for both operation modes than the LW houses. However there was no significant difference between the summer performances of these two construction types for single storey houses in the free running operation mode. This indicates that the warm season behaviour is similar to that in the Sydney climate in the free running mode.



a) Winter performance

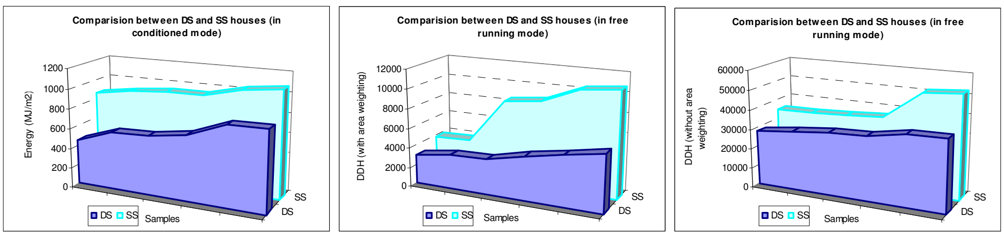


b) Summer performance

Figure 5- 11 Comparison of base house seasonal performances for HW and LW construction in the Canberra climate

d) A comparison between house types

The range of predicted annual energy requirements and degree discomfort hours among the typical DS and SS houses is shown in Figure 5-12. Double Storey houses in this climate achieved better thermal performance, for the same reasons as mentioned in Section 5.2.1 (d). The implication from both of these observations is that in order to obtain an accurate evaluation system of thermal performance that avoids undervaluing SS houses, it may be better to separate DS houses from SS houses.



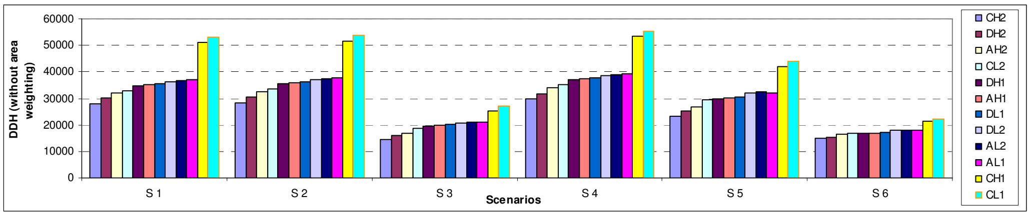
a) Conditioned mode (MJ/m^2), b)Free running (DDH with area weighting), c)Free running(DDH without area weighting)

Figure 5- 12 The range of predicted annual energy requirement and degree discomfort hours among SS and DS in the Canberra climate

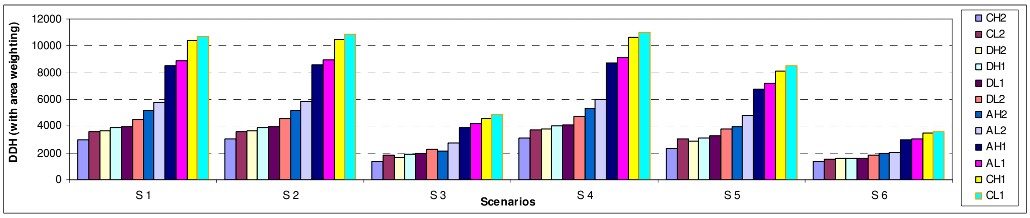
e) A comparison between multiple occupancy scenarios

Figure 5 - 13 (a & b & c) compares the ranking of typical houses on the basis of their thermal performance for the six different occupancy scenarios. As was observed for the Sydney climate, the figure demonstrates a slight dissimilarity between the rankings of the houses in the different scenarios. The dissimilarity occurred in both the conditioned and the free running operation mode. However it was less noticeable in the free running

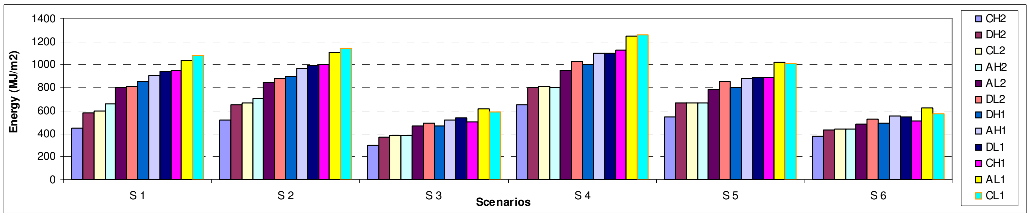
operation mode probably related to the limitations of the software in dealing with the physical parameters correlating with occupancy.



a) Free running performance (DDH without area weighting)



b) Free running performance (DDH with area weighting)



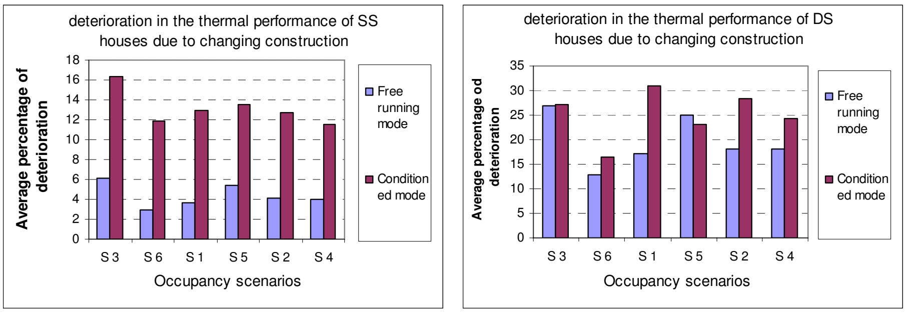
c) Conditioned performance on the basis of energy (MJ/m^2)

Figure 5- 13 Comparison between rankings of the free running performance of the typical houses for six occupancy scenarios

Houses with HW construction gave a better performance than those with LW construction for all occupancy scenarios. Apparent deterioration in the thermal performance of the houses when changed from HW to LW varied depending on the occupancy scenario and the house operation mode. This situation can be seen in the illustrations of Figure 5-14. The figures compare the average deterioration in the predicted thermal performance of the typical SS houses (a) and DS houses in different operation modes when changed from HW to LW.

This observation not only highlights the importance of the occupancy scenario in making a performance assessment, but also demonstrates that the responses of house performance in the multiple occupancy scenarios will not be the same for different house operation modes.

It can be seen from Figure 5-14 that apparent deterioration in the thermal performance of houses, as a result of changed construction, was mostly greater in the conditioned mode for both house types. However, this situation was more noticeable in SS houses because of greater external surface and the design feature described before.



a) Single Storey houses **b) Double Storey houses**

Figure 5- 14 Comparison between average deterioration on the thermal performance of typical houses in response to changing their construction from HW to LW in different operation modes

5. 3 Conclusion

The following conclusions can be drawn from the outcomes of the simulations described in this chapter:

- The evaluation of the thermal performance of houses in free running mode and on the basis of thermal comfort appears to be reliable for the purpose of rating schemes so that the aspects of efficient architecture design can be addressed and be improved through this sort of evaluation.
- No significant difference was observed between the evaluation of buildings on the basis of DDH with and without area weighting. Therefore, calculating DDH without area weighting is more likely to be appropriate for the purpose of rating, to avoid any discrimination between bigger and smaller houses.
- Rating houses in the free running mode produces different results from rating such houses in conditioned operation mode. This means that an efficient design for a free running house may differ significantly from an efficient design for that house in conditioned mode. This is a preliminary confirmation of the major hypothesis and will be investigated in the parametric sensitivity analysis in the next chapter.
- Houses with heavy weight construction often present better thermal performance than those same houses with light weight construction in temperate climates;

however, light weight houses are amenable to provide a comparable thermal performance to heavy weight houses, particularly in free running operation mode. LW construction could therefore be an appropriate response to the need for efficient design for free running houses in a moderate climate. To confirm this supposition, it would need to be investigated for other climate types as well. This study has concentrated only on a moderate climate.

- Lightweight houses are more likely to present better summer performance than houses with heavyweight construction in the free running operation mode, particularly when a house is single storey. From this result it would appear that lightweight houses are suitable for warm climates if the houses are to be primarily used in free running mode.
- Since the range of numerical values of the thermal performance of double storey houses differs considerably from that of single storey houses, it may be better to separate DS houses from SS houses for an accurate evaluation system of houses thermal performance, in order to avoid undervaluing SS houses.
- The sensitivity of the thermal performance of typical houses in response to multiple occupancy scenarios depended on the house operation mode. However, owing to the limitations of the software, this study does not fully investigate this variable as a part of a proposed revised rating framework.

Chapter 6

Parametric sensitivity analysis

The purpose of this chapter is principally to examine the hypothesis that free-running and conditioned houses have unequal responses to variations in design features applied for energy efficient architecture design because of their different thermal characteristics. This was necessary as a preliminary step for developing a new house rating scheme, which was defined as a main objective (See Section 1.4).

It reports on the parametric sensitivity analysis, comparing the results of the simulations with variations of design features, which were specified in Section 4.6, in conditioned and free running houses for the two climates of Sydney and Canberra. Simulations were conducted for the first occupancy scenario which was specified in Section 4.5.1.1. The results for other occupancy scenarios are not reported here because restrictions of the software (See Section 4.2.1.1) masked the relevant effects of variations in the occupancy scenario.

As mentioned in Section 4.6, the effect of each of the parameters was tested separately and is reported for the purpose of this study. The combined effects are not reported. In a real situation the effect of each parameter is likely to modify the impact of the other parameters, and so a designer would need to consider this in designing an energy efficient building. However the purpose of this study is not to "propose an efficient building design", and the sensitivity analysis is only intended to function as a partial test of the hypothesis, as described in the methodology. While further analysis to consider the effect of a combination of the mentioned parameters is beyond the limitations of this study, this effect should be considered in any future research that has the purpose of perhaps producing explicit guidelines for an efficient building design.

The findings are divided into two sections for the climates of Sydney and Canberra. Under each section the outcomes of simulations are comparatively reported in the following four categories for each parameter.

1) house operation mode (free running / conditioned)
2) house construction (heavyweight (HW)/ lightweight(LW)

3) house type (single storey (SS)/ double storey (DS))
4) seasonal performances (summer/winter)

Observations are reported based on the absolute value or relative (percentage) changes in the predicted thermal performance of base cases resulting from a modification on one of their design parameters. As the main concern of the comparisons is to find any difference between the thermal performances of houses in each of these categories, differences are noted even if the numerical value of changes in the thermal performance may not be significant.

The order of the above categories in reporting the findings is changed depending on the importance of the observation in each category. Priority is given to any factor which may have the potential to explain the reason for any unexpected observation in the first category, namely a variation in thermal performance in different operation modes. It should be noted that this chapter does not attempt to be comprehensive in reporting an explanation for any interesting or unexpected observations of thermal performance. In some instances such outcomes may need to be investigated through further study.

Area weighting for Degree Discomfort Hours

As previously defined in Section 4.5.4, thermal performance of free running houses was evaluated on the basis of Degree Discomfort Hours (DDH), with and without area weighting. However as noted in Chapter 5, with respect to the base case analysis, the sensitivity of patterns which were found in parametric sensitivity analysis of the free running house performance was relatively similar for both treatments of DDH (with or without weighting). Therefore, the result of an evaluation of the thermal performance of free running houses in terms of DDH with area weighting is not reported here.

House construction (HW/ LW)

The effect of each variable on the thermal performance of houses was compared for HW and LW houses to seek any significant difference between the effects of each variable on the thermal performance of these two constructions in different operation mode. (See objective in Section 1.3).

House type (SS/ DS)

Comparisons were made between the thermal performances of the two house types, Single Storey and Double Storey, to investigate any significant differences. The comparison was important in this study since it could lead to recommendation separate these two house types in a new rating system. (See Sections 5.2.1(d) and 5.4)

Seasonal performance

As noted before, seasonal thermal performance is routinely aggregated to form an indicator of annual thermal performance in the present rating schemes. However this aggregation can hide the reasons for different performances observed in different operation modes of the house. Thus seasonal performances have been analysed in more detail to investigate the reasons for different effects of any variable on the thermal performance of houses in different operation modes. Detailed graphs showing the seasonal performances are given in Appendix D to supplement the summary report in this chapter.

In each section of this chapter the effect of each variable on the thermal performance of all typical houses with different constructions (12 base models) is depicted in two graphs for the two different operation modes. Each graph makes a comparison between the sensitivity of thermal performance of all typical base houses in response to altering one design parameter. These initial graphs are referred to in the notes on all four categories outlined above. Gathering all samples in one graph may have the effect of masking visual clues regarding small fluctuations in the thermal performance of samples because the scale of variations for each different mode, SS, DS, HW and LW is different. Where necessary, any significant change is described in the text and is highlighted in a separate graph for clarification.

6.1. Thermal performance of dwellings in the Sydney climate

The following section reports the result of the simulations for the Sydney climate.

6.1.1 Ceiling insulation

Free running and conditioned mode

In both free running and conditioned mode the thermal performance was found to be improved by the use of bulk ceiling insulation refer to Figure 6-1. The addition of R2 insulation to the ceiling of a typical house gave an average reduction in annual energy requirements of 42.5%. In free running mode, the annual degree discomfort hours was decreased by 32.9%. The application of insulation greater than R2 produced a minimal change in the thermal performance of both house modes. Employing ceiling insulation as a technique for improving design efficiency, therefore, creates a greater reduction in annual energy requirements in conditioned houses than it produces a decrease in the annual discomfort degree hours in free running houses.

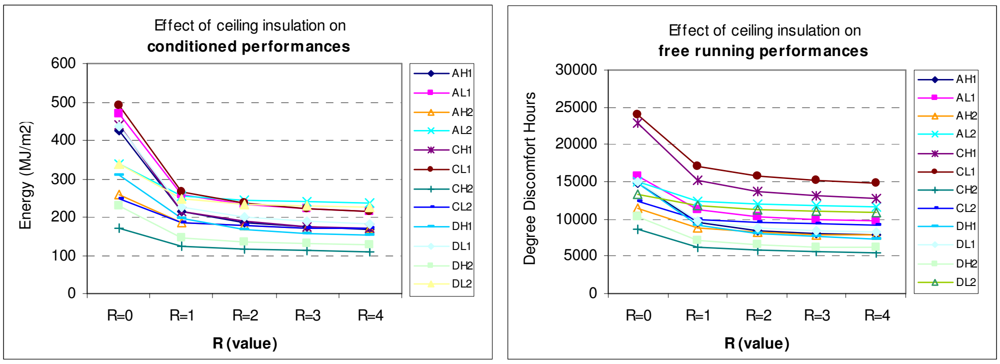


Figure 6- 1 Projected effect of ceiling insulation on the annual thermal performances of typical houses in conditioned and free running operation modes in the Sydney climate

Seasonal performance

Ceiling insulation improved both summer and winter performance in both operation modes. This is illustrated in Figure D-1 and D-2, Appendix D. A greater improvement in the seasonal performance of houses in conditioned mode was found when R2.0 insulation was added to the ceiling, with an average improvement of 41% to 44% respectively in both summer and winter performances. In free running mode the improvements were 32% and 42% respectively. This indicates that the seasonal performance of houses in the conditioned mode is more sensitive to any change in ceiling insulation.

Heavyweight and Lightweight

The improvement in thermal performance was greater for HW houses than for the same houses with LW construction. The addition of R.3 insulation to the ceiling produced a greater improvement in free running mode (10%) than in conditioned mode (8%) in HW houses.

Single Storey and Double Storey

Although adding ceiling insulation affected the thermal performance of both SS and DS houses, this effect was greater in SS houses, whether the house was in free running or conditioned mode. The application of R3 insulation improved the annual thermal performance of SS houses approximately 1.5 times more than in DS houses in both modes. The main reason for this appears to be the typical placement of the bed zone above the living zone in the DS houses. As previously noted this particular arrangement substantially *isolates* the living zone ceiling from the outdoor environment. Accordingly, heat transfer between the living zone and the outdoor environment through the ceiling is reduced and ceiling insulation does not change this phenomenon. Since the thermal performance of the living zone (in DS) is not greatly sensitive to ceiling insulation, and the sensitivity of a house's thermal performance depends to a great extent on the sensitivity of its living zone, the thermal performance of the DS houses do not greatly change when an insulation layer is added to the ceilings.

This result may differ in other occupancy scenarios, depending on the number of hours that the living zone is occupied. It could also change if the location of the living zone was transferred from the ground floor to the first floor. However this interpretation would require an examination by further simulation of other occupancy scenarios and other house types, which is beyond the scope of this study.

6.1.2 Wall insulation

Wall insulation has been nominated as a useful technique for improving the thermal performance of all construction types in conditioned mode in the Sydney climate (Willrath, 1998). However this study has found that while adding insulation would enhance the performance of a conditioned house, this was not the case for some houses in free running mode.

Free running and conditioned mode

Figure 6-2 depicts a situation in which an increase in wall insulation would result in:

- a decrease on annual energy requirements,
- a general decrease on annual degree discomfort hours,
- an increase on annual degree discomfort hours for single storey heavyweight houses.

The addition of R2 insulation to the external walls of typical houses resulted in an average 14% improvement in their annual thermal performance in conditioned mode, but the improvement was only an average of 6.9% for all houses in free running mode. This average improvement does not include Single Storey houses with heavyweight construction as this group of simulated models appeared to be an exception to this general observation.

Heavyweight, single storey houses presented a slight deterioration in their free running annual thermal performances (0.8%) when insulation was added to their external wall. The reason for this overall deterioration is apparent when their seasonal performances are examined, and is discussed in more detail in the relevant section below.

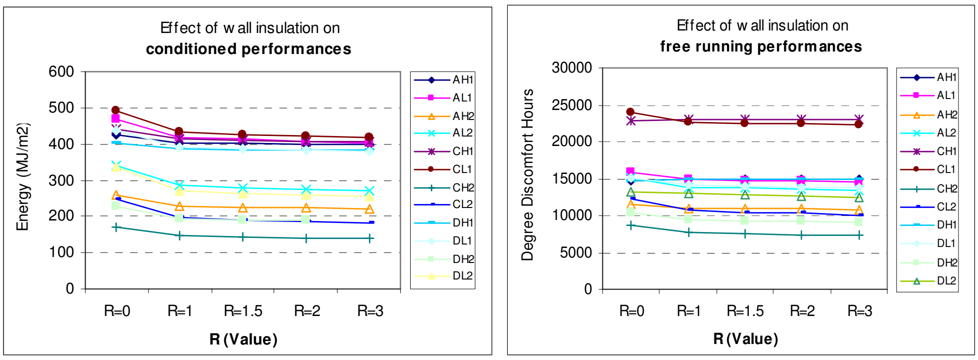


Figure 6- 2 Projected effect of wall insulation on the annual thermal performances of typical houses in conditioned and free running operation modes in the Sydney climate

Note: the following comparisons between SS & DS and HW& LW do not include the thermal behaviour of SS HW houses.

Single Storey and Double Storey

DS houses achieved a greater improvement in their thermal performance when insulation was added to their external walls than did SS houses. In free running mode the improvement was an average of 7% more in DS houses; and in conditioned mode it was about 10%. This is shown in Figure 6-3.

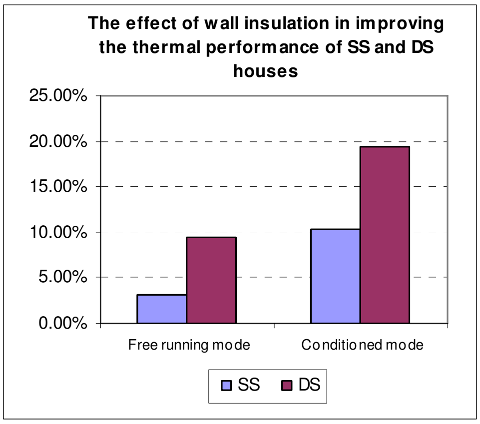


Figure 6- 3 A Comparison between the average effect of wall insulation in improving the thermal performance of Single Storey (SS) and Double Storey (DS) houses in the Sydney climate

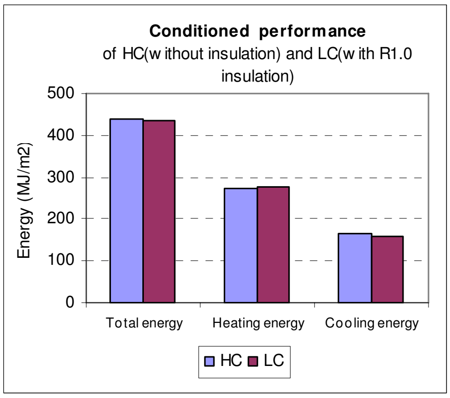
A reason for the greater improvement in DS houses seems to be the replacement of the bed zone above the living zone, which performs as an insulation layer above the living zone (above its ceiling) in that typical design of DS houses. By insulating external walls, all external sides of a living zone in a DS house appear to be insulated, while in SS house there is more heat transfer through the ceiling. Although the situation of the bed zone in both house types is similar, the thermal performance of a living zone is more important in evaluating annual thermal performance of a house based on the first occupancy scenario, in which 75% of the time the living zone is occupied.

Heavyweight and Lightweight

The typical houses with lightweight construction achieved more improvement in their thermal performances than those with heavyweight construction in response to the addition of insulation to the external walls. Greater improvement was observed in both conditioned and free running modes. With the addition of R.2 insulation, typical LW houses presented an average of 8.7% reduction in annual degree discomfort hours and 17.5% reduction in annual energy requirements. HW houses showed an average of 4.6% reduction in annual DDH and 11.3% reduction in energy requirements.

When R1.0 insulation was added to external walls of LW single storey houses, they achieved an aggregate thermal performance equivalent to that of HW SS ones without insulation (Figure 6-4). This finding therefore seems to confirm the suggestion in

Chapter 2 that LW SS buildings are able to achieve annual thermal performance comparable to those with HW construction in the Sydney climate.



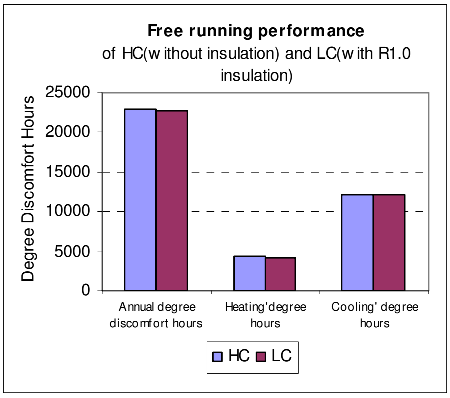


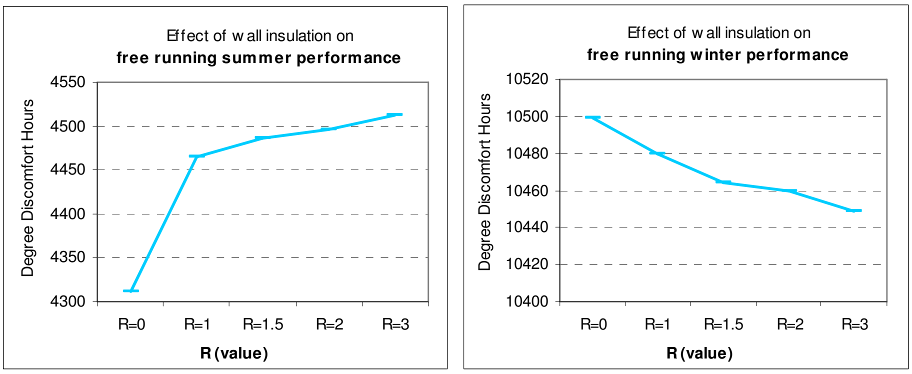
Figure 6- 4 Comparison of the thermal performance of a HW SS house in the Sydney climate without an insulation (HC) layer and a LW house with R.1 insulation in its external walls (LC)

Seasonal performance

The effect of wall insulation on the seasonal performance of typical houses is illustrated in Figure D-3 and D-4, Attachment D.

As previously noted, for typical houses in conditioned mode adding insulation to external walls resulted in a predicted reduction of heating and cooling energy requirements. However, the summer performance of single storey houses with heavyweight construction appeared to be unresponsive to wall insulation. This observation implies that wall insulation would not be a useful technique to improve the thermal performance of single storey detached dwellings in warmer climates. This observation would need to be tested by repeating the simulations for warmer climates, but that is beyond the scope of this study.

Also as noted previously, external wall insulation improved the free running winter performance of typical houses, with the exception of single storey, heavyweight houses. The SS, HW winter performances were found to be unresponsive to wall insulation (an average of 0.2% change), while the summer performances deteriorated by about 2%. Thus the slight deterioration that was observed in their annual performance in response to increased insulation would appear to be the result of degradation in their summer performances. This situation is depicted in Figure 6-5 for a typical SS HW house.



a) Summer performance **b) Winter performance**

Figure 6- 5 Projected effect of wall insulation on the free running seasonal performance of a SS HW house in the Sydney climate

6.1.3 Floor insulation

A slab on the ground floor without carpet gives the best performance in the Sydney climate (Willrath, 1998). However in the housing market the majority of the floor area is usually covered by carpet. In this study, therefore, in order to simulate typical houses, slab floors in heavyweight houses were simulated as covered by carpet. For HW houses an insulation layer was added under the slab floor.

The timber floor of typical houses with LW construction was suspended 60cm above the ground. This type of floor was not covered by carpet, and insulation for these cases was added under the suspended floor.

Free running and conditioned mode

In free running mode adding a level of insulation under the ground floor of the typical houses caused a slight degradation in annual thermal performances of all of them, whereas in conditioned mode, depending on the type and construction of houses, this addition produced varying changes.

As shown in Figure 6-6, adding R1 insulation resulted on average in 3.9% deterioration in the annual free running performance of the typical houses. In the conditioned mode this addition produced two different patterns of annual energy requirement for SS and DS houses, and will be described in the following section. It is worth noting that in both house modes a higher level of insulation produced a minimal change of less than 1% in their annual thermal performances.

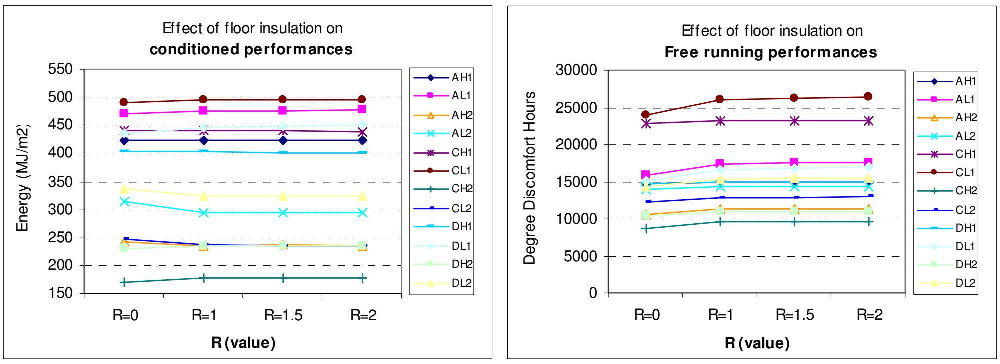


Figure 6- 6 Projected effect of floor insulation on the annual thermal performances of typical houses in conditioned and free running operation modes in the Sydney climate

Heavyweight and Lightweight

Overall patterns of thermal performance of the typical HW houses showed no significant sensitivity toward the addition of under-floor R1.0 insulation. The houses with LW construction achieved a slight improvement on annual thermal performance in the conditioned mode (average 1.15%), but an apparent deterioration in their free running performance (average 6.5%). Possible reasons for the latter unexpected observation are explored in the following section.

Single Storey and Double Storey

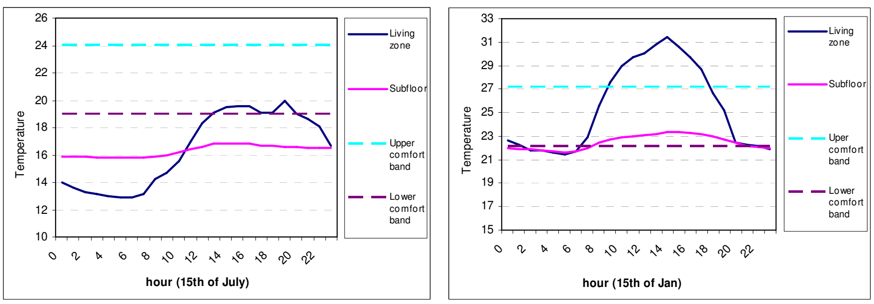
In the free running operation mode no significant difference was observed between sensitivity in thermal performance of DS and SS houses in response to the insertion of under-floor insulation. In the conditioned operation mode a marginal deterioration (0.8%) was observed in response to the addition of R.1 insulation under the floor, while the same change made a slightly greater (2.4%) improvement in the performance of DS houses. The different effect of floor insulation appears to be attributable to more improvement in the winter performance of DS houses and will be described in the following.

Seasonal performances

The effectiveness of floor insulation was investigated in the seasonal behaviour of the typical houses. Figure D-5 and D-6 in Appendix D depicts the patterns of seasonal behaviour of the houses in response to the addition of three different levels of under floor insulation.

The insertion of an R.1 insulation layer under the floor of uninsulated typical houses resulted in an apparent deterioration in both seasonal performances in the free running mode, with an average of 8.3% and 5.3% deterioration in the summer and winter performances respectively. The responses in the winter performance become more interesting when we note that deterioration in the winter performance of LW houses (5.8%) was significantly more than that in HW houses (0.014%). A reason for this phenomenon would appear to be the effect of those times when the temperature in the suspended floor zone is higher than the indoor temperature of spaces on the ground floor such as the living zone. In this situation, insulation reduces the benefits of subfloor temperatures by reducing heat transfer between subfloor and ground floor. The likelihood of this explanation being correct was tentatively confirmed by examining the zone temperatures from the simulation outputs for relevant day[29]. This finding points to the inapplicability of floor insulation to improving the thermal performance of a free running house.

[29]A comparison was made between the hourly temperature of the living zone and the suspended floor for one of the LW typical houses in the free running operation mode when R2 insulation was added under the suspended floor. The following figure shows the hourly zone temperature for a warm and cold day respectively on the 15th of January and July. Both figures illustrate that the temperature of the suspended floor zone is closer to thermal comfort temperature than the temperature of the living zone for more hours of the day. Floor insulation restricts heat transfer between these two zones and therefore in effect reduces the benefits of a suspended floor for a free running building in such ambient conditions.



Comparison between temperature of living zone and sub floor zone of a lightweight house for 15th July and January in the Sydney climate

The winter performance of a conditioned house can be improved overall by insulating its floor. Applying R.1 insulation under the floors of typical houses in conditioned mode resulted in:

- an average of 2.8% reduction in their heating energy requirement. The reduction in DS houses (4.9%) was greater than that in SS houses (0.8%).
- an average of 3.5% increase in their cooling energy requirement. This was the same for both SS and DS houses.

Therefore the observed improvement in the annual thermal performance of DS houses was because the improvement in the winter performance of these houses outweighed the deterioration in their summer performances.

6.1.4 Wall colour

External surface colour has a significant effect on the thermal performance of buildings. This is shown in a theoretical and experimental study in Bansal et al (1992). Dark and light colours respectively reduce under-heating and overheating. The impact of external colour on the annual thermal behaviour of a building correlates with the climate. That is to say, a light external colour is effective in reducing cooling energy requirements in a warm climate. In Sydney, when dark external colours were replaced by light colours, the annual energy requirement of an uninsulated house with standard mass[30] was reduced by 13% (Willrath, 1998). Though the light external colour enhanced the annual thermal performance of a conditioned house, this colour did not cause an enhancement in the annual thermal performance of the same house in free running mode. This will be explored in the following.

---

[30] Standard mass refers to a house with brick veneer RFL in external walls, R2.5 in ceiling and no floor insulation.

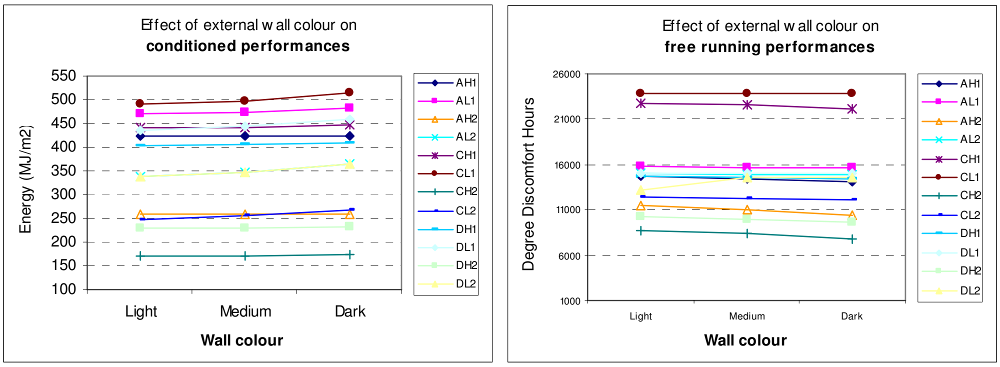


Figure 6- 7 Projected effect of external wall colour on the annual thermal performances of typical houses in conditioned and free running operation modes in the Sydney climate

Free running and conditioned mode

The colour of the external wall had various effects on the thermal performances of houses in different modes. Figure 6-7 clearly demonstrates these differences. When light colour on the external wall was replaced by dark colour, an average of 3.5% enhancement occurred in the thermal performances of typical houses in the free running mode. The same change produced an average of 3.6% deterioration in the thermal performance of the houses in the conditioned mode. Seasonal behaviour is likely to be the main reason for this variation.

Seasonal performance

Applying dark colour with 85% absorbance instead of light colour on the external wall improved a house's winter performance and degraded its summer performance in both modes. Figure D-7 and D-8, Appendix 7 illustrates this situation among the typical houses.

The amount of improvement and apparent deterioration in the seasonal performance of an uninsulated house depended on the operation mode. The summer performance was more sensitive to changing external wall colour in the conditioned mode than in the free running mode, whereas the winter performance in free running mode was more sensitive to such changes. By applying a dark instead of light external wall colour, deterioration on the summer performance of houses in conditioned mode was more than that in the free running mode (about 7%). The same change, by contrast, gave slightly more improvement in the winter performance of houses in the free running mode (2%).

The lower degradation in the summer performance of free running houses is related to the capability of such houses to reduce the number of overheating degree hours. The impact of the exterior dark colour is lessened because of the natural ventilation which benefits these houses during hot months. Although this benefit exists in conditioned mode[31], it is not as significant as it is in the free running mode.

The different effects of the external wall colour that are seen in the annual thermal performances are due to the high degradation in its the summer performance in the conditioned mode. This means that advice appropriate for improving the performance of the conditioned houses may not necessarily be applicable in the case of the free running operation mode.

Heavyweight and Lightweight

The impact of external wall colour on the thermal behaviour of a house was related to the construction of the building. HW houses showed more sensitivity to changes in the external colour of the wall in free running mode with the thermal performance improving by 5.8%, while LW houses displayed more sensitivity to the same change in conditioned mode, with a deterioration of 6% in thermal performance. This observation again reinforce that the house operation mode is a significant consideration when making a decision about adopting appropriate advice for efficient architectural design.

Single Store and Double Storey

There was a greater change in the thermal performance of DS houses than in SS houses in response to variation in external wall colour. An average of 6.1% reduction occurred in the heating energy requirement of SS houses with the replacement of a dark colour for a light one, while the reduction was roughly 1.5 times greater (9.2%) in DS houses. This observation was similar whether the houses were in the conditioned or free running operation mode. The reason seems to be due to the typical design of DS houses in this study, as explained previously, for which the effect of any changes on the external wall, such as wall insulation and wall colour, produces more changes in the thermal performance of DS houses.

---

[31] AccuRate software counts the effect of air ventilation for prediction of cooling energy requirement (see Chapter 4 for more clarification)

6.1.5 Roof colour

Absorptance is the thermal property related to material surface and colour. The absorptance of a roof has a considerable effect on energy loads compared to that of external walls (Shariah, Shalabi, Rousan et al., 1998). Givoni (1976) has pointed out that the external surface of the roof is often subject to the largest temperature fluctuations, depending on what type it is and on its external colour. The simulations in this study similarly demonstrated a considerable impact from roof absorptance on the indoor environment, particularly in single storey houses and in conditioned mode.

Free running and conditioned mode

A change in the external roof colour from light (30% absorptance) to dark colour (85% absorptance) degraded a house's annual thermal performance by between 4.5% and 44% for all typical houses in conditioned mode. In free running mode different effects on the annual thermal performance were found, depending on whether the houses were single or double storey (Figure 6-8).

Single Storey and Double Storey

Two different effects were observed among the free running houses from a change in roof colour. The application of a dark colour resulted in a deterioration of 7.4% to 11.7% in SS free running houses. In the performance of DS houses there was a marginal improvement of 3.7%. The reason for this is that in DS houses in this sample, the bed zone is designed to be above the living zone. Because of this, the number of 'cooling degree hours' caused by the effect of solar radiation absorptance on the dark roof is reduced in the living zone. On the other hand, the dark colour advantages DS houses over the cold months by reducing 'heating' degree hours in the bed zone in winter, without affecting over-heating of the living zones during the hot months.

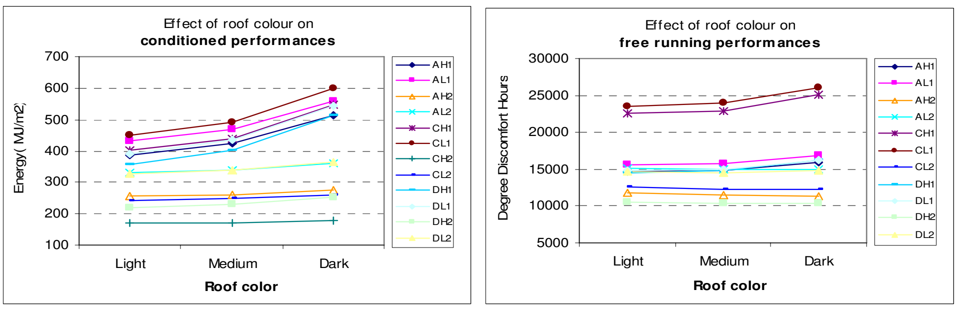


Figure 6- 8 Projected effect of roof colour on the annual thermal performances of typical houses in conditioned and free running operation modes in the Sydney climate

Heavyweight and Lightweight

Typical houses with LW construction in free running mode, showed more sensitivity to external roof colour change in their thermal performance than those houses with HW construction. There was slightly more sensitivity (1%- 3%) in annual thermal performance of LW houses in this mode than in HW houses when light colour was replaced by dark colour. This situation was reversed in the conditioned mode.

Seasonal performance

Figures D-9 and D-10 illustrate a breakdown of the seasonal performance of typical houses in response to the variations in external roof colour. The figures depict an improvement in the winter performances and degradation in the summer performances of houses in both free running and conditioned mode. Free running buildings taking more advantage of natural ventilation have the ability to adjust (reduce) overheating caused by a dark roof colour.

In the Sydney climate, therefore, an appropriate external roof colour seems more important for improving the thermal performance of a conditioned house than for a free running house. However it should not be ignored that in free running mode the DDHs may stay high.

6.1.6 Orientation

A building's orientation to the sun will impact on the house's ability to optimize passive heating and cooling, and natural ventilation. Solar heat gained through the external surface of a building depends on the orientation of the surface (azimuth). The influence of orientation along with its interaction with other building envelope parameters on the indoor temperature are well documented (Givoni, 1976). Orientation, therefore, is an important parameter in an efficient architectural design. The following investigates any difference between the sensitivity of houses' thermal performances in different operation modes in response to changing orientation.

Free running and conditioned

The findings of this study indicate a relatively small variation in the thermal performances of houses in response to changes in its orientation. Figure 6-9 shows the outcomes of changing the orientation by 45^{o} increments (over eight orientations), which produced an average variation of 5% in the annual thermal performance in free running mode, while in conditioned mode the variation was on average 5.5%. The explanation for this small variability is the design of all typical house plans with relatively equally sized windows, which are distributed on all sides.

The variation depends largely on the changes in the thermal performance of the living zone, because this zone is occupied for the most time (18 hours per day) for the first specified occupancy scenario. Therefore to improve the thermal performance of a house, the highest priority would be to optimize the orientation of the living zone.

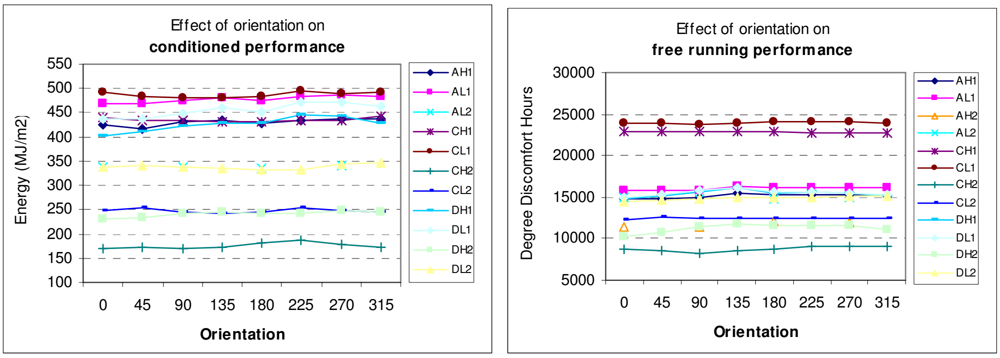


Figure 6- 9 Projected effect of orientation on the annual thermal performances of typical houses in conditioned and free running operation modes in the Sydney climate

Heavyweight and Lightweight

The influence of variations in house orientation on a house with HW construction is greater than its effect on the same house with LW construction, because of the substantial potential of thermal mass to delay transferring heat gains. In response to incrementally rotating the orientation of the typical houses by 45^{o}, the variation in the thermal performances of HW houses was on average 3 times greater than that for houses with LW construction in free running mode, but was only about two times greater in condition mode.

Seasonal performance

A breakdown of seasonal performance in response to variation in orientation is given in Figure D-11 and D-12 Appendix D. It was observed that the impact of orientation on the variation of 'cooling' degree hours and cooling energy (summer performance) was greater than its impact on the variation of 'heating' degree hours and heating energy (winter performance). This observation implies the importance of building orientation to take advantage of wind direction for natural ventilation, particularly for free running buildings, in addition to making use of solar heat gain over winter.

Single Storey and Double Storey

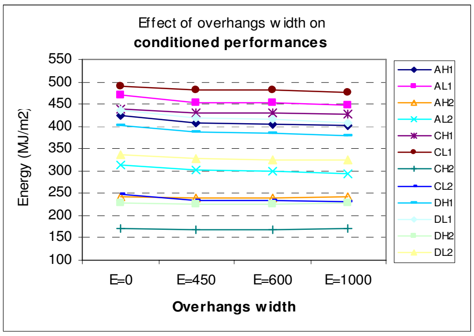
No significant difference was observed between the average changes on the annual thermal performance of DS and SS houses as a result of changing the house orientation. DS houses showed slightly more sensitivity (about1%) to various house orientations in thermal performance than did SS houses in this study. As mentioned before, the thermal performance of a house depends strongly on the thermal performance of the house's living zone. In DS houses the living zones are designed on the ground floor and under the bed zone, and therefore there is no direct heat gain from the roof in this zone. This means that the thermal performance of a DS house is reasonably sensitive to the external wall orientation, whereas the thermal performance of the living zone in the SS houses is significantly affected by the thermal effects of the roof. The fluctuations in the winter performances of DS houses in response to the various orientations depend on the external wall area of the living zone.

6.1.7 Overhangs depth

Solar gain through windows is obviously the largest load component, and window shading can have a significant impact on solar loads. Shading provided by overhangs at the top of windows with no offset distance was studied and its effect on energy and degree discomfort hours was calculated.

Free running and conditioned

Adding an overhang above all windows improved annual thermal performance of the typical houses in conditioned mode. However, this was not the case for the houses in free running mode. The houses presented different patterns of annual thermal performance in the different modes, responding to increments in overhang width. This situation is shown in Figure 6-10. Increases in overhang width of 1m resulted in an average of 4.8% enhancement in the house's annual thermal performance in conditioned mode. The same overhang generally caused 3.7% deterioration in annual free running performance, while a slight improvement was observed in thermal performance in some cases. The reason for these different results is made clear when comparing the seasonal performances of each house in two different house modes.



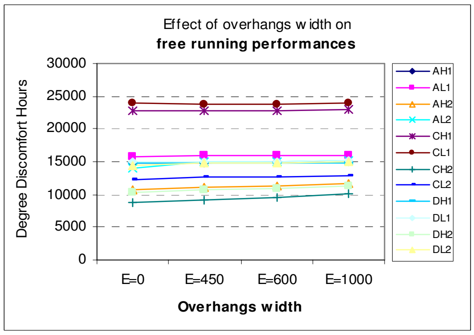


Figure 6- 10 Projected effect of overhangs width on the annual thermal performance of typical houses in conditioned and free running operation modes in the Sydney climate

Seasonal performance

The setting of overhang at the top of all windows with no offset is beneficial for improving summer performance. The benefit is greater for a conditioned house than for a free running house. When all the overhang widths were increased to 1m, the summer performance improved by an average of 26.6% in conditioned mode. The improvement decreased to an average of 8% for all houses in free running mode. The winter performance of the typical houses in this situation deteriorated by an average of 8.2% in conditioned mode and 11.7% in the free running mode. Thus the deterioration that was observed in the annual free running performance of some of the houses in response to the setting of overhang with a width of 1m for all windows would appear to owe more to deterioration in their winter performance and less improvement in their summer performance in free running mode than in conditioned mode. (See Figure D-13 and D-14 in Appendix D). Thus obviously operable overhangs are useful for different house operation modes.

Heavyweight and Lightweight

HW houses were twice as sensitive to changes in the width of overhang as LW houses, in free running mode. This result was reversed for LW houses in the conditioned mode.

It should be noted that in an efficient architectural design a suitable overhang width would be designed in relation to window area and orientation. The purpose of the analysis here is to examine the discrepancy between thermal performances in two different building modes in response to the same conditions. Thus a series of overhangs of the same width was applied for all windows, regardless of the orientation.

Single Storey and Double Storey

A comparison was made between the average percentage changes in the annual thermal performance of the DS and SS houses when adding overhang above the windows. It was found that in free running mode the average change in the DS houses was 12 times greater than that in the SS houses. In contrast, in conditioned mode the average annual performance of the SS houses was 1.5 times greater than that in the DS houses. This observation confirms the importance of house types in the interaction with house modes.

6.1.8 Glazing type

The performances of the typical houses were simulated using a range of glazing types. Figure 6- 11 shows the patterns resulting from changes in performance when all glazing was changed from single glazing to other specified types (See Section 4.6.6 for glazing specifications).

Free running and conditioned modes

Figure 6-12 depicts the situation of typical houses in annual thermal performance when all their glazing (SG Clr) was replaced by other specified types. All typical houses in free running mode showed the same patterns in their annual thermal performances in response to the application of different glazing types. These patterns were slightly different from those in the conditioned mode.

The replacement of all SG Clr with SG tone resulted in an average of 4.6% degradation in free running annual thermal performance, while in the conditioned mode there was significantly less degradation (0.3).

DG improved the thermal performance of houses in both modes. In a study by Willrath (1998) replacement of SG with DG reduced the annual energy requirement between 12% and 17%, depending on the window frame type. The finding in this study showed an average of 6.2% reduction in the annual energy requirement of typical houses in response to the same glazing replacement, with an aluminium frame. This replacement caused a reduction of 2.1% in annual degree discomfort hours in free running mode.

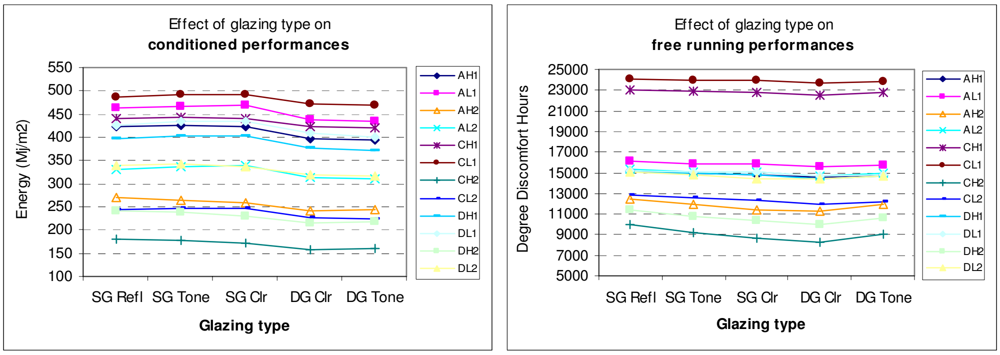


Figure 6- 11 Projected effect of glazing types on the annual thermal performances of typical houses in conditioned and free running operation modes in the Sydney climate

As noted above, the thermal performance of a house is affected by the type of glazing, whether it is in free running or conditioned mode. Nevertheless, the percentage of degradation or improvement depends on the house operation mode, which is discussed in detail in the following. This phenomenon again highlights the significance of house operation mode in providing particular advice for improving design efficiency.

Double Storey and Single Storey

A comparison of SS and DS performances in free running mode demonstrated that the thermal performance of DS houses was more sensitive to the type of glazing. For instance, by replacing SC Clr with SG Refl. the range of deterioration in the annual thermal performance of DS houses was between 15.5% and 1.8%, while this range for SS houses was only between 2.9% and 0.5%.

The above observations illustrates that the potentiality of DS houses to improve their thermal performance differs from that of SS houses.

Seasonal performance

The influence of four different glazing types on the seasonal performance of the houses is illustrated in Figure D-15 and D-16, Attachment D. The illustration shows the patterns of summer and winter performances in both free running and conditioned modes. The pattern is the same for both modes. However, the summer performance of conditioned houses was more affected by variations in glazing. For instance, in conditioned mode the houses achieved an enhancement of 7.67% on average in their summer performance when changing SG Clr to SG tone. This change improved their free running performance by an average of 4.8%. Their winter performance was degraded by 4.5% in conditioned mode and by 3.5% in free running mode.

Heavyweight and Lightweight

The thermal performance of a HW house was relatively more sensitive to changes in glazing type than the thermal performance of the same house with LW construction in both building modes. For instance, replacing all SG Clr glazing by SG tone produced an average of 2.7% deterioration in the annual free running thermal performance of typical houses with HW construction. This deterioration was reduced to 1.1% for houses with LW construction.

6.1.9 Window covering

A building's thermal performance can be improved by using openable internal window covering. This improvement depends on the level of resistance, transmittance and absorptance of the window covering. Simulations were undertaken for four types of indoor window covering with different levels of resistance.

Free running and conditioned modes

The setting of different window coverings produced similar patterns in annual thermal performance in both free running and conditioned modes. However, the simulations with four different window coverings showed that there was slightly more sensitivity among the conditioned houses. For instance, all typical houses showed an enhancement in their annual thermal performance when 'heavy drape' covering (R=0.055) was applied to the windows. The range of enhancement was on average 7.4% in the free running mode and 9% in conditioned mode. It is worth noting that no enhancement in performances could be achieved by adding a pelmet to a heavy drape cover in the Sydney climate, even though this addition increases the effective resistance of window covering (R = 0.33). (See Figure 6-12)

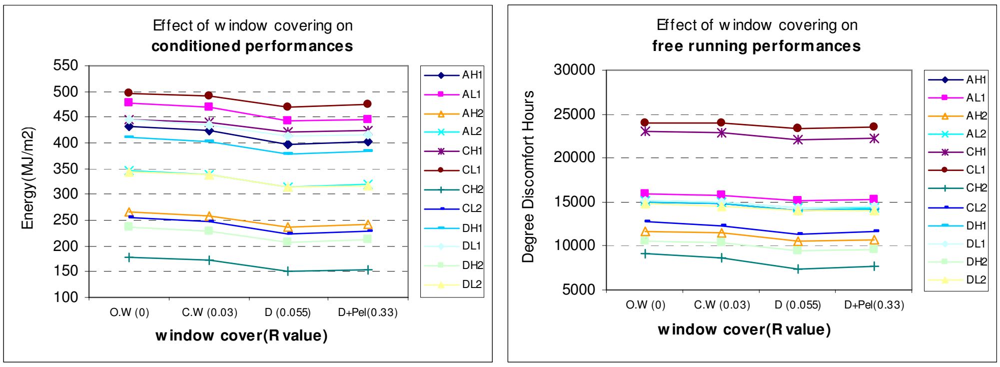


Figure 6- 12 Projected effect of window covering on the annual thermal performances of typical houses in conditioned and free running operation modes in the Sydney climate

Seasonal performance

The improvement in a house's annual thermal performance from window covering was due to improvement in the houses winter performance, which occurred because of a reduction in heat transmission through the windows. There were only marginal changes in the summer performance of houses. Figures D-17 and D-18 Attachment D depict the breakdown of seasonal thermal performances of both house modes in response to the addition of window covering. The addition of drape covering (R = 0.055) caused an average of 7.9% enhancement in winter thermal performance in the free running operation mode. This enhancement improved performance by about 4% for houses in the free running mode.

Heavyweight and Lightweight

The effect of window covering on the thermal performance was the same whether the house construction was heavyweight or lightweight. However, the addition of drape covers to windows gave 3% greater improvement in the annual thermal performance of HW houses than LW houses.

Double Storey and Single Storey

If the windows are evenly distributed on all sides of a building the effect of window covering on a house's thermal performance depends on the total window area. The improvement will be greater for a house with a larger window area. Since the window area in typical DS houses is greater than in typical SS houses, as represented in the study sample, the average improvement in annual thermal performance of the DS houses was found to be 5% greater in both house operation modes.

6.1.10 Openable windows

A building's performance is affected by many features related to windows such as window size, window frame, distribution of windows in all orientations, window to wall ratios and percentage of openable windows. This last factor seems to be an important aspect of the thermal behaviour of a free running house, largely by improving summer behaviour. To compare the sensitivity of a house's thermal behaviour both in free running and conditioned mode, the application of three different levels of openable windows was simulated.

Free running and conditioned

A house's annual thermal performance could be improved by increasing the percentage of openable windows. An increase from 25% to 75% on the openable window area resulted in an average reduction of 8.7% in annual energy requirement in conditioned mode and 6.7% in annual degree discomfort hours in free running mode (Figure 6-13). These reductions were due to improvements in their summer performance, which is described in the following.

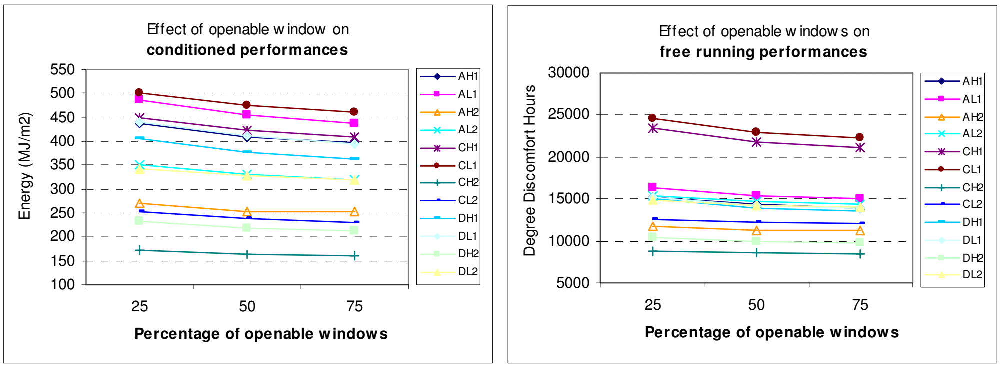


Figure 6- 13 Projected effect of openable window area on the annual thermal performances of typical houses in conditioned and free running operation modes in the Sydney climate

Seasonal performance

An increase in the percentage of a building's openable windows considerably altered the building's summer performance owing to an increase in natural ventilation. By increasing the percentage of openable window areas in typical houses from 25% to 75%, without changing the glazed area, their 'cooling' degree discomfort hours decreased by an average of 28.5%. The same change decreased their cooling energy requirement by an average of 24.5%. This situation is shown in Figure D-19 and D-20 Attachment D.

Winter performances were insensitive to variations in openable windows, unless such variation is connected with changing the window area, which was not considered in this study.

It can be understood that the annual improvement was due to the great improvement in the summer performance of houses. However, the summer benefits are almost masked in annual performances by the dominance of the absolute numbers of the heating energy requirement in conditioned operation mode, and the heating degree hours in free running operation mode.

Contrary to our assumption, there was no significant difference in improvement between the two different house modes. This was because of the nature of the AccuRate software which automatically counts the beneficial use of natural ventilation to compute the cooling energy requirement of a building in conditioned mode as described in Section 4.2.1.1. However in reality the effect of openable windows in improving the summer performance of a conditioned house depends on the operation of its windows, which in turn depends on the house's occupancy. Depending on how occupants are adapted to indoor temperature, therefore, the role of openable windows in reducing cooling energy requirements might be less than was observed in this study.

Lightweight and Heavyweight

The summer performance of LW houses in both house modes was slightly more sensitive to an increase in the percentage of openable windows than that of HW houses. The potential of a LW construction to change the indoor temperature quickly is accelerated by taking advantage of natural ventilation. By increasing the percentage of openable window area from 25% to 50% the percentage of improvement in summer performance of the typical houses with LW construction was about 2% more than with HW construction in both house modes.

Single Storey and Double Storey

As noted above, increasing the percentage of openable window improved the summer performance of SS and DS houses. This improvement was greater in SS than DS houses. It was also greater in their free running mode. By increasing the percentage of openable windows to 50% the summer performance of typical SS houses was improved by 8% more than that of DS houses in free running mode.

The greater improvement in SS houses is related to the situation of the living zone in these houses. By increasing the percentage of openable windows the degree of natural ventilation in SS living zones increased more than in the DS living zone. This is because they are also affected by an increase in the percentage of openable windows in the bed zone, while in DS houses living zones and bed zones are separated on two levels. Thus the rate of increase in natural ventilation computed by software and likely in reality is greater in SS houses than in DS ones when the percentage of openable windows is increased similarly for both house types.

6.1.11 Window to wall ratio

The effect of window to wall ratio was simulated. The series of simulations was undertaken in two stages. First the window area in the North (N) and South (S) facades was increased by 15% then 25%, without changing the area of West (W) and East (E) windows. In the second stage a similar increase was applied for W/E windows without changing the area of N/S windows.

Free running and conditioned

In both house modes, increasing the percentage of the window area by 25% made marginal changes in the annual thermal performance. Increasing the window area, whether for N/S or E/W windows, resulted in a slight deterioration in the house's performance in conditioned mode. However, the thermal performances improved slightly in free running mode.

Figure 6-14 depicts the situation where an increase in the ratio of N/S windows caused an average: 1.1% (0.1 – 3.3%) enhancement in thermal performance of houses in free running mode, and 1.3% (2.7 – 0.1%) deterioration in their performance in conditioned mode. The results from changing the percentage of E/W windows are shown in Figure

6-15. The figures do not make clear the slight changes in the thermal performance because of the large differences in the ranges of absolute numerical value of thermal performance indicators of the 12 samples. For more clarification the sensitivity of one of the samples (DH2) in response to an increase in the ratio of window to wall area in N/S sides is separately shown.

The reasons for these overall differences between the performances of houses in different modes in response to the same application became apparent when their seasonal performances were examined and this is described in the following.

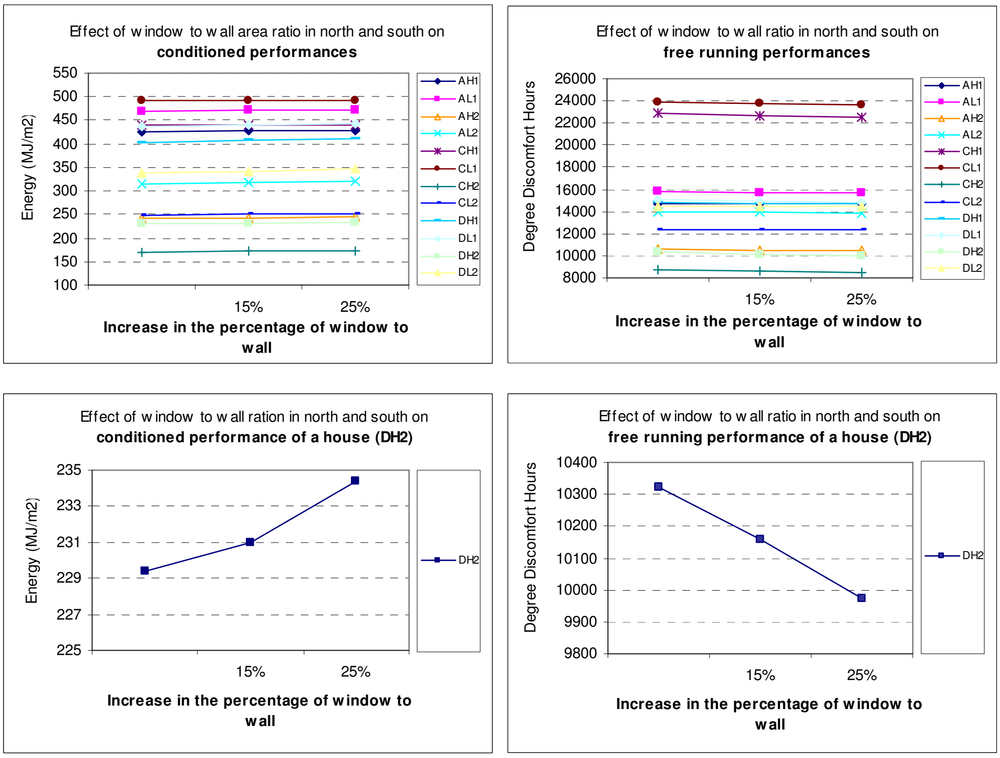


Figure 6- 14 Projected effect of window to wall ratio in north and south orientation on annual thermal performances of typical houses in conditioned and free running operation modes in the Sydney climate

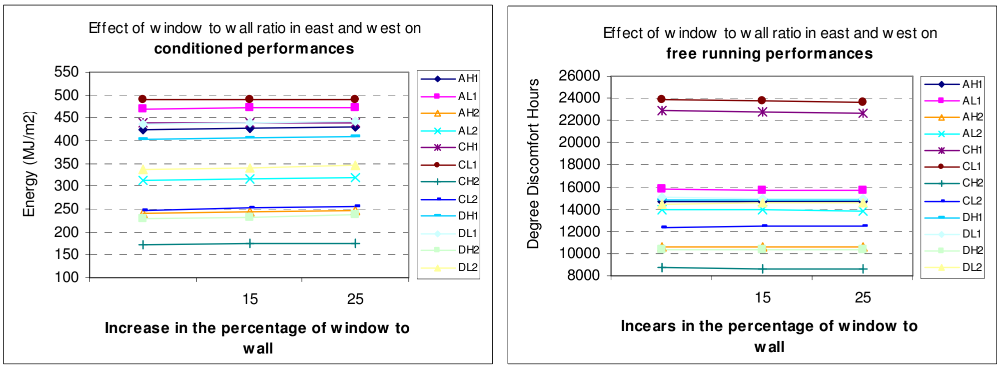


Figure 6- 15 Projected effect of window to wall ratio in east and west orientation on annual thermal performances of typical houses in conditioned and free running operation modes in the Sydney climate

Seasonal performance

East and west windows influence the summer performance of a building and N&S windows affect the winter performance of the building. The north vertical surfaces receive more irradiation in winter than in summer and east & west vertical surfaces are more influenced by solar radiation in summer than in winter.

The winter performances in conditioned mode were not sensitive to variations in window area whether the changes were made on the N&S windows or E&W windows. There was only a slight improvement in free running performance of 1.6% on average for an increase in the N&S windows area and 0.9% for the W&E window area.

Houses in both modes benefited from larger window areas in improving their daytime winter performance, since solar radiation enters through the windows and directly heats the building interior. In conditioned mode, however, the amount of artificial heating energy lost through the windows overnight was the same or even greater than the amount of obtained heat. Therefore a smaller window area is appropriate for improving the winter performance of a conditioned house.

As is shown in Figure D-22 and D-24, Attachment D, the summer performances of conditioned houses were slightly more sensitive to changes in the window area. When the window areas were changed in both the N&S and E&W orientations, an average increase of 4.2% and 5.1% respectively in the cooling energy requirements of the typical houses were observed.

The effect of increasing the window area on the summer performance of free running houses depends on the house types and is described in the following.

Single Storey and Double Storey

A comparison between the summer performance of the DS and SS houses, in response to an increase in the ratio of windows to walls, demonstrated a considerable difference in the behaviour of these two house types. Unlike in DS houses, the summer performance of SS houses, in free running mode, was improved by increasing the window area. For instance a 25% increase in the area of N/S windows resulted in an average of 1.03% improvement in the summer performance of SS houses and 2.2 % degradation in the summer performance of DS houses.

The difference appears to be that in SS houses the improvement in natural ventilation outweighs the increase in overheating hours. Such a pattern was not observed in DS houses.

Larger window areas improve natural ventilation but increase overheating hours during summer time. In this climate zone therefore, the simulation suggests that improvement due to natural ventilation outweighs the penalty of overheating conductive gain and solar loads.

Lightweight and Heavyweight

Heavyweight houses are more affected by changes in the window area. This is due to the effect of thermal mass, which delays heat conduction (transmission), and means that the quality of the indoor environment is maintained for a longer time than with lightweight construction. Increasing the window area in HW houses reduces the effect of the mass by accelerating heat transfer. Since LW houses have this potential characteristic, their sensitivity to changing the window size is less that that in HW houses.

6.1.12 Internal wall

In a typical construction where no additional insulation is considered, the mass of an internal wall is a key issue in improving the thermal behaviour of a conditioned zone, particularly when the wall is built between a conditioned and an unconditioned zone. In this situation, the role of the internal wall is relatively similar to that of an external wall in improving the thermal conditions of its adjacent spaces. The amount of heat transfer between two rooms depends on the massiveness of the internal wall.

To demonstrate the influence of internal walls on the thermal performance of a house in different modes, typical houses were simulated with four different internal wall constructions and these were compared. Figure 6-16 shows the annual thermal performance of typical houses in free running and conditioned modes, with internal plasterboard as well as with other specified materials (See Section 4.11.2 for other specifications)

Free running and conditioned

It was found that the performances in both the conditioned and free running modes were considerably affected by the type of internal wall construction. The effect was greater in free running buildings.

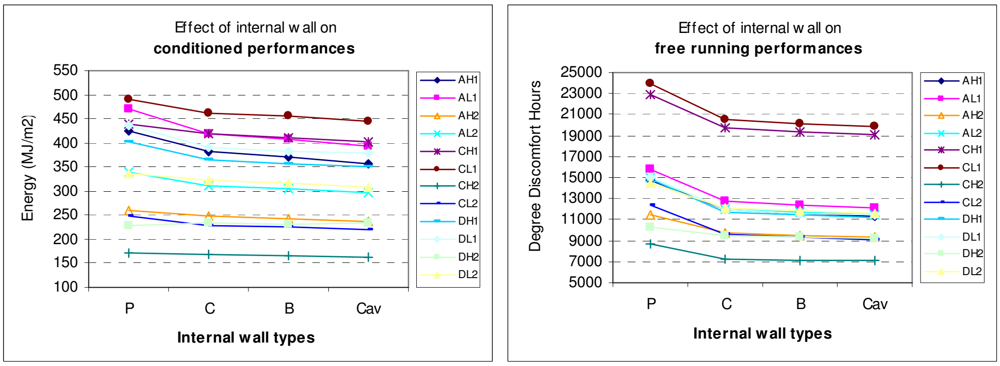


Figure 6- 16 Projected effect of internal wall on the annual thermal performances of typical houses in conditioned and free running operation modes in the Sydney climate

The annual thermal behaviour in conditioned mode was enhanced by an average of 8.2% when plasterboard was replaced by brick. This enhancement increased to an average of 19.1% in free running mode. The reasons for this greater improvement become apparent when comparing the houses' seasonal performance as follows.

Seasonal performance

A breakdown of seasonal performance (Figure D-25 and D-26, Attachment D) demonstrates that both the summer and winter performances of free running houses were more affected by the internal wall mass than were those in the conditioned mode. In the latter an average of 6.4% and 11.3% reduction in the annual heating and cooling energy requirement respectively was observed when plasterboard internal walls were replaced by brick. In free running houses the reduction on average was 20.7% and 15.7%. The greater overall improvement in this case therefore would appear to be the result of a greater improvement in winter performance.

Lightweight and Heavyweight

The thermal performance of a house with LW construction was considerably more affected by an increase in the internal wall mass than when the construction was HW. Indeed this alteration changed the characteristic of a LW house to HW. In some cases, a change in the internal walls of LW houses from plasterboard to brick resulted in quite similar and even better thermal performance than was observed in the HW base models. This situation was particularly observed among typical single storey houses in free running mode. Of course this observation accords with convectional wisdom related to the relative effectiveness of internal and external thermal mass in a temperate climate.

Single Storey and Double Storey

Brick walls produced a greater improvement in the thermal performance of SS houses than in DS houses in both house modes. This was particularly noticeable for those with LW construction which achieved indoor thermal quality close to or even better than the thermal quality of HW SS houses with plasterboard internal walls. Figure 6-17 illustrates this situation for a typical house (A1).

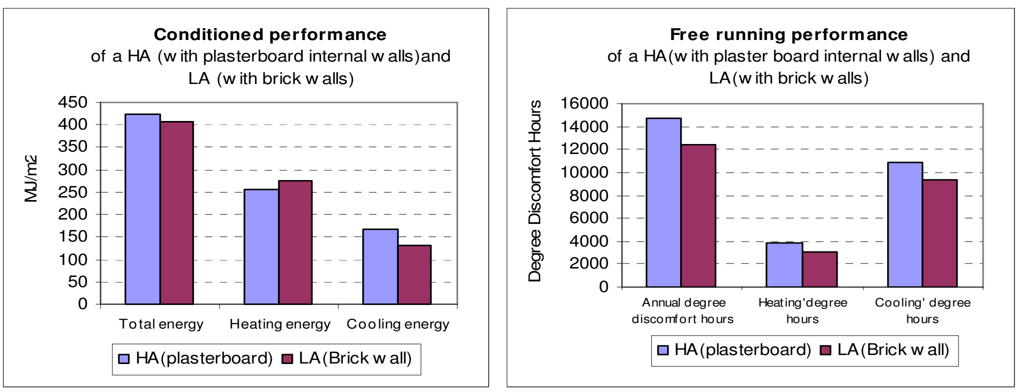


Figure 6- 17 Comparison between the thermal performances of a Single Storey house (A1) in the Sydney climate when its construction is HW with plasterboard indoor walls and when its construction is LW with brick internal walls

6.1.13 Infiltration

An increase in the infiltration rate has been found to deteriorate the annual thermal performance of conditioned houses in other studies and in other climates (Krichkanok, 1997; Willrath, 1998). This study tested the observation for free running houses as well as those in conditioned mode.

For this purpose, three different infiltration rates were simulated. The infiltration rate was increased from 1 to 5 air change per hour (AC/hr). Indeed 5 AC/hr already starts to be ventilation rather than just infiltration; however, the purpose of choosing this parameter is to highlight the significant differences between its effects on the thermal performance of houses when considering its interaction with house operation mode.

Free running and conditioned

Increased infiltration rates degraded the thermal performance of a house in both free running and conditioned modes. This situation is depicted in Figure 6-18 for all the houses when the infiltration rate increased to 5 air changes per hour.

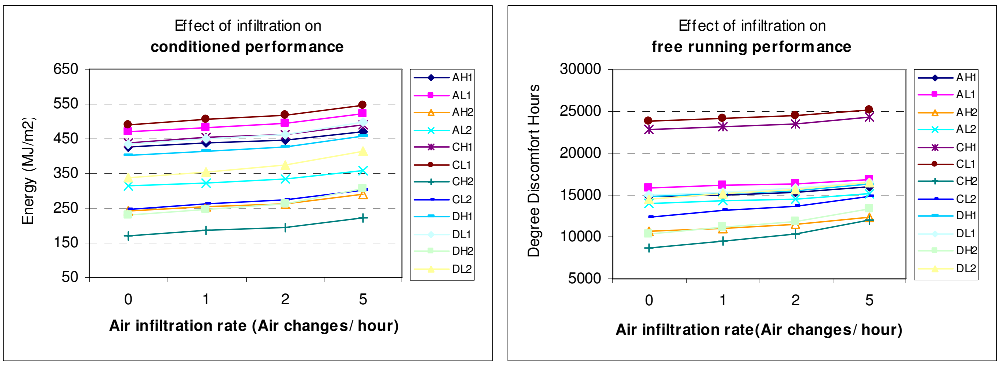


Figure 6- 18 Projected effect of infiltration on the annual thermal performances of typical houses in conditioned and free running operation modes in the Sydney climate

With this increase the annual thermal performance of the houses deteriorated by an average of 17.8% in conditioned mode and 14.7% in free running mode. The slightly greater deterioration in the performance of conditioned houses became clear in separating their annual performance into seasonal performances as is shown in the following.

Seasonal performance

The effect of infiltration on the seasonal performance of houses is illustrated in Fig D-27 and D-28; Attachment D. Higher infiltration rates significantly degraded the winter performance of the houses in both modes. Changes in the infiltration rate from 0 to 5 air change per hour caused an average deterioration of 27.2% in their winter performance in conditioned mode, while it was 20.8% for those in free running operation.

The response to increased infiltration rate changes in the summer performance of a house depends on the house mode. By increasing the rate of infiltration (5 air changes per hour), the summer performance for free running houses improved slightly (5.4%), whereas there were no noticeable changes in summer performance in the conditioned mode. Moreover, double storey houses recorded a slight deterioration in their conditioned mode summer performance.

Infiltration causes a latent cooling load in this climate for a conditioned house. By increasing the infiltration rate (5 air changes per hour) in typical houses, the latent cooling increased on average by 32.3% while ‘sensible’ cooling was reduced by 5%. Depending on the amount of increase in latent cooling energy (MJ/M^2) the total cooling energy requirement of a house can increase by increasing the infiltration rate. The infiltration rate, therefore, is an important parameter in architectural design in a humid summer climate.

Heavyweight and Lightweight

The effect of increasing infiltration rates on the thermal performance of the houses with HW construction was greater than on those with LW construction. By increasing the infiltration rate to 5 air changes per hour, deteriorations in the thermal performance of HW houses were on average 7% greater than in LW houses in free running mode and 4% greater than in LW houses in conditioned mode.

6.2 Thermal performance of dwellings in the Canberra climate

The following findings are the result of a simulation of the typical houses in the Canberra climate in response to changes in their building envelope properties. The process for reporting the findings is similar to that for the Sydney climate in the preceding section 6.

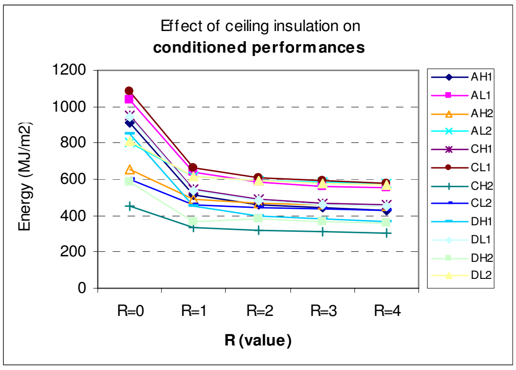
6.2.1 Ceiling insulation

The installation of ceiling insulation in a building greatly enhances the building's annual thermal performance, largely by improving its winter performance. This demonstrates that ceiling insulation is particularly effective for a cold climate.

Free running and conditioned mode

As was observed in the Sydney climate, ceiling insulation improved the thermal performance in both building modes in the Canberra climate. However the amount of improvement in response to the same level of insulation was relatively less than that in the Sydney climate. In conditioned mode, the addition of R.2 insulation in the ceilings of the typical houses caused an average of 38.3% improvement in their annual thermal performance. In free running mode this installation improved performance by 20.03%.

Levels of insulation greater than R2.0 did not make any significantly greater improvement than did R.2.0 in both modes. As the Australian Standard (AS 2627.1-1993) recommends R 3.5 insulation in ceilings for the Canberra climate, the above observation is surprising and requires more investigation for DS and SS houses. In that average the DS houses seem to mask the effect of ceiling insulation on the SS houses.



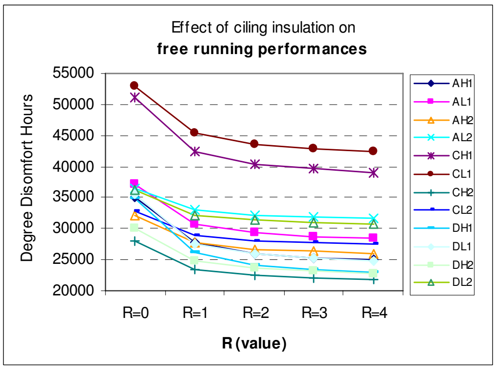


Figure 6- 19 Projected effect of ceiling insulation on the annual thermal performances of typical houses in conditioned and free running operation modes in the Canberra climate

Single Storey and Double Storey

The SS houses showed more improvement than the DS houses when insulation was added in their ceiling. By the installation of R.2 and R.3 insulation the annual thermal performance of the SS houses was improved by 1.5 times more than that of DS houses in both house modes. This result is similar to that for the Sydney climate and the reason for the smaller improvement in DS than SS houses is related to the design type of DS houses which was described before.

Figure 6-20 illustrates that insulation greater than R.2 did not produce a greater improvement in the thermal performance of both house types (DS and SS) than did R.2. This result was similar whether the houses were in conditioned or free running mode. Therefore the above assumption, that DS masks the effect of R.3 insulation on the thermal performance of houses, cannot apply. The effect of ceiling insulation in improving thermal performance is likely to be greater if the other house elements such as wall and floor are insulated. Further study, which is beyond the scope of this project, is required to examine the effect of other kinds of ceiling insulation in interaction with other parameters on the thermal performance of houses.

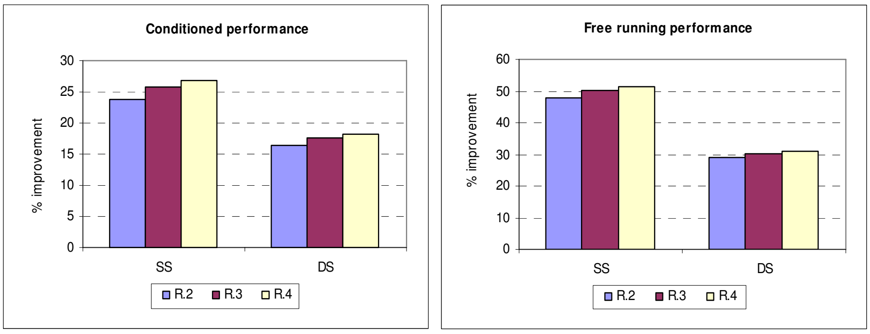


Figure 6- 20 Comparison between the percentage of improvement in the thermal performance of DS and SS houses due to adding different insulation in the ceiling

Heavyweight and Lightweight

The effect of ceiling insulation in improving the thermal performance of a building depends on the building construction, HW/ LW. Simulations in the Canberra climate showed that, in conditioned mode the effect of ceiling insulation on improving the thermal performance of houses with HW construction was on average 5.4 % greater than its effect with LW construction. The result was 8.0% greater for those at the free running mode.

The addition of R.1 insulation in the ceiling of the LW single storey houses enhanced their thermal performance to be better than was found in HW single storey houses without insulation (Figure 6-21). This again hints at the ability of LW buildings to achieve annual thermal performance comparable to HW constructions depending on other design variables.

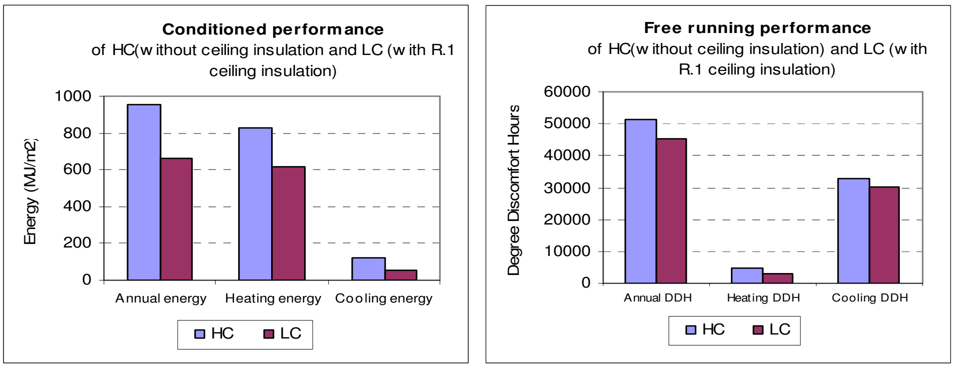


Figure 6- 21 A Comparison between thermal performances of a single storey house with heavyweight construction (without ceiling insulation) and that house with lightweight construction (with R 1.0 ceiling insulation)

Seasonal performance

Ceiling insulation improved the seasonal, summer and winter, performances of a house in both modes in the Canberra climate. Figure D-29 and D-30 Attachment D illustrates the seasonal performance improvement in response to the addition of R.2 ceiling insulation. The houses in the conditioned mode achieved a greater improvement in both seasonal performances than those in free running mode. In conditioned mode the houses achieved an average of 36.7% and 48.8% improvement, respectively, in their summer and winter performances. The improvement in their free running performance was 19.2% and 26.43%. This comparison suggests that the thermal performance of houses in conditioned mode is more sensitive than that of free running houses to changes in ceiling insulation.

6.2.2 Wall insulation

The thermal performance of a wall depends on its mass and its level of insulation. The effect of wall insulation in the Canberra climate was similar to that in the Sydney climate but more beneficial for both house operation modes in the Canberra climate.

Free running and conditioned modes

Figure 6-22 illustrates a situation where adding insulation improved annual thermal performance in both house modes. The addition of R.2 insulation to the external walls resulted in an average of 16% improvement in conditioned mode and an average of

6.7% improvement in their free running performance. The reason for greater improvement in the conditioned performance of houses is connected to the greater impact of wall insulation on the winter performance of conditioned houses and will be described in the following section.

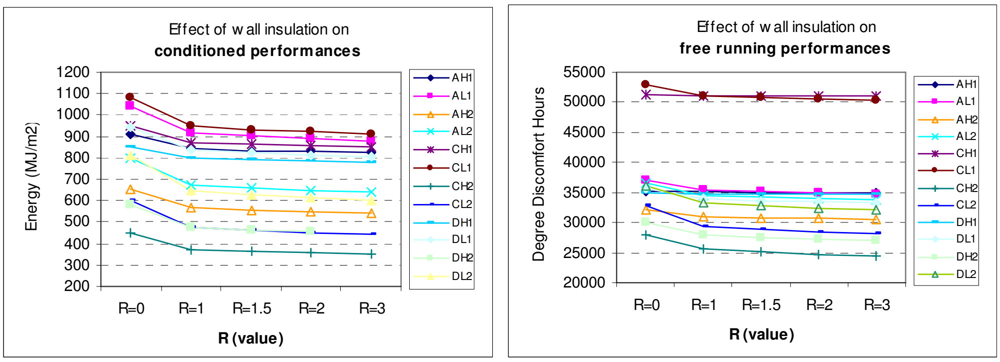


Figure 6- 22 Projected effect of wall insulation on the annual thermal performances of typical houses in conditioned and free running operation modes in the Canberra climate

Seasonal performances

The effect of wall insulation on seasonal performance is depicted in Figure D-31 and D-32 Attachment D. It shows a considerable improvement in winter performance in both house modes. The improvement in conditioned mode was considerably greater than that in free running mode. When the resistance of the insulation layer was increased from 0 to 3 KW/m^2 the winter performance in conditioned mode improved on average by 19% and in free running mode by 7.5%.

Installing wall insulation does not appear to be appropriate advice for improving the summer performance of houses. In conditioned mode, adding R.3 insulation to typical house walls gives a marginal improvement in their summer performance. This level of wall insulation in free running mode degrades the summer performance in some cases, particularly observed among heavyweight houses. Thus the improvement observed in the annual performance of houses is strongly related to improvement in their winter performance. Wall insulation is more effective for improving thermal performance of buildings in a cold climate.

Heavyweight and Lightweight

The influence of wall insulation on the improvement of the thermal performance of LW houses is greater than on that of HW houses. As mentioned before, an insulation layer modifies the characteristics of a lightweight wall so that they become close to those of a heavyweight wall. LW houses achieved 4% more improvement in their annual thermal performance than HW houses for R2.0 in both house modes.

A house with LW construction is able to achieve a thermal performance similar to that with HW construction. This situation was observed among the SS houses and is shown in Figure 6-23, which compares the thermal performance of a SS house (C1) having heavyweight construction (HC1) and having lightweight construction in addition to R.1 insulation in its external walls (LC1).

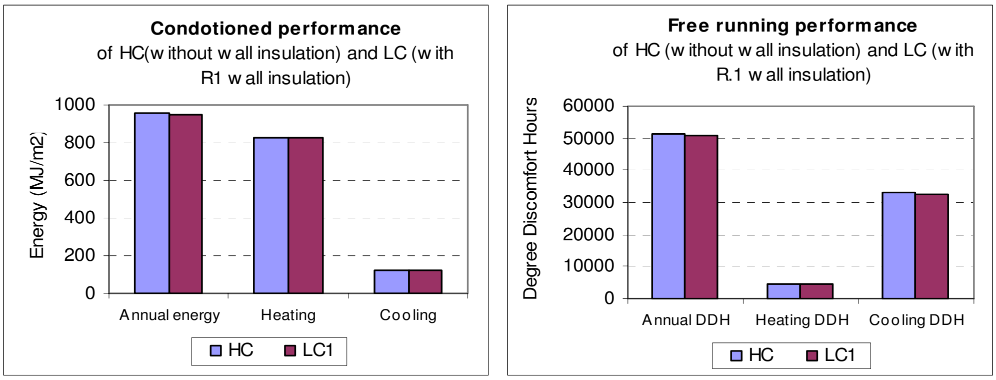


Figure 6- 23 A comparison between thermal performances of a single storey house with heavyweight construction (without wall insulation) HC and that house with lightweight construction (with R.1 wall insulation) LC in the Canberra climate

Single Storey and Double Storey

Wall insulation produces a greater improvement in the thermal performance of DS houses than in SS houses. For instance, in response to R.1 their enhancement in free running mode was an average 7% more than that in SS houses, while the conditioned mode it was 10%. This observation was similar to that for the Sydney climate and is shown in Figure 6-24.

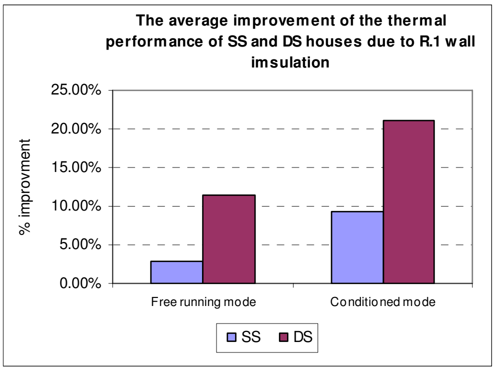


Figure 6- 24 Comparison between the effect of wall insulation in average improvement of the thermal performance of Single Storey (SS) and Double Storey (DS) houses in the Canberra climate

6.2.3 Floor insulation

The effect of floor insulation on thermal performance in this climate was slightly different from that in the Sydney climate. This appears to be due to the fact that the winter in Canberra is more severe than in Sydney. Floor insulation was seen to be beneficial for improving the thermal performance of all typical houses in the conditioned mode in the Canberra climate, while in the Sydney climate improvement in conditioned houses depended on the house type and construction.

Free running and conditioned mode

Floor insulation had no useful effect on improving thermal performance in the *free running* houses whether it was employed under the suspended floor of LW houses or under the slab floor of HW houses and in some houses led to a slight deterioration in their annual thermal performance. In contrast, floor insulation improved the annual thermal performance of all typical houses in the conditioned mode. The addition of R1 insulation under the floor caused an average enhancement of 5% in their annual thermal performance.

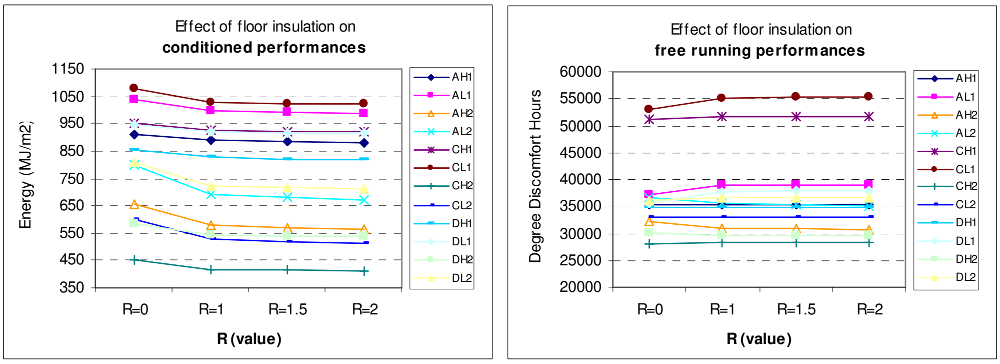


Figure 6- 25 Projected effect of floor insulation on the annual thermal performances of typical houses in conditioned and free running operation modes in the Canberra climate

Figure 6-25 illustrates the effect of floor insulation. It shows that for insulation beyond R.1 there was no sensitivity in the free running performance of the houses and marginal improvement (1%) in their conditioned performance.

Although slight changes may not be important in the context of energy efficiency, the different effects of floor insulation on the thermal performance of free running and conditioned houses is of value here because it demonstrates a key difference between efficient design for conditioned houses and that for free running houses.

Seasonal performances

Floor insulation deteriorated the summer performance of the houses in both modes. The addition of R.1 under the floor produced an average 8.7% and 7.7% deterioration in summer performance in the free running and conditioned mode respectively. The same change improved the winter performance of all houses in the conditioned mode. However, it was not seen to improve the winter performance of those houses with LW construction in the free running operation mode (See Figures D-33 and D-34). This situation is discussed in the following related section.

In conditioned mode, improvement in the winter performance outweighed the degradation in summer performance of the houses. This resulted in an improvement in the annual thermal performance of conditioned houses.

Heavyweight and Lightweight

As described above, floor insulation does not appear useful for improving thermal performance of houses in the free running mode and this situation was more significant for houses with LW construction. The reason appears to be related to the function of the sub floor in improving the comfort temperature of the ground floor for some of the times.

Single Storey and Double Storey

Both typical house types displayed deterioration in their annual free running performance and improvement in their conditioned performance. However, in the free running mode the thermal performance of SS houses was more sensitive to insertion of floor insulation, while in conditioned mode DS houses showed more sensitivity in their annual thermal performance. An explanation for that difference appears to be the difference in insulated floor area in SS and DS houses, as obviously the insulated floor area in a SS house is larger than that in a DS house with the same plan area as a SS house.

6.2.4 Wall colour

The choice of a building's external colour to improve its thermal performance should depend on climate type. A building's performance, in a cold climate, for instance, would be expected to be enhanced with the use of a dark external colour. The application of a dark external colour for typical houses in the Canberra climate was beneficial in both house modes while this was not the case in the Sydney climate for the houses in free running operation mode.

Free running and conditioned mode

In both house modes the thermal performance of all the houses achieved an improvement in their annual performances when their external light wall colour was exchanged for a dark colour (Figure 6-26).

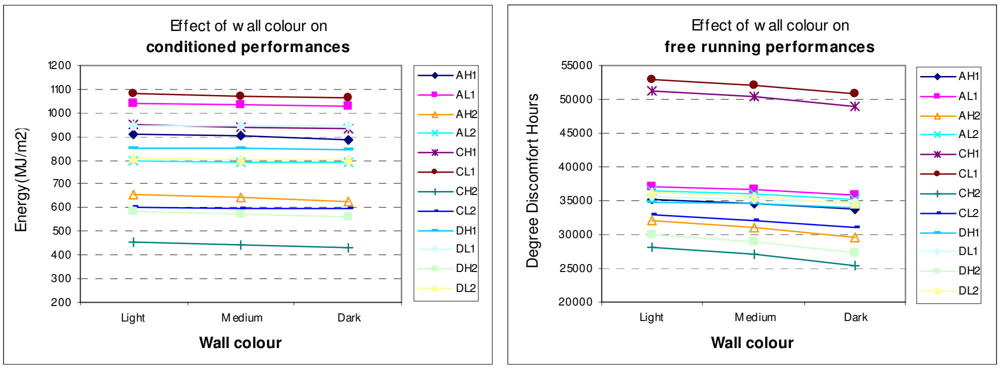


Figure 6- 26 Projected effect of external wall colour on the annual thermal performances of typical houses in conditioned and free running operation modes in the Canberra climate

The improvement in their free running performances was on average 2.5 times greater than in the conditioned mode. The reason for this greater improvement is illustrated when comparing the seasonal performances of the houses in different modes and is reported in further detail in the following.

Seasonal performance

A dark external wall colour caused an enhancement in the winter performance of houses and deterioration in their summer performance in both house modes (Figure D-35 and D-36 Attachment D). However, the amount of improvement and degradation depended on the house mode. As a result of replacing a light colour by a dark one on the external walls the average improvement in the winter performance of free running houses was about 1.3% more than that in the conditioned mode. On the other hand the average apparent deterioration in the summer performance of free running houses was 0.5% more than for the same houses in the conditioned mode. Accordingly, aggregating the seasonal thermal performances resulted in more improvement in the free running mode than in conditioned mode, as was mentioned above.

Lightweight and Heavyweight

The thermal performance of HW houses compared to LW houses was more affected by changing the external wall colour in the Canberra climate, with a dark colour producing a comparatively greater improvement in conditioned HW houses than in the free running mode. In the conditioned mode, the average improvement in HW houses was 3.5 times greater than in those with LW construction. In free running mode, this improvement was 1.6 times greater than in LW houses.

This points to the importance of the operation mode in addition to the significance of the building construction in giving advice on making improvements in the thermal performance of a building.

6.2.5 Roof colour

The effect of roof colour on the thermal performance of typical houses in this climate was slightly different from what was observed in the Sydney climate. The difference was noted in both house operation modes.

Free running and conditioned mode

The effect of roof colour depended on the house operation mode. By replacing a light roof colour with a dark colour, enhancement was produced in free running houses by between 3.1% and 8.9%. In the conditioned mode, this change produced different effects, depending on whether the house was single storey or double storey. This situation is shown in Figure 6-27.

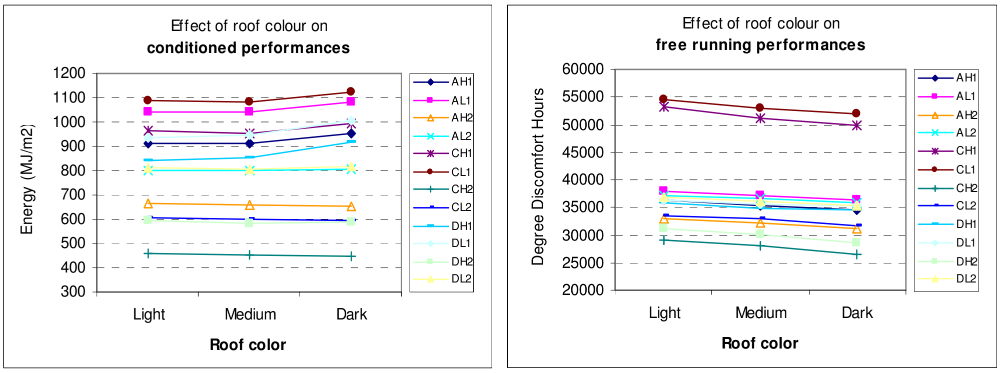


Figure 6- 27 Projected effect of roof colour on the annual thermal performances of typical houses in conditioned and free running operation modes in the Canberra climate

Single Storey and Double Storey

Two different effects were observed among the conditioned houses when their roof colour was changed. The application of a dark instead of a light colour on the roof caused an average 5.9% deterioration in the annual thermal performance of the SS houses, and a 1.6% enhancement in DS houses. The reason relates to the seasonal performance of houses and will be described in the following.

Seasonal performances

A dark external colour degraded the summer performance and improved the winter performance of the typical houses in both operation modes. However, in the single storey houses the amount of increased cooling energy overweighed the amount of reduction in heating energy. Since the annual thermal performance of houses is an aggregation of their seasonal performances, SS houses showed the deterioration which is mentioned above. Enhancement in the thermal performance of DS houses was also due to a reduction in the heating energy outweighing the amount of increase in the cooling energy requirement.

Overall, houses showed more sensitivity in their summer performance in response to external roof colour changes in both house modes. The sensitivity among the conditioned houses was more than in the free running houses. For instance, by changing the external light colour to a dark colour, the amount of cooling energy requirement was more than doubled in the conditioned mode. This change in free running mode increased the 'cooling' degree hours of the typical houses by about 1.6 times. Free running houses, taking advantages of natural ventilation, are more able to reduce the number of 'cooling' degree hours. Due to this the thermal performance of free running houses was less sensitive to changes in the external roof colour. The effect of roof colour on the seasonal performance of typical houses is illustrated in Figure D-37 and D-38 Attachment D.

The winter performances of the typical base houses in the free running operation mode were more sensitive to changes in the external roof colour. They achieved on average 3% more improvement in their annual thermal performance with a dark roof.

Heavyweight and Lightweight

A comparison between the changes in the performance of HW and LW houses in response to the roof colour change showed that in conditioned mode LW houses were more sensitive to roof colour change while in free running mode HW houses were more sensitive to this change. This is contrary to what was observed in the Sydney climate.

6.2.6 Orientation

Orientation is expected to be important for the beneficial use of solar gain and natural ventilation. The proper orientation of a building with respect to prevailing wind is essential to the success of natural ventilation. In Canberra, which has colder weather during winter than Sydney does, therefore, an appropriate building orientation would be expected to give preference to solar gain in an efficient architectural design.

Free running and conditioned

A slight difference was observed between the variations in the performance of houses in different operation modes in response to variation in orientation. The performance of houses in free running mode was slightly more sensitive to the variation of house orientation than that in conditioned mode. This may be because of the thermal performance of a house in free running mode is affected by both solar gain and wind direction, while in conditioned mode solar gain is more effective in changing the thermal performance of the house.

The result of simulations in this study showed that when a house orientation changed the fluctuation in the thermal performance of a free running house was not like that of a conditioned house in some cases, such as CH2. This is illustrated in Figure 6-28. Percentage changes in annual thermal performance was between 0% - 8% in their free running mode and between 0% – 6% in the conditioned mode. The result of a comparison between the effect of orientation on the performance of a house in free running and conditioned mode has the implication that a designer should not expect a similar effect on the thermal performance of a house in different operation modes in response to a particular orientation.

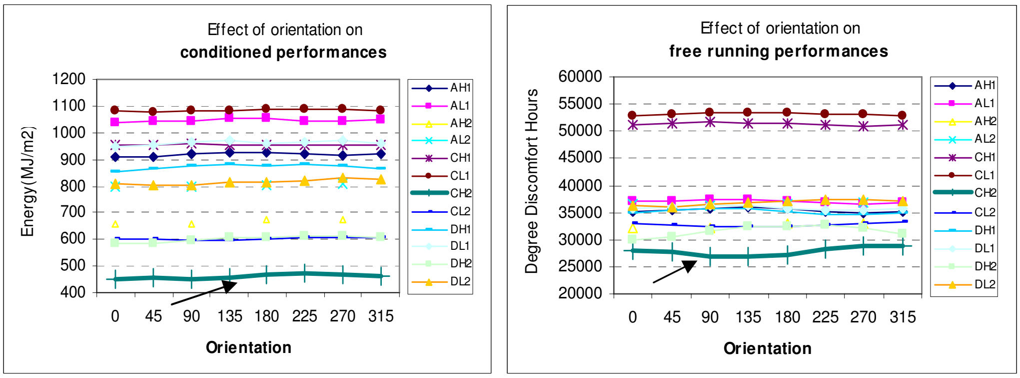


Figure 6- 28 Projected effect of orientation on the annual thermal performances of typical houses in conditioned and free running operation modes in the Canberra climate

Note markedly different orientation sensitivity of house type CH2.

Heavyweight and Lightweight

The annual thermal performance of the typical HW houses was more influenced by changing the houses orientation than in LW houses, being about 2% more than in houses with LW construction.

Single Storey and Double Storey

The thermal performances of double storey houses in this climate, similar to that in the Sydney climate, were slightly more sensitive to changes in building orientation. It was 2% more than that of SS houses. The performance of a SS house was affected by heat gain through all external surfaces that is through both walls and roof, while heat gain and loss from the roof did not affect the performance of a typical DS house as much, apparently due to the design of DS houses described before. Therefore, the effect of wall orientation on the indoor environment of a DS house is more than its effect on the indoor environment of a SS house. This observation highlights some substantial differences that should be considered in designing for DS and SS houses.

Seasonal performances

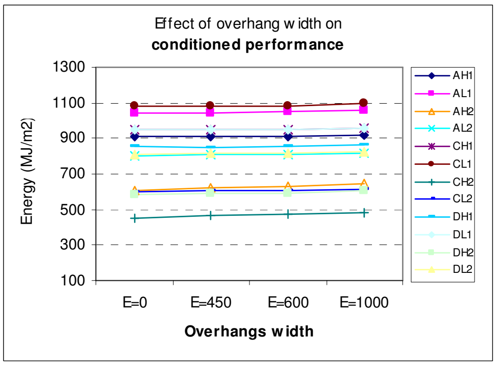
Figures D-39 and D-40 Attachment D show the breakdown of the seasonal thermal performances of the houses when the houses orientation changed incrementally by 45 degrees. The figures show more sensitivity in the summer performance in conditioned houses and more sensitivity in the winter performance of free running houses. This implies that the effect of orientation should be considered differently in designing a conditioned house than a free running one.

6.2.7 Overhang depth

An appropriate width for overhangs to improve the thermal performance of a building depends on the climate. A comparison between the effect of overhang width on the thermal performance of the typical houses in Sydney and Canberra showed significant differences between conditioned and free running houses. This appears to be due to the colder winter in Canberra. The effect of overhang width on the thermal performance of houses in the both operation modes in the Canberra climate is described in the following.

Free running and conditioned modes

In Canberra, the addition of overhang above all windows degraded the annual thermal performance of these houses in both house modes (Figure 6-29). The apparent deterioration in conditioned mode was less than that in the free running mode. The application of a 1m overhang for all windows produced on average 3.8% and 6.18% degradation in conditioned and free running mode, respectively. The apparent deterioration of thermal performance in a free running house is therefore twice that in the same house in conditioned mode. This observation implies that that the effectiveness of advice regarding this feature depends on the house mode, and therefore again suggests that techniques to improve the thermal performance of a free running house may differ from those for conditioned house.



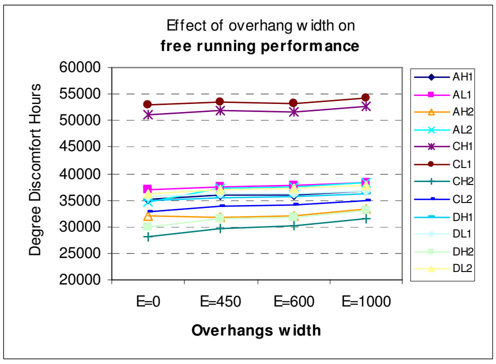


Figure 6- 29 Projected effect of overhangs width on the annual thermal performances of typical houses in conditioned and free running operation modes in the Canberra climate

Heavyweight and Lightweight

As was observed in the Sydney climate, HW houses showed more sensitivity to the addition of overhangs in the Canberra climate than did LW houses.

Single Storey and Double Storey

A comparison between the average decline in the annual thermal performance of SS and DS houses showed that this was greater in DS than in SS houses, whether the houses were in free running or conditioned mode. In both modes the average percentage deterioration in the DS houses was 2 times greater than in SS houses.

Overhangs produce shading and as a result reduce solar gain through the external surfaces. The application of overhangs for typical houses created more shading in the external surface of the DS houses than in the SS houses, because the number of windows in the former was more than in the latter. Accordingly, the winter performance of the DS houses was more affected (degraded) by the application of overhangs for all windows than that of the SS houses.

Seasonal performance

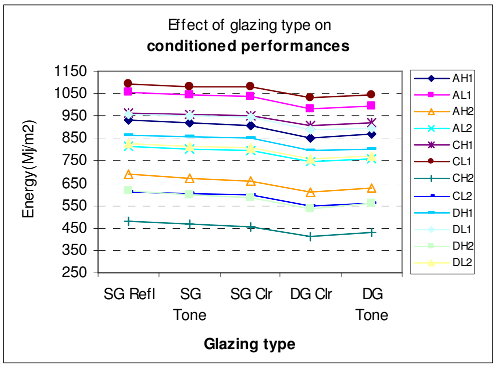
The rate of improvement in the summer performances of the houses was greater than the rate of deterioration in their winter performance where an overhang was added above all the windows. This was similar for both house operation modes but more significant in conditioned mode. For instance, the application of 1m overhang for all windows caused on average 28.0% improvement in the summer performance and 6.8% deterioration in the winter performance in the conditioned mode. However the absolute numerical value of the deterioration on the houses winter performance was greater than the absolute numerical value of the improvement on the houses summer performance; and thus, the amount of deterioration in the winter performance outweighed the amount of improvement in the summer performance in both operation modes. Therefore the observed deterioration in the annual thermal performance in both modes, which was caused by the addition of overhangs, was due to a greater deterioration in the winter performance of all the houses.

6.2.8 Glazing Type

The effect of glazing type on the thermal performance of the typical houses in the Canberra climate was similar to that in the Sydney climate.

Free running and conditioned modes

Figure 6-30 shows the patterns of the annual thermal performance of the houses in free running and conditioned mode, when their single clear glazing type was replaced by other specified glazing. A slight difference can be seen between the patterns in free running and in conditioned mode. The sensitivity of the thermal performance in free running houses was slightly greater than that in the conditioned mode. For instance the replacement of all SG Clr glazing with SG Refl caused on average a 4.7% deterioration in the annual performance of free running houses. The same replacement resulted in 2.5% deterioration in conditioned mode.



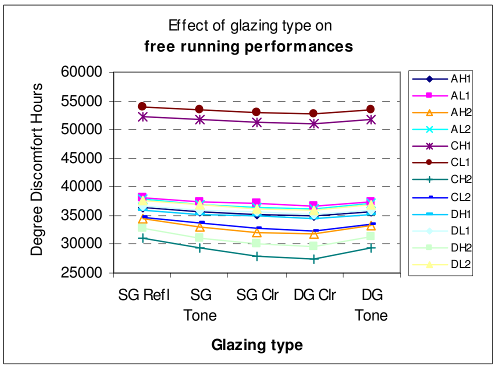


Figure 6- 30 Projected effect of glazing on the annual thermal performances of typical houses in conditioned and free running operation modes in the Canberra climate

Seasonal performance

In response to changes in glazing types, greater sensitivity was found in the thermal performance of the conditioned houses in summer, while in winter the free running houses demonstrated a greater sensitivity. For instance, replacement of all SG Clr glazing of the typical houses by SG refl. resulted in:

- an improvement in the winter performance of all houses, with 6.12% improvement for the conditioned and 4.6% improvement for the free running houses.
- deterioration in the summer performance of all houses, with 23.6% for the conditioned and 12.6% for the free running houses.

The lesser sensitivity of summer performance of the free running houses in response to the changes in the glazing is most likely due to the effect of natural ventilation in removing the overheated hours. The effect of the four various glazing types in the seasonal performances of the typical houses is illustrated in Figures D-43 and D-44 Attachment D.

Heavyweight and Lightweight

The sensitivity of the thermal performance of the houses with HW construction in response to the changes in the glazing type was significantly greater than those with LW construction. This is true for both house modes. The average percentage changes for HW construction was 2 times more than for LW construction, in both free running and conditioned mode.

Single Storey and Double Storey

The changes in the DS houses were greater than in the SS houses (roughly double), whether in free running or conditioned mode. This is because the window area in DS houses was greater than in SS houses

6.2.9 Window covering

Window covering improved the annual thermal performance of houses in the Canberra climate largely by improving the houses' winter performance. This is similar to the effect of window covering in the Sydney climate.

Free running and conditioned mode

The thermal performance of all houses in both operation modes improved by the addition of a covering to all the houses' windows. As is illustrated in Figure 6-31, the improvement in the conditioned houses was considerably greater than in the free running houses. For instance the application of 'heavy drape' cover (R=0.055) to all windows improved the annual thermal performance by 10.2% in conditioned houses and by 5.3% in free running houses. This observation again evidences the difference between the characteristics of free running and conditioned houses. Even if a particular measure has the same effect on the thermal performance of a house in both operation modes, the significance of the effect is not the same for both house modes.

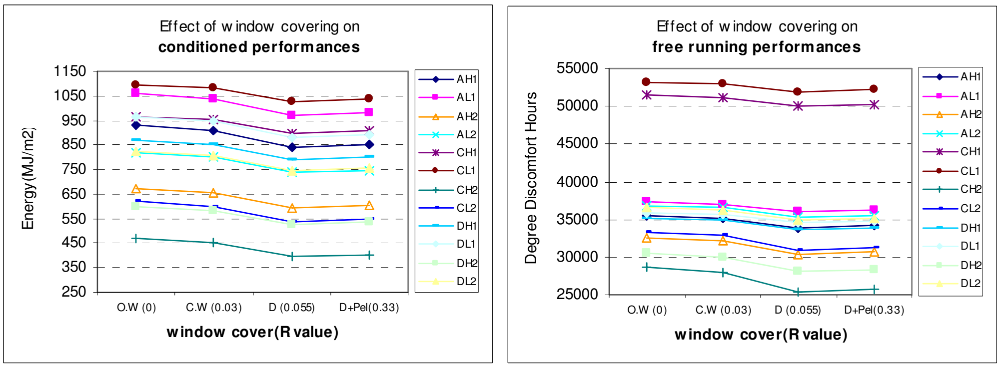


Figure 6- 31 Projected effect of window covering on the annual thermal performances of typical houses in conditioned and free running operation modes in the Canberra climate

Seasonal performance

Figures D-45 and D-46 Attachment D depict the seasonal performance of the typical houses in response to the addition of four different window coverings. It shows a great improvement in the houses' winter performance unlike the marginal changes in their summer performance. This was true in both house modes. By adding 'heavy drape' covers winter performance improved on average by 9.5% and 5.1% in the conditioned and free running modes respectively. In summer the addition of this cover produced an average degradation of 0.2% in free running houses and, an average improvement of 0.4% in the conditioned ones. Although the effect on the summer performance was marginal, the different impacts observed in the different operation modes have implications for different strategies that may be applied to improve the thermal performance of houses.

Heavyweight and Lightweight

A comparison between HW and LW house performance with the addition of window covering demonstrated more sensitivity in the thermal performance of the HW houses in both house modes. Covering all windows with 'heavy drape' resulted on average in a 6.45% and 4.3% improvement in the HW and LW houses, respectively in free running mode. In conditioned mode the improvement was 11.06% and 9.3% for HW and LW construction, respectively.

Single Storey and Double Storey

DS houses, having a higher proportion of windows than SS ones show more sensitivity in their thermal performance to the addition of a window covering. This situation was true whether the house was free running or conditioned. Adding a 'heavy drape' window improved the performance of the DS houses by about 4 % more than that the SS ones in both operation modes.

6.2.10 Openable windows

Increasing the percentage of openable windows produced similar effects on the performance of the houses in the Canberra climate as was observed in the Sydney climate. However, the sensitivity of thermal performance of houses in Canberra was slightly less than that observed in the Sydney climate.

Free running and conditioned mode

The thermal performance of a house in free running mode was more affected by variation in openable windows than was the case in the conditioned mode. Increasing the percentage of openable windows from 25% to 75% caused an enhancement in the performances in both house modes. In the free running mode they achieved 2.5% enhancement, but it was only 1.8% in the conditioned mode.

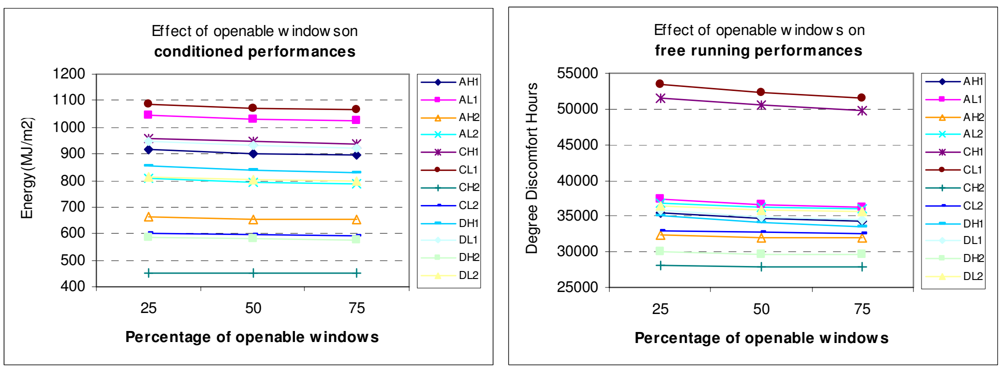


Figure 6- 32 Projected effect of openable windows area on the annual thermal performances of typical houses in conditioned and free running operation modes in the Canberra climate

Seasonal performance

The slight improvement in the annual performances of houses was due to a noticeable enhancement in their summer performance. As described before for the Sydney climate, the significance effect of bigger openable window in improving summer performances is completely masked in patterns of annual performances because of the domination of the absolute numbers for both heating DDH and MJ/m^2 in winter.

The summer performance of all the houses was significantly enhanced by increasing the openable window area. The enhancement was greater in the free running houses. Increasing the percentage of openable windows from 25% to 75% without changing the glazing area, enhanced their summer performance on average by 23.07% in the free running mode and 18.74% in the conditioned mode. The greater enhancement in the free running houses was due to the greater effect of natural ventilation in these houses.

The winter performance did not show general sensitivity to the various percentages of openable windows in the Canberra climate but there would be considerable changes in the winter performance if the percentage of glazing area changed, due to the effects of solar gain and heat transmission through the external surface.

Heavyweight and Lightweight

A comparison between HW and LW houses, showed no significant difference (less than 1%) when the openable window area increased. There was a similar result for both house modes.

Single Storey and Double Storey

As mentioned above, increasing the openable proportion of the overall window area significantly enhanced the summer performance of SS and DS houses in both modes. The enhancement in free running mode was greater in SS than in DS houses, while in conditioned mode the enhancement was the same for in both. In free running mode a 50% increase in the percentage of openable windows enhanced the summer performance of the SS houses by 7% more than in the DS houses. The reason for this result is similar to that described for the Sydney climate in Section 6.1.10.

6.2.11 Window to wall ratio

As previously described, a slight increase of 15% and 25% in the window area of the houses was employed without changing the proportion of openable window area. Window areas were simulated first to the north and south and then in the east and west orientations to examine the effect of window orientation on the building's thermal performances as well. The effect of this in the Canberra climate was similar to that in the Sydney climate.

Free running and conditioned modes

In the both house modes, an increase in the percentage of window area produced marginal changes. However, the change was not the same in both house modes. In the conditioned mode, an increase in the proportion of windows, whether in N/S or E/W orientation, caused a slight deterioration. By contrast, the performance of the houses in the free running mode improved under the same conditions.

Figure 6-33 depicts the situation when increasing the ratio of N/S windows, resulting in, on average:

- 1.5% improvement in the thermal performance of the houses in free running operation
- 0.7% deterioration in conditioned operation mode

As slight changes cannot be clearly illustrated in the figures which contain all the samples, the sensitivity of one of the samples (DH2) is shown separately for more clarity.

Relatively similar changes can be seen in the performance of the houses when the percentage of the windows in the E/W facades was increased (Figure 6-34).

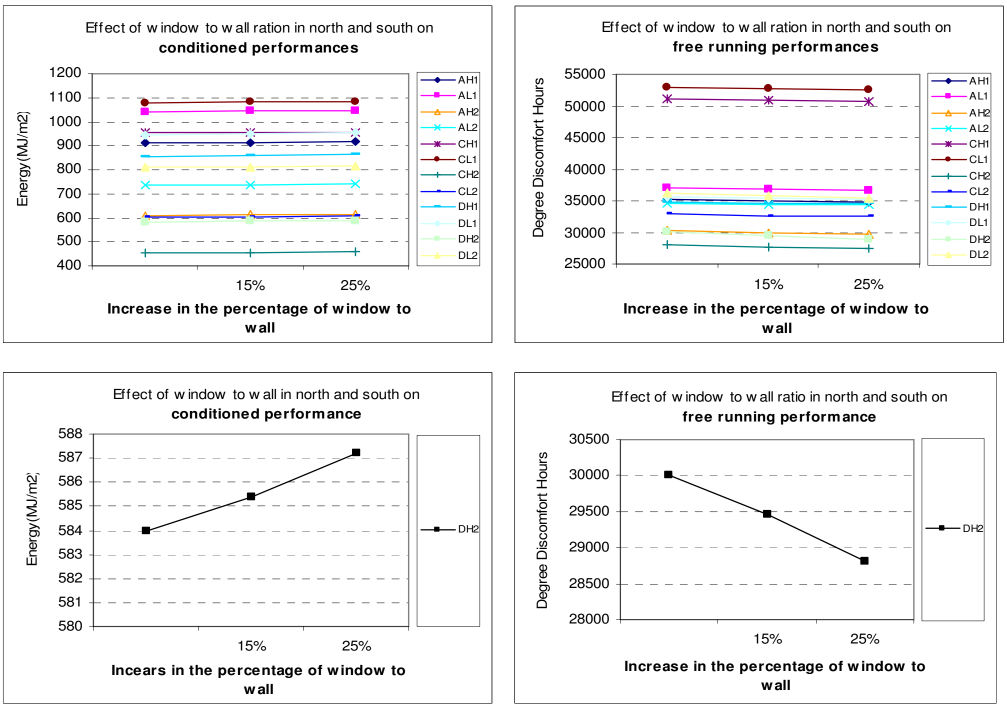


Figure 6- 33 Projected effect of window to wall ratio in north and south orientation on the annual thermal performances of typical houses in conditioned and free running operation modes in the Canberra climate

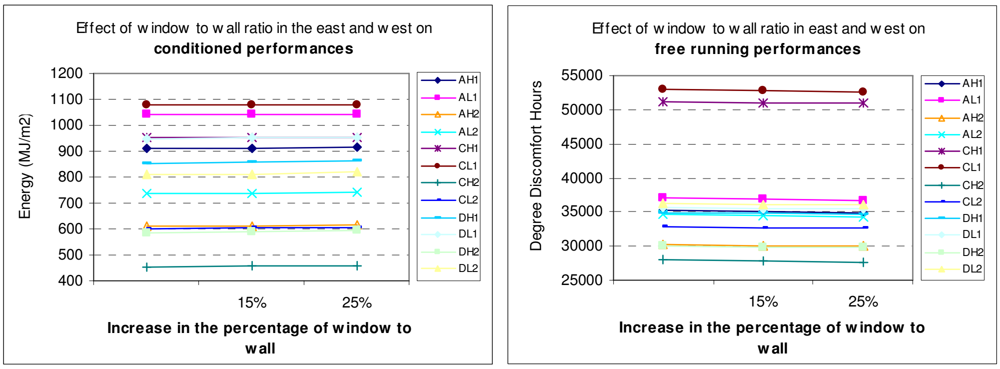


Figure 6- 34 Projected effect of window to wall ratio in east and west orientation on the annual thermal performances of typical houses in conditioned and free running operation modes in the Canberra climate

The main reasons for the different effects of the window ratio in the two operation modes became apparent when their seasonal performances were examined and are described in the following.

Seasonal performance

The winter performances of the conditioned houses were not sensitive to an increase in window area in either orientation, while the free running houses showed a marginal improvement. This improvement was on average 1.6% when the area of N/S windows was increased by 25% and 0.9% when the area of E/W windows was increased by the same amount. This was also observed in the Sydney climate and highlights a difference between the behaviour of a house in free running and conditioned mode.

A comparison between the summer performances of the houses illustrated degradation when the proportion of windows was increased. This result was the same in both operation modes. However degradation in conditioned houses was greater than in the free running mode. This is illustrated in the Figures D-49, 52 Appendix D.

Single Storey and Double Storey

As noted above, increasing the window to wall ratio resulted in an improvement in the thermal performance of both DS and SS houses in the free running mode and deterioration in their performance in conditioned mode. However the thermal performance sensitivity of DS houses was slightly higher than that of SS houses, because the total proportion of area in typical DS houses is greater than in typical SS houses.

Heavyweight and Lightweight

Increasing the window to wall ratio produced similar effects on the performance of both HW and LW houses in both modes. In both cases there was a slight improvement in free running mode and a deterioration in conditioned operation mode.

6.2.12 Internal Wall

Changes in the internal wall construction produced a similar effect the Canberra climate as observed in the Sydney climate although houses in the Sydney climate showed slightly more sensitivity in both operation modes.

Free running and conditioned modes

Thermal performance was significantly affected by the construction (or mass) of internal walls. This effect is illustrated in Figure 6-35 for both house operation modes. It was greater in the free running houses, just as in the Sydney climate. For instance, the performance in the conditioned mode was enhanced on average by 4.7% when all their plasterboard walls were replaced by brick. This enhancement increased to an average 10.7% in the free running operation mode.

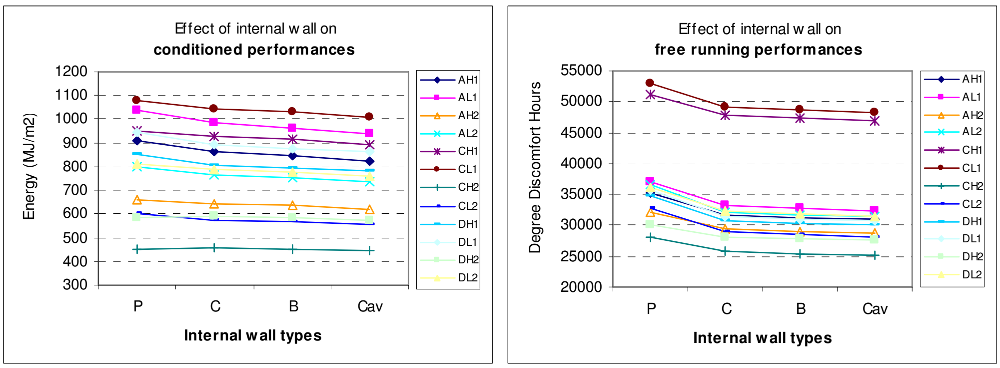


Figure 6- 35 Projected effect of internal wall construction on the annual thermal performances of typical houses in conditioned and free running operation modes in the Canberra climate

The greater improvement in the thermal performance of free running houses relates to their winter performance and will be describe in the following.

Seasonal performance

A breakdown of seasonal performance in response to changes in all the internal walls is illustrated in Figures D-53 and D-54 Appendix D. It shows more improvement in the free running houses, particularly in their winter performance. The replacement produced an average of 8.7% and 1.4% improvement in performance in free running and conditioned operation modes, respectively. The improvement in the summer performance of the houses in free running mode was 18.8% and in conditioned mode it was 17.3%.

Lightweight and Heavyweight

The thermal performance of a house with LW construction is more affected by an increase in the internal wall mass than that of the same house with HW construction. As mentioned, the effect was greater for the free running mode. Changing the mass of interior walls in single storey houses with LW construction changed their performance to closely resembling that of HW houses. This is described in the following.

Single Storey and Double Storey

The effect of internal walls with high mass was greater in improving the performance of SS houses than of DS houses in both modes. The average percentage improvement of the typical SS houses in conditioned operation mode was 2 times greater than that of the DS houses when all their internal plasterboard walls were replaced by brick. The same replacement improved the thermal performance of both house types by an average of 10.7%.

The replacement of all plasterboard internal walls with brick in SS houses with LW construction improved their performance by an average of 11.9%. This brought their annual performance close to that of houses with HW construction. This situation is illustrated in Figure 6-36 for one of the SS houses (A1). The figure compares the predicted thermal performance of a typical SS house with HW construction (HA) with that house with LW construction and internal brick walls. The comparisons are depicted for both house operation modes. They illustrate that the replacement of walls with LW construction (LA) made its performance similar to and even better than that of a HW house in the free running operation mode. However this did not occur in the conditioned mode. This observation demonstrates the capability of LW SS houses to achieve better thermal behaviour. However this does not appear to be a case in conditioned performance.

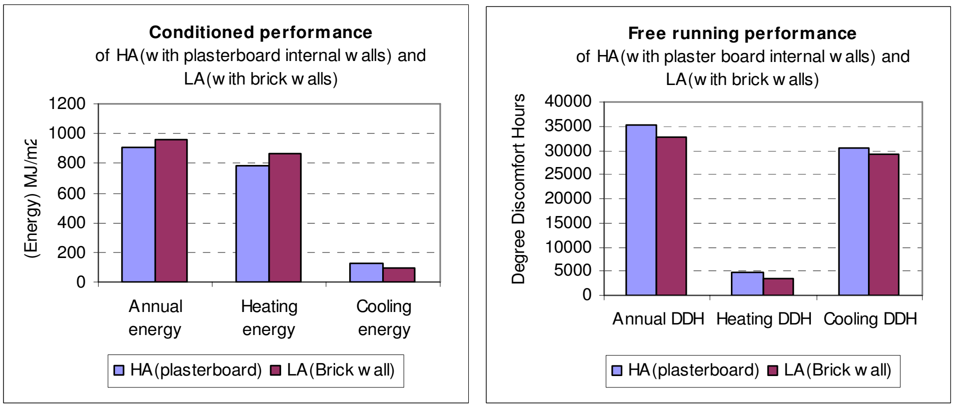


Figure 6- 36 Comparison between thermal performance of a SS (A1) in the Canberra climate when its construction is HW with plasterboard indoor walls and when its construction is LW with break indoor walls

6.2.13 Infiltration

Increasing the rate of infiltration decreases the performance of buildings largely by degrading the winter thermal performance. A comparison showed that in free running mode the degradation in the annual thermal performance of the houses in the Sydney climate was slightly more than that in the Canberra climate. This result was reversed when the house mode was changed to the conditioned mode. This finding points to the significance of the house mode in an efficient climatic design.

Free running and conditioned mode

Figure 6-37 depicts the apparent deterioration in the annual thermal performance of the houses that resulted from increasing the infiltration rate. This was greater among the conditioned houses. In creasing the infiltration rate to 5 air changes per hour caused an average of 10.14% and 18.5% degradation in free running and conditioned mode respectively.

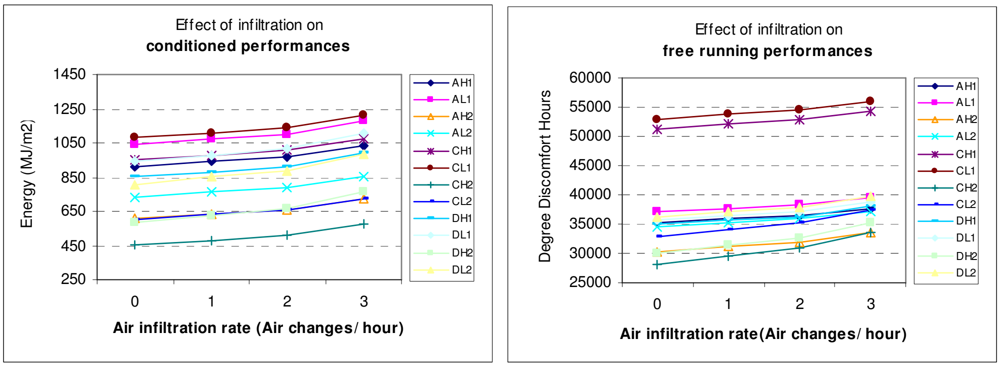


Figure 6- 37 Projected effect of infiltration on the annual thermal performances of typical houses in conditioned and free running operation modes in the Canberra climate

Seasonal performance

The higher infiltration rate significantly deteriorated the winter performance of houses in both modes. However it was greater among the conditioned houses. Increasing the infiltration rate from 0 to 5 air changes per hour caused on average 21.47% and 12.4% deterioration in the conditioned and free running mode, respectively. This increase caused a similar improvement (4.8%) in the summer performance in both operation modes. The different results, therefore, reflect the effect of infiltration on the winter performance of the houses.

Heavyweight and Lightweight

HW houses were more sensitive (on average 9%) to changes in the infiltration rate. This was the same for both house operation modes.

6.3 Conclusion

The following conclusions can be drawn from the analysis of the results of simulations of conditioned and free running houses using the Sydney and Canberra climates.

- Comparisons between the thermal performances of the typical houses in free running and conditioned mode in response to the various conditions demonstrated that, the variation in the thermal performance of the houses in response to variations in design features was often markedly dependent on the house operation mode. The free running performance of the houses was clearly different from their performance in conditioned mode. Thus any effort to improve the thermal performance of a house in conditioned mode does not necessarily improve its thermal performance in the free running operation mode.

In fact, an effective technique for enhancing the thermal performance of a conditioned house could actually diminish its free running performance. Even if the thermal performance in both free running and conditioned modes of a house is improved, the extent of the improvement is not necessarily the same in both modes. These significant differences between the performances of houses in different operation modes are evidence that the rating of an efficient design for a free running house should be different from that for a conditioned house.

- The effect of changes in a design parameter on the seasonal performance of the houses depended on the house operation mode. Sometimes the seasonal trade-offs were different for each house operation mode. Even if a particular modification in a design parameter produced a similar effect in different operation modes, the relative changes were not the same for both modes.

- A comparison between the thermal performance of houses with LW and HW construction illustrates that the LW houses are sometimes able to achieve a comparable performance to HW construction, particularly when they are in free running mode. LW houses, therefore, could under certain circumstances achieve a more favourable result in a free running rating scheme than in an energy-based rating scheme.

- From all comparisons between the thermal performance of DS and SS houses it was found that the numerical range of annual thermal performance for DS houses was less than that for SS houses, whether in free running or conditioned mode. Figure 6- 38 shows this situation in the Sydney climate.

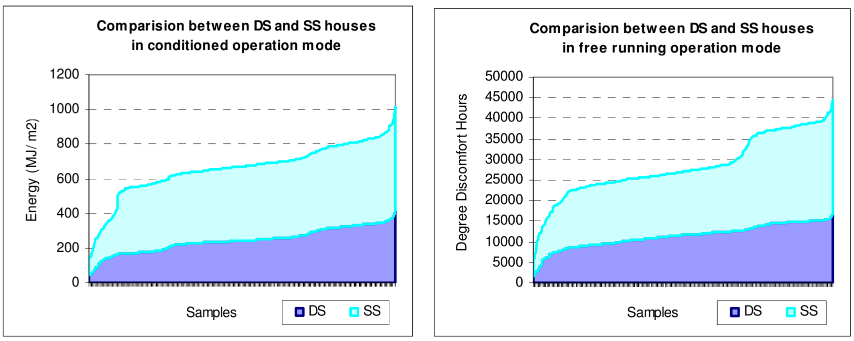


Figure 6- 38 Comparison between the range of numerical values of the thermal performance of DS and SS houses in conditioned and free running modes and in the Sydney climate

DS houses compared to SS houses, therefore, are most likely to get better values in a rating system. This is most likely due to their being a higher proportion of envelope in the SS houses for a given volume. In conditioned mode, therefore, the fabric heat flux per unit of floor area is greater in the SS houses.

In free running mode, although the indicator is free of area weighting, DS houses still achieve better grades in an assessment system. This phenomenon in free running mode is the result of the type of design of DS houses. Constructing the bed zone above the living zone considerably reduces the external fabric area for the living zone. Since the thermal performance of a building depends heavily on the performance of its living zone, reducing the external surface of the living zone results in a considerable improvement in the performance of the DS house. However, in a DS design in which the living zone is constructed on the upper floor this result may be different.

For an accurate evaluation system of the thermal performance of a building, it may be better to separate the score bands for SS and DS houses.

- A comparison between the thermal performance of houses in the Sydney and Canberra climate showed that the moderate climate of Sydney is more favourable for designing free running houses. Canberra with its more severe winter needs more sophisticated design to provide acceptable thermal comfort for its occupants during winter in free running operation mode.

  It was observed that the application of any technique to improve the winter performance of a house often degraded the summer performance of that house. This situation in particular was observed in the predicted performance of free running houses. From this observation it would appear that in a climate such as Canberra's, with cold winters, conditioned houses are more suitable, while the Sydney climate is more appropriate for free running house design.

  Above all, it can be concluded that a national rating scheme should be flexible enough to deal with free running and conditioned house design separately.

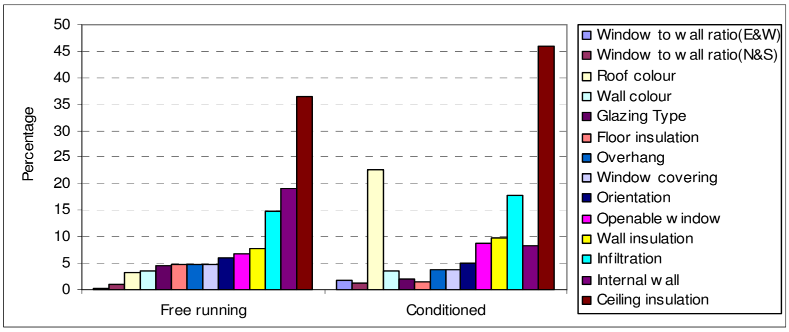
- From the results obtained, the importance of design features can be evaluated according to their potential for improvements in efficiency. The relative strength of each variable affecting the thermal performance of the typical base houses is given in Table 6-1. The percentages for conditioned houses indicate the average annual energy variations and for free running houses indicate annual degree discomfort hour variations corresponding to the changes in the parameters from their base case values.

Table 6- 1 Percentage variations in annual thermal performance of the typical houses in free running and conditioned modes

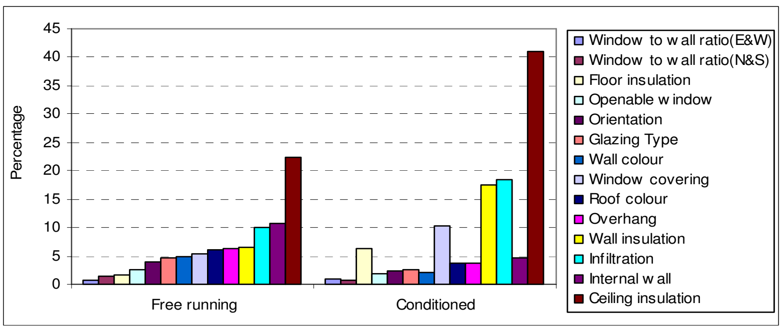
Parameters	Percentage thermal performance variations (Sydney)		Percentage thermal performance variations (Canberra)	
	Free running (without area weighting)	conditioned	Free running (without area weighting)	Conditioned
Ceiling insulation (non to R4.0)	36.4%	46.1%	22.5%	41.1%
Wall insulation (none to R4.0)	7.8%	9.7%	6.6%	17.5%
Floor insulation (none to R2.0)	4.7%	1.6%	1.7%	6.3%
Wall colour (0.30 to 0.85 absorbance)	3.5%	3.6%	5%	2%
Roof colour (0.30 to 0.85 absorbance)	3.16%	22.6%	6%	3.7%
Orientation	6%	5%	4%	2.4%
Window overhang (non to 1m)	4.8%	3.7%	6.18%	3.8%
Glazing type (SG Clr to SG Refl.)	4.6%	2.1%	4.7%	2.5%
Window covering (open W. to Drape)	7.4%	9%	5.3	10.2
Openable window (0.25 to 0.75)	6.7%	8.7%	2.5%	1.8%
Window to wall ratio (N&S)	1.1%	1.3%	1.4%	0.69%

Parameters	Percentage thermal performance variations (Sydney)		Percentage thermal performance variations (Canberra)	
	Free running (without area weighting)	conditioned	Free running (without area weighting)	Conditioned
Window to wall ratio (E&W)	0.24%	1.7%	0.75%	0.82%
Internal wall (Plasterboard to Brick)	19.1%	8.2%	10.7%	4.7%
Infiltration (0 to 5 air change per hour)	14.7%	17.8%	10.14%	18.5%

When the building parameters are ranked in order of the percentage of their effect on the thermal performance of the houses in free running mode, this ranking does not correspond with the rank order of the conditioned houses. This situation is shown in Figure 6-39 for both Sydney and Canberra climates. The finding demonstrates that the choice of application of any measure to improve a house thermal performance depends on the house operation mode. This will be discussed in further detail in next chapter.



a) Sydney climate



b) Canberra climate

Figure 6- 39 A comparison between the effectiveness of design features in improving thermal performance of the typical houses in

It is important to note that while the results show the potential of various design features for improving design efficiency of typical houses, their contribution to actual thermal performance and the relationship among them is not known. A regression analysis is described in the next chapter to illustrate their actual contribution to changing a house's thermal performance.

Chapter 7

House thermal performance analysis using regression model

An important part of this study, as it is the principal test of the basic hypothesis, is concerned with examining the effects of different building parameters on a building's performances in different operation modes. Significant differences were observed in the parametric study between the performances of houses in different operation modes. However, it is necessary to illustrate how the contribution of the various design features differs in improving the thermal performance of a house in different operation modes; and how far the different performances of a house are correlated. For this purpose statistical analyses were employed.

This chapter reports the results of statistical analysis of the numerical values of the indicators of projected thermal performance of simulated houses in different operation modes. First this analysis investigates a probabilistic correlation between the indicators of house performances in free running and conditioned operation modes. This is followed by an investigation of the contribution of design features to the thermal performance of houses in different operation modes, using multi-regression analysis, in order to compare their significance in an efficient design for a free running and conditioned house.

It should be noted that since the only purpose of the statistical analysis in this case is to examine the hypothesis, additional observations of interesting statistical factors that arise from the study are not pursued here, although they could be expanded in a further study.

7.1 Correlation coefficient

The correlation coefficient is used to indicate the extent to which a pair of numerical values of two variables lies on a straight line. It shows the strength of the relationship between the variables. The relationship is often expressed by squaring the correlation coefficient (r^2) and multiplying it by 100. This expression can be interpreted as: what proportion expressed as a percentage of one variable can be explained or predicted by the other variable? Several kinds of correlation have been introduced in statistics that differ in the details of calculation. The most common is known as the Pearson, which is appropriate to use if both variables are approximately normally distributed.

The Pearson correlation coefficient has been applied in this study to measure the extent to which the thermal performances of the simulated samples in different operation modes are linearly related. It is also used to estimate the strength of the relationship between the thermal performance of houses in conditioned mode and their performance in the free running mode in the data set of simulations. The normality of the variables was checked to ensure the applicability of this coefficient[32].

The simulated samples used for the purpose of parametric sensitivity analysis in the previous chapter have been used again to identify the correlation. Predicted energy requirements and degree discomfort hours as indicators of the thermal performance of houses in the conditioned and free running mode respectively were again used in this analysis.

As described in Section 4.5.4, Degree Discomfort Hours were computed in two manners, with and without area weighting. The correlation between energy and both DDHs was investigated and is reported here to illustrate how far the addition of area weighting affects the strength of the correlation between the two indicators of energy performance and comfort performance.

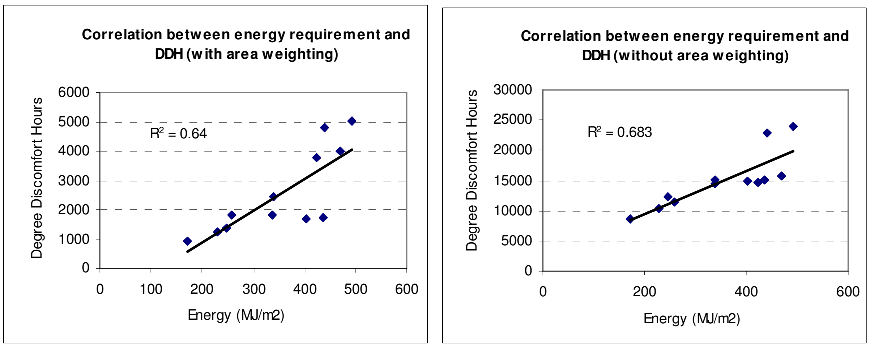
7.1.1 Correlation between thermal performances of the typical houses in different modes

The correlation between the thermal performances of the simulated houses in different operation modes has been investigated for the six typical houses with two different constructions (HW and LW) and with six occupancy scenarios. The result was relatively similar for all occupancy scenarios. Therefore, the results reported here are only for the first occupancy scenario. For more information on the results for the other occupancy scenarios see Appendix E.

---

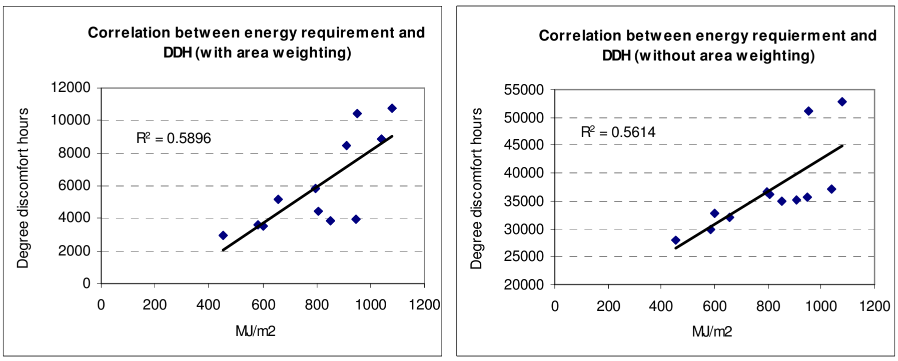
[32] The normal distribution for SS and DS houses is presented in chapter 8 Section 8.1.

The scatter plot of the indicators of the thermal performance of the typical houses in conditioned and free running mode is illustrated in Figure 7-1 and 7-2. It shows a linear relationship with a strong correlation (r^2 >0.5) between these two indicators. However the correlation is stronger when their free running performance is indicated by degree discomfort hours *without* area weighting.



a) DDH with area weighting **b) DDH without area weighting**

Figure 7- 1 Correlation between thermal performances of the typical houses in different operation modes in the Sydney climate

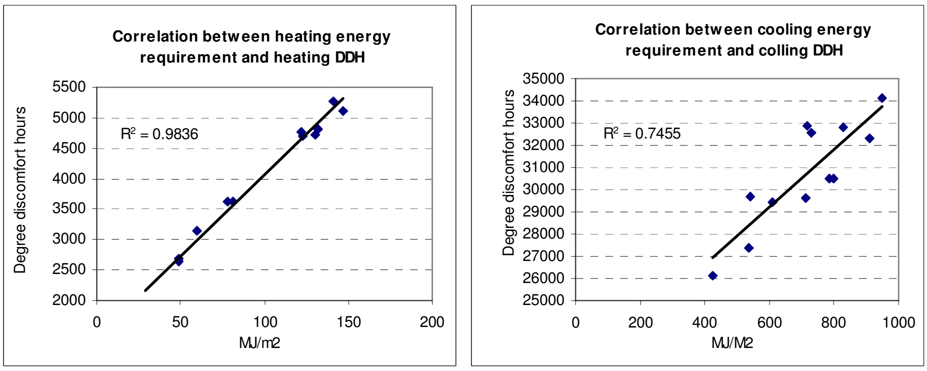


a) DDH with area weighting **b) DDH without area weighting**

Figure 7- 2 Correlation between thermal performances of the typical houses in different operation modes in the Canberra climate

As discussed before, the evaluation of a house thermal performance in terms of thermal comfort should logically be free of area weighting. This issue was discussed in Section 2.5.3 as a shortcoming in the current rating systems and was investigated in Section 5.1. In this study the purpose of the addition of area weighting to the degree discomfort hours was originally assumed to be necessary to make a better match between the two indicators of a house thermal performance in different modes. However the finding of this section shows that area weighting is not relevant for this purpose. Therefore at this time the thermal performance of free running houses is reported in degree discomfort hours *without* area weighting.

One of the key issues concerning the evaluation of annual thermal performance of houses previously identified is seasonal performance. The correlation study was also used in order to investigate the strength of the correlation between the seasonal behaviours of the houses. The result shows a stronger correlation in their winter performance than their summer performance (Figure 7-3). This observation accords with the greater effect of natural ventilation in improving the summer performance of free running houses. While the AccuRate software accounts for the effect of natural ventilation in computing cooling energy requirements, this observation nevertheless points to a key difference between the characteristics of the summer performance of free running and of conditioned houses.



a) Winter performance **b) Summer performance**

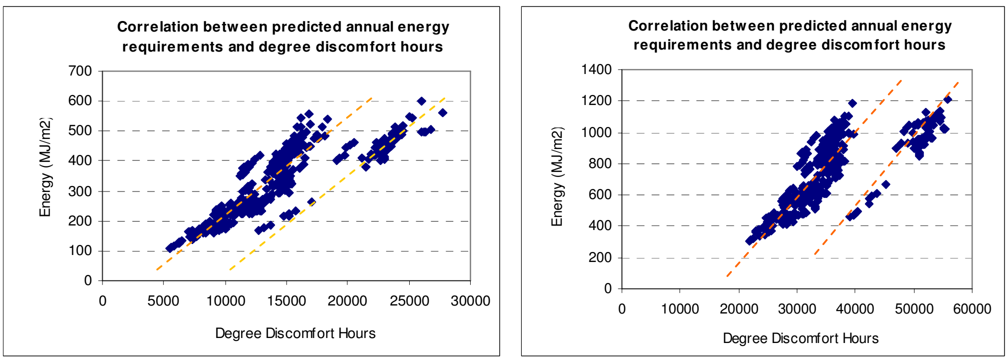
Figure 7- 3 Correlation between the seasonal performances of the typical houses in the Canberra climate

The above observation, which shows that only about 26% of the cooling energy requirement cannot be predicted by degree cooling discomfort hours, raises some doubts about the apparently different conclusions by Ghiaus (2006). She demonstrated that free running temperature may be used instead of balanced temperature in an energy estimation method and proposed a measurement related to the energy saving and the applicability of free cooling by the probabilistic distribution of degree-hours as the function of outdoor temperature and time. However, she ignored the effect of occupancy, which is a main parameter influencing variation in indoor temperature. Her method needs to be tested for other climate types to examine its accuracy.

7.1.2 Correlations between the thermal performances of the simulated houses in different operation modes

The correlation between the indicators of house thermal performances was investigated for all simulated samples and in both climates of Sydney and Canberra. Input data for the analysis was the output of simulations for the typical houses that were reported in Chapter 6. A total number of 620 samples simulated separately in free running and conditioned mode for the Sydney and then Canberra climate were applied to the data set.

Figure 7-4 notes that the correlation between these indicators is, as was expected, positive and strong. It was strong in both the climates of Sydney (r^2 = 0.69) and Canberra (r^2 = 0.56). On a bivariate basis, it suggests that 69% and 56% of the variation in predicted energy (MJ/m^2) in the Sydney and Canberra climates respectively can be explained statistically by its relation to DDH. The scatter diagrams in Figure 7-4 demonstrate the strength of that relationship. Nevertheless, a close observation of the points in the figure for both climates suggests that there appear to be at least two, or maybe three, separate linear clusters of points. Because of this observation it was decided to separate the simulated models into the specific pairs, namely SS/DS and HW/LW.

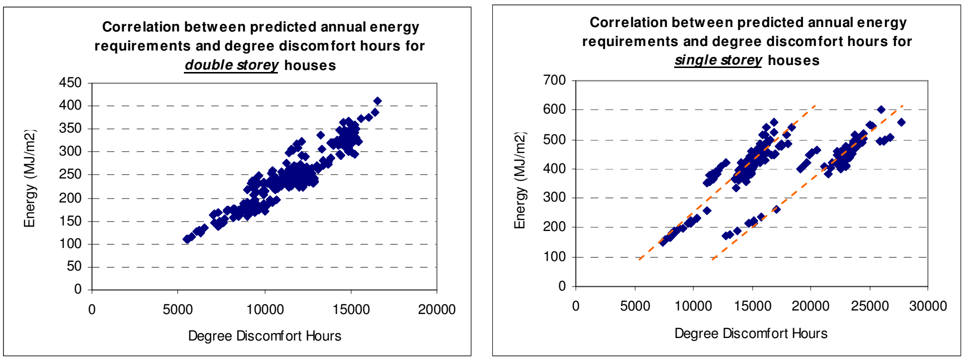


a) Sydney (r^2 = 0.69) b) Canberra (r^2 = 0.56)

Figure 7- 4 Correlation between the indicators of house thermal performance in Sydney and Canberra climates

Earlier a significant difference was observed between the thermal performances of the SS and DS houses in the parametric sensitivity analysis. To clarify the relationships in Figure 7-4 further, parallel correlation analyses were then conducted for double-storey and single-storey houses (Figure 7-5). The process was performed for both Sydney and Canberra climates. As similar results were observed among the data for both Sydney and Canberra, for clarity the result here is reported only for the Sydney climate.

The data points in Figure 7-5 (a), which are limited to the double storey cases, describe a much clearer linear relationship between the variables, with r^2 = 0.88. The results for single storey cases are equally clear- there are two separate linear clusters of data points. Given the evident spread between those two clusters, it is not surprising that for the single storey cases as a whole the correlation, though still strong, is now (r^2 = 0.39).



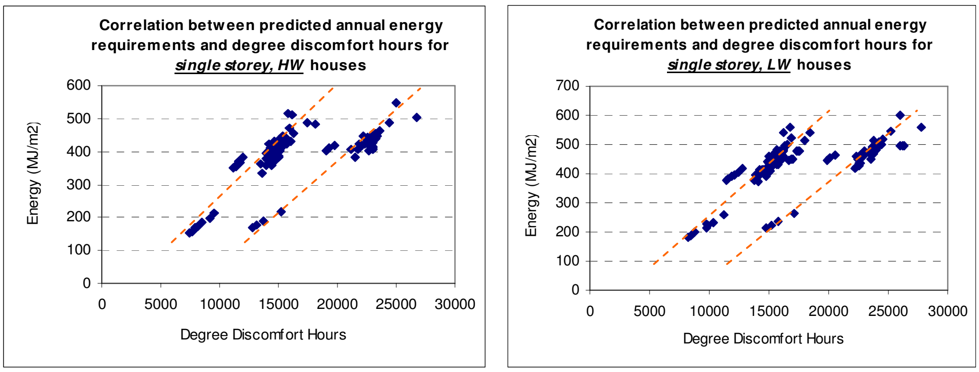
a) Double Storey (r^2 = 0.88) **b) Single Storey (r^2 = 0.39)**

Figure 7- 5 Correlation between the indicators of house thermal performance among DS and SS houses in the Sydney climate

The strong correlation in DS houses is related to the architectural design of these houses. As noted before, the thermal performance of a house strongly depends on the thermal performance of its living zone, because this zone is occupied for the majority of time in all defined occupancy scenarios. Because the bed zone is generally disposed above the living zone in the DS houses, the external surface area of the living zone in this house type is typically less than that in single storey houses. Therefore the free-running performance of a single storey house is more affected by outdoor climate than that of a DS house. The difference between the free-running and conditioned performances of a single storey house is then greater than that in a double storey house.

This observation points to a key difference between the characteristic thermal performance of two storey and single storey houses, and reflects immediately on the likely reliability of any system which assesses those house types together under a single rating framework.

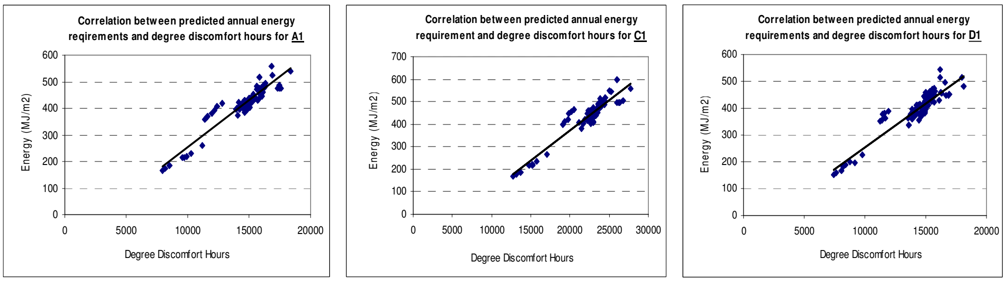
Figure 7-5 (b), shows that there appear to be two or three separate linear clusters of points in single storey houses. This observation led to a decision to separate the samples into the two generic house construction forms: ‘heavyweight’ and ‘lightweight’, which are a key variable in the simulation data set. Figure 7-6 (a) and (b) focuses on the single storey cases and describes the impact of the LW versus HW variable on the relationship indicated in the previous scatter plot (in Figure 7-5, a). As it happens, the introduction of the HW/LW variable did nothing to clarify the meaning of the two clusters of linear points that appeared in Figure 7-6(a).



a) Heavy Weight (r^2 = 0.38) **b) Light Weight (r^2 = 0.40)**

Figure 7- 6 Correlation between the indicators of house thermal performance among SS houses with different construction in the Sydney climate

Parallel correlation analyses were then conducted for three groups of the single storey houses, which were modelled on the basis of the typical SS models, A1, C1 and D1 as specified in Section 4.4. The correlation for all three groups was strong (r^2 = 0.8); however, the distribution of points on the scatter plots in Figure 7-7 suggest more than one linear cluster of points in each group. These observations suggest that the effects of the building envelope on the quality of the thermal performance of the building depend on its operation mode. This interpretation, which already was a conclusion in the parametric sensitivity analysis, is taken further in the following section to find the contribution of each parameter to improving the thermal performance of a house in different modes.



a) (r^2 = 0.88) **b) (r^2 = 0.87)** **c) (r^2 = 0.86)**

Figure 7- 7 Correlation between the indicators of house thermal performance among SS houses in the Sydney climate

7. 2 Multivariate regression analysis

Multivariate regression analysis is one of the most widely used statistical techniques for investigating and modelling the relationship between one variable referred to as a response or dependent variable, and one or more other variables, called predictor or independent variables. It is typically used to identify those variables among a series of predictors that best predict the variation in a dependent variable, and to provide an estimate of how much variation in the dependent variable can be explained by variation in those predictor variables. Applications of regression are numerous in every field and occur in the building performance research whether based on experimental or simulated data (Krichkanok, 1997; Thornton, Nair and Mistry, 1997; Ben-Nakhi and Mahmoud, 2004). Also of interest is that regression analysis applied exclusively to simulated data underpins the development of some current rating tools (for example FirstRate, the mandated house energy rating tool in the state of Victoria, Australia) and the regulatory impact studies that support them (Energy Efficient Strategies, 2002).

A multivariate regression analysis was applied in this study to determine which parameters of building design features contributed most to overall thermal performance improvement. The main objective of this task was to compare the contribution of the parameters to improving the thermal performance of houses in different operation modes or, in other words, to reducing the annual energy requirement and the degree discomfort hours of houses. Therefore, even a limited contribution of a parameter is important for the purpose of this study.

It should be mentioned that the methodology, and specifically regression coefficients, are valid for use only in configurations with parameters within the range used in this study. Nonetheless the building parameters used in the simulations covered a broad range of possible house configurations in NSW. The data used was generated from certain types of building and location. Other locations and different types of buildings, such as town houses, duplex houses and apartments may yield different regression coefficients. However the general trends observed in this project can be applied to other residential models, provided there is sufficient understanding of the study's limitations.

7.2.1 Data preparation

The simulations for six typical houses were selected to produce the data-base for multivariate regression analysis. The main parameters of design features simulated in the sensitivity analysis were carefully selected for the parametric simulations. Table 7-1 lists the 17 variables which were amenable to appropriate variation by the simulation software, and were considered likely to have significant impact on predicted annual energy requirements and degree discomfort hours.

A total number of 2328 simulations was undertaken for the following multivariate regression analysis. This number is a combination of 1164 simulations, which were run two times separately for the Sydney and then the Canberra climate. This number is sufficient for a reliable regression analysis.

7.2.2 Categorical independent (or predictor) variables

One of the most important tasks in regression modelling is the selection of appropriate predictor variables (Gunst and Mason, 1980; Montgomery and Runger, 1999; Beirlant, Goegebeur, Teugels et al., 2005) to be used in subsequently defining the response variable. In most instances it is desirable that the selected variables make physical sense as well as being useful predictors. Sometimes previous experience or underlying theoretical considerations can help to establish the predictor variables (Montgomery and Runger, 1999).

For the purpose of this study fourteen parameters, which are specified in Section 4.6, were selected as the main predictors of thermal performance of a house. The likely effect of these parameters was observed from the sensitivity analysis. These parameters also are those identified in other studies as the main fabric building variables which affect the thermal performance of buildings (Krichkanok, 1997; Willrath, 1998).

It was also observed that the main differences between the annual thermal performances of simulated houses were related to three main characteristics of the base models, namely house construction (heavyweight and lightweight), house type (single storey and double storey) and house plan (6 typical house designs). Therefore, these three main 'design' characteristics of base models as three parameters were selected to be added to the previous fourteen 'fabric' predictors. The basic parametric set of predictor variables is presented in Table 7-1.

'Climate' could be added as a variable in the parametric set because a building performance obviously depends on the climate, and an efficient house design is strongly concerned with the type of climate involved. The Sydney and Canberra climates both are classified as moderate; however the climate of the latter is somewhat severe, particularly in winter. Therefore, as was noted from the parametric sensitivity analysis, a design for the Sydney climate would differ from that for the Canberra climate. However, this analysis is concerned with the strength and contribution of a building's fabric in improving the thermal performance of buildings, and climate is an environmental variable. The climate therefore was not included in the set of predictor variables and the process of multivariate regression analysis was divided into two parallel processes for the two climates of Sydney and Canberra.

Table 7- 1 Basic parametric set for multi variates' regression analysis

	Variable	Design feature (building fabric)	Parametric set
1	X01	Ceiling insulation (Resistance)	0, 1, 2, 3, 4
2	X02	Wall insulation (resistance)	0, 1, 1.5, 2, 3
3	X03	Floor insulation (Resistance)	0, 1, 1.5, 2
4	X04	Internal wall (U value)	
5	X05	Infiltration (Air change per hour)	0,1,2,5
6	X06	Window covering (Resistance)	0, 0.03, 0.055, 0.33

	Variable	Design feature (building fabric)	Parametric set
7	X07	Openable window (%)	25(base), 50%, 75%
8	X08	Shading device (Eave length)	0, 450, 600, 1000mm
9	X09	Orientation (Degree)	0, 45, 90, 135, 180, 225, 270, 315
10	X10	Glazing type (Shading coefficient)	1, 0.52, 0.70, 0.88, 0.60
11	X11	Roof colour (Absorbance)	30%, 50%, 85%
12	X12	Wall colour (Absorbance)	30%, 50%, 85%
13	X13	Window to wall ratio (N&S) (%)	0(base)[33], 15%, 25%
14	X14	Window to wall ratio (E&W) (%)	0(base), 15%, 25%
15	X15	House type	Single storey, Double storey
16	X16	House construction	Heavy weight, Light weight
17	X17	House plan	6 typical plans

7.2.3 A multivariate analysis of building thermal performance

To determine the contribution of each of the specified 17 parameters in predicting the thermal performance of a house, the multivariate regression analysis required that all variables be entered into the analysis in a single step. A method which is known as 'Enter'[34] procedure was adopted in this study using SPSS software.

The standardized coefficients correspond to beta weight and a pseudo r^2 statistic is available to summarize the strength of the relationship between the parameters of the design features and indicators of house thermal performance. A standardized coefficient was used in the interpretation, as each parameter was measured in different units.

Using the multiple regression analyses, Table 7-2 indicates how important the 17 variables are as predictors in two contexts: predicting energy (MJ/m^2) for conditioned houses and predicted DDH for free running houses. This table indicates that the 17 variables (or parameters) do very well in explaining any variation in energy as the

---

[33] 0 (base) refers to the percentage of window to wall ratio in the typical houses which is different for different models. It does not mean that the ratio of window to wall is 0.

[34] There are several selection methods for specifying how independent variables are entered into an analysis. These methods are: enter, stepwise, remove, backward and forward. Enter is a procedure for variable selection in which all variables in a block are entered in a single step.

dependent variable, where r^2= 0.84 in the Sydney climate and r^2= 0.81 in the Canberra climate.

In contrast, these predictors explain only 53% and 40% of the variation in the DDH for free running houses in the Sydney and Canberra climate, respectively. In other words, the same 17 variables do not explain nearly half the variation in DDH for free running houses.

Table 7- 2 Estimated r^2 from multivariate regression analysis between the annual thermal performances and design features for the Sydney and Canberra climates

Climate	Predicted variable	predictor variables	r^2
Sydney	Conditioned performance (MJ/m^2)	17 design features	0.84
	Free running performance (DDH)	17 design features	0.53
Canberra	Conditioned performance (MJ/m^2)	17 design features	0.81
	Free running performance(DDH)	17 design features	0.40

This result indicates a significant difference between a desirable design for conditioned houses and that for free running houses. The amount of unexplained variance for free running houses should certainly be a starting point for further research.

From Table 7-2 it can be inferred that free running houses are more sensitive to different climates than are conditioned houses. When the simulated climate was changed from Sydney to Canberra the effect of the 17 parameters on predicting the annual energy requirements of conditioned houses changed only by 3% (84%- 81% = 3%), whereas the effect of these parameters on predicting DDHs for free running houses changed by 13% (53% - 40% = 13%). This implies that climatic parameters are more important in designing an efficient free running house than for an efficient conditioned house.

This significant effect of climate on the thermal performance of a free running house compared to that on conditioned houses means that if a designer wishes to design a naturally ventilated house rather than an air-conditioned one, a focus on the immediate climate impact is likely to give significantly greater dividends than attention to the fabric of the building. That, however, is not to say that the quality of the fabric cannot help in improving the thermal performance of a free running house. This is to highlight that different design types require different attitudes for the provision of an efficient design.

The relative importance of each of the seventeen building fabric variables (design features) explaining the variations of thermal performances of the simulated houses is the focus of Tables 7-3 and 7-4. Although the values of some of these are not statistically significant, all of the variables have been retained for further analysis as effective parameters for improving the thermal performance of buildings.

Generally a statistically insignificant value for some of the parameters is explained by the range considered for changing those parameters in the typical base cases. For instance, 'windows to wall ratio' with a significance greater than 0.05 is not statistically an important variable for predicting annual thermal performance of a house. Parametric sensitivity analysis also illustrated that increasing the proportion of windows in the typical houses by 15% and 25% could only make about 1% changes in the annual thermal performance of those houses. However, a greater increase in the size of windows will result in greater changes in the annual thermal performance of the typical houses and therefore this parameter could then have significant value in the statistical analysis. Moreover the effect of this parameter will change under the interaction effect of other parameters. The absolute size of windows is relevant for the thermal performance of buildings in relation to cooling needs in summer (Persson, Roos and Wall, 2006). It has been identified as an important parameter by experts, home-buyers and stakeholders in a general sense in the development of house ratings (Krichkanok, 1997) and specifically as a parameter which plays an important role in improving the energy efficiency of buildings. Therefore even design features with low (statistical) significance have not been removed in the following analysis.

A comparison has been made between the importance of the 17 design features in different house modes and on the basis of different indicators. By a considerable margin the most variation in the thermal performance of the typical houses was related to the house type (X15), namely double storey and single storey houses. This situation can be seen in both conditioned and free running mode operations. It is also similar in both Sydney and Canberra climates. This provides evidence of the significant effect of house type in evaluating the thermal performance of a house; which should be taken into consideration in an accurate house evaluation system.

Table 7- 3 Ranking of design features due to their importance on the houses' thermal performance (based on standardised regression coefficient) for the Sydney climate

Sydney climate								
Free running (Degree Discomfort Hours without area weighting as indicator)					**Conditioned mode (Energy MJ/m² as indicator)**			
Rank	Variable	|β|	Sig.		Rank	Variable	|β|	Sig.
1	X15	0.6	0		1	X15	0.749	0
2	X1	0.265	0		2	X1	0.36	0
3	X16	0.242	0		3	X16	0.274	0
4	X5	0.084	0.005		4	X5	0.099	0
5	X3	0.068	0.025		5	X11	0.091	0
6	X9	0.059	0.056		6	X2	0.079	0
7	X4	0.049	0.089		7	X17	0.059	0.001
8	X10	0.046	0.13		8	X9	0.057	0.002
9	X8	0.042	0.165		9	X12	0.039	0.025
10	X17	0.038	0.202		10	X4	0.024	0.16
11	X11	0.027	0.352		11	X13	0.023	0.194
12	X2	0.023	0.457		12	X14	0.023	0.179
13	X6	0.021	0.483		13	X3	0.018	0.311
14	X14	0.015	0.619		14	X6	0.016	0.343
15	X13	0.011	0.711		15	X7	0.01	0.563
16	X12	0.01	0.734		16	X10	0.01	0.573
17	X7	0.002	0.935		17	X8	0.006	0.722

Table 7- 4 Ranking of design features due to their importance on the houses' thermal performance (based on standardised regression coefficient) for the Canberra climate

Canberra climate								
Free running (Degree Discomfort Hours without area weighting as indicator)					**Conditioned mode (Energy MJ/m² as indicator)**			
Rank	Variable	|β|	Sig.		Rank	Variable	|β|	Sig.
1	X15	0.531	0		1	X15	0.692	0
2	X1	0.227	0		2	X1	0.377	0
3	X16	0.207	0		3	X16	0.327	0
4	X5	0.089	0.008		4	X2	0.124	0
5	X8	0.065	0.054		5	X5	0.121	0
6	X10	0.061	0.071		6	X17	0.093	0
7	X17	0.048	0.157		7	X9	0.047	0.014

Canberra climate								
8	X9	0.045	0.195		8	X8	0.039	0.038
9	X2	0.04	0.24		9	X3	0.036	0.052
10	X3	0.04	0.236		10	X10	0.022	0.249
11	X4	0.039	0.22		11	X11	0.02	0.254
12	X11	0.019	0.563		12	X4	0.019	0.299
13	X6	0.018	0.573		13	X13	0.018	0.311
14	X12	0.014	0.678		14	X14	0.018	0.32
15	X14	0.008	0.803		15	X7	0.015	0.408
16	X7	0.008	0.809		16	X6	0.014	0.446
17	X13	0.003	0.921		17	X12	0.011	0.549

In parallel analyses shown in Tables 7-3 and 7- 4, for both conditioned and free running modes and in both climates, the most important predictors, in order, were house type (X15), ceiling insulation (X3) and house construction (X17). Beyond that point both the sequence and the statistical significance of the variables (according to their beta coefficient) vary considerably. For instance, in the Sydney climate, roof colour (X11) and wall insulation (X2) are clearly significant in the conditioned mode analysis, but are well down the list and far from statistically significant in the free running houses. Only the multivariate analyses have shown other factors to be more important.

These observations once again have the clear implication that it cannot be assumed that a design for good predicted building performance in conditioned mode achieves good thermal performance in free running mode. A design for conditioned buildings is reasonably related to the building envelope characteristics and to the fabric of the building. Ultimately it relates to those attributes that protect or isolate the building interior from environmental loads in order to maintain indoor thermal comfort conditions with minimum energy consumption used to overcome those loads. The determinants of free-running performance are more complex, as has long been implied by the alternative terminology ‘climate responsive’. Evidence for this argument was seen before in the parametric sensitivity analysis.

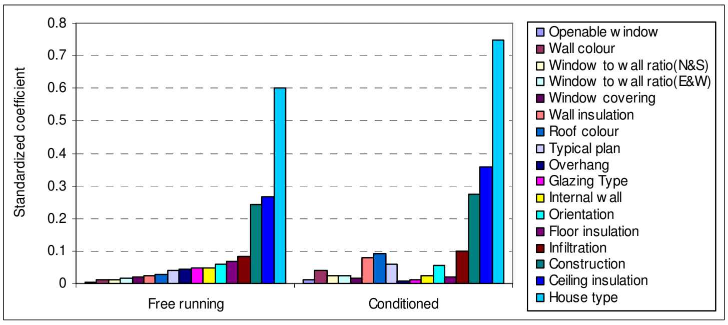
7.3 Conclusion

The use of multiple regression analysis in this study is somewhat different from the way it is used in studies which are developed on the basis of real data. This is mainly due to the inclusion of insignificant parameters. The significance of parameters is important from the statistician's point of view when it is intended to develop a model of prediction based on the significance of predictor variables. However, the importance of the 17 parameters considered here has been demonstrated in other studies, as mentioned above. Moreover, if more sample types were included in order to consider the interaction effect of all the parameters, simulations of more than ten thousand models would be required, which is well beyond the scope of this study. In this case it has simply been proved that the 17 parameters in this study are important, as was also observed in the parametric sensitivity analysis reported in Chapter 6. The purpose of the multivariate regression analysis in this case was to investigate whether the effect of each parameter on the performance of a house is similar in both conditioned and free running operation mode or not, in order to establish the factors that need to be considered by those attempting to design efficient buildings in different operation modes.

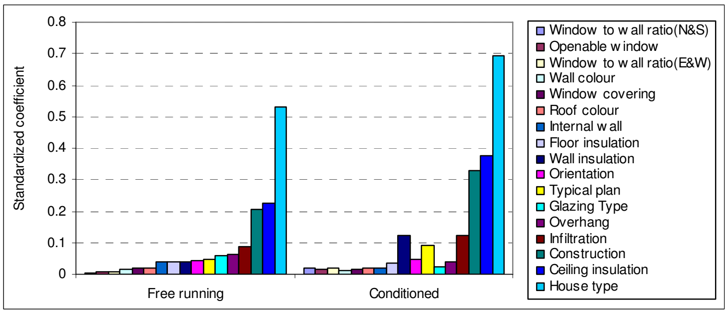
The results reported in this Chapter effectively confirm the hypothesis. It has been shown that the contribution of design features or building fabric to the improvement of the thermal performance of a house depends on the house operation mode.

Priorities in application for changing design features to improve the thermal performance of a house in free running mode are illustrated in Figure 7-8. This figure depicts the situation in which design features were ranked in order, on the basis of their strength in changing the thermal performance of the simulated houses in the free running operation mode. This ranking is not the same for modifying the thermal performance of the same houses in conditioned operation mode.

The result of this statistical analysis, confirming the results from parametric sensitivity analysis, demonstrates that design advice inferred from a rating tool to improve the thermal performance of a free running house should differ from that for a conditioned house. It therefore implies that the regulatory framework for rating free-running houses should be different from that for conditioned houses. The objective of proposing such a framework will be developed in the next chapter.



a) Sydney



b) Canberra

Figure 7- 8 A comparative analyses on the rankings of design feature in different house modes

Chapter 8

Application of a new framework for House Rating Schemes

This chapter describes the final outcome of the study and addresses its main objective, namely the proposal of a suitable house running rating scheme. For this purpose a framework for producing an aggregation of free running and conditioned rating schemes is put forward. The reliability of the proposed rating framework is supported by a demonstration of its theoretical sensitivity in improving efficient design quality.

8.1 Rating of building thermal performance

A house rating system scores a house by comparing its thermal performance with other houses, which are given the same conditions of climate, user behavior patterns and house operation. An accurate house rating system should not discriminate against any type of house design. Chapters 6 and 7 have reached the preliminary conclusion that the current energy-based rating schemes, as exemplified by AccuRate, are likely to discriminate against single storey houses as opposed to double storey houses, and free running houses as against conditioned houses. To avoid such discrimination the following steps are proposed for rating schemes:

- Separating free running houses from conditioned houses
- Separating double storey houses from single storey houses
- Determining the score boundaries for each group separately
- Aggregating the score bands of a house for its free running and conditioned performances to produce one score for the final evaluation of the thermal performance of the house

It would appear from an investigation into existing rating schemes (see Chapter 2) that there is no standard method for defining performance bands ratings based on five stars, such as the NatHERS, or ten stars, such as AccuRate. The choice of procedure used for determining the boundaries of each star-scale varies from place to place, depending on the particular legislation involved in the promotion of energy efficiency. However, the star categories provide sufficient and meaningful differentiation between the relative efficiencies of different houses in the same condition and operation mode.

To determine the score bands for the ratings in this study, first five separate efficiency categories were adopted for free running (HFRS) and conditioned houses (HERS) separately, in which a range of scores is represented by stars. Then, in order to combine the two rating systems, a ten star rating scheme was adopted. The ten categories differentiate sufficiently between the efficiency of houses' architectural design in both their free running and conditioned performances.

One method used for specifying the star bands is based on the theory of educational measurement and evaluation (Krichkanok, 1997). The five letter system (A, B, C, D, and F) is commonly used in education and attempts to classify individuals in terms of their performance. There are two types of measurements related to specific standards, namely 'criterion- referenced' and 'norm- referenced' grading (Ebel and Frisbie, 1991). The essential difference between these two measurements is in the quantitative scale used to express how efficient an individual performance is.

Criterion referenced measurement is based on absolute standards. Grading by this system depends on a specific performance being demanded for a certain category and is used when individuals are measured against defined criteria. This method can be used to define the score bands in HRS if the range of categories to achieve required performance levels is specified. However, there is no one standard set of criteria available, as these differ from place to place, and to establish definite specifications would require an investigation into a broad range of architectural designs and varieties of house sizes in order to find all the possible worst and the best performances. This was beyond the scope of this study so that this method could not be used here for grading houses.

Norm- referenced measurement is based on relative standards. The purpose of a norm-referenced instrument is to compare the performance of an individual with the performance of other individuals. The scale is usually anchored on the middle of some average level of performance for a specific set of individuals. The units on the scale represent the distribution of performance above and below the average level. For the development of score bands for HRS in this study, norm-referenced grading was adopted for the range of available data. The scales will change from place to place depending on the performance figures available and so grading was separated for Sydney and Canberra.

'Grading on a curve' is a common technique for grading performance in norm-referenced measurement. It is based on frequency distribution, in which the curve should represent a normal distribution. The categories should represent equal intervals on the score scale. Mean and standard deviation of the distribution of performance scores is generally used for determining the range of each category. The range of the normal curve can then be divided into equal segments of standard deviation according to the number of expected categories.

In adopting the *grading on the curve* technique, in this procedure the 1212 estimated values of thermal performance of simulated houses in different operation modes, which were representative of house thermal performances in Sydney and Canberra, were used. As previously noted, the process was staged separately for free running houses and then for conditioned houses. The score bands were also determined separately for single storey and double storey houses in each operation mode.

Figures 8-1 (a, b) and 8-2 (a, b) show the frequency distribution of the annual energy requirements of conditioned houses and the annual degree discomfort hours of free running houses in the Sydney climate. The distribution seems to be normal, although in terms of skewness[35] and kurtosis[36] it can be seen that the distributions are not completely normal. However, as these deviations are relatively slight, the assumption of normal distribution was accepted.

The range of energy requirements and degree discomfort hours is dealt with separately in defining star bands for single storey and double storey houses, with star bands for conditioned houses being defined on the basis of the mean of annual energy requirements and standard deviation for each group, while the star bands for these houses in the free running mode are defined on the basis of the mean of annual degree discomfort hours and standard deviation of the related group. The proposed range of

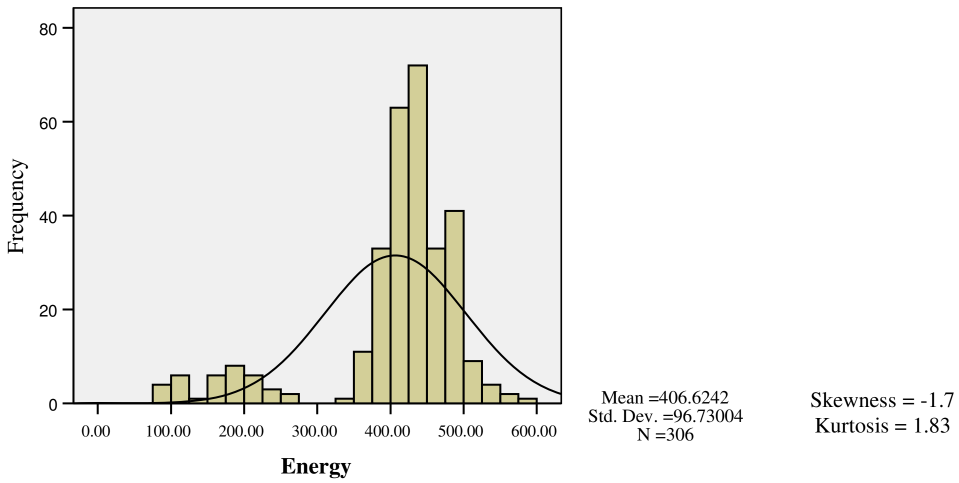
---

[35] Skewness is a measure of symmetry

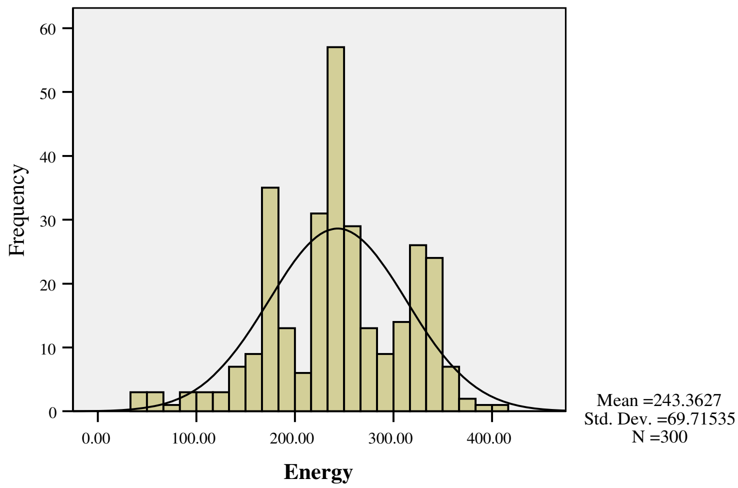
[36] Kurtosis is a measure of whether the data are peaked or flat relative to a normal distribution

energy requirements and degree discomfort hours for each star rating is presented in Tables 8-1 and 8-2 for the Sydney climate, and in 8-3 and 8-4 for the Canberra climate.

The *distributions* of energy requirements and DDHs for the Canberra climate appeared to be normal and similar to those observed for the Sydney climate, and therefore the figures for the former climate are not separately illustrated here. However, the mean values and standard deviations in each climate were different for each house type (DS and SS). Therefore, the star bands for each group in each climate were, of course, determined on the basis of the standard deviation and mean values related to that group.

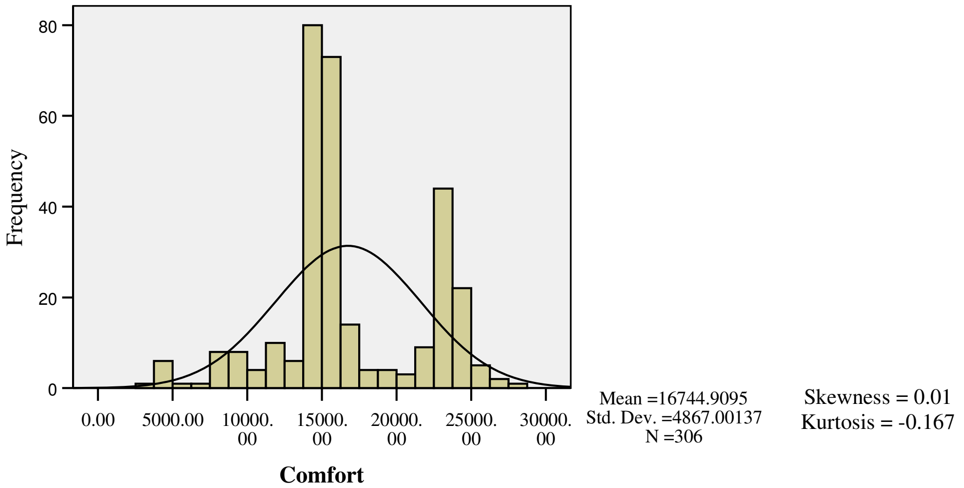


a) Single storey houses

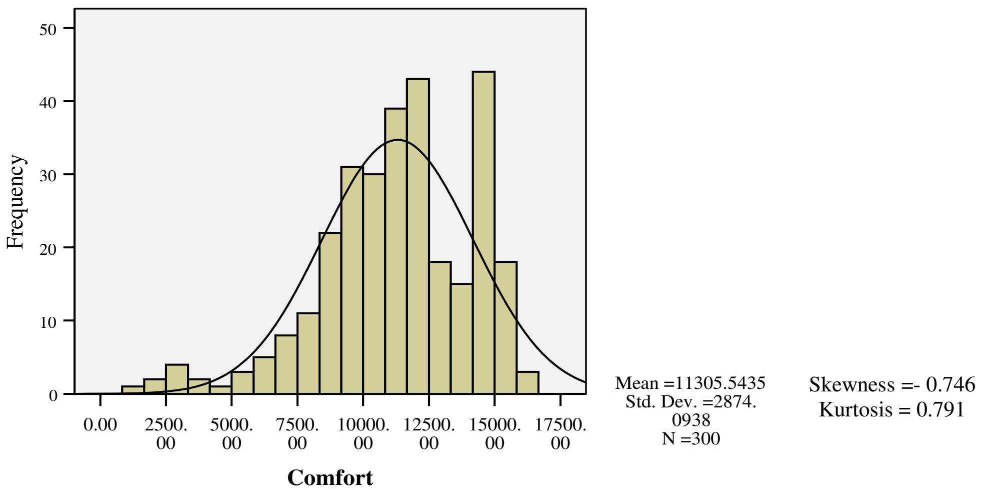


b) Double storey houses

Figure 8- 1 Distribution of estimated annual energy requirements in the Sydney climate



a) Single storey



b) Double storey

Figure 8- 2 Distribution of annual degree discomfort hours in the Sydney climate

Table 8- 1 Proposed range of energy requirements and degree discomfort hours for each star rating for single storey houses in Sydney

Degree Discomfort Hours (DDH)	Energy requirement (MJ/m^2)	Rating of energy performance	Range on normal curve (from mean)
5794 or less	188 or less	5 Star	- 2.25 Std dev. or lower
5794<DDH≤ 8227.5	188<E≤ 237	4.5 Star	- 2.25 to - 1.75 Std dev.
8227.5<DDH≤ 10661	237<E≤ 285	4 Star	- 1.75 to - 1.25 Std dev.
10661<DDH≤ 13094.5	285<E≤ 334	3.5 Star	- 1.25 to - 0.75 Std dev.
13094.5<DDH≤ 15528	334<E≤ 382	3 Star	- 0.75 to - 0.25 Std dev.
15528<DDH≤ 17961.5	382<E≤ 430	2.5 Star	- 0.25 to + 0.25 Std dev.
17961.5<DDH≤ 20395	430<E≤ 479	2 Star	+ 0.25 to + 0.75 Std dev.
20395<DDH≤ 22828.5	479<E≤ 527	1.5 Star	+ 0.75 to + 1.25 Std dev.
22828.5<DDH≤ 25262	527.5<E≤ 576	1 Star	+ 1.25 to + 1.75 Std dev.
25262<DDH≤ 27695.5	576<E≤ 624	0.5 Star	+ 1.75 to + 2.25 Std dev.
More than 27695.5	More than 624	0 Star	+ 2.25 Std dev. or higher
Mean = 16744.9095 Std. Dev.= 4867.00137	Mean = 406.6242 Std.Dev.= 96.73004		

Table 8- 2 Proposed range of energy requirements and degree discomfort hours for each star rating for double storey houses in Sydney

Degree Discomfort Hours (DDH)	Energy requirement (MJ/m^2)	Rating of energy performance	Range on normal curve (from mean)
3402or less	86.8 or less	5 Star	- 2.25 Std dev. or lower
4839<DDH≤ 6276	86<E≤ 121	4.5 Star	- 2.25 to - 1.75 Std dev.
6276<DDH≤ 7713	121<E≤ 156	4 Star	- 1.75 to - 1.25 Std dev.
7713<DDH≤ 9150	156<E≤ 191	3.5 Star	- 1.25 to - 0.75 Std dev.
9150<DDH≤ 10587	191<E≤ 226	3 Star	- 0.75 to - 0.25 Std dev.
10587<DDH≤ 12024	226<E≤ 261	2.5 Star	- 0.25 to + 0.25 Std dev.
12024<DDH≤ 13461	2601<E≤ 296	2.Star	+ 0.25 to + 0.75 Std dev.
13461<DDH≤ 14898	296<E≤ 331	1.5 Star	+ 0.75 to + 1.25 Std dev.
14898<DDH≤ 16335	331<E≤ 366	1 Star	+ 1.25 to + 1.75 Std dev.
16335<DDH≤ 17772	366<E≤ 400	0.5 Star	+ 1.75 to + 2.25 Std dev.
More than 17772	More than 400	0 Star	+ 2.25 Std dev. or higher
Mean = 11305.5435 Std. Dev.= 2874.0938	Mean = 243.3627 Std. Dev.= 69.71535		

Table 8- 3 Proposed range of degree discomfort hours and energy requirements for each star rating for single storey houses in Canberra

Degree Discomfort Hours (DDH)	Energy requirement (MJ/m^2)	Rating of energy performance	Range on normal curve (from mean)
18312 or less	451or less	5 Star	- 2.25 Std dev. or lower
18312 <DDH≤ 22984	451<E≤ 549	4.5 Star	- 2.25 to - 1.75 Std dev.
22984<DDH≤ 27656	549<E≤ 646	4 Star	- 1.75 to - 1.25 Std dev.
27656<DDH≤ 32328	646<E≤ 743	3.5 Star	- 1.25 to - 0.75 Std dev.
32328<DDH≤ 37000	743<E≤ 840	3 Star	- 0.75 to - 0.25 Std dev.
37000<DDH≤ 41672	840<E≤ 937	2.5 Star	- 0.25 to + 0.25 Std dev.
41672<DDH≤ 46344	937<E≤ 1034	2.Star	+ 0.25 to + 0.75 Std dev.
46344<DDH≤ 51016	1034<E≤ 1131	1.5 Star	+ 0.75 to + 1.25 Std dev.
51016<DDH≤ 55688	1131<E≤ 1228	1 Star	+ 1.25 to + 1.75 Std dev.
55688<DDH≤ 60360	1228<E≤ 1325	0.5 Star	+ 1.75 to + 2.25 Std dev.
More than 60360	More than 1325	0 Star	+ 2.25 Std dev. or higher
Mean = 39336.7957 Std. Dev.= 9344.12218	Mean = 889. 4722 Std. Dev.= 194.4951		

Table 8- 4 Proposed range of degree discomfort hours and energy requirements for each star rating for double storey houses in Canberra

Degree Discomfort Hours (DDH)	Energy requirement (MJ/m^2)	Rating of energy performance	Range on normal curve (from mean)
183943 or less	239.6or less	5 Star	- 2.25 Std dev. or lower
18393 <DDH≤ 21182	239.6<E≤ 319.4	4.5 Star	- 2.25 to - 1.75 Std dev.
21182<DDH≤ 23971	319.4<E≤ 399.2	4 Star	- 1.75 to - 1.25 Std dev.
23971<DDH≤ 26760	399.2<E≤ 479	3.5 Star	- 1.25 to - 0.75 Std dev.
26760<DDH≤ 29549	479<E≤ 558.8	3 Star	- 0.75 to - 0.25 Std dev.
29549<DDH≤ 32338	558<E≤ 638	2.5 Star	- 0.25 to + 0.25 Std dev.
32338<DDH≤ 35127	638<E≤ 718	2.Star	+ 0.25 to + 0.75 Std dev.
35127<DDH≤ 37916	718<E≤ 798	1.5 Star	+ 0.75 to + 1.25 Std dev.
37915<DDH≤ 40704	798<E≤ 878	1 Star	+ 1.25 to + 1.75 Std dev.
40704<DDH≤ 43493	878<E≤ 957	0.5 Star	+ 1.75 to + 2.25 Std dev.
More than 43493	More than 957	0 Star	+ 2.25 Std dev. or higher
Mean = 30943.8994 Std. Dev.= 5577.45934	Mean = 598. 734 Std.Dev.=159.62371		

Ideally the score of a house performance should be represented by one indicator only, in order to simplify the condition for comparing and rating buildings, and this is found in international rating systems. However, since in this study it was found that performances differed between conditioned and free-running houses, two separate scores were computed for HFRS and HERS. In order to reduce this to one single score for the architectural design of a house, a combination of the two ratings was thought to be desirable. A technique for combining the two rating systems is the aggregation of the scores of free running and conditioned performances of a house described below.

8.2 The combination of two rating systems

A new star band could be obtained by simply adding the scores obtained from the free running and conditioned performances of a house. However such a simple aggregation would not differentiate between the value of an efficient design for a conditioned house and one for a free running house. For instance if a house achieves 5 stars in its free running rating and 2 stars in its conditioned rating, its final score (7 stars) would be similar to that of a building with 5 stars in its conditioned rating and 2 stars in its free running rating. However, these two houses should not achieve a similar score, because, their design efficiency and their characteristics are different. The first one would be suitable for free running operation while operating it as a conditioned house would result in more energy consumption for space heating and cooling than the second one.

An algorithm therefore can be employed for aggregating the two rating systems that gives more value to either an efficient free running house or an efficient conditioned house. Either of those would be rewarded depending on the policy for reducing energy requirement in the building sector. For instance, where the climate is suitable for taking the most advantages of the outdoor environment, free running houses should have priority for promoting efficient architectural design. This situation would reverse for promoting efficient conditioned houses if there is a reason for not constructing free running houses.

The method should be flexible enough to make it also applicable for all regions, whether the policy is to promote efficient conditioned houses or free running houses. This potential will make the method applicable and adjustable for national or even international use for HRS.

However this study is concerned specifically with promoting efficient free running houses. Thus it aims to give more value to these houses in a moderate climate such as Sydney's as a matter of policy in the context of sustainable development. It is intended to encourage the public to adopt free running houses in order to reduce energy consumption for space heating and cooling.

The proposed algorithm for this purpose is shown in Figure 8-3. A 10 star rating scheme is proposed for aggregating the scores of a 5 star free running and 5 star conditioned rating. The algorithm is most conveniently executed as a 'lookup table' illustrated at Figure 8-3. The 11 cells of the table correspond to the initial range of possible 'half star' ratings for conditioned performance. In each cell of the table:

- the first column allocates the probabilistic score for the conditioned performance of a house in a 5 star rating;
- the second column allocates all probabilistic scores for the free running performance of the house in a 5 star rating;
- the third column allocates the final aggregated score in which:
  - the top score is obtained from adding the conditioned rating score to the 5 star rating of the house in free running performance,
  - the other final scores allocated in the third column are produced by taking 1 score away from the resulting upper final score. This establishes a different value to the different performances of a house by rewarding the free running performance of the house.

In this sort of aggregation the final score is mostly less than the score produced from simply adding the scores of both ratings. For instance, in the first group, by adding the first two grades of free running (5) and conditioned (5) ratings, the result will be 10, which is the top star rating in the new rating system. The addition of the second grades in this group, free running (5) and conditioned (4.5), gives a sum of 9.5 but a score of 9 (10-1=9) stars is given in the proposed method of aggregation. Likewise, third grade in the same group produces 8 stars (9-1=8), for aggregating (5) stars for conditioned performance and (4) stars for the free running performance of a house.

Conditioned mode Score	Free running Score	Final Score
5	5	10
	4.5	9
	4	8
	3.5	7
	3	6
	2.5	5
	2	4
	1.5	3
	1	2
	0.5	1
	0	0
4.5	5	9.5
	4.5	8.5
	4	7.5
	3.5	6.5
	3	5.5
	2.5	4.5
	2	3.5
	1.5	2.5
	1	1.5
	0.5	0.5
	0	0
4	5	9
	4.5	8
	4	7
	3.5	6
	3	5
	2.5	4
	2	3
	1.5	2
	1	1
	0.5	0
	0	0
3.5	5	8.5
	4.5	7.5
	4	6.5
	3.5	5.5
	3	4.5
	2.5	3.5
	2	2.5
	1.5	1.5
	1	0.5
	0.5	0
	0	0
3	5	8
	4.5	7
	4	6
	3.5	5
	3	4
	2.5	3
	2	2
	1.5	1
	1	0
	0.5	0
	0	0
2.5	5	7.5
	4.5	6.5
	4	5.5
	3.5	4.5
	3	3.5
	2.5	2.5
	2	1.5
	1.5	0.5
	1	0
	0.5	0
	0	0
2	5	7
	4.5	6
	4	5
	3.5	4
	3	3
	2.5	2
	2	1
	1.5	0
	1	0
	0.5	0
	0	0
1.5	5	6.5
	4.5	5.5
	4	4.5
	3.5	3.5
	3	2.5
	2.5	1.5
	2	0.5
	1.5	0
	1	0
	0.5	0
	0	0
1	5	6
	4.5	5
	4	4
	3.5	3
	3	2
	2.5	1
	2	0
	1.5	0
	1	0
	0.5	0
	0	0
0.5	5	5.5
	4.5	4.5
	4	3.5
	3.5	2.5
	3	1.5
	2.5	0.5
	2	0
	1.5	0
	1	0
	0.5	0
	0	0
0	5	5
	4.5	4
	4	3
	3.5	2
	3	1
	2.5	0
	2	0
	1.5	0
	1	0
	0.5	0
	0	0

Conditioned mode Score | Free running Score | Final Score

Figure 8- 3 An algorithm for aggregating the scores of HERS and HFRS

A regression analysis is employed in this case to examine the sensitivity of the final score (as a dependent variable) in relation to the free running and conditioned scores (as independent variables).

The regression obtained (8.1) confirms the greater dependency of the final score on the free running performance of a house. The standardized coefficient for free running performance is 0.87 where that for the conditioned performance is 0.4.

$S = 0.40S_1 + 0.87\ S_2$ (8.1)

In other words, to produce the final score for the thermal performance of the house, the proposed new HRS gives more value to the free running performance of houses to the extent that the effect of the free running score is more than double the effect of the conditioned score. As a result a designer would be likely to give priority to free running design for improving the thermal performance of the house in order to achieve an acceptable score in the HRS. This supports the objective of the rating framework to encourage the public and architects to opt for free running houses.

However, depending on the appropriate policy for reducing energy consumption, the method could also be applied to give more value to conditioned houses, simply by transforming the method of aggregation of the two ratings. In its simplest form, where the conditioned and free running scores are transposed in the lookup table, the higher coefficient (0.87) would apply to the score for the conditioned performance of a house.

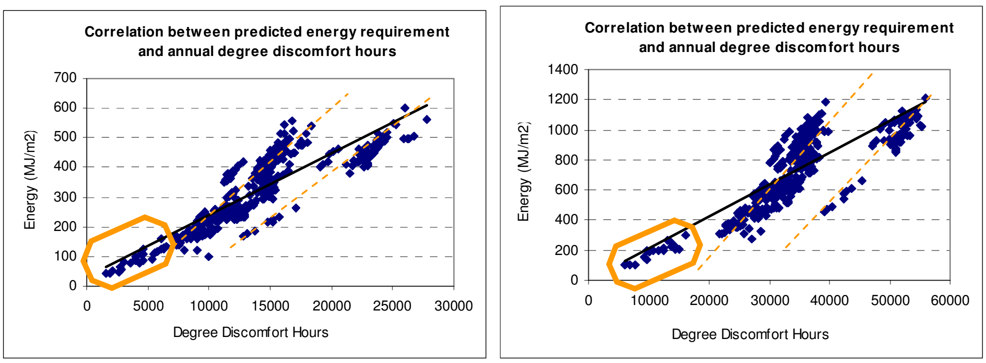
8.3 Reliability of the framework

One way to test the reliability of the proposed framework would be to test it on real houses by employing it for improving their thermal performance. However, this would need at least a few years to construct the houses and then check their performances for a year when they are occupied. This was well beyond the scope of this research, and would require further study.

In this study the reliability of the proposed framework is tested for its theoretical sensitivity to improvements in efficient design. A simulated improvement in response to the composed rating was employed to determine if the framework delivers expected sensitivity. For this purpose the following steps were taken:

- The design quality of the typical houses was improved by modifying design features in order to enhance, first the free running performance, then the conditioned performance of the houses.
- The resulting annual energy requirements and DDHs were input in a regression model to determine the correlation between the indicators of free running and conditioned performances for these 'improved' houses.
- All simulated houses were scored on the basis of the proposed rating scheme to check how their scores on the HERS changed in relation to the changes in their score on the free running component.

The linear regression showed a strong correlation between the annual energy requirements and degree discomfort hours of houses when their thermal performances were improved. The scatter plot of this situation is depicted in Figure 8-4. For specific attention the scatter plots for 'improved' houses are circled in this figure. A strong linear relationship between thermal performances of 'improved' houses is obvious. The correlation was 0.86 for the Sydney climate and 0.76 for the Canberra climate



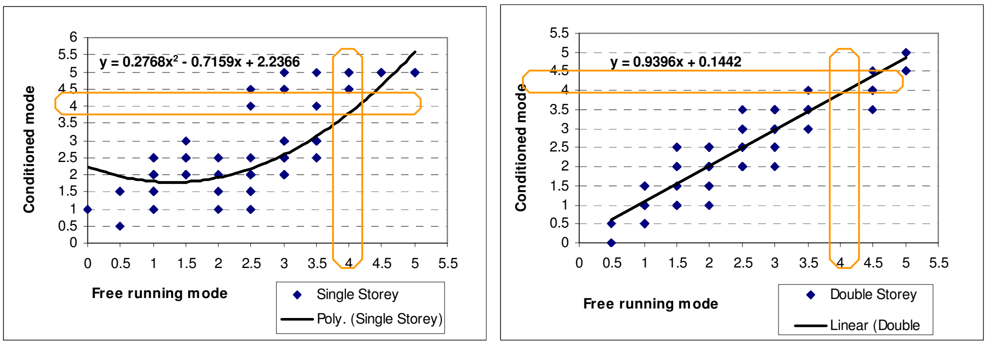
a) Sydney (r^2= 0.86 for area circled) b) Canberra (r^2= 0.76 for area circled)

Figure 8- 4 Correlation between energy requirements and degree discomfort hours

Before the improvement the correlations were 0.69 for the Sydney climate and, 0.56 for the Canberra climate (see Section 7.1.2).

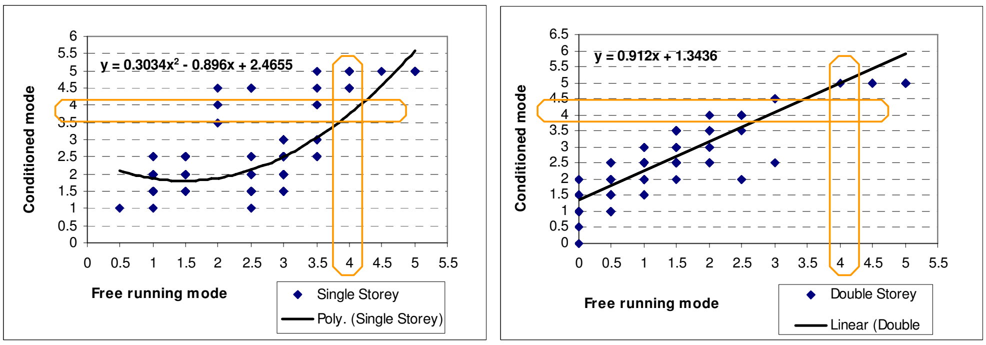
This observation implies that an efficient house design can result in good performances for a house in both operation modes if its design quality is improved greatly for either its free running or conditioned operation modes.

This implication was checked against the proposed score bands to see the relationship between the scores of houses in free running (HFRS) and conditioned ratings (HERS). All simulated samples therefore were scored on the basis of the proposed rating. The relationship between the scores is shown in Graphs 8-5 and 8-6 for the Sydney (a) and Canberra (b) climates. It can be seen that there is a linear relationship between the scores of double storey houses in different modes in both climates. However, the relationship would appear to be polynomial among the single storey houses. This is evidence again of a significant difference between the characteristics of SS and DS houses that requires a rating system to separate these two house types for evaluation.



a) **Single storey houses** b) **Double storey houses**

Figure 8- 5 Correlation between the score of houses in free running and conditioned modes in the Sydney climate



a) **Single storey houses** b) **Double storey houses**

Figure 8- 6 Correlation between the score of houses in free running and conditioned modes in the Canberra climate

A remarkable point in this approach is that houses with 4 stars in free running mode get at least 3.5 stars in their conditioned performances, but houses with 4 stars in their conditioned performance do not necessarily get a score higher than 3 stars in their free running performance. In other words, an efficient design for a free running house could improve the performance of that house in the conditioned mode if its free running score is not less than 4. This condition will be included in the proposed prototype framework for HRS.

Under these circumstances it appears that the proposed aggregation of HFRS and HERS is an appropriate response to the objective of HRS in this study as specified at Section 1.4. It does not compromise the value of the conditioned performance of houses, while highlighting the value of free running houses, in which energy requirements for space heating and cooling will be significantly reduced.

8.4 Prerequisites for an efficient design in the proposed HRS

A minimum star level is generally required for designation of efficiency in an architectural design. This varies according to the State or Territory and is proposed by authorities in each jurisdiction. For example, the initial regulatory framework of NatHERS in Australia established a maximum of 5 stars for HERS, with 3.5 stars as the prerequisite for an efficient house design. This is now superseded by the 10 star system of AccuRate, which requires 5 stars as a prerequisite for an efficient design in the States of Australia in which AccuRate is approved as a mandated tool.

A 10 star rating is proposed in this study for HRS, with aggregates of 5 stars for HERS and HFRS. It is recommended that 6.5 stars is the minimum requirement for an efficient design, in which a house would achieve at least 4 stars for its free running performance. As observed above, a house with 4 stars in free running mode will achieve 3.5 stars in conditioned operation mode. The combination of 4 and 3 star is 6.5, which is thus defined as the minimum requirement for energy efficient design.

Figure 8-7 illustrates the position of acceptable states in the proposed framework in conjunction with stars taken from HFRS and HERS. The final rating score is displayed as the size of the bubble marker. The highest score is 10 and its position is indicated in the Figure 8-7.

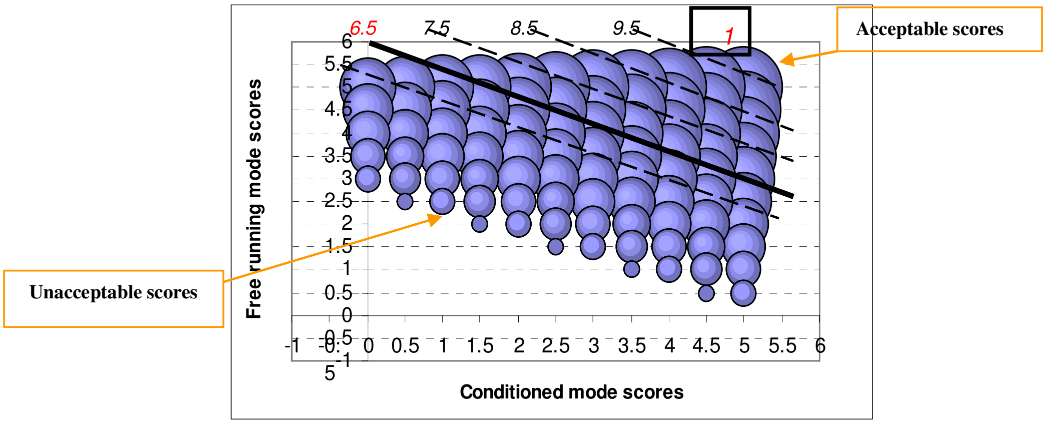


Figure 8- 7 Pictorial expression of the proposed framework

8.5 Conclusion

The main objective of this study was to develop a method for HRS that would give appropriate value to the free running performance of houses, which is missing in the current house rating schemes, so as to encourage the adoption of free running houses. In order to achieve this, an aggregation technique was developed to differentiate the value of free running performance and conditioned performance of a house, in which the efficiency of a designed house is evaluated for grading on the basis of its performances in both the modes, and which awards more value to free running performance, but which in application also generally improves conditioned performance. However, the proposed system remains flexible enough to give higher value to either free running or conditioned performances, which therefore makes it adjustable for the promotion of any kind of efficient architectural design, depending on the relevant policy for reducing energy consumption.

The proposed HRS modifies the current rating scheme by introducing the following changes:

- It separates double storey houses from single storey houses to remove discrimination in favour of the value of SS against DS houses.
- It rates the house thermal performance separately for its free running and conditioned operation, then aggregates the star bands to produce a single star rating for final comparative evaluation.

- It establishes the criterion (in the number of stars) for assessing an efficient architectural design in order to confirm the efficiency of house design in *both* operations.

Chapter 9

Conclusion and recommendations

This chapter summarises the main findings of this study that are described in detail in the previous chapters, identifies some of its limitations and makes recommendations for further study.

9.1 Summary and conclusion

This study hypothesised that the inability of current energy based house rating schemes to appropriately asses free running houses is caused by the fact that efficient design for free running houses differs from that for conditioned houses. Because rating frameworks are expected to influence the ranking of a design, the aim of the study was to develop a new House Rating Scheme (HRS) by which designs could be assessed without unrealistically compromising the value of any particular approach. Other shortcomings of the current rating schemes, in particular the issue related to a conservative standard occupancy scenario, were also addressed.

The hypothesis was confirmed by the outcomes of a parametric analysis and multivariate regression analysis of the results of the simulated performances of 6 typical houses with 13 different variables for the moderate climates of Sydney and Canberra; which demonstrated that design parameters contribute differently to the optimisation of free-running and conditioned mode performance.

That conclusion led to the development of a new framework for a HRS, namely an aggregation of a House Free running Rating Scheme (HFRS) and House Energy Rating Scheme (HERS), in which the score of a simulated house performance is determined on the basis of its thermal performances in both its free running and conditioned modes.

An approach to the incorporation of multiple occupancy scenarios in HERS was also developed. Preliminary testing established that improvement in the accuracy of HERS could be achieved, but the inability of the simulation tool to appropriately deal with key parameters that are contingent on occupancy, leaves this issue to be dealt with by future research.

The following section summarises the stages by which these conclusions were reached and by which the proposed rating scheme was developed and tested.

9.1.1 House Rating Schemes (HRS)

The purpose of house rating schemes (HRS) is to encourage energy efficiency in architectural design, but current energy based rating schemes do not assess free-running residential construction and can therefore be said to be inadequate for their stated purpose.

The first step therefore was to define an indicator of thermal comfort for the evaluation of the thermal performances of houses in the free running operation mode, the second was to investigate the differences between efficient design features for a house in free running and conditioned operation modes, and the third and most important, to develop a new HRS that overcomes the shortcomings in the current rating schemes.

9.1.2 Thermal comfort

A major aspect involved in the evaluation of the performance of a building is the determination of criteria for the provision of thermal comfort in that building. For this purpose it is necessary to identify what constitutes thermal comfort for the residents. The criteria should be determined on the basis of a building's operation mode because the building's operation affects the behaviour of occupants and the characteristics of the building. This requires different standards to be employed for the determination of comfort.

Although the principal work on comfort by Fanger and related comfort models are quite comprehensive and complex, the steady state condition on which Fanger's model has been developed makes this model inapplicable for free running buildings, because the effect of acclimatization in free running houses is not accounted for. An adaptive comfort model is therefore more appropriate for evaluating free running houses. Although such comfort models are not comprehensive, the lack of an existing comprehensive model developed for free running houses led to the decision to employ in this study the adaptive model developed by de Dear, which is accepted as standard in ASHRAE -55(2004).

Using this model, the comfort zone for free running houses was determined for 90% occupant acceptability by a 5^{o} K band centred on the thermal neutrality calculated for each month. Humidity was accounted for as relative humidity, employing ASHRAE Standard ET lines. Since the humidity of indoor spaces was not known, indoor absolute humidity was assumed to be the same as outside absolute humidity. Obviously this is only an approximation.

Since the objective of this study was to compare the current rating scheme with a new free running rating scheme, the current settings for thermal comfort in conditioned houses were not changed. In other words, the thermostat setting defining the comfort zone for conditioned houses was set to be the same as that in the AccuRate software package which is used for HERS. The top boundary for humidity was the 12g/kg moisture content line. The comfort zone was expanded for air movement above 0.2 m/s.

9.1.3 Evaluation of houses' thermal performances

In order to evaluate the thermal performance of houses in both operation modes, a simulation of typical houses in the chosen climate zones was employed in this study. Although a simulated performance may differ slightly from the actual performance of a house, simulation is recognised as the most appropriate method to evaluate and improve the thermal performance of a house at the design stage. Moreover, this method has been the foundation for developing the current HERS.

A software package (AccuRate) programmed for the purpose of HERS was used to identify aspects of potentially misleading assessment in relation to free-running houses occurring in the building assessment system currently used. Since this study was conducted in a moderate climate in Australia, the AccuRate software, which is mandated software for HERS in Australia, was the obvious choice.

9.1.4 Indicators of efficient design for different house operation modes

To evaluate the thermal performance of free running houses, an indicator of thermal comfort, namely Degree Discomfort Hours (DDH), was accepted. Discomfort hours are the times when indoor conditions fall outside the range of thermal neutrality as determined on the basis of the de Dear model.

While the estimation of energy requirements for the provision of thermal comfort in a conditioned house is strongly related to the house area, this should not be the case in the estimation of DDH, indicating the thermal condition of a free running house. Despite this apparently logical assumption, in the set of simulations DDH were weighted by proportion of conditioned zones area in order to explore the effect of this weighting on the correlation between the two indicators of energy and DDH. Two different algorithms were developed to compute annual DDH. One of these added a factor based on the proportion of the area of conditioned zones to degree discomfort hours of that zone (area of a conditioned zone/ total conditioned area), then aggregated the DDH of all zones, and was called *DDH with area weighting*, while the other did not include the proportion of area in aggregating degree hours and was called *DDH without area weighting*. The comparison of the correlation between predicted energy requirement (MJ/M^2) and DDH without area weighting; and predicted energy requirement (MJ/M^2) and DDH with area weighting confirmed that area weighting does not effectively change the correlation coefficient between the two indicators. This observation led to the recommendation that DDH without area weighting should be regarded as an appropriate and sufficient indicator of the thermal performance of free running houses.

9.1.5 HRS and multiple occupancy scenarios

Although ratings are not able to predict actual energy consumption, the accuracy of a system is important for the credibility of that system. In effect, actual energy consumption and consequently the accuracy of predictions of the energy requirements for a house are dependent on the actions of the house occupants, and thus occupancy scenarios are a major parameter affecting the accuracy of a HERS. However, the standard occupancy scenario that is currently used appears to discriminate against the value of lightweight houses in a moderate climate. For this reason it is recommended that multiple occupancy scenarios are used in HRS. In this study multiple occupancy scenarios were considered specifically for different times and zones of occupation in a house.

By considering two types of occupied zone and classifying a day into four categories of occupation time, forty-eight (48 = 4! * 2!) occupancy scenarios could be developed. For this study, six scenarios were selected to compare their effect on the evaluation of the thermal performance of houses in different operation modes.

It was initially assumed that, depending on the occupancy scenario, lightweight houses would exhibit better thermal performance than heavyweight ones, particularly in a moderate climate, if a free running operation mode was chosen. However, the inflexibility of AccuRate software in dealing with the proposed multiple occupancy scenarios limited the ability of this study to test this part of the hypothesis properly. The observation of better performance for houses with heavyweight construction than lightweight construction among the six occupancy scenarios may not be found to be correct in reality and needs to be tested by other suitable software. However, the thermal performance of lightweight houses utilizing free running operation can be improved by optimizing the operation of openings and blinds.

One of the constraints of this study was the inflexibility of AccuRate software in taking optimization variables into account. For all intents and purposes the software simulates relatively unconstrained automatic controls, which results in some notable inconsistencies regarding the effect of these controls in occupied and unoccupied dwellings. This suggests the need for further inquiry and leads to the recommendation that the developers of the software improve the package by refining the AccuRate program in order to make it more flexible and therefore more reliable.

9.1.6 Simulation of thermal performance of houses

The thermal performance of houses is influenced by a combination of several building parameters, which have been called design features in this study. The parameters that were investigated in order to compare their effect on six typical houses in free running and conditioned mode were: two different constructions (heavyweight and lightweight), ceiling insulation, wall insulation, floor insulation, external colour, window size, openable size of windows, internal window coverings, orientation, glazing type, eave width, infiltration and internal wall mass.

Over one thousand house variations (1288) were simulated for the two climates of Sydney and Canberra and the annual and seasonal thermal performances of the houses were predicted. The results of the simulations of house variations for the Sydney and Canberra climates were compared for the different operation modes, different constructions, two different seasons and two different house types. The following conclusions were drawn from the parametric sensitivity analysis of the results of the simulations:

- The effect of changing design features on improving the thermal performance of a house in free running operation differs from that for the same house in conditioned operation mode.
- The application of any measure to improve the annual thermal performance of a house does not necessarily improve the performance of that house in both seasons. This is more significant among free running houses than conditioned houses, and leads to the recommendation that the grading of a house in a rating system could be better based on separating the summer and winter performance of that house. The prototype rating framework developed in this study does not employ this suggestion because it is not aimed at changing the current energy based rating scheme itself. However this suggestion might be considered if the proposed rating scheme is expanded in future research.
- Lightweight houses are able to achieve a comparable performance to heavyweight houses in a moderate climate, particularly in their free running operation mode. This result is reflected in a HRS in which the free running performance of a house is one of the criteria for assessment of the house performance.
- There is a significant gap between the range of numerical values in the prediction of annual thermal performance of Double Storey houses and Single Storey houses in both house operation modes. This suggests that a rating system in which SS and DS houses are rated separately should be introduced and implemented. Such separation is important to avoid miss-assessment of SS houses versus DS houses.
- The moderate climate of Sydney makes it favourable for efficient free running house design, while the more severe winter climate in Canberra makes this location more appropriate for efficient conditioned house design. This result reinforces the recommendation that a national HRS should be able to properly evaluate both free running and conditioned houses. This would achieve flexibility by giving more value to either free running or conditioned houses, depending on the policy drivers for the development of sustainability.

9.1.7 Statistical analysis

In this study statistical analysis was applied for two purposes:

- to investigate the correlation between the indicators of thermal performances of houses in free running and conditioned operation modes, and
- to illustrate the contribution of design features to improvements in the thermal performance of houses in different operation modes.

A significant correlation was found between the two indicators. The correlation was found to be strongly linear among double storey houses, but not among the single storey houses. The reason appears to be the significant differences in the thermal behaviours of single storey houses in different operation modes.

The relative importance of design features was ranked on the basis of their standardized coefficients taken from the multivariate regression analysis. It was found that the contribution of design features to improvements in the thermal performance of free running houses differs markedly from that of conditioned houses. This result confirms the result of the parametric sensitivity analysis and confirms the hypothesis that an efficient design for a conditioned house is not essentially the same as an efficient design for that house in free running operation. This outcome is again evidence that the regulatory framework for free running houses should be different from that for conditioned houses and leads to a call for the development of a house free running rating scheme.

The recommendation that arises from these findings is that the development of such a rating scheme should first and foremost be the concern of policy-makers. This is because the objective of developing sustainability strategies for reducing energy consumption and greenhouse gas emissions should involve support for the construction of free running houses wherever possible. The secondary target should be the general public and designers, who should be encouraged to employ free running design, both through education and support, by more value being given to such houses.

9.1.8 Rating application

As a result of the findings of the above analysis this study proposes a prototype integrated rating framework for which the following steps are taken.

1) Separation of double storey houses from single storey houses into two categories is desirable to avoid discriminating against SS houses. This criterion is proposed because the parametric sensitivity analysis found that these two house types showed different thermal characteristics in response to similar changes on their design features, and a significant difference was observed between the range of numerical values of the thermal performance of these two house types in both operation modes. The house type was also observed from multivariate regression analysis to be the first and the main variable in predicting thermal performance.

2) Based on accepted and understood ‘star rating’ schemes, houses are graded into 5 discrete categories, separately for their free running performance and conditioned performance because characteristics differ, depending on the house operation. Norm-referenced measurement was adopted to define the range of these 5 categories. Grading on a curve was then applied by using mean and standard deviations of the normal distribution of the performance scores to determine the category range. This approach ensures a reasonable and appropriate range for the rating system.

3) A 10 star rating scheme is adopted to integrate the five star rating scheme of HERS and HFRS, subject to building performances in terms of annual energy requirement per unit area (MJ/M^2/year) for houses in the conditioned operation mode and in terms of annual degree discomfort hours for the same houses in the free running operation.

The new grades of 10 categories for this rating system are defined by an algorithm on the basis of the score bands of the free running and conditioned ratings. The use of the algorithm can give more value to an efficient design for free running or conditioned houses, as is shown in the following expression (See Section 8.2, P 203).

$$S= 0.40\ S_1+ 0.87\ S_2$$

The coefficients conform with the intention that this approach should give more value to an efficient design for free running houses. However the developed algorithm for aggregation provides a flexible condition for modification if required to support efficient conditioned house design. This flexibility is an advantage of the proposed method, making it applicable to programming at the policy level for promoting either free running or conditioned house design.

The proposed prototype rating framework can be summarized as follows:

1) single storey houses are separated from double storey houses;
2) the evaluation is based on the house performance in both free running and conditioned mode;
3) a house is given two separate scores in a 5 star rating scheme for its free running and conditioned performances;
4) the scores of free running and conditioned performances are combined under a developed algorithm to produce a final score in a 10 stars range;
5) the proposed algorithm gives more reward to the free running than the conditioned performance of a house; however it is flexible enough to be changed, depending on the policy;
6) achieving 6.5 stars is the main criterion for acceptable house design, for which a house would get at least 4 stars from HFRS.

The proposed framework has been validated in this study by testing it against its theoretical sensitivity to improvements in design. It was demonstrated that a house which satisfies the criteria of this framework for achieving an acceptable score produces a favourable performance in its conditioned operation as well as in its free running performance. Needless to say, when applying this framework the free running performance is likely to be always better than the conditioned performance. As stated previously, the intention behind this strategy is to encourage architects as well as the public to consider passive architectural design as a promising method for providing the required thermal comfort for the occupants of a house.

Overall, this study has attempted to offer useful recommendations and the required applications for the implementation of its proposals. It is believed that the employment of this approach is more likely than the present house rating schemes to meet the objectives of sustainability by reducing energy demands for heating and cooling as it encourages the prevalence of free running houses.

9.2 Recommendations for further research

This study identifies the main differences between an efficient design for free running and conditioned houses. Although the findings provide adequate information for the development of more accurate and reliable HRS, there are a number of limitations. These limitations and recommendations for further study are as follows.

The adaptive thermal model in the ASHRAE standard used in this study is more appropriate and applicable to free running houses than the Fanger model. However it does not include the non-climate parameters and the effect of air velocity and humidity. The applicability of this model thus needs to be tested for a more humid climate. The adaptive model also does not show the percentage of dissatisfied people beyond 80% acceptability. Further study to define the percentage of dissatisfied people beyond 80% will help to compute more accurate DDH as an indicator for evaluating the thermal performance of free running houses.

The study has been limited to a moderate climate; the differences between the thermal performances of free running and conditioned houses needs to be tested for other climates, particularly a warm humid climate.

The influence of defined multiple occupancy scenarios could not be simulated properly owing to the limitations of the software. This issue should be considered in any future development of AccuRate software, and it should be tested by using other appropriate software in further studies.

A comprehensive technical investigation of the impact of design features, and of house operations (including opening windows, shutters and shading) on the thermal behaviour of free running houses should be conducted as part of the development of a free running house scheme. Although the use of building simulation tools can technically quantify the thermal performance of free running houses, it has some limitations and so further research is required in this area. The development of an architectural design approach for better handling of these design features should result in valuable strategies for the efficient design of free running houses.

This study has been limited to six typical detached houses, both single storey and double storey. The validity of the applications derived from the study is thus limited to a certain type of dwelling and location, of heightened relevance in the current Australian house market. It is recommended that further studies on other types of housing should be undertaken.

This study used simulation to demonstrate a significant difference between an efficient design for a house free running house and a conditioned house. The findings should be validated against the actual thermal performance of houses in the field.

An important finding was that optimizing the performance of a house in free running operation under a particular condition (See Section 8.3) can also improve the performance of that house in conditioned operation mode. This result needs to be checked against real data in further research.

Another important area of research would be a comparative study on the cost effectiveness of efficient design for free running and conditioned houses. It is evident that lower costs would be an added benefit, which is likely to accrue from the conservation of energy. Thus, a study on cost effectiveness, including cost benefits in terms of environmental conservation and reduction of GHG emissions, should provide even more support for a recognition of the value of promoting the design of free running houses wherever possible.

Bibliography

AECB. (2006). *Minimising CO_2 Emissions from New Homes: a review of how we predict and measure energy use from new homes* (2nd edition): Association for Environment Conscious Building, available on line: http://www.aecb.net/

AGO. (2002). *Understanding Greenhouse Science*. Retrieved 23November 2005, from http://www.greenhouse.gov.au/

Akbari, H., Samano, D., Mertol, A., Bauman, F., & Kammerud, R. (1986). The effect of variations in convection coefficients on thermal energy storage in buildings Part I - Interior partition walls. *Energy and Buildings, 9* (3), 195-211.

Al-Homoud, M. S. (2000). Computer-aided building energy analysis techniques. *Building and Environment, 36* (4), 421-433.

Allen, D. R. (1999). Canada ratings warming up. *Home Energy Magazine Online*. Available online: http://hem.dis.anl.gov/eehem/99/990910.html

Andersen, P. D., Jorgensen, B. H., Lading, L., & Rasmussen, B. (2004). Sensor foresight--technology and market. *Technovation*, *24* (4), 311-320.

ASHRAE. (1981). *ASHRAE Handbook - 1981 Fundamentals*. Atlanta: American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.

ASHRAE. (2004). *ASNI/ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy*. Atlanta: American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.

Atkinson, M. (2006). *The Impact of Building on the Environment - What's Needed to Change the Status quo?* Green Building Council Australia, Retrieved 30August 2006, from www.gbcaus.org

Auliciems, A. (1981). Towards a psycho-physiological model of thermal perception. *International Journal of Biometeorology, 25* (2), 109-122.

Auliciems, A., de Dear, R. (1986). Air Conditioning in Australia I - human thermal factors. *Architectural Science Review, 29* (3), 67-75.

Auliciems, A., Szokolay, S. V. (1997). *Thermal Comfort*. Brisbane, Qld.: PLEA in association with Dept. of Architecture, University of Queensland.

Australian Bureau of Meteorology. (2006). Retrieved 15September 2006, from http://www.bom.gov.au/lam/

Australian Standards. (1993). *Australian Standard Thermal Insulation of Dwellings Part1: Thermal Insulation of roof/ceiling and walls in dwellings* (No. As 2627.1- 1993). NSW: Standards Association of Australia.

Aynsley, R. (2007). Modelling efficient building design: a comparison of conditioned and free-running house rating approaches. *Architectural Science Review*.(Letter to Editor) 50 (2), 91-93

Azer, N. Z., & Hsu, S. (1977). The prediction of thermal sensation from a simple model of human physiological regulatory response. *ASHRAE Transaction,* 83 (Pt 1).

Baker, N., & Standeven, M. (1996). Thermal comfort for free running buildings. *Energy and Buildings, 23*(3), 175-182.

Ballinger, J. A. (1988). The 5 star design rating system for thermally efficient, comfortable housing in Australia. *Energy and Buildings, 11* (1-3), 65-72.

Ballinger, J. A. (1991). *Towards an Energy Rating Scheme for Residential Buildings in the Northern Territory*. Paper presented at a workshop held at Darwin, Australia, 8May 1991.

Ballinger, J. A., Samuels, R., Coldicutt, S., Williamson, T. J., & D'Cruz, N. (1991). *A National Evaluation of Energy Efficient Houses* (No.1274 ERDC Project). Sydney: National Solar Architecture Research Unit, University of New South Wales.

Ballinger, J. A., & Cassell, D. (1994). Solar efficient housing and NatHERS: an important marketing tool. *Proceedings of the Annual Conference of the Australian and New Zealand Solar Energy Society*, Sydney. pp. 320- 326.

Ballinger, J. A. (1998a). *The Nationwide House Energy Rating Scheme for Australia* (BDP Environment Design Guide No.DES 22). Canberra: The Royal Australian Institute of Architects.

Ballinger, J. A. (1998b). *The Nationwide House Energy Rating Software (NatHERS)* (BDP Environment Design Guide No.DES 23). Canberra: The Royal Australian Institute of Architects.

Bansal, N. K., Garg, S. N., & Kothari, S. (1992). Effect of exterior surface colour on the thermal performance of buildings. *Building and Environment, 27* (1), 31-37.

Barbara, C. F. (2000). *Pilot States Program Report: Home Energy Rating Systems and Energy - Efficient Mortgages* (No.NRER/TP- 550- 27722). Colorado: National Renewable Energy Laboratory.

Beirlant, J., Goegebeur, Y., Teugels, J., & Segers, J. (2005) in *Statistics of Extremes* Walter A. Shamuel, S. Wilks (Ed), Electronic book.

Ben-Nakhi, A. E., & Mahmoud, M. A. (2004). Cooling load prediction for buildings using general regression neural networks. *Energy Conversion and Management, 45* (13-14), 2127-2141.

Benzinger, T. H. (1979). The physiological basis for thermal comfort*. First International Indoor Climate Symposium*, Copenhagen: Danish Building Research Institute. pp. 441- 476.

Berglund, L. (1978). Mathematical models for predicting the thermal comfort response of building occupants. *ASHRAE Transactions, 84,* 735-749.

Birkenland, J. (2002). *Design for Sustainability: A Sourcebook of Ecological Design Solutions*: Earthscan, UK.

Boland, J., Kravchuk, O., Saman, W., & Kilsby, R. (2003). Estimation of thermal sensitivity of a dwelling to variations in architectural parameters. *Environmental Modelling and Assessment, 8*, 101-113.

Boland, J. (2004). *Timber Building Construction* (N03.1210): The School of Mathematics and Statistics, University of South Australia.

Bordass, B., & Leaman, A. (2005). Occupancy- Post- occupancy evaluation. In W.F.E. Preiser & J.C. Vischer (Eds.), *Assessing Building Performance*. Sydney: Elsevier.

Botsaris, P. N., & Prebezanos, S. (2004). A methodology for a thermal energy building audit. *Building and Environment, 39* (2), 195-199.

Bouden, C., & Ghrab, N. (2005). An adaptive thermal comfort model for the Tunisian context: field study results. *Energy and Buildings, 37*(9), 952- 963.

Brager, G. S., & de Dear, R. J. (1998). Thermal adaptation in the built environment: a literature review. *Energy and Buildings,* 27 (1), 83-96.

Brager, G. S., & de Dear, R. (2000). A standard for natural ventilation. *ASHRAE Journal,* 42 (10), 21-28.

Brager, G. s. d. D., Richard. (2001). Climate, comfort and natural ventilation: a new adaptive comfort standard for ASHRAE standard 55. *Conference Proceedings: Moving Thermal Comfort Standards into the 21st Century*, Cumberland Lodge, Windsor, UK. Oxford Brookes University. pp. 60- 77.

Breesch, H., & Janssens, A. (2004). Uncertainty and sensitivity analysis of the performances of natural night ventilation*, 9th International Conference on Air*

Distribution in Rooms, Coimba, Portugal. Retrieved September17 2006 from http://hdl.handle.net/1854/2713

Briggs, R. S., Lucas, R. G., & Taylor, Z. T. (2002). *Climate classification for building energy codes and standards.* Retrieved 10August 2006 from http://www.**energycodes**.gov/implement/pdfs/**climate**_paper_review_draft_rev.pdf

Brundtland, G. H. (1987). *Our Common Future - Report of the World Commission on Environment and Development*. Oxford: Oxford University Press.

Buyukalaca, O., Bulut, H., & Yilmaz, T. (2001). Analysis of variable-base heating and cooling degree-days for Turkey. *Applied Energy, 69* (4), 269-283.

Cammarata, G., Fichera, A., & Marletta, L. (1993). Sensitivity analysis for room thermal response. *International Journal of Energy Research, 17*, 709- 718.

Chappells, H., & Shove, E. (2004). *Comfort Paradigms and Practices* in *Future Comforts: Re-conditioning the Urban Environment,* Workshop. London: The Policy Studies Institute. Retrieved 10July 2005 from http://www.comp.lancs.au.uk/sociology/research/projects/futcom/documents/webpaper.htm

Chau, C., K., Lee, W., L., Yik, F., W., H., & Burnett, J. (2000). Towards a Successful Voluntary Building Environmental Assessment Scheme. *Construction Management and Economics, 18*, 959 - 968.

Christenson, M., Manz, H., & Gyalistras, D. (2005). Climate warming impact on degree-days and building energy demand in Switzerland. *Energy Conversion and Management, 47* (6), 671 -686.

Chung, T. M., & Tong, W. C. (1990). Thermal comfort study of young Chinese people in Hong Kong. *Building and Environment, 25* (4), 317-328.

Chung, W., Hui, Y. V., & Lam, Y. M. (2006). Benchmarking the energy efficiency of commercial buildings. *Applied Energy, 83* (1), 1-14.

Clarke, D. (2006). *The Importance of Being Accurate (The Role and Importance of Thermal Modelling in Reducing Energy Consumption in Australian Buildings* (No 1): Association of Building Sustainability Assessors.

Clark, J. A. (1982). Computer applications in the design of energy-conscious buildings. *Computer-Aided Design, 14* (1), 3-9.

Clarke, J. A. (2001). *Energy Simulation in Building Design* (Second ed.). Oxford and Boston: Adam Hilger.

Cook G. D., Hackler R. N., Smith P. A. (1997). Clothing and laundry techniques to save energy. In *Energy Information Handbook* (Energy information document 1028): University of Florida.

Davis Energy Group. (2004). *Comfort Reports* (No. P500-04-009-A4). California: California Energy Commission.

de Dear, R. J., Fountain, M. E., Popovic, S., Watkins, S., Brager, G., Arens, E., et al.(1993). *A Field Study of Occupants Comfort and Office Environment in a Hot- humid Climate* (Final report ASHRAE RP-702). Sydney: Macquarie University.

de Dear, R., Brager, G. S., Cooper, D. (1997). *Developing an Adaptive Model of Thermal Comfort and Preference* (Final Report on ASHRAE RP-884). Sydney: MRL

de Dear, R. J., Brager, G. S. (1998). An adaptive model of thermal comfort and preference. *ASHRAE Transactions, 104* (1a), 145- 167

de Dear, R., Brager, G. S. (2001). The adaptive model of thermal comfort and energy conservation in the built environment. *International Journal of Biometeorology, 45* (2), 100-108.

de Dear, R. J., & Brager, G. S. (2002). Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. *Energy and Buildings, 34* (6), 549-561.

de Dear, R., Hart, Melissa. (2002). *Appliance Electricity End-Use: Weather and Climate Sensitivity*. Sydney: Division of environmental and life sciences, Macquarie University.

de Dear, R. (2004). Thermal comfort in practice. *Indoor Air, 14* (7), 32-39.

de Dear, R. J. (2005). Personal Communication. 25 August 2005.

Deeble, V. C., Prasad, D. K., & Ballinger, J. A. (1988). Validation methodology for Australian thermal performance design tools*, Proceedings of People and Technology: Sun, Climate and Building Conference, Brisbane.* Australia and New Zealand Architectural Science Association and the Solar Energy Society. pp. 107-111.

Delsante, A. (1987). *Computer User Manual for Program CHEETAH*. Melbourne: CSIRO Division of Building Research.

Delsante, A., & Mason, M. D. (1990). An expanded climatic data bank for Australia*, AIRAH Federal Conference*, Adelaide.

Delsante, A. (1995a). A comparison of CHENATH, The Nationwide House Energy Rating Scheme simulation engine, with measured test cell data*, Renewable Energy: The Future in Now*, Hobart. Australia and New Zealand Solar Energy Society. pp. 441-446.

Delsante, A. (1995b). Using the building energy simulation test (best test) to evaluate CHENATH, the Nationwide House Energy Rating Scheme simulation engine*, Renewable Energy: The Future in Now*, Hobart. Australia and New Zealand Solar Energy Society. pp. 447-453.

Delsante, A. (2004). *A Validation of the "AccuRate" Simulation Engine Using BESTEST* (No. CMIT(C)-2004-152). Canberra: CSIRO.

Delsante, A. (2005). Is the new generation of building energy rating software up to the task? - A review of AccuRate*, ABCB conference, Building Australia's Future 2005*, Surfers Paradise. CSIRO manufacturing and infrastructure technology.

Delsante, A. (2006). *Thermostat setting in AccuRate* . Personal communication*.* July10, 2006.

Department of Environment, Food and Rural Affairs (DEFRA). (2005). *The Government's Standard Assessment Procedure for Energy Rating of Dwellings*. BRE, Garston, Watford. Retrieved 15 January2006, from www.bre.co.uk/sap2005

Drysdale, J. W. (1975). *Designing Houses for Australian Climates* (3rd ed.). Canberra: Australian Government Publishing Service.

Ebel, R. L., & Frisbie, D. A. (1991). *Essentials of Educational Measurement* (5th ed.). USA: Prentice-Hall, Inc.

Energies- Cites. (2003). *Energy Management in Municipal Buildings*. Retrieved 10November 2006 from http://www.display-campaign.org/IMG/pdf/case-study_odense_en.pdf

Energy Efficiency Partnership for Homes. (2006). *Measuring up the Home Energy Ratings*. Retrieved 28July 2006 from http://www.est.org.uk/partnership/energy/lead/index.cfm?mode=view&news_id=559

Energy Efficient Strategies. (2002). *Comparative Cost Benefit Study of Energy Efficiency Measures of Class 1 Buildings and High Rise Apartments in Victoria* (Final report for the Sustainable Energy Authority of Victoria). Melbourne.

Energy Information Administration. (2006). *International Energy Outlook* (No. DOE/EIA-0484 (2006)). Washington, DC: Office of Integrated Analysis and Forecasting.

EIA. (2007). *Energy Demand.* Retrieved 6 Jun 2007, from http://www.eia.doe.gov/oiaf/aeo/pdf/trend_2.pdf

Environmental Protection Agency. (2000). *Energy Efficient Appliances* (No. EAP 430-F-97-028). US: EAP.

Fairey, P., J. Tait, D. Goldstein, D. Tracey, M. Holtz, and R. Judkoff. (2000). *The HERS Ratings Method and the Derivation of the Normalized Modified Loads Method* (No. FSEC-RR54-00). Florida: Florida Solar Energy Centre, Cocoa.

Fanger, P. O. (1967). Calculation of Thermal Comfort: Introduction of a Basic Comfort Equation. *ASHRAE Transactions*, *73* (part 2), III.41-III44.20.

Fanger, P. O. (1970). *Thermal Comfort*. Copenhagen: Danish Technical Press.

Fanger, P. O., & Toftum, J. (2002). Extension of the PMV model to non-air-conditioned buildings in warm climates. *Energy and Buildings, 34* (6), 533-536.

Farhar, B., C., Collins, N., E., & Walsh, R., W. (1996). *Linking Home Energy Rating Systems with Energy Efficiency Financing: Progress on National and State Programs* (No. NREL/TP-460-21322): National Renewable Energy Laboratory.

Feriadi, H., & Wong, N. H. (2004). Thermal comfort for naturally ventilated houses in Indonesia. *Energy and Buildings, 36* (7), 614-626.

Fisette, P. (2003). *Windows: Understanding Energy Efficient Performance*. Retrieved 6June 2006 from http://www.umass.edu/bmatwt/publications/articles/windows_understanding_energy_efficient_performance.html

Forwood, G. (1995). What is thermal comfort in a naturally ventilated building? In F. Nicol, M. Humphreys, O. Skes & S. Roaf (Eds.), *Standards for Thermal Comfort, Indoor Air Temperature Standards for the 21st Century*, pp. 176- 181. London: E& FN Spon.

Foster, R. (2006). *Setting Occupancy Factors for Thermal Performance Modelling of Australian Households*. Victoria, Australia: Energy Efficient Strategies.

Fountain, M., Brager, G., & de Dear, R. (1996). Expectations of indoor climate control. *Energy and Buildings, 24* (3), 179-182.

Gagge, A. P., Herrington, L. P., & Winslow, C.-E. A. (1937). The thermal interchanges between the human body and its atmospheric environment. *American Journal of Hygiene, 26*, 84-102.

Gagge, A. P., Stolwijk, J. A., & Hardy, J. D. (1967). Comfort and thermal sensations and associated physiological responses at various ambient temperatures. *Environmental Research*, *1*, 1-20.

Gagge, A. P., Stolwijk, J. A. J., & Nishi, Y. (1971). An effective temperature scale based on a simple model of human physiological regulatory response. *ASHRAE Transactions, 77*, 247-262.

Gagge, A. P. (1973). Rational temperature indices of mans thermal environment and their use with a 2-nude model of his temperature relation*, Federation Proceedings*. pp. 1572-1582.

Gellender, M. (1992). *Energy Rating and/or Energy efficiency standards for new houses: issues and options for Queensland*: Presented at a workshop sponsored by the Queensland Energy Information Centre.

Ghiaus, C., & Allard, F. (2006). Potential for free-cooling by ventilation. *Solar Energy Urban Ventilation, 80* (4) 402-413.

Givoni, B. (1976). *Man, Climate and Architecture*: London: Applied Science Publishers Ltd.

Givoni, B. (1998). *Climate Considerations in Building and Urban Design*. New York: Van Nostrand Reinhold.

Gray, E. (1998). *NatHERS Effect of Dimension on Star Energy Rating* (A report prepared for WA Office of Energy).

Grivel, F., & Candas, V. (1991). Ambient temperatures preferred by young European males and females at rest. *Ergonomics, 34*, 365-378.

Gunst, R. F., & Mason, R. L. (1980). *Regression Analysis and Its Application: A Data Oriented Approach*. New York: Marcel Dekker.

Haas, R. (1997). Energy efficiency indicators in the residential sector: What do we know and what has to be ensured? *Energy Policy, 25* (7-9), 789-802.

Hasson, F., Keeney, S., & McKenna, H. (2000). Research guidelines for the Delphi survey technique. *Journal of Advanced Nursing, 32* (4), 1008-1015.

Haberl, J., Bou-saada, T., Reddy, A., & Soebarto, V. (1998). An evaluation of residential energy conservation option using side-by-side measurements of two habitats for humanity houses in Houston, Texas*, Proceedings of the 1998 ACEEE Conference, American Council for an Energy Efficient Economy*, California.

Hanby, V. I. (1995). Error estimation in bin method energy calculations. *Applied Energy, 52* (1), 35-45.

Harrington, L., Foster, R., Wilkendfeld, G., Treloar, G. J., Lee, T., & Ellis, M. (1999). *Baseline Study of Greenhouse Gas Emissions From the Australian Residential Building Sector to 2010*. Canberra: Australian Greenhouse Office.

Hensen, J. M. (1990). Literature review on thermal comfort in transient conditions. *Building and Environment, 25* (4), 309-316.

Holm, D., & Engelbrecht, F., A. (2005). Practical choice of thermal comfort scale and range in naturally ventilated buildings in South Africa. *Journal of the South African Institution of Civil Engineering, 47* (2), 9-14.

Hong, T., Chou, S. K., & Bong, T. Y. (2000). Building simulation: an overview of developments and information sources. *Building and Environment, 35* (4), 347-361.

Humphreys, M. A. (1975). *Field studies of thermal comfort compared and applied* (BRE- CP 76/75). Garston: Building Research Establishment.

Humphreys, M. A. (1976). Field studies of thermal comfort compared and applied. *Building Services Engineer, 44*, 5- 27.

Humphreys, M. A. (1978). Outdoor temperature and comfort indoors. *Building Services Engineer, 6* (2), 92- 105.

Humphreys, M. A., & Nicol, J. F. (1995). An Adaptive Guideline for UK Office Temperatures. In F. Nicol, M. Humphreys, O. Skes & S. Roaf (Eds.), *Standards for Thermal Comfort, Indoor Air TemperatureSstandards for the 21st Century*, London: E& FN Spon.

Humphery, M., & Nicol, J. F. (1998). Understanding the adaptive approach to thermal comfort. *ASHRAE Technical Data Bulletin, 14* (1), 1-14.

Humphreys, M. A., & Fergus Nicol, J. (2002). The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. *Energy and Buildings, 34* (6), 667-684.

Hunt, S. (2003). Focus on Construction Quality*, Monthly Newsletter* US: IBACOS.

Hyde, R. (1996). Climatic design: a study of housing in the hot humid tropics*, The Proceedings of the Australian and New Zealand Energy Society*, Darwin.

Hyde, R. (2000). *Climate Responsive Design: A Study of Buildings in Moderate and Hot Humid Climates*. New York: E & FN Spon.

Ihab, M. K. E. (2002). Designing for indoor comfort: a system model for assessing occupant comfort in sustainable office buildings, *Proceedings of the Solar 2002 Conference*, Reno, Nevada. American solar energy society, American Institute of Architects Committee on the Environment. pp. 485- 494.

International Energy Agency. (2003). *IEA ECBCS Annex 36:* Energy Concept Adviser for Technical Retrofit Measures- *Energy Audit Procedures*. (Jan de Boer ed). December 2003

International Energy Agency. (2006). *Energy projection*. Retrieved 10 October 2006 from http://www.iea.org/Textbase/subjectqueries/keyresult.asp?KEYWORD_ID=4107

International Standards Organisation. (2003). *ISO/DIS 7730 Ergonomics of the Thermal Environment- Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort*: International Standards Organisation.

Isaacs, T. (2004). *Revision of the Energy Efficiency Provisions for Housing to Better Allow for the Impact of Ventilation.* Canberra: ABCB.

Isaacs, T. (2005). *AccuRate: 2nd Generation Nationwide House Energy Rating Software*. Canberra: The Royal Australian Institute of Architects.

ISSO. (1990). *Design of Indoor Conditions and Good Thermal Comfort in Buildings* (in Dutch) (No. ISSO Research Report 5). Netherlands.

ISO 7730. (1995). *Moderate Thermal Environment - Determination of the PMV and PPD Indices and Specifications for Thermal Comfort*. Geneva, Switzerland: International Organisation for Standardisation.

ISSO. (2004). *Thermal Comfort as Performance* (No. ISSO Research Report 58.2). Rotterdam. Netherlands.

Jones, B. W. (2001). Capabilities and limitations of thermal models. *Conference Proceedings: Moving Thermal Comfort Standards into the 21st Century*, Cumberland Lodge, Windsor, UK. Oxford Brookes University. pp. 112-121.

Judkoff, R., & Neymark, J. (1995). *International Energy Agency Building Energy Simulation Test (BestEST) and Diagnostic Method* (No. NREL/TP-472-6231). US: International Energy Agency.

Karynono, T., H. (1996). Thermal comfort in the tropical South- East Asian region. Architectural Science Review, *39* (3), 135 - 139.

Klainsek, J. C. (1991). Glazing and its influence on building energy behaviour. *Renewable Energy, 1* (3-4), 441-448.

Klein, S. A. (1983). Computer in the design of passive solar systems. *Passive Solar Journal, 2* (1), 57- 74.

Kordjamshidi, M., King, S., & Prasad, D. (2005a). An Alternative Basis for a Home Energy Rating Scheme (HERS). *Proceedings of PLEA, Environmental sustainability: the challenge of awareness in developing societies*, Lebanon. pp. 909- 914.

Kordjamshidi, M., King, S., & Prasad, D. (2005b). Towards the Development of a Home Rating Scheme for Free Running Buildings. *Proceedings of ANZSES, Renewable Energy for a Sustainable Future- A challenge for a post carbon world.* New Zealand. Dunedin University.

Kotsaki, K., & Sourys, G. (2000). *Critical Review and State of the Art of the Existing rating and Classification Techniques* (Group Building Environmental Studies) Greece: University of Athens.

Krichkanok, S. (1997). *A Collaborative Approach to the Development of a House Energy Rating Scheme for Bangkok: A Pilot Project.* Unpublished PhD thesis, University of New South Wales, Sydney.

La Gennusa, M., Nucara, A., Rizzo, G., & Scaccianoce, G. (2005). The calculation of the mean radiant temperature of a subject exposed to solar radiation--a generalised algorithm. *Building and Environment, 40* (3), 367-375.

Lam, J. C., & Hui, S. C. M. (1996). Sensitivity analysis of energy performance of office buildings. *Building and Environment, 31* (1), 27-39.

Lam, J. C., & Li, D. H. W. (1999). An analysis of day lighting and solar heat for cooling-dominated office buildings. *Solar Energy, 65* (4), 251-262.

Lee, J.-Y., & Choi, J.-W. (2004). Influences of clothing types on metabolic, thermal and subjective responses in a cool environment. *Journal of Thermal Biology, 29* (4-5), 221-229.

Lee, T., & Snow, M. (2006). The Australian climate data bank project. *Proceedings of the IBPSA Australia 2006 Conference: Investigating the Roles and Challenges of Building Performance Simulation in Achieving a Sustainable Built Environment,* Adelaide: The university of Adelaide.

Littler, J. G. F. (1982). Overview of some available models for passive solar design. *Computer Aided Design, 14* (1), 15-19.

Lomas, K. J., & Eppel, H. (1992). Sensitivity analysis techniques for building thermal simulation programs. *Energy and Buildings, 19* (1), 21-44.

Lovins, A. (1992). *Air Conditioning Comfort: Behavioural and Cultural Issues*: E Source, Inc., Boulder, Colorado. Available from: http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=55564

Luxmoore, D. A., Jayasinghe, M. T. R., & Mahendran, M. (2005). Mitigating temperature increases in high lot density sub-tropical residential developments. *Energy and Buildings, 37* (12), 1212-1224.

Lyons, P., Arasteh, D., & Huizenga, C. (1999). Window performance for human thermal comfort. *ASHRAE Transactions, 73* (2), 4.0- 4.20.

Lyons, P. (2006). *Window Performance for Human Thermal Comfort* (Final report to the national fenestration rating council). Melbourne: Centre for the Built Environment.

Markus, T. A., & Morris, E. N. (1980). *Building Climate and Energy*. London: Pitman.

Mayer, E. (1993). Objective criteria for thermal comfort. *Building and Environment, 28* (4), 399-403.

McNall, P. E. J., Jaax, J., Rohles, F. H., Nevins, R. G., Springer, W. (1967). Thermal comfort (thermally neutral) condition or three levels of activity. *ASHRAE Transactions, 73* (part 1).

Meier, A., Olofsson, T., Lamberts, R. (2002). What is an energy-efficient building? *Proceedings of the ENTAC 2002- IX Meeting of Technology in the Built Environment*, Brazil.

Melikov, A. K. (1996). Air Movement at the Neck of the Human Body. *Proceedings of Indoor Air*, Nagoya, Japan. pp. 209- 214.

Melikov, A. K. (2004). Personalized ventilation. *Indoor Air, 14* (7), 157-167.

Miguez, J. L., Porteiro, J., Lopez-Gonzalez, L. M., Vicuna, J. E., Murillo, S., Moran, J. C., et al. (2006). Review of the energy rating of dwellings in the European Union as a mechanism for sustainable energy. *Renewable and Sustainable Energy Reviews, 10* (1), 24-45.

Mills, E. (2004). Inter-comparison of North American residential energy analysis tools. *Energy and Buildings, 36* (9), 865-880.

Milne, M. (1976). Sun motion and control of incident solar radiation. In H. J. Cowan (Ed.), *Man, Climate and Architecture*. London: Applied Science Publishers Ltd.

Montgomery, C., Douglas, & Runger, C., George. (1999). *Applied Statistics and Probability for Engineers*. (W. Anderson Ed.). New York.

Nakano, J., Tanabe, S, & Kimura, K. (2002). Differences in perception of indoor environment between Japanese and non-Japanese workers. *Energy and Buildings, 34* (6), 615-621.

National Renewable Energy Laboratory Washington. (1992). *A National Program for Energy-Efficient Mortgages and Home Energy Rating Systems: A Blueprint for Action* (No. NREL/TP-261-4677). Washington, D. C.

Nicol, F., Aulicien, A. (1994). *A Survey of Thermal Comfort in Pakistan: Toward New Indoor Temperature Standards* (Final Report to the Overseas Development) UK: Administration .Oxford Brookes University, School of Architecture.

Nicol, F., & Roaf, S. (1996). Pioneering new indoor temperature standards: the Pakistan project. *Energy and Buildings, 23* (3), 169-174.

Nicol, J. F., Raja, I. A., Allaudin, A., & Jamy, G. N. (1999). Climatic variations in comfortable temperatures: the Pakistan projects. *Energy and Buildings, 30* (3), 261-279.

Nielsen, T. R., Duer, K., & Svendsen, S. (2001). Energy performance of glazings and windows. *Solar Energy, 69* (Supplement 6), 137-143.

O`Callaghan, P. W. (1978). *Building for Energy Conservation*. New York: Oxford: Pergamon Press.

Office of Energy Efficiency. (2005). *The State of Energy Efficiency in Canada* (No. M141-7/2004). Canada: The Office of Energy Efficiency of Natural Resources.

Office of the UK Deputy Prime Minister. (2004). Government Moves Ahead with Developing New Code for Sustainable Buildings, Retrieved 27July 2005 from http://www.odpm.gov.uk/pns/DisplayPN.cgi?pn_id=2004_0181

Offiong, A., & Ukpoho, A. U. (2004). External window shading treatment effects on internal environmental temperature of buildings. *Renewable Energy, 29* (14), 2153-2165.

Olesen, B. W. (2004). International standards for the indoor environment. *Indoor Air, 14* (supplement 7), 18-26.

Olesen, B. W., Seppanen, O., & Boerstra, A. (2006). Criteria for the Indoor Environment for Energy Performance of Buildings: A New European Standard, *Windsor Conference*. Retrieved 21September 2006 from: http://nceub.org.uk/uploads/Olesen.pdf

Olgyay, V. (1963). *Design with climate: bioclimatic approach to architectural regionalism*. Princeton: Princeton University Press.

Olofsson, T., Meier, A., & Lamberts, R. (2004). Rating the energy performance of buildings. *The International Journal of Low Energy and Sustainable Buildings, 3,* 1-18.

Omar, E. A., & Al-Ragom, F. (2002). On the effect of glazing and code compliance. *Applied Energy, 71* (2), 75-86.

Parsons, K. C. (2001). The effects of physical disability, gender, acclimation state and the opportunity to adjust clothing, on requirements for thermal comfort*, Conference Proceedings :Moving Thermal Comfort Standards into the 21st Century*, Cumberland Lodge, Windsor, UK. Oxford Brookes University.

Parsons, K. C. (2003). *Human Thermal Environments*. London and New York: Taylor and Francis.

Patterson, M. G. (1996). What is energy efficiency? : Concepts, indicators and methodological issues. *Energy Policy, 24* (5), 377-390.

Persson, M.-L., Roos, A., & Wall, M. (2006). Influence of window size on the energy balance of low energy houses. *Energy and Buildings, 38* (3), 181-188.

Pettersen, T. D. (1994). Variation of energy consumption in dwellings due to climate, building and inhabitants. *Energy and Buildings, 21* (3), 209-218.

Planning. (2006). *New 5 Star Requirements: Making Your Home More Energy Efficient*. Government of South Australia. Retrieved 7October 2006, from www.planning.sa.gov.au

Poupard, O., Blondeau, P., Iordache, V., & Allard, F. (2005). Statistical analysis of parameters influencing the relationship between outdoor and indoor air quality in schools. *Atmospheric Environment, 39* (11), 2071-2080.

Preiser, W. F. E. (2005). Building performance assessment--from POE to BPE, a personal perspective. *Architectural Science Review, 48* (3), 201-204.

Preiser, W. F. E., & Vischer, J. C. (2005). The evolution of building performance evaluation: an introduction. In W. F. E. Preiser & J. C. Visscher (Eds.), *Assessing Building Performance* (pp. 3-13). Oxford, UK: Elsevier.

Richalet, V. & Henderson, G. (1999, September/October 1999). Europe Union Not Unified on Home Ratings. *Home Energy Magazine Online*. Retrieved 17September 2004, from http://hem.dis.anl.gov/eehem/99/990911.html

Richalet, V., Neirac, F. P., Tellez, F., Marco, J., & Bloem, J. J. (2001). HELP (house energy labelling procedure): methodology and present results. *Energy and Buildings, 33* (3), 229-233.

Roulet C-A., F. F., Santamouris M., Koronaki I., Daskalaki E., Richalate V. (1999). *ORME-Office Building Rating Methodology for Europe* (Office Project Report). University of Athens.

Roulet, C.-A., Flourentzou, F., Labben, H. H., Santamouris, M., Koronaki, I., Dascalaki, E., et al. (2002). ORME: A multicriteria rating methodology for buildings. *Building and Environment, 37* (6), 579-586.

Roulet, C., A.,, Johner, N., Oostra, B., Foradini, F., Aizlewood, C., & Cox, C. (2005). Multi-criteria analysis of health, comfort and energy efficiency of buildings*, The 10th International Conference on Indoor Air Quality and Climate*, Beijing. pp. 1174- 1178.

Santamouris M. (1995). *Energy Retrofit of Office Buildings. Athens*: CIENE; University of Athens.

Santamouris, M., & Dascalaki, E. (2002). Passive retrofitting of office buildings to improve their energy performance and indoor environment: the OFFICE project. *Building and Environment, 37* (6), 575-578.

Santamouris, M. (2005). *Energy Performance of Residential Buildings: A Practical Guide for Energy Rating and Efficiency*. UK and USA: James& James/Earthscan.

Santamouris, M., Mihalakakou, G., Patargias, P., Gaitani, N., Sfakianaki, K., Papaglastra, M., et al. (2007). Using intelligent clustering techniques to classify the energy performance of school buildings. *Energy and Buildings, 39* (1), 45-51.

Shariah, A., Shalabi, B., Rousan, A., & Tashtoush, B. (1998). Effects of absorptance of external surfaces on heating and cooling loads of residential buildings in Jordan. *Energy Conversion and Management, 39* (3-4), 273-284.

Sjosten, J., Olofsson, T., Golriz, M. (2003). Heating energy use simulation for residential buildings*, Eight International IBPSA Conference*, Eindhoven, Netherlands pp. 1221- 1226

Soebarto, V. I., Williamson, T. J. (1999). Design orientated performance evaluation of buildings*, Building Simulation '99. Sixth International IBPSA Conference*, Kyoto, Japan. International Building Performance Simulation Association. pp. 225-232.

Soebarto, V. I. (2000). A Low-Energy House and a Low Rating: What is the Problem, *Proceedings of the 34th Conference of the Australia and New Zealand Architectural Science Association*, Adelaide, South Australia pp. 111-118.

Soebarto, V. I., & Williamson, T. J. (2001). Multi-criteria assessment of building performance: theory and implementation. *Building and Environment, 36* (6), 681-690.

Soebarto, V., Williamson, T., Radford, A., & Bennetts, H. (2006). The performance of award winning houses, *The 23rd Conference on PLEA*, Geneva, Switzerland. pp. 855- 860.

SOLARCH. (2000). *Project Homes: House Energy Rating, New South Wales Industry Impact Study* (A report prepared for the Sustainable Energy Development Authority): University New South Wales.

Sonderegger, R. C. (1978). Movers and stayers: The resident's contribution to variation across houses in energy consumption for space heating. *Energy and Buildings, 1* (3), 313-324.

Sowell, E. F., & Hittle, D. C. (1995). Evolution of building energy simulation methodology. *ASHRAE Transactions*, *101*(P.1) 850-855.

SRC. (1991). *Review of Home Energy Rating Schemes: Findings and Recommendation* (No. 03-412-8900). Melbourne, Victoria: SRC Australia Pty Ltd.

Stein, J. R. (1997a). *Accuracy of Home Energy Rating Systems* (No. 40394). US: Lawrence Berkeley National Laboratory.

Stein, J. R. (1997b, September/October 1997). Home Energy Rating Systems: Actual Usage May Vary. *Home Energy Magazine Online*. Retrieved 10May 2004, from http://hem.dis.anl.gov/eehem/97/970910.html

Stein, J. R., & Meier, A. (2000). Accuracy of home energy rating systems. *Energy,* 25 (4), 339-354.

Sullivan, R., Nozari, S., Johnson, R., & Selkowitz, S. (1985). Commercial building energy performance analysis using multiple regressions. *ASHRAE Transaction, 91*, (Part 2A), 337- 345.

Sutherland, J. W. (1971). The solution of psychometric problems using a digital computer. *Air. Cond. and Heating, 25* (4), 43-49.

Szokolay, S. V. (1980). *Environmental Science Hand Book for Architects and Builders.* London: The Construction Press.

Szokolay, S. V. (1991). *Handbook of Architectural Technology*. New York: Van Nostrand Reinhold.

Szokolay, S. (1992a). An energy rating system for houses. In *Energy-efficient Ratings and Standards for New Houses*. Brisbane: Queensland Energy Information Centre Department of Resource Industries.

Szokolay, S. v. (1992b). *HERS: Proposal for a Nationwide Home Energy Rating Scheme* (report to Dept. of Primary Industries and Energy).

Szokolay, S. V. (2004). *Introduction to Architectural Science: The Basis of Sustainable Design.* Oxford: Architectural Press.

Tarantola, S., & Saltelli, A. (2003). SAMO 2001: methodological advances and innovative applications of sensitivity analysis. *Reliability Engineering and System Safety, 79* (2), 121- 122.

Tavares, P. F. d. A. F., & Martins, A. M. d. O. G. (2007). Energy efficient building design using sensitivity analysis--A case study. *Energy and Buildings, 39* (1), 23- 31.

Thomas, P. C., & Thomas, L. (2000). A study of an energy consumption index normalised for area in house energy rating schemes. *Proceedings of the 38th Annual Conference of the Australian and New Zealand Solar Energy Society: From Fossils to Photons Renewable Energy Transforming Business*, Brisbane. pp. 113-121.

Thornton, S. B., Nair, S. S., & Mistry, S. I. (1997). Sensitivity analysis for building thermal loads. *ASHRE Transactions, 103*, 165- 175.

Turrent, D., & Mainwaring, J. (1990). Saving Energy on the Rates. *RIBA Journal*, September 1990, 85-86.

United Nations. (1998). *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. United Nations. Retrieved 15January 2007, from http://unfccc.int/kyoto_protocol/items/2830.php

United Nations. (2004). *Framework Convention on Climate Change* (Report on the in-depth review of the third national communication of the United States of America. No. FCCC/IDR.3/USA) New York: United Nations.

US Department of Energy. (1995). *Model Energy Code Compliance Guide Version 2.0*: Us Department of Energy Building Standards and Guidelines Program.

US Department of Energy. (2006). *Building energy software tools directory*. Retrieved 10April 2006 from http://www.eren.doe.gov/buildings/tools-directory/

van der Linden, K., Boerstra, A. C., Raue, A. K., & Kurvers, S. R. (2002). Thermal indoor climate building performance characterized by human comfort response. *Energy and Buildings, 34* (7), 737-744.

van der Linden, A. C., Boerstra, A. C., Raue, A. K., Kurvers, S. R., & de Dear, R. J. (2006). Adaptive temperature limits: A new guideline in The Netherlands: A new approach for the assessment of building performance with respect to thermal indoor climate. *Energy and Buildings, 38* (1), 8-17.

Vine, E., Barnes, B. K., & Ritschard, R. (1988). Implementing home energy rating systems. *Energy, 13* (5), 401-411.

Walsh, P. J., Gurr, T. A. (1982). *A Comparison of the Thermal Performance of Heavyweight and Lightweight Construction in Australian Dwellings* (No. TP44). Australia: CSIRO Division of Building Research.

Wathen, G. (1992). Energy-efficient Rating Schemes and Building Standards in Victoria. In *Energy-efficient Ratings and Standards for New Houses*. Papers presented at a workshop sponsored by the Queensland Energy Information Centre, April 29, 1992, pp 1-16.

Watt, J. R. (1963). *Evaporative Air Conditioning*. New York: The Industrial Press.

Williamson, T. J., Coldicutt, S., & Riordan, P. (1995). Comfort preferences or design data? In F. Nicol, M. Humphreys, O. Skes & S. Roaf (Eds.), *Standards for Thermal Comfort, Indoor Air Temperature Standards for the 21st Century*, pp. 50- 58. London: E& FN Spon.

Williamson, T., & Riordan, P. (1997). Thermostat strategies for discretionary heating and cooling of dwellings in temperate climates. *Proceeding of 5th IBPSA Building simulation Conference*, Prague: International Building Performance Simulation Association. pp. 1-8

Williamson, T. J. (2000). A critical review of home energy rating in Australia, *Proceedings of the 34th Conference of the Australia and New Zealand Architectural Science Association*, Adelaide, South Australia. pp. 101-109.

Willrath, H. (1997). Thermal sensitivity of Australian houses to variations in building parameters, *35th Annual Conference of the Australian and New Zealand Solar Energy Society*, Canberra.

Willrath, H. (1998). *The Thermal Performance of Houses in Australian Climates.* Unpublished PhD thesis, University of Queensland, Brisbane.

Winslow, C.E. A., Herrington, L. P., & Gagge, A. P. (1937). Relations between atmospheric conditions, physiological reactions and sensations of pleasantness. *American Journal of Hygiene, 26*, 103-115.

Wong, N. H., Feriadi, H., Lim, P. Y., Tham, K. W., Sekhar, C., & Cheong, K. W. (2002). Thermal comfort evaluation of naturally ventilated public housing in Singapore. *Building and Environment, 37* (12), 1267-1277.

Wray, C., P., Piette, M., A. , Sherman, M., H., Levinson, R., M. , Matson, N., E., Driscoll, D., A., et al. (2000). *Residential Commissioning: A Review of Related Literature* (No. LBNL_44535). US: Lawrence Berkeley National Laboratory.

Xavier, A. A. de Paula, Lamberts, R. (2001). Thermal comfort zones for conditioned and free running buildings in Florianopolis, South Brazil. *Conference Proceedings Moving Thermal comfort standard into the 21st century*, Cumberland Lodge, Windsor, UK. Oxford Brookes University. pp. 235- 245

Yaglou, C. P. (1927). The comfort zone for men at rest and stripped to the waist. *Transactions of the American Society of Heating and Ventilation Engineers, 33*, 165-179.

Yoshida, J. A., Nomura, M., Mikami, K., & Hachisu, H. (2000). Thermal comfort of severely handicapped children in nursery schools in Japan*, Proceedings of the IEA 2000/HFES Congress*, San Diego, USA. pp. 712- 715.

Young, A. J. (1991). Effects of Aging on Human Cold Tolerance. *Experimental Aging Research, 17,* 205-213.

Young, A. J., & Lee, D. T. (1997). Aging and human cold tolerance. *Experimental Aging Research, 23,* 45-67.

Zhai, Z. J., & Chen, Q. Y. (2006). Sensitivity analysis and application guides for integrated building energy and CFD simulation. *Energy and Buildings, 38* (9), 1060-1068.

Zmeureanu, R., Fazio, P., DePani, S., & Calla, R. (1999). Development of an energy rating system for existing houses. *Energy and Buildings, 29* (2), 107-119.