Concept(s) of the Energy-Efficient House in the Temperate Regions of Australia: A Critical Review

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A thesis submitted to The University Of Adelaide in fulfilment
of the requirements for the degree of Doctor of Philosophy

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July 1997

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ASPECTS of the MATHEMATICAL BASIS of *EnCom2*

***EnCom2* Data, Version 4.4, 1996**

ABSTRACT

During the 1970's phrases such as 'passive design', 'solar architecture', 'low energy housing' and 'solar housing' became familiar to building designers. This rhetoric was a response to emerging concerns regarding the depletion of non-renewable resources, the deterioration of the natural environment, and to what some saw as the inappropriate use of technology in our society. Design strategies emerged for the temperate regions in Australia expressed as rules-of-thumb related to a *solar-efficient* prototype house.

This thesis investigates the hypothesis that *for the temperate climate regions of Australia the presentation of advice for energy-efficient house design in the form of rules-of-thumb associated with the concept of the solar-efficient prototype is inadequate and in many circumstances can direct designers away from more applicable solutions.*

A historical review describes the emergence of the concept of the solar-efficient house and the scope of the problem addressed by the rules-of-thumb design strategies. Recent research work which has improved our understanding of the thermal performance of dwellings, including actual household energy consumption and the thermal preferences of householders, together with the issue of the validity of computer simulation of the thermal performance of dwellings are discussed.

In order to comprehend the shortcomings of the rules-of-thumb in practice the theoretical framework of an ignorance-based approach (a controversial method for dealing with issues of uncertainty and relevance) is introduced as a way of understanding the nature and use of applicable knowledge in the design process for energy-efficient housing.

Using case studies for Adelaide and Melbourne locations the limits of the rules-of-thumb are examined. Heating and cooling delivered energy consumption is calculated using the thermal performance computer program *EnCom2*. This is combined with dwelling embodied energy estimates to determine the total life-cycle energy and CO_2 emissions. A multi-criteria analysis is used to compare a number of common energy-efficient performance objectives and the life-cycle costs of achieving these objectives. Contrary to what the solar-efficient prototype approach would suggest this analysis demonstrates that there is a range of appropriate solutions and that these solutions are contextual.

The thesis concludes that the uncritical use of the rules-of-thumbs design strategies derived from the concept of the solar-efficient prototype house results in a high level of built-ignorance, a high level of irrelevance, and errors which could result in many circumstances in substantially higher levels of energy consumption, cost and/or discomfort, than could otherwise be achieved.

Signed Statement

This thesis contains no material which has been accepted for the award of any other degree or diploma in any University. To the best of my knowledge and belief, it contains no material previously published or written by another person, except where due reference is made in the text. I consent to this thesis being made available for photocopying and loan if applicable if accepted for the award for the degree.

Terence J. Williamson

ACKNOWLEDGMENTS

A number of people have contributed in a substantial way to this work. To these I wish to express my appreciation.

I wish to acknowledge, first, my gratitude and indebtedness to Alan and Beth (deceased, 1995) Coldicutt who, many years ago, first stimulated my interest in the topic of energy-efficient housing and continued for over two decades to provide enthusiastic encouragement for the work.

I thank my colleague Ass. Prof. Susan Coldicutt who has been a partner in research for many years and has provided invaluable comments, suggestions and assistance as this work progressed.

I thank my supervisor Prof. Antony Radford who has provided the encouragement to complete the work and sound thought-provoking advice on the presentation of the information.

I thank my many colleagues, too numerous to mention, who have contributed in many ways to my understanding of the issues. I am grateful to Stephen Pullen for providing me with his embodied energy spreadsheet.

Finally, I thank my family, Dany my wife and children Jessica, Daimhin and Anna, who have been supporting me in this endeavour for as long as they can remember.

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CHAPTER 1
OUTLINE OF THESIS

1.1 Introduction

Within the discursive practice of a discipline the organization of concepts and strategies into themes can be seen to arise at certain times in history. Continuities, small shifts or radical transformations or substitutions of concepts can be affected by institutional settings, political events, changes in technologies, scientific discoveries or economic practices and processes. In this context a strategy to achieve a conceptual outcome, that is the means employed to attain a certain end, occurring at any point in time in a discourse must be understood as one in a range of theoretical possibilities. The adoption of a restricted range of strategic options operates to regulate the discourse and the ways of practicing the discipline. For Foucault (1972) strategies are to be,

> *"....described as systematically different ways of treating objects of discourse.....of manipulating concepts (of giving them rules for their use, inserting them into regional coherences, and thus constituting conceptual architectures)."* (Foucault, 1972, p.70)

and the problem is,

> *"....to discover how they [concepts & strategies] are distributed in history.....[are they] successive solutions to one and the same problem? Or chance encounters between ideas of different origin, influences, discoveries, speculative climates, theoretical models......or more or less well-constituted wholes?"* (Foucault, 1972, p.64)

For almost two decades the concept of the *solar-efficient* house has dominated thinking on the means to improve dwelling energy-efficiency in the temperate climate regions of Australia. Efforts to provide information to designers and education to the public has seen the promotion of rules-of-thumb design strategies associated with a prototype *solar-efficient* dwelling. Because in Australia, unlike in most other developed countries, no comprehensive regulatory framework has been established for energy-efficient dwelling design, little other authoritative advice has been available[1]. This thesis will examine the development of ideas on energy-efficient house design in temperate Australia and will question the efficacy of the singular rules-of-thumb approach. To position the formation of the rules-of-thumb strategy within a prevailing knowledge framework, and as a base for comparing changes over time of, firstly, the conceptual system and theoretical strategic choices

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[1] Limited regulations do exist. Mandatory thermal insulation levels for walls, floors and ceilings of residential buildings are in the Appendix of the Building Code of Australia (BCA) for the State of Victoria. A rating scheme, VicHERS, is an alternative compliance mechanism in that State. Some local government Councils (of note are Ku-ring-gai, Camden and Leichhardt in Sydney) have introduced, as part of their planning requirements, energy-efficient housing policies which require all new residences to be designed to minimum specified standards. These standards generally imitate the rules-of-thumb.

and, secondly, the status and institutional setting of the discourse, reference is made to a paper presented in September 1974 in Melbourne to a Symposium on the Utilization of Solar Energy in Dwellings entitled *Comparison of Performances of Conventional and Solar Houses: A Computer Simulation* (Williamson & Coldicutt, 1974, reproduced and annotated in Appendix A of this thesis). This paper provides a concrete example as a starting point for the thesis.

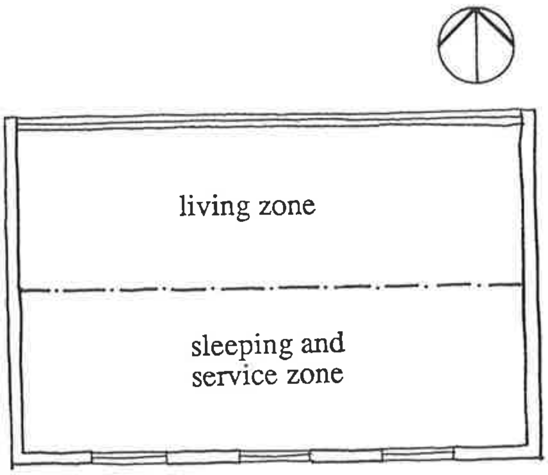
The conclusions in the paper on suitable features to be incorporated into a Solar House provide an insight into the conceptual shift associated with the general acceptance from the mid to late 1970's of this kind of description of the essential elements of a prototype *solar-efficient* energy-efficient dwelling for the temperate climate locations of Australia. Around this time the discourse changed in several ways; "energy" issues became more central to the house design problem and the rhetoric of design information embraced the ideal of focusing on the integrated whole building as the product.

Various publications, both Government sponsored and private, (for example, Architects Advisory Service, 1982; G.M.I., 1985; N.S.W. Department of Energy, 1988; Baverstock & Paolino, 1986; Den Ouden, 1980; Department of Construction, 1977; Department of Housing and Construction, 1985; Jenkins & James, 1978; NCDC, 1977) emerged in the late 1970's and 1980's containing energy-efficient design strategies for the temperate regions of Australia; these strategies usually established design rules-of-thumb which collectively describe the *solar-efficient* prototype. More recent publications have continued to affirm the same "theories" or "principles" (Ballinger, Prasad, & Cassell, 1992; E.I.C., 1993; Energy Victoria, 1994; Hollo, 1995; Department of Housing and Regional Development, 1995; Department of Housing and Urban Development, 1995). Most publications which describe examples of Australian temperate climate energy-efficient dwellings (for example, Szokolay & Sale, 1979; Cole & Parnell, 1983; Greenland & Szokolay, 1985; Hollo, 1995) deal almost exclusively with the *solar-efficient* concept. Some familiarity with this background literature is assumed of the reader of this thesis.

The main rules-of-thumb usually given to assemble the prototype *solar-efficient* dwelling are given below, together with some illustrative examples.

- **Zoned design with living rooms to the north and bedrooms to the south. Main heating in living areas.**

> *Living spaces are undoubtedly more useful and enjoyable when they are located on the north side of the house.* (GMI, 1985, p.2)
>
> *The living zones are used more than any other during waking hours, and so preference should be given to their orientation for maximum thermal comfort. In New South Wales, this means facing north.......* (Ballinger et al, 1992, p.21)



Zones within a house

(Ballinger et al, 1992, p.22)

The main living areas (family room, kitchen, dining and lounge areas) are best placed on the warmer side of the house, facing north. (Department of Housing and Urban Development, 1995, p.7)

The south side of the house is cooler because it receives no direct sun, so bedrooms on this side will be more comfortable....(Department of Housing and Urban Development, 1995, p.7)

Buildings are sited and designed to maximise solar access to north-facing windows of living areas ......(Department of Housing and Regional Development, 1995, p.191)

- **A length-to-width ratio of approximately 1 to 1.5 on the E-W axis.**

  The ideal shape for a climatically responsive house is generally thought to be a single storey[2] *rectangular plan with the long side facing north, maximising exposure to the sun on this side and minimising it on the less desirable east and west.* (Ballinger et al, 1992, p.22)

  Look for a site or design that maximises northern orientation of the most used areas of the house, enabling winter collection of solar energy through windows. (Energy Victoria, 1994, p.25)

  A well-designed house should therefore be elongated to open towards a private garden to the north. In this way the shorter eastern and western sides of the house are exposed to the low-angle summer sun in the morning and afternoon. (Hollo, 1995, p.20)

- **Cavity/solid brick and slab-on-ground construction**

  For a home to be energy efficient, the concrete slab floor and solid walls must be able to absorb as much heat as possible during the day and then release that stored heat into the room at night. (E.I.C., 1993, p.3)

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[2] This mention of the number of storeys is somewhat unusual. The number of storeys is typically not mentioned explicitly in the literature although, based on illustrations etc., there seems to be a general assumption that housing is single storey.

A concrete slab covered with carpet is the most thermally efficient floor in cold weather. The insulating properties of carpet, however, diminishes the ability of the thermal mass of the slab to reduce temperatures in hot weather. Hard floor coverings, for example tiles, expose the thermal mass to the air. (GMI, 1985, p.1)

In all but alpine climates, use construction materials with high thermal mass (the ability to store heat) to improve year round comfort and reduce total annual heating and cooling requirements by about 25%. (Energy Victoria, 1994, p.41)

[C]oncrete floors (with hard finishes such as ceramic tiles) and internal masonry walls can soak up the sun's heat and release it when the sun is no longer available. (Ballinger et al, 1992, p. 28)

Materials of high thermal mass are used for living areas and are located to maximise the absorption of heat from air circulating in the dwelling and from the winter sun. (Department of Housing and Regional Development, 1995, p.191)

- **Ceiling and walls insulated (recommended values may vary with climate)**

Insulating your house is the best defence against unwanted heat and cold. (E.I.C., 1993, p.4)

Thermal insulation is an essential part of the energy-efficient house in Australia. (GMI, 1985, p.1)

Ceiling and wall insulation is provided to at least the level recommended in AS2627.1-1993 for the locality. (Department of Housing and Regional Development, 1995, p.189)

Insulation [is required] to reduce unwanted heat loss or heat gain through the roof, walls and floors. (Hollo, 1995, p.19)

- **North facing windows, sometimes with a recommended area given as a function of floor area**

The greatest percentage of glass should face between 30 degrees east and 20 degrees west of north where solar gain and loss may be controlled to the greatest advantage. (N.S.W. Department of Energy, 1988, p.7)

High energy efficiency is achieved when the optimum area of north facing windows for winter solar gain is used, east and west windows are minimised and the total glass area is kept within acceptable limits. (Energy Victoria, 1994, p.30)

Large amounts of north facing glass will let sun enter in the winter, while a standard eave will shade the house in summer. . . (E.I.C., 1993, p.2)

Windows to north-facing living areas receive at least 3 hours of sun between 9am and 5pm on 21June over a portion of their surface. (Department of Housing and Regional Development, 1995, p.191)

- **No or minimum glass facing east and west**

An energy efficient home will have minimal or no windows facing east or west, because they let in so much heat in the summer. (E.I.C., 1993, p.3)

Glass facing east should not exceed 3% of the total floor area and glass facing west should not exceed 2% of the total floor area. (N.S.W. Department of Energy, 1988 p.7)

> *East and west windows are best kept small and should be fitted with shutters, outside blinds or vertical shading such as lattices or trees and shrubs.* (Department of Housing and Urban Development, 1995, p.8)

- **Shading devices to windows during summer (often expressed as an eaves projection or by using deciduous trees or vines for north facing windows and blinds etc. for east and west facing windows)**

> *All north, east and west facing glass must be provided with solar shading of not less than 0.3 to be eligible for a Five Star Design Rating.* (GMI, 1985, p.3)
>
> *..the width of the [north facing] overhang should not exceed 45% of the vertical height to be shaded.* (Energy Victoria, 1994, p. 6)
>
> *Windows are appropriately sized and shaded to reduce summer heat load.....*(Department of Housing and Regional Development, 1995, p.191)
>
> *Well designed shading adds greatly to your summer and winter comfort. Good shading keeps sun and heat out of your home in summer (when you don't want it)....* (Department of Housing and Urban Development, 1995, p.15)

- **Minimum winter ventilation rate**

> *Doors, windows and other openings have adequate draught control.* (Department of Housing and Regional Development, 1995, p.189)
>
> *Fit draft-excluders to outside doors and sealing strips to outside windows and doors.* (Department of Housing and Urban Development, 1995, p.14)

In a *temperate* climate the balance between the summer and the winter thermal performance of the building, and the summer and the winter thermal requirements of the occupants, are crucial factors which usually influence the nature of design advice. The failure of the one-dimensional preoccupation with the *solar-efficient* prototype comes into sharp focus in these climates because the rules-of-thumb design strategies do not adequately defined *ends*. The *ends* being the aims, goals, preferences, requirements, wants, needs, desired states or anything that any stakeholder in the energy-efficient house process may propose for consideration as an outcome.

1.2 Aims of this Thesis

The aims of this thesis are to examine conceptions of the energy-efficient dwelling for the temperate climates of Australia, to examine how published advice for the design of energy-efficient houses derives from these conceptions, and to examine the adequacy of the published advice as a basis for good design decisions. A main topic to be addressed in the thesis is the identification of the scope of energy-efficient goals within the broader design problem. The issues which will be raised by this examination include,

- the fundamental multi-dimensional nature of the problem

- the nature of assumptions and the extent to which clarity of ends and criteria are possible
- the appropriateness of means advocated for achieving energy-efficient housing solutions
- the logic of prototype solutions and rules-of-thumb associated with prototypes
- the validity of thermal analysis techniques, including computer simulation as a means of legitimating a prototype solution

1.2.1 Research Hypothesis

The hypothesis of this thesis is: that appropriate energy-efficient housing design is essentially contingent, depending on many factors such as,

- the relative importance of the ends to be addressed, including for example, environmental issues and occupant preferences such as desired thermal "comfort"
- local factors including climate and available fuel types
- occupant factors such as household use patterns and plant types used, and
- cost and the relative benefits of competing use of capital for promoting energy-efficiency

Therefore, *for the temperate climate regions of Australia the presentation of advice for energy-efficient house design in the form of rules-of-thumb associated with the concept of the solar-efficient prototype is inadequate and in many circumstances can direct designers away from more applicable solutions.*

1.3 Methodology

Appropriate problem definition is basic to this endeavour. This is equivalent to asking the right questions: if the wrong questions are assumed then it is only by chance that a 'right' answer may be found, and even then it is doubtful if it would be possible to recognise that it was 'right'. The currently complex problems of energy-efficient building design can be addressed more effectively if the problem definition is reinterpreted. This is the reason for the methodology and structure of this thesis.

The nature of the issues to be investigated requires the adoption of several modes of investigation which intertwine throughout the work,

- a historical perspective, to locate and identify what is perceived in the context to be the scope of the problem,

- a scientific/computational dimension, because many of the factors can usefully be presented within a normal scientific paradigm,
- an economic view, because within the whole design problem, energy-efficiency is only one factor affecting resource allocation,
- a theoretical outlook, to provide a language and framework for examining the whole problem.

The scope of the energy-efficient house design problem which is seen as being relevant in the Australian temperate climates is first investigated on a historical basis. This examination acts to reduce the scope of the problem from the potentially endless range of possibilities.

Chapters 2, 3 and 4 are primarily a review of the literature in three periods. Chapters 2 and 3 outline the background which lead to the conception of a *solar-efficient* prototype and hence the rules-of-thumb. Chapter 2 *Design for Climate: Thermal Performance Research In Australia 1946-1974* will review the literature concerning thermal performance research and design recommendations for dwellings in the temperate climates of Australia, beginning at the end of World War II. This Chapter provides background to the 1974 Williamson & Coldicutt paper by identifying the state of knowledge and practice with respect to the design and construction of energy-efficient dwellings that existed at the time. In Chapter 3 *Design, Economics and Energy* the basis of the 1974 paper will be further examined by outlining the general context of the time, including emerging methods of design analysis and evaluation, the understandings of performance requirements and concerns about environmental and energy supply issues.

Looking forward in time from the mid-1970's, Chapter 4 *New Insights* reviews more recent research work which has added to our comprehension of the thermal performance of dwellings, including research on actual household energy consumption and the thermal preferences of householders.

Computer program calculation of the complex thermal performance of a building is described in much of the literature as a legitimate tool to improve understanding of the problem. In Chapter 5 *Design Evaluation* the issues of computer simulation of thermal performance of dwellings will be discussed including efforts to reduce error by assessing their validity.

Having identified the main elements comprising the scope of the problem Chapter 6 *(Re)Framing the Issues* introduces the theoretical framework of an ignorance-based approach to discuss the nature and use of applicable knowledge in the design process for energy-efficient housing. The ideas introduced in this Chapter provide a methodology to examine and question problem definition and certain key assumptions regarding existing design advice.

Chapter 7 *Limits of the Prototype* asks the question "Given all that we know now, is the concept of a *solar-efficient* dwelling prototype, as the means of imparting energy-efficient design advice, still valid?" Because the scope of the problem is identified as multi-dimensional and contextual, a technique enabling multi-criteria investigations is introduced. Some selected case studies will be examined with the aim of highlighting limitations of the rules-of-thumb approach.

Chapter 8 *Summary and Conclusions* will provide a synopsis of the findings and discusses their implications, including their relevance to future energy-efficient housing design advice.

1.4 Background to Thesis

The conjecture behind this thesis is that the promotion of one energy-efficient house prototype in temperate Australia has occurred to a large extent neglectful of or in ignorance of the context and constructs behind the concept. The following sections outline something of the context and the key constructs and therefore provide the background to this work.

1.4.1 Definitions of an Energy-efficient House

What definitions of energy-efficient housing do we find in publications on the topic?

The key Government sponsored publication *Energy Efficient Australian Housing* (Department of Housing and Construction, 1985) does not offer a specific definition but explains in the Introduction that the publication is intended,

> *"to assist people who are building new houses or who wish to know what to do to improve the thermal performance of existing dwellings so that they will require as little energy as possible to remain comfortable without the dwellings being excessively expensive to construct or operate." (p x.)*

Elsewhere in this book it is stated that "the buildings themselves cannot achieve optimum performance without personal operation and management" and that "this suggests that a change in attitude and behaviour of occupants will probably be necessary to some extent in order to make energy-efficient designs function."

In the early 1980's the glass, brick masonry and thermal insulation industries (forming the GMI Council of Australia) together with Federal and State Governments combined in a scheme "to promote the construction of energy-efficient dwellings." Around $3.5M was spent in developing and promoting the scheme. The *Five Star Design Rating* (FSDR) scheme was directed mainly at encouraging and assisting builders to design and market a range of energy-efficient designs. Of a Five Star Home (GMI, 1985) we are told "It is a more comfortable home", it "is a low maintenance home" and that "you can turn low energy consumption into low energy bills". Elsewhere we are told that the Five Star Design Rating scheme is concerned with "the design, siting and construction of the building envelope and the selection of fixed appliances and lighting and the implications of these factors on energy-efficiency and thermal comfort." Energy-efficiency is never explicitly defined.

During the late 1970's and the 1980's "passive design", "solar architecture", "low-energy housing", "solar housing" and "solar design" became familiar terms to building designers, terms which were roughly synonymous with energy-efficiency. The publication *Solar Efficient Design for Housing* by the Victorian Government Solar Energy Council states that,

> *"Solar efficient design is a total universal concept for designing and building houses. It is an intelligent concept which utilises sunlight and traditional building products to naturally heat and cool the home." (Foreword, VSEC, 1990)*

Overseas the ASHRAE and American National Standard, *Energy Efficient Design of New Low-Rise Residential Buildings* (ASHRAE, 1990) states as its purpose "to provide design requirements for energy-efficient new residential buildings" but does not define "energy efficiency".

Ballinger (1992) suggests that living in an energy-efficient house brings many benefits such as lower energy bills, greater comfort, higher home resale value, greater awareness of the climate and being environmentally responsible. In a similar fashion Hollo (1995) says the benefits of living in an energy-efficient house are improved comfort and response to the climate, money saved on energy bills and reduced dependence on non-renewable resources. Although such "benefits" may be related to general energy-efficient housing ends, the survey of these and other publications reveals that rarely are the multi-dimensional aspects of the issue confronted in other than relatively trivial terms.

Energy-efficient housing, if defined at all, is described in limited and essentially instrumental terms as being concerned with the form, components and appliances which comprise the dwelling. The benefits are imputed to flow from following design rules-of-thumb associated with a *solar-efficient* prototype.

There would appear to be a need to clarify the goals which may apply to the concept of energy-efficient housing and to relate design alternatives directly to these goals.

1.4.2 Goals of Energy-efficient Housing

"Energy-efficiency" related to dwellings is potentially a complex and confusing concept. As noted above the term is used loosely to describe aspects of the energy-related design of a house, but is also concerned with the performance and the general operation of the house. Formally we can associate several distinct meanings with the term, such as;

end-use efficiency, meaning *either* reducing aggregate energy input while maintaining a level of performance (the "Energy Efficient" house) *or* holding input steady while performance levels increase (the "Comfortable" house). The notion of 'efficiency' implies a concern with the ratio of benefits to costs, but often the exact nature of both benefits and costs is left unclear. There is a lack of clarity concealed behind the ratio (benefit/cost) concept. Cited benefits often include thermal comfort, yet, the subtlety and complexity of all components of comfort are rarely considered in all their spatial and temporal aspects. This means that, even focusing narrowly on thermal comfort, end-use benefits cannot easily be defined. The "cost" part of the ratio is equally problematic. This goal is often presented in terms of a minimum life-cycle cost while holding the level of comfort at a constant value. Both the comfort and cost problems are discussed further in Chapter 3.

energy conservation, which is usually taken to denote a reduction in aggregate energy (depletable source) use (the "Low Energy" house) and is generally assumed to be accompanied by a net reduction in energy costs. An issue when addressing this goal is the definition of the problem boundary: do we deal only at the building scale or at a more extensive scale? The inclusion or exclusion of embodied energy (Pullen, 1995), and the necessary interrelationship between building design and fuel/appliance choice for heating and cooling, involve assumptions which are rarely made clear.

load management, which is concerned with reducing the peak load requirements for installed plant and appliances. This has the advantage at the household level of reducing capital costs and at the level of the reticulated energy (electricity and gas) supply of reducing or delaying expenditure on infrastructure. Here the issue of boundary definition may also be important as the goals of householders may conflict with the goals of energy supply authorities.

fuel/energy supply substitution, involving the use of a specific fuel/energy source because of either overall supply or wider environmental concerns (for example, the "Solar" house). During the late 1970's broad Government policies directed householders away from the use of oil as a heating fuel, and more recent publicity suggests the use of gas for heating rather than electricity in order to reduce Greenhouse gas emissions (ACA, 1991).

minimum environmental impact, which is related to reducing adverse influences on the natural environment because of concerns for the deterioration of its quality. Notions of ecological sustainability are linked to this aim. The issue of global warming caused by greenhouse gas emissions is a particular concern in recent times and means are recommended to reduce CO_2 production by reducing fossil fuel usage (N.G.S.C., 1992).

These last two goals or ends illustrate the complexity of energy-efficient dwelling design, because in these cases the primary end being addressed is only indirectly a question of energy *per se*.

1.4.3 Public Policy and Energy-efficient Housing

Prior to 1978 public policy in Australia did not address the issue of energy-efficient housing. In March 1978 The Australian Minerals and Energy Council (AMEC), in response to Australia's perceived vulnerability to overseas disruptions to energy supplies, in particular liquid petroleum fuels, initiated a National Energy Conservation Programme (NECP). Included in the broad aims of this programme were to:

- moderate the growth of energy demand
- improve the efficiency of energy extraction, conversion, distribution and utilisation
- eliminate wasteful practices
- develop renewable and alternative sources of energy
- minimise the environmental impact of energy developments (Department of National Development, 1979)

Efforts in Australia to encourage energy-efficient housing as a public policy can be traced to this time and provided an impetus for increased research, development and promotion. Emphasising energy savings in the home was an integral part of the initial programme. Development of energy conservation in a familiar environment, such as the home, was perceived as a first step to the extension of these attitudes to other areas. Some efforts were made to discover people's knowledge, attitudes and behaviour (Crossley, 1980). These studies generally concluded that social and institutional "barriers" prevented people from adopting energy-efficient practices. Occupant behaviour was often described as a "psychological barrier" (Luxton, 1982) and more of a nuisance than an issue worthy of serious investigation. Energy advisory services and media campaigns were mechanisms introduced to overcome these barriers.

In 1986 the 'energy crisis' emphasis of the NECP was replaced by a National Energy Management Program (NEMP) with a purported emphasis on encouraging energy-efficiency. Walsh and Kerby (1990) document the developments in this national energy policy and in a critique of the NEMP programme they suggest,

> *"The fact that the NEMP has not been defined well enough to allow performance objectives to be set has meant that implementation activities have tended to become the program's goal. Activity milestones (such the number of workshops held, number of booklets distributed or the number of appliances labelled) tend to become the goals." (Walsh & Kerby, 1990)*

In 1990 the then Commonwealth Minister for Minerals and Energy, the Rt. Hon. Alan Griffiths, produced an information booklet aimed at promoting the idea of energy-efficient housing. The Preface aims at dispelling fears by explaining,

> *"When we talk of conserving energy or using it more efficiently....we are not talking about reverting to a Spartan existence. Energy conservation does not mean going without; it does not mean lowering our standard of living; it does not require fundamental changes in lifestyle." (Griffiths, 1990)*

The possibilities of energy-efficient housing were described in rather exaggerated terms by,

> *"....an energy efficient home uses up to 90% less energy than the average of current housing stock"*

and

> *"....in the next 15 years energy use per housing unit could be improved by as much as 50 per cent if all of the currently available cost-effective energy efficient options were taken" (Griffiths, 1990, p10)*

The booklet recommends compliance with the design guidelines of the Five Star Design Scheme as a significant first step in achieving these possibilities.

More recently, public policy on energy-efficient housing has been motivated, at least in the rhetoric of Government pronouncements, by another concern. In 1990 Australia signed the UN Framework Convention on Climate Change. This Convention sets an international objective,

> *"to stabilise greenhouse gas emissions (not controlled by the Montreal Protocol on Substances that Deplete the Ozone Layer) based on 1988 levels, by the year 2000 and to reduce these emissions by 29% by the year 2005" (N.G.S.C., 1992)*

Following this signing, the Council of Australian Governments in 1992 endorsed the *National Greenhouse Response Strategy*. The goal of this strategy is,

> *"to contribute towards effective global action to limit greenhouse gas emissions and enhance greenhouse gas sinks; to improve knowledge and understanding of the enhanced greenhouse effect; and to prepare for potential impacts of climate change in Australia." (N.G.S.C., 1992)*

As one response action, Governments, through ANZMEC (Australian and New Zealand Minerals and Energy Council), agreed to the development of a National House Energy Rating Scheme (NatHERS) intended for implementation throughout Australia by 1994.

In the first stage of its development NatHERS has been limited to assessing the general performance of the exterior envelope of a dwelling as it relates to heating and cooling loads for an assumed use pattern and a defined climate (Cassell & Ballinger, 1996). The scheme will *not* address the broader issues mentioned above such as performance differences due to plant or fuel type, embodied energy or life-cycle costs. Nor will a NatHERS house rating involve an assessment of Greenhouse gas emissions other than the implicit assumption that a reduction in energy load will correspond to a reduction in CO_2 emissions. By early 1997 the national scheme had still not been launched[3].

Early in 1995, in conjunction with the UN sponsored World Conference on Climate Change, the Minister for the Environment, Sport and Territories, Senator John Faulkner, issued a statement entitled ***Greenhouse 21c*** in which an expanded plan of action for the Greenhouse Response Strategy was announced. This new plan was said to be based on environmental and economic objectives which were seen as central to an ecologically sustainable future. The plan called for the development of new expertise in various areas, including energy-efficient building, materials and techniques.

Also during 1995, the Federal Minister for Housing and Regional Development, the Rt. Hon. Brian Howe, released *AMCORD-A National Resource Document for Residential Development* (Department of Housing and Regional Development, 1995). This document was aimed at promoting good design in Australian urban areas at State, Territory and Local Government levels to meet economic, social and cultural needs. The document was developed in a partnership between government (at all levels) and industry. AMCORD is described as,

> *"......a manual of best practice....adopting an integrated, performance based approach to urban development which provides a practical alternative to outdated prescriptive methods......" (Department of Housing and Regional Development, 1995, Foreword)*

The AMCORD section *Design for Climate* provides Performance Criteria and Acceptable Solutions which are essentially formulations of the rules-of-thumb associated with the *solar-efficient* prototype as described above.

Because energy-efficient housing will most likely continue to be an element, at least in the declamation of government policy, it is essential that there is a thorough and realistic understanding of the issues.

The aim of this work is to contribute to that end.

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[3] NatHERS was launched *[prematurely]* in Western Australia during June 1996 and provided house rating assessments based on tentative NatHERS software.

CHAPTER 2

DESIGN FOR CLIMATE

THERMAL PERFORMANCE RESEARCH IN AUSTRALIA

1946-1974

2.1 Introduction

This Chapter outlines the major contributions to research on the thermal performance of dwellings during the period from World War II to 1974. The discussion concentrates on Australian research but does include some references to work carried out overseas where it relates to Australian work. The historical investigation reveals the perceived scope of the problem of the thermal design of buildings during the period and establishes the features of the discourse on design advice prior to the mid-1970's. It is from this background that the concept of the energy-efficient house emerged.

During this period three basic aspects were generally considered important in relation to the thermal design of buildings. These are summarised by Van Straaten (1967) as,

> *"evaluation...of indoor environmental conditions most conducive to comfort, health and general well-being of the occupants......to describe representative or typical weather conditions that must be taken into account when developing the best design.....[and to show] how design procedures and physical properties of different structural materials can be utilized to ensure the best possible control of living and working environments."* (Van Straaten, 1967, p1)

These three aspects can be seen as the main concerns of the research efforts in Australia.

2.2 Research Organizations in Australia

Thermal performance research work in Australia was dominated initially by two organizations, the Department of Works[1], Commonwealth Experimental Building Station (CEBS) located in Ryde in Sydney, and the CSIRO, Division of Building Research[2] (DBR) situated in Highett in Melbourne. The work of these organizations is described in some detail in this Chapter. From 1963 the CSIRO, Division of Mechanical Engineering (DME) also undertook several projects concerning the thermal performance design of buildings but dealing mainly with air-conditioning plant and requirements. Because DBR and DME shared the same site (and the same staff tea room) there were several joint projects and important interactions.

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[1] The Department of Works had several changes of name in the period under consideration

[2] Initially called the Building Research Laboratory (BRL)

Other research groups, mainly in universities, also made valuable contributions to knowledge in the area but their work usually remained in the academic arena and was not widely disseminated to the public and the design professions.

2.2.1 Research Coordination

In 1948 a Building Research Advisory Committee, comprising representatives of the various research laboratories concerned with building together with representatives of the building industry was established to oversee the effectiveness of all building research work being undertaken by Commonwealth organizations. The task of the Committee was to direct activities to the problems most important to the building industry and also to ensure that the results of research were widely distributed. Although one of the objectives seen by the Committee for building research was achieving "high standards for comfort and convenience" there is no evidence that this Committee or the building industry in general saw thermal performance research as a high priority. Because of the nature of this Committee it was never possible to develop an integrated strategic approach to building research. Although some important and highly innovative thermal performance research was carried out in the period its piecemeal nature reflects both its relatively low priority and a lack of collaboration between the groups.

2.3 Climatic Determinism

The notion that the form and construction of dwellings should be determined by the climate was (and is) an axiom under-pinning thermal performance research and the resulting design advice. Pre-occupation with this idea is seen to be particularly strong in Australia which has a wide climate range. The two principles of building envelope design as either modifying the external environment (for example, repelling the effects of solar radiation on hot days) or admitting beneficial effects such as sunlight and fresh air, are well entrenched in the conventional wisdom on the subject. O'Sullivan (1994) refers to these two building design approaches as "climatically rejective" and "climatically interactive". The idea that energy consumption for heating and cooling when used to maintain acceptable indoor conditions is predominantly a function of climate severity is also well accepted. The titles of many of the classical texts on thermal performance design, both in Australia and overseas, proclaim the connection between building design and climate verifying the status of this view since WWII. For example,

Design for Climate I and II (CEBS, 1949, 1951)

Designing Houses for Australian Climates (Drysdale, 1952)

Climate and Architecture (Aronin, 1953)

Design with Climate (Olgyay & Olgyay, 1963)

Buildings, Climate and Energy (Markus & Morris, 1980)

Building in Hot-Dry Climates (Saini, 1980)

Man, Climate and Architecture (Givoni, 1981)

As the idea of climatic determinism can be seen to dominate the thinking about thermal performance research of the period, the following sections provide some background to the notion. Its validity will be discussed in Chapter 4.

2.3.1 Building Design and Climate

Climatic determinism is not a recent phenomenon. As Rapoport points out,

> *"Climatic determinism has been widely accepted in architecture as well as in cultural geography, although in the latter it has recently found rather less favour. One need not deny the importance of climate to question its determining role in the creation of built form.......In architecture the climatic determinist view, still rather commonly held, states that primitive man is concerned primarily with shelter, and consequently the imperatives of climate determine form." (Rapoport, 1969)*

Some of the earliest known writings on architecture deal with climate as a principal factor governing design. The Greek scribe Xenophon writing on the teachings of Socrates around 400BC says,

> *Again his dictum about houses, that the same house is both beautiful and useful, was a lesson in the art of building houses as they ought to be.*
>
> *He approached the problem thus:*
>
> *"When one means to have the right sort of house, must he contrive to make it as pleasant to live in and as useful as can be?"*
>
> *And this being admitted, "Is it pleasant," he asked, "to have it cool in summer and warm in winter?"*
>
> *And when they agreed with this also, "Now in houses with a south aspect, the sun's rays penetrate in to the porticoes in winter, but in summer the path of the sun is right over our heads and above the roof, so that there is shade. If, then, this is the best arrangement, we should build the south side loftier to get the winter sun and the north side lower to keep out the cold winds. To put it shortly, the house in which the owner can find a pleasant retreat at all seasons and can store his belongings safely is presumably at once the pleasantest and the most beautiful."* (Xenophon, 1923)

The housing design advice given by Vitruvius in the first century AD for the far flung Roman Empire was influenced by an awareness of the climate,

> *If our designs for private houses are to be correct, we must at the outset take note of the countries and climates in which they are built. One style of house seems appropriate to build in Egypt, another in Spain, a different kind in Pontus, one still different in Rome,......because one part of the earth is directly under the sun's course, another is far away from it.......hence, as the position of the heaven with regard to a given tract on the earth leads naturally to different characteristics......it is obvious that designs for houses ought similarly to conform to the nature of the country and to diversities of climate.* (Vitruvius, 1960)

More modern views of climatic determinism would seem to have their roots in the ideas of environmental "determinism" and "possibilism" of human geography.

For Vidal del la Blache, the eminent geographer who established the French school of geography, the *genre de vie* ("ways of life") are influenced by the environment;

> *"A town, a village or a hamlet, all are descriptive traits of any region. Shape and building materials as well as adaptation to a mode of life, - rural or urban, agricultural or pastoral, as the case may be, - all throw light upon relations between man and the environment.......Conditions of soil and climate have determined whether wood, earth or stone should predominate."* (Vidal de la Blache, 1926, p238)

More extremist views of climatic determinism found expression in architectural writing of the 1930's and building science literature post WWII. Principal among these were the writings of Huntington, Mills and Markham. E. Huntington in *Climate and Civilization* (1915) developed the hypothesis that,

> *"...a certain peculiar type of climate prevails wherever civilization is high. In the past the same type seems to have prevailed wherever a great civilization arose. Therefore, such a climate seems to be a necessary condition of great progress. It is not the cause of civilization but it is infinitely deeper."* (Huntington, 1915,p9)

Mills in *Climate Makes the Man*, (1944) developed a similar theme but is more direct,

> *"Temperate-zone nations are leaders in world affairs. Their people, activated by cool climates, have had the energy to build great power plants, skyscrapers, dams, bridges, and a legion of impressive monuments to human initiative. They visit the tropics mainly for trade and war, and have long benefited from tropical raw material wealth which the natives are too sluggish to exploit.."* (Mills, 1944, p44)

F.H.Markham the one time Parliamentary Secretary to the English Prime Minister, Ramsay MacDonald, in *Climate and the Energy of Nations*,(1944) says,

> *".....One of the basic reasons for the rise of a nation in modern times is its control over climatical conditions......civilisation to a great degree depends upon climate control in a good natural climate."*

And elsewhere,

> *"...where indoor temperatures are above 60°F and below 76°F, and the relative humidities between 40 per cent and 70 per cent, sedentary men work harder and more efficiently that at temperatures and humidities outside this zone."* (Markham, 1944)

Referring to Queensland he says that the great progress (prior to 1947) had been achieved because immigrants brought their energies with them but,

> *"...for a time* <the progress in> *these areas are bound to reflect these energies...But sooner or later climate will tell."* (Markham, 1944).

He then goes on to suggest that if Queensland is to continue its progress climate control must be acquired, as acclimatization to hot and humid weather has resulted in a gradually lowering working efficiency. Mills, however, had questioned the use of air-conditioning on a large scale saying,

> *"The difference* <between heating and cooling> *lies in the fact that winter heating is essential while summer cooling is more or less a luxury. Hot-weather comfort is particularly costly in tropical climates, where the cooling load is heavy and electricity rates are high.....While proper conditioning of man's indoor habitat may add greatly to his comfort and health, it is questionable whether it can go far toward overcoming the more profound effects of given climates upon whole masses of people."* (Mills, 1944, p123)

Just one year after the publication of the works of Mills and Markham, "scientific evidence" of household behaviour and actions which did not conform to the simplistic models of assumed thermal behaviour, and therefore questioned some basic notions of climatic determinism, seems to have gone unnoticed by researchers, as will be discussed below.

2.3.2 Findings Which Confound the Belief

A report by the UK Heating and Ventilation Committee of the Department of Scientific & Industrial Research (Heating and Ventilation (Reconstruction) Committee, 1945) included the results of an extensive survey into the heating practices and requirements in 5260 working-class dwellings throughout England, Wales and Scotland. The results of several of the questions asked in the survey should perhaps have rung alarm bells in the thermal performance/comfort research community.

One section of the report provides an analysis of annual household expenditure on heating by Heating Degree Days which was expected to reveal a direct relationship between these two variables. The results given in Table 2.1 in fact show little variation across the range of climates.

Table 2.1: Average Annual Expenditure in Houses Analysed by Heating Degree-Day Regions

Degree-day Regions	5000-5500	4500-5000	4000-4500	under 4000	National
Mean Expenditure	£16 19 5	£16 6 1	£16 19 5	£16 19 8	£16 15 11

The commentary in the report on this data suggests that the approximate equal expenditure across the degree-day regions could be explained, in part,

> *"by the lower price of coal in the North of England and the populous parts of Scotland"* (Heating and Ventilation (Reconstruction) Committee, 1945, p112).

This claim, however, seems not to explain the results. Elsewhere in the report we find details of the cost of coal, shown as Table 2.2, which shows that apart from the London and South region the mean cost per Cwt was approximately uniform throughout the remaining regions. There is no explanation as to why a Midlands town generally in the 4000-4500 degree-day range would have approximately the same annual heating expenditure as towns in Scotland where the degree-day range would be 5000-5500.

Table 2.2: Mean Cost of Coal per Cwt Analysed by Geographical Regions

Scotland	North	Midlands	London and South, etc	South-West and Wales
2s 5d	2s 2d	2s	3s 11d	2s 7d

Another result from this survey which also provides confounding information comes from the answers to the question : *"Would you like central heating in all rooms and constant hot water in the bathroom and kitchen?"* The results given in Table 2.3 show an inverse relationship to climate severity measured in terms of heating degree-day.

Table 2.3: Answers to Central Heating Question, % of responses, analysed by Degree-Day Regions

Degree-day Regions *Answer*	5000-5500	4500-5000	4000-4500	under 4000	National
Yes	45	71	74	80	75
No	55	29	26	20	25

The commentary on this data concludes with the statement that,

> *"attitudes to central heating requirements were not related to heating needs"*
> (Heating and Ventilation (Reconstruction) Committee, 1945, p128).

This example illustrates that design decisions based on some simple notions of occupants' thermal behaviour could be at variance to people's practices and expressed preferences. Research and design information which take climatic determinism as a basis run the risk of being mis -directed. This is to be discussed further in later Chapters.

2.4 Homes in the Sun

Before proceeding to a detailed discussion of specific thermal performance research mention must be made of a small book *"Homes in the Sun"* written by Walter Bunning (1945) an architect with the Commonwealth Housing Commission. The book was intended to set the scene for a new era in housing design following WWII. H.E.Coombs, the then Director-General for the Ministry of Post-War Reconstruction, in the Foreword says,

> *"The last two years have been difficult times for those interested in housing. Many were aware of the desperate urgency of the problem and alive to the preparatory work which should have been undertaken if the problem was to be expeditiously handled when the war was over.........."*

The book is unique in that it adopts an architectural style of describing a series of prototype solutions. The optimism at the end of the war is evident throughout the book.

> *"People everywhere are looking ahead to the promise that the future holds out to them. Remembering the bitter disillusionment of the last peace, they are seeking to ensure that this time there will be a square deal for everyone........This book seeks to draw a picture of the way Australian homes could be built to admit fresh air, to have healthy surroundings, peace and quiet, and to suit our climate and traditions...."*
> (Bunning, 1945)

One particular solution, coining a phrase ahead of its time, is described as a ***Solar House.***

> *"This solar house is designed on the scientific principle that the eaves of the roof extend just far enough so that the sun's rays penetrate in the rooms in Winter, but not in Summer. All the main rooms face north behind a virtually unbroken expanse of clear glass. If the eave is the right width it excludes the direct rays of the high Summer sun and renders interiors cool, but when the Winter sun swings low on the northern horizontal its beams slant in under the eave and flood the house with heat and light......."*. (Bunning, 1945)

The idea appears to be based largely on a similar design in America (source not given) where it is claimed the Solar House design cuts heating requirements by one-third. Bunning suggests however that such a large saving would not be achieved in Australian climates. The modified house adopted in the 1974 Williamson & Coldicutt paper had most of the characteristics suggested by Bunning for his Solar House.

2.5 The Work of the CEBS

CEBS was established in 1944 and at an early stage a report of the Commonwealth Housing Commission was referred to it for consideration. This report stressed the need to study the design of buildings in relation to climate because of extreme indoor conditions being experienced during hot summers. Investigations aimed at providing standards for construction which would alleviate the extreme heat of summer were commenced almost immediately and were given a high priority. The aim of this research was to make recommendations for the design and form of the construction of houses suited to the various climatic zones of Australia.

Initially the work reviewed existing data and their applicability for Australian conditions. An early report published during 1947 entitled *Climate and House Design* (Drysdale, 1947) summarised the previous work which directed "attention to the relationship which should *(my emphasis)* exist between climate and house design to improve comfort indoors" and in which "attention was drawn to the apparent disregard, in this country, of the prevailing climatic conditions, and to the irrational use of traditional materials." Drysdale pointed out that "Generally, the results of this disregard has been unfavourable indoor conditions, usually during summer, as the greater part of Australia experiences its most severe climatic conditions during that season" (Drysdale, 1947, piii). The report concluded that vital information was lacking and field investigations were recommended.

An initial part of the work required defining suitable climate zones in Australia. Zoning on a strictly climatological basis was found to be impractical and too detailed for interpretation in terms of building construction. A zoning on an "arbitrary" subdivision was therefore chosen. This classification comprised three types of climate each with two subdivisions (Drysdale, 1950).

Climate Classification	**Hot humid**	**Hot dry**	**Temperate**
Sub-divisions	Tropical humid	Hot arid	Temperate
	Sub-tropical humid	Dry warm temperate	Cool temperate

Drysdale's climate classification map reproduced as Figure 2.1 is still often used.

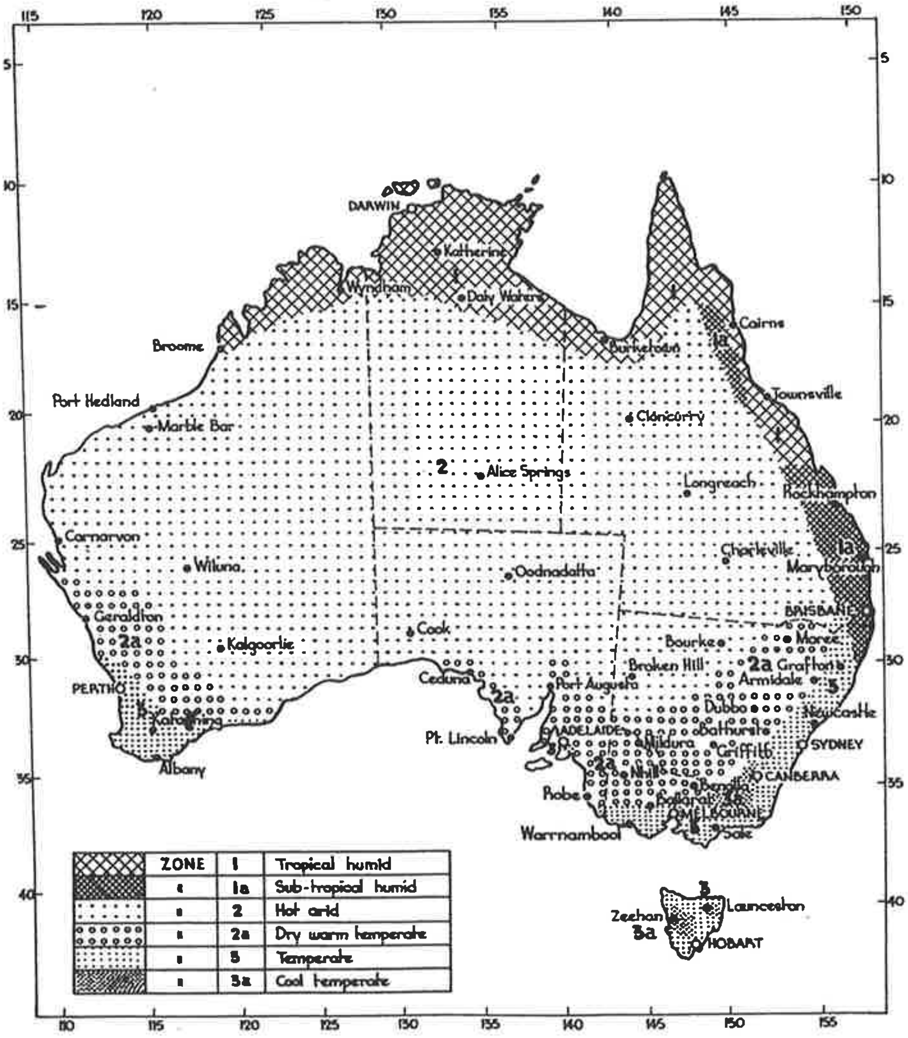


Figure 2.1: Broad Classification of Australian Climates
Note: Taken from Drysdale, 1950.

2.5.1 Design Data

As part of the overall project to improve dwelling design some important design data and information were produced. The annual and diurnal climate details relating to design variables, temperature, sunshine hours, humidity and the prevailing wind speed and direction for particular localities, were compiled from existing meteorological records and made available in a summary form useful to designers.

In the introduction to *Selected Australian Climatic Data for Use in Building Design*, Keough (1951) again outlines the belief in the desirability of climatic determinism. He says,

> *"Throughout the ages man has sought protection from the elements, and has developed structures to meet his several needs. Initially one class of structure sufficed, and served as both dwelling and workshop; but with the development of society and industry other functional units have been devised for purposes of commerce, industry and social welfare......in selecting the materials for their construction, the designer's consideration of climate factors often does not extend beyond allowances for weather tightness......the data presented are intended to be applied when implementing the principles of designing for climate...."* (Keough, 1951)

In May 1948, a publication, *Sunshine and Shade in Australasia,* by R.O.Phillips, produced perhaps the first example of a planar projection of the sun's path to be used to determine appropriate shading devices at a particular latitude (Phillips, 1948). The preface to this document says,

> *"There is little doubt that architects, town-planners, and the public generally are becoming increasingly conscious of the need for designing buildings for sunlight, whether for maximum penetration in cold climates, or adequate shading for hot conditions. However desirable this may be, information available on the subject has not proved adequate for most designers to give it the attention which it deserves." (Phillips, 1948)*

The technique used employs stereographic diagrams of the sun's path throughout the year. Individual charts covered the principle cities in Australia, New Zealand and New Guinea.

2.5.2 The Experimental Work

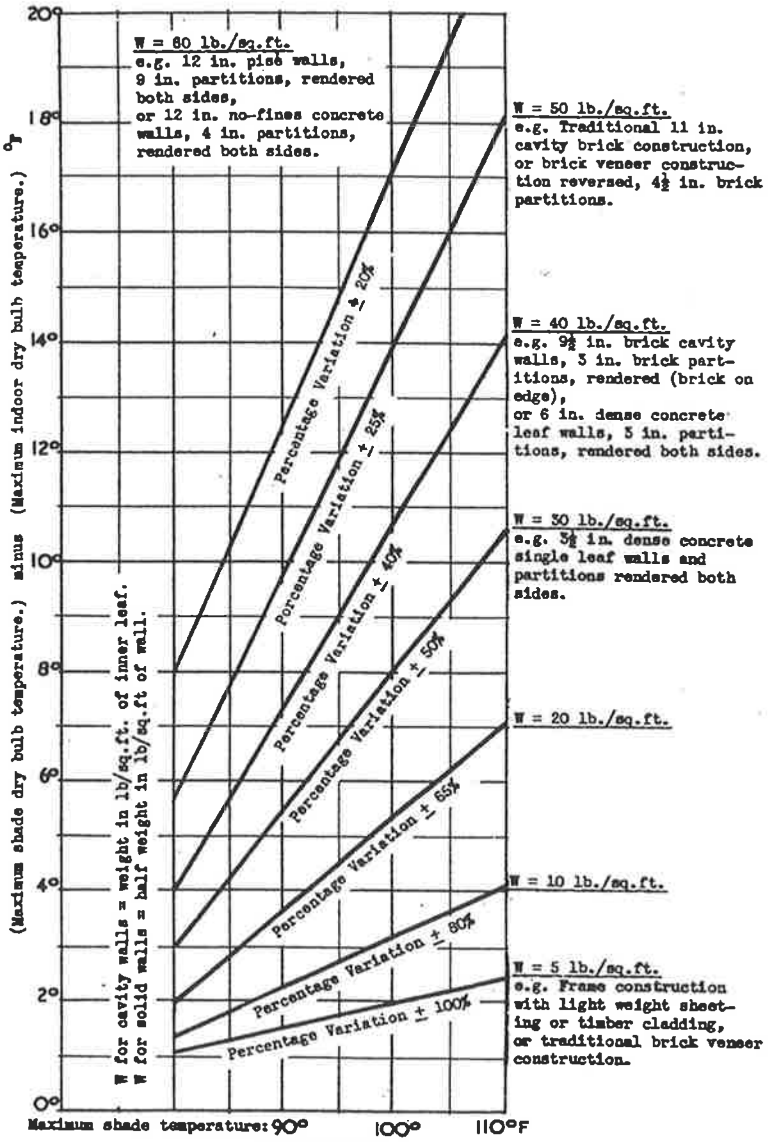
The early experimental work involved field observations in houses in the various climates. These however proved relatively inconclusive due to the variation in house design and climate. The effects, for example, of insulation treatments in ceilings and walls, or concrete versus timber floors, could not be discerned from these observations. Although the observations added to the understanding of the thermal behaviour of dwellings, they yielded little upon which generalised design rules could be established. To overcome this difficulty an experiment was conceived involving thermal models. A colony of models of six different forms of construction - single leaf brick, timber frame, brick veneer, reverse brick veneer, single leaf concrete and brick cavity wall construction - were tested under identical conditions, each construction being used to observe the effects of exposure to sunshine, ventilation and insulation. The experiments involved treating one model of a pair and observing the difference from a second, all other conditions including the daily climate being identical for the pair.

These models measured 3ft x 3ft in plan with a 1ft ceiling height. A typical house and larger models of 10ft x 6ft x 2ft3ins were built later to check the results with the smaller models.

By 1949 sufficient data had been collected to suggest empirical results for the following effects:

- the influence of solar radiation and the contribution to internal temperature rise and heat flow through roof and walls.
- the response to external temperature at different rates of ventilation and with varying thickness of insulation.

A first design chart (see Figure 2.2) was published by Drysdale in the early 1950's and showed the influences of various construction types on the maximum internal temperature. The design chart appeared in several versions during the following 20 years or so.



THERMAL BEHAVIOUR OF DWELLINGS

Chart for assessing approximate temperature differences maintained by different forms of construction, applicable for sunny summer conditions when the diurnal temperature range exceeds 20°F, and normal natural ventilation is provided. Temperature differences determined from the chart will be subject to the percentage variations shown for the various weights of construction.

NOTE. The chart is directly applicable only when materials of external walls and partitions bear conventional relationship, e.g. 11 in. brick cavity walls and 4½ in. partitions, or timber frame walls and partitions.

Figure 2.2: Thermal Behaviour of Dwellings

Note: Taken from Drysdale, 1952.

To relate experimental observations to the thermal properties of building materials an analytical technique was required which could estimate the dynamic thermal effects with variable heat flows "which is of importance to the relative discomfort in houses day and night when there is no temperature control by heating or cooling appliances - the condition of interest in the Australian design problem." (Alexander, no date)

Hand calculations were seen as impractical and work was undertaken at the CEBS with an electrical analogue with plug-in units to represent the walls, floor, roof-ceiling and ground of a typical dwelling. A diurnal excitation was applied to enable tabulation of internal temperatures at selected times of the day. This electrical circuit model provided the key to the development of a mathematical treatment for the thermal response of a building using two "new" thermal properties of building elements - the transfer impedance and the internal impedance together with their respective lags (Alexander, no date). This work was almost complete when in 1955 the CEBS saw its thermal work as substantially complete and this exercise was abandoned. The BRE Admittance method published some twenty years later was a very similar technique (Milbank & Harrington-Lynn, 1974).

2.5.3 Dissemination of Research Findings

CEBS produced a number of Technical Study reports as duplicated documents detailing the various research activities but two major publication series, *Notes on the Science of Buildings* (NSB) and the *Technical Bulletin Series* (TBS), were the main vehicles for the dissemination of research findings to design professionals and the building industry.

NSB *Design for Climate* was published first in August, 1949, and discusses the design of domestic buildings for the Hot Arid and Hot Humid climates of Australia. The introductory paragraph echoes the writings of Mills and Markham.

> *"The loss of energy and efficiency experienced by white people in hot climates is difficult to assess, but it is appreciable, and justifies considerable attention to the improvement of physical conditions of both working and living."* (CEBS, 1949)

Two years later followed *Design for Climate II* dealing with issues of thermal performance design in the temperate regions of Australia (CEBS, 1951). In both publications the design/construction recommendations are presented as a series of issues which the designer should address in order to achieve a satisfactory result.

TBS *Designing Houses for Australian Climates* was published first in 1952 and provides a comprehensive discussion of the design recommendations determined from the research investigations (Drysdale, 1952). This publication has been updated in several editions since that time.

2.6 The Work of CSIRO, DBR

Building thermal performance research commenced at the CSIRO Building Research Laboratory (BRL) during 1945. The first project undertaken at BRL involved research into the thermal conductivities of building materials. In 1949 the report of BRL signals the start of research into thermal analysis methods which continue throughout the whole period to 1974. The thermal investigations in the early stages were however rather slow, being hampered by a lack of space and staff resources.

2.6.1 Thermal Analysis Techniques

The initial project in thermal analysis proposed to repeat and refine the work of CEBS using an electrical analogue technique.

> *"It is a relatively simple matter to calculate the heat flow into or out of an enclosure when the internal and external conditions remain constant. To perform the same calculation under varying conditions is a prohibitively difficult task and becomes impossible if the conditions of heat transfer vary with time or temperature. The heat flow can, however, be determined by use of an electrical "analogue" which consists of an electrical network having a circuit corresponding to the thermal transfer case, replacing thermal resistance and capacity with electrical resistance and capacity. By feeding appropriate signals into the electrical circuit, it is possible to measure the electrical response at any given point in the circuit and to transfer the result into terms of the thermal case. It is proposed to construct such an analogue and investigations have been made to determine the minimum number of capacity "lumpings" tolerable and the electrical circuit for the case of a dwelling."* (Building Research Laboratory-CSIRO, 1949)

In the 1950 DBR Annual Report "the electrical analogue instrument is nearing completion" and in 1951 "the electrical analogue has been wired and is being checked against theoretically known cases and thermograph readings taken during the summer in two houses of different wall types" In 1952 the Division suffered a 18% cut back in staff which resulted in many programmes being suspended. It appears that no papers were ever produced from the electrical analogue experiments. It is at this time however that Muncey wrote a seminal paper entitled, *Calculation of Temperatures Inside Buildings Having Variable External Conditions* (Muncey, 1953). In this paper he describes the usual methods for estimating the temperature inside houses and other buildings exposed to fluctuating external temperatures as employing either the thermal models as proposed by Drysdale or by electrical analogues. Because of their complexity, analytical methods had, up to then, been applied to only one transfer element (such as a wall) in which that element was overwhelmingly important from the thermal point of view. These techniques, he pointed out, can obviously become laborious if many variables of climate and construction are to be handled. He went on to describe the evolution of a new mathematical technique applicable to all types of building and which was faster, more accurate and much less costly than experimental methods. It was based on the principle that if the surface temperatures and hence the heat flows at the two faces of an infinite slab of material are harmonic, they are related to two simultaneous equations in which the coefficients depend on the properties of the material. Non-sinusoidal temperature cycles could be treated by analysing them into harmonics. In the paper Muncey states that the method, which marked an important development in the study of free-running buildings under summer conditions, had been verified by experiments on model houses subjected to cyclic external temperatures.

Work continued over the next 10 years on the mathematical modelling of temperatures inside buildings. Results from monitoring a timber floor house and a "solar" house (see Section 2.6.4) were compared with predictions using a harmonic technique (Fourier analysis) and found to be "better than expected". Final calculations were carried out using a computer, the first reference to such a method. A quaint reference from the 1957 Annual Report states, "....the usefulness of an automatic computer was not realised until this work was almost completed....". A suite of four programs were devised for the calculations, tested and made available on the Melbourne University CSIRAC computer for general use. The harmonic technique program was named CARE (Division of Building Research-CSIRO, 1960).

In 1963 Muncey detailed a step-function or response factor technique for calculating variable heat flows in the paper *Thermal Response of a Building to Sudden Changes of Temperature or Heat Flow* (Muncey, 1963). Response factor methods up until that time had involved obtaining response factors for individual heat flow paths. Muncey proposed an alternative to this time-consuming procedure by calculating the response factors for the total building. The technique provided the basis for the computer program STEP whose development commenced in 1964 using the Fortran language. Some demonstrations of the accuracy of the technique were attempted and presented in the paper *The Calculation of Internal Temperatures-A Demonstration Project* (Muncey & Holden, 1967). The conclusion of this paper somewhat belittles the advance:

> *"The temperatures measured inside a concrete box structure were found to agree very well with the corresponding temperatures calculated from the observed external conditions......The discrepancies which do occur may be caused by both the experimental error and deficiencies in the theory..."*

Long term climatic data to be used as input to the computer programs was assembled during this period by DME. Data from the Bureau of Meteorology was compiled and stored on magnetic tape for processing by modern high speed computers. In 1965 DME began work on their own computer program for air-conditioning calculations. The technique based on the finite difference method was developed over several years and was released commercially as TEMPER in 1974.

Two papers presented by DBR personnel at the First Symposium on the Use of Computers for Environmental Engineering Related to Buildings, held in Gaithersburg, USA during 1970, *A Conceptual Survey of Computer-Orientated Thermal Calculation Methods* (Gupta, Spencer, & Muncey, 1970) and *Methods for Thermal Calculations Using Total Building Response Factors* (Muncey, Spencer, & Gupta, 1970) give a good summary of the international state-of-the-art, and show DBR at the forefront.

Modifications to the programs CARE and STEP to enable "efficient" design studies were progressively introduced. These included the handling of variable ventilation rates and the operation of heating and cooling thermostats. By 1972 the program CARE was essentially abandoned and all development work concentrated on the STEP program. In 1974 the STEP program was substantially revised to include multi-zone computations and renamed ZSTEP (Z for zones). Periods of "real" climatic data were also compiled for use as program input. ZSTEP however remained, by today's standards, a rather crude and difficult to use research tool. A survey of DBR publications of the period indicates that although the nature of the heat flow calculations through opaque building components was discussed in some detail, at no stage were the development or details of the methods of the thermal analysis computer programs open to scrutiny.

2.6.2 Thermal Conductivity, Sol-Air Temperature and Ventilation

In 1946 Barned compiled a data summary (Barned, 1946) based mainly on overseas information, and in 1949 work commenced on the design and installation of instruments to measure the thermal conductivity of Australian building materials "so as to gain a more detailed knowledge of their behaviour than is available from the results of overseas tests on similar materials" (Division of Building Research-CSIRO, 1950). A large and small guarded hot plate apparatus were planned for construction, but these suffered from several delays and were not operational until 1952. In 1958 this equipment was completely redesigned and rebuilt. In 1970 O'Brien revised the original document and added Australian data which had been derived in the intervening period (Barned & O'Brien, 1970).

Progress in thermal analysis techniques was continually seen as being held back by a lack of basic information. Of particular concern was the formulation of the sol-air temperature, a temperature which when applied to external surfaces produced the same heat flow as the combination of air temperature, solar and long wave radiations. In 1950 work commenced to determine sol-air temperatures on vertical and horizontal surfaces. A literature review had not provided the detailed information required for the accurate determination of sol-air temperatures so a project was commenced to undertake measurements to predict absorption co-efficients, the intensity of solar radiation and the heat conductance of the surface air film. Although initial experiments were conducted during the 1950's, the culmination of this work came with the publication in 1970 of *Some Investigations on the Sol-Air Temperature Concept* by Rao and Ballantyne (1970).

In the years 1959 to 1961 a project, believed to be the first of its type in Australia, was conducted to investigate the ventilation rates in houses. The ventilation rates were measured in the houses using the decay of a tracer gas (nitrous oxide) and later an infra-red gas analyzer. The influence of fixed ventilators and fireplaces was evaluated. Several underfloor ventilation rates were also measured and found to be approximately 8 air changes per hour (ACH) in moderate wind speeds. Three hundred and sixty measurements of room ventilation rates were carried out in five timber framed houses. The results were grouped into wind directions and the results related to Bureau of Meteorology data for typical wind conditions for the Melbourne area. The results of this project were not published until 1966 (Howard, 1966), possibly a reflection of the sensitive political nature of this topic in relation to the activities of the Housing Commission of Victoria[3]. The ventilation investigations were suspended in 1961 when it was decided that the tests required to develop a general ventilation model were beyond the resources of the Division (Division of Building Research-CSIRO, 1962).

2.6.3 Solar Radiation Tables

The 1952 Report of the Building Research and Development Committee says *inter alia*,

> *"Architects have requested information concerning the intensity of sunshine and technical data as to sunshine penetration through openings to assist in their work of designing specific buildings..."* (Building Research and Development Committee, 1952)

During 1959 DBR investigated the failure of some glass spandrel panels and as part of the study estimated the maximum solar radiation load on the building facade. It was very quickly realised that by using the recently available automatic processing facilities of the CSIRO (CSIRAC) computer, the method used could also be employed to tabulate the direction and estimated intensity of solar radiation on surfaces at various orientations and latitudes. Calculation of the direct solar radiation was based on the Parry Moon calculations for cloudless sky values. The diffuse solar

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[3] The Housing Commission of Victoria at the time was engaged in a massive public housing construction operation employing a prefabricated concrete panel technique. Condensation and mould problems were widely reported in these dwellings. This was alleviated in part by forming large permanent ventilation openings but the resulting adverse affect of the large ventilation rate on winter comfort also received publicity. For more details see White, Sutton, Pears, Mardon, Dick, & Crow, 1978).

radiation for the first series of tables was estimated by a technique suggested by Berlage in a 1928 edition of *Meteorologische Zeitschrift*. The Tables for Sydney and Melbourne were the first to be produced. These Tables became known as the Spencer Tables (see for example, Spencer, 1960).

During 1963 improvements were made to algorithms for calculating the solar position and the estimates of solar radiation. Measurements of radiation at CSIRO, Division of Meteorological Physics at Aspendale in Melbourne helped to improve the accuracy of predictions, in particular diffuse radiation and ground-reflected contributions. In 1965 a new series of Tables were produced for Melbourne, Canberra, Adelaide and Darwin. In 1968 the Sydney Tables were also updated.

In 1974 the Tables were converted to SI units and again up-dated with the addition of several features including sunrise and sunset times and Solar Heat Gain Factors for different window break angles (Spencer, 1974).

2.6.4 Monitoring of Buildings

The early monitoring of the thermal behaviour of buildings, like the work at CEBS, involved measurements with models. The data was used to check heat flow calculation methods that were being developed.

During the winter of 1956 a study was made of the thermal behaviour of three buildings in the grounds of the Division at Highett. Two of these were identical tiled-roof weatherboard structures, except that one had a conventional suspended timber floor and the other a concrete slab-on-ground floor. (These buildings had been used during the previous year to compare the effects of these floor types on the floor temperatures.) The third was a building of a "solar" design, having a large glass wall facing slightly east of north and a concrete slab-on-ground floor. The relative performance of these buildings was monitored. Temperatures were recorded continuously by thermocouples and plotted on a chart recorder, heating being applied during the day. The 1956-57 Annual Report states that the most notable feature of the results was that, almost without exception, the temperatures in the solar building were at all times of the day higher than the others (Division of Building Research-CSIRO, 1957). Although the measurements from the monitoring were apparently used to check mathematical techniques for calculating the internal temperatures in buildings exposed to fluctuating external conditions, no report of this monitoring exercise was produced. Ballantyne (personal communication) believes that the effort of transcribing the readings from the chart recorder was so tedious that, given the shortage of resources, it was deemed not worthwhile.

Two years after this somewhat unproductive project a research project, sponsored by the State Electricity Commission of Victoria, was commenced to test the effectiveness of briquette-fired heating units. The space heating properties of various heating systems were studied in two test rooms of 21ft by 21ft together with six physical "thermal" models of the rooms, two quarter-scale and four ninth-scale. A total of 65 temperatures in the rooms and models were measured hourly using thermocouples and recorded on teleprinter tape for the purpose of automatic computer processing. The experiment was to test a variety of systems for the efficient transfer of heat to the rooms. Correlations between temperatures in the test rooms and the models showed that discrepancies rendered the models of little value for this investigation (Bautovich & Muncey, 1961).

Despite this finding, the difficulties of measuring all the variables in "real" buildings in order to check computer calculations meant that measurements from scale models continued to be used in the early 1960's to test the predictions from the analytical methods under development. Measurements from a 5ft square by 4ft high concrete box are reported in several papers of the time (see, for example, Muncey & Holden, 1967).

2.6.5 Thermal Insulation

Improved calculation techniques, in particular the ability to consider intermittent and part-house heating enabled calculations of economical values of thermal insulation for Australian capital cities. The Muncey paper, *Optimum Thickness of Insulation for Australian Houses* (Muncey, 1955), provided estimates of fuel savings for typical timber framed and cavity brick houses. The calculations involved many assumptions and guesses. For example, the ventilation rate was taken as 3 ACH and the comfort temperature "somewhat lower than the temperatures maintained in American houses" was taken as 68°F. The amount of insulation that can be economically justified in a house was seen also to depend on the period during which comfort heating was required and no data was available to assess this period under Australian conditions. An estimate was made based on records kept by 80 families in Melbourne for a period April to September, 1954. From these data the approximate hours of heating during winter months in the various Australian capital cities was calculated by comparing the average external temperatures at 2100 hr. In general, a thickness of around 2 inches of mineral wool insulation was claimed to be justified for Canberra and Hobart, 1½ inches for Melbourne and less for the other cities.

2.6.6 Concrete Floors

Shortly after WWII it was realised that considerable savings of timber (and, on flat sites, labour) could be effected if concrete floors were generally accepted in dwelling construction. There was, however, considerable resistance with the suggestion that such floors were uncomfortable. CEBS results had shown that indoor temperatures were lower in summer above bare concrete floors than above bare timber floors, and that on cold winter mornings the temperatures above the bare concrete floors were higher. The sceptics (or perhaps the timber industry) remained unconvinced arguing that it was a matter of foot comfort. Experiments with "artificial" feet were conducted by DBR during 1950 but proved inconclusive because the temperature gradient in heated rooms was not considered. A new experiment was commenced in 1951 with 17 "real" subjects. The investigations concluded " that the air temperature near the floor had the most important effect on foot comfort." (Muncey, 1954). The paper suggests that thermostatic controls should be located near the floor. A later, more detailed report says,

> *"From investigations on the suitability of concrete floors for domestic dwellings it appears that such floors are comparable in performance with the conventional timber floors and, in fact, have some advantages."* (Muncey & Holden, 1959)

2.6.7 Dissemination of Research Results

In 1970 after 25 years of building research involving thermal investigations the DBR Annual Report lists the significant achievements as,

- greatly improved methods of calculating temperatures within buildings and also air-conditioning loads
- detailed solar position and radiation tables for a large number of locations in Australia and elsewhere
- optimization of house insulation for different climatic conditions
- preferred internal environmental conditions in the tropics.

However, the real impact of these achievements is difficult to assess. Unlike CEBS, and perhaps in keeping with its status as a "scientific" research organisation, DBR did not have a publication series directed specifically at design professionals and the building industry during this period. Research findings were generally first published in either scientific journals or conference proceedings with a more substantial account of projects written up as DBR Technical Reports, in some cases years after completion. The lack of a clearly delineated overall strategy on the means by which a dwelling designer or builder could implement the various findings of the research certainly reduced their worth.

2.7 Thermal Comfort Criteria

Along with efforts to understand and describe the thermal behaviour of dwellings, thermal comfort was a focus of research effort during the period. The provision of comfortable conditions in a dwelling was viewed as the main design goal and establishing appropriate thermal comfort criteria was a necessary starting point for design calculations.

Probably the first investigations on thermal comfort carried out in Australia were the work of Douglas Lee, Professor of Physiology, University of Queensland. Lee wrote several comprehensive papers on man's[4] reaction to tropical climates and made recommendations on the physiological principles which he saw as important for the design of tropical housing in the various climates of Queensland (Lee, 1940; 1944). Lee (1944) provides "design aids" showing the annual variations of climate conditions (temperature and humidity) and the comfort zone for a number of Queensland towns.

At an early stage in the CEBS investigations the hot conditions of summer were seen as presenting most concern but that orthodox thermal comfort limits would have serious practical and economic limitations. Drysdale states,

> *"When field investigations commenced, accepted thought on physiological requirements indicated that the problem was to ascertain the influence of climates on different forms of construction......and then to recommend that form of construction irrespective of the actual temperatures occurring indoors..*<it was admitted however>*...It would have been unreasonable to have accepted the view that any reduction in temperature was worthwhile....."* (Drysdale, 1950)

As a consequence thermal comfort criteria established by overseas research based on effective temperature (for example, see Houghton & Yagloglou, 1923) was replaced as a design criterion with a single critical maximum temperature which should not be exceeded on a hot day. The temperature chosen (85°F) was suggested by Winslow, Herrington and Gagge (1938) as corresponding to the onset of general sweating. The Thermal Behaviour Chart, (Figure 2.2), was seen as presenting a balance between this temperature criterion and practical economic considerations.

MacFarlane, Professor of Physiology, University of Queensland[5] in association with the CEBS in Sydney conducted a limited laboratory-based inquiry into preferred temperature using a small number of subjects (MacFarlane, 1958). He saw the main aim of thermal comfort research of this time as being the desire to provide some consistent empirical formulation,

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[4] The Introduction to the 1940 work talks of *homo sapiens* and the *human body*. One could assume therefore that "man" is to be taken as a generic description. However, most experimental subjects referred to in the work appear to be men.

[5] Douglas Lee had left this position to take a chair of Physiological Climatology at the John Hopkins University, USA.

> *"As a concept relating to inhabited places comfort is an affective state, subjective and individual as appetite or fatigue. Many variables are integrated by the subject to be judged as comfort: and everyone is his own authority on the matter. Until subjective sensation or feeling states may be translated into other terms there can be no answer to the question of what comfort is. Some answer of a statistical nature can be given to the question "In what range of environmental circumstances does a population say it is comfortable or behave as though it were?". Empirical determination of this range has been attempted in most parts of the world; but the underlying physiology and psychology (which are probably the same thing) are only partly elucidated."* (MacFarlane, 1958)

MacFarlane concluded that "temperatures below 70°F seem uncomfortable to tropical people, and above 80°F for cold temperate people" (MacFarlane, 1958).

In 1959 Hindmarsh and MacPherson (School of Public Health and Tropical Medicine, University of Sydney), collected 2172 thermal comfort votes in the field over a one year period (Hindmarsh & MacPherson, 1962). The most generally preferred temperature was found to be 73°F (22.7°C) and a comfort zone in the range of 66°F (18.8°C) to 81°F (27.2°C), although it was suggested "...such a range is quite unacceptable in air-conditioning practice." Their research also investigated the commonly held notion that heat discomfort was due to the presence of unevaporated sweat on the skin. They found the "somewhat surprising" result that sweating did not closely relate to the environmental temperature (and therefore the preferred temperature). Sweating was detected at temperatures as low as 70°F where all subjects reported feeling comfortable. The incidence of sweating was found to parallel the sensation of excessive warmth. All subjects reported sweating at a temperature of 86°F which corresponded to 100% reporting a sensation of "too warm".

In December 1962 DBR established a branch office in Port Moresby[6] to undertake investigations of the problems associated with tropical buildings. One project was to compare the indoor environments of four "government" houses. The study, among other things, aimed to determine the preferred temperature in the houses. An environment assessment card was devised for occupants to record their subjective thermal sensation vote, together with apparel worn, activity and other information. Indoor conditions were recorded continuously with thermographs (Ballantyne, Barned, & Spencer, 1967). Analysis of the thermal sensation data employed the technique of probit analysis which avoided the equal interval assumption[7]. The range of temperatures for a neutral assessment were found to be between 23.4°C and 27.6°C, with the comfort zone (as defined by Hindmarsh & MacPherson) extending from around 21.2°C to 29.6°C. The preferred temperature was estimated at 25.4°C. This information was used in a later computer study to examine design and construction options for houses in Port Moresby (Ballantyne & Spencer, 1972).

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[6] The Territory of Papua and New Guinea

DME also undertook a large scale investigation on thermal comfort. During 1966 an analytical study developed a thermal comfort model to predict preferred temperatures based on three parameters, the physical mechanism of heat and mass exchange between the body and its surroundings, on the physiological behaviour of the body and on the available data on thermal sensations. Variables included in the analysis were type of clothing, air velocities and degree of activity. An exact solution was found to the formulation by applying the assumption that thermal comfort is accompanied by no sweating. Although predicted preferred temperatures for thermal comfort were reported initially to agree well with published data derived from sensation votes under laboratory and field conditions (Morse & Kowalczewski, 1967), subsequent analysis of Kansas State University[8] data indicated that the model assumption that comfort was accompanied by no sweating was incorrect. This was not a surprising conclusion given that this fact had been reported four years earlier by Hindmarsh and MacPherson.

In 1971 a test facility was established at DME consisting of a controlled temperature and humidity room for experimental work on human comfort. Studies were conducted to investigate the effect of air velocities on preferred temperatures. In 1974 Robeson and Burton reported "...that subjects generally preferred higher velocities than those predicted by Fanger's equation" (Robeson & Burton, 1975). In March-April 1974 Ralph Nevins (fellow of the John B Pierce Foundation, Yale University) visited DME and conducted an experiment to test the hypothesis that subjects from both tropical and temperate climates would have the same preferred temperature. The fact that such a project was conceived indicates the belief at the time that comfort conditions could be determined independently of local environment and context, but no reference to any results of this work could be located.

2.8 Summary

During the period from World War II to 1974 some remarkable results were achieved by Australian researchers on understanding the scope of issues concerning the thermal performance design of houses. In particular the work of Drysdale *et al.* at CEBS investigating the thermal behaviour of dwellings using models and electrical analogues, Muncey *et al.* at CSIRO, DBR on thermal modelling using computer simulation and in providing basic understandings of the physics of heat flow (eg. sol-air temperature, ventilation rates), the sunshading techniques of Phillips, the solar tables of Spencer and the thermal comfort studies of Lee, MacFarlane, MacPherson & Hindmarsh and Ballantyne, were all at the leading edge of research for their time. However, the history of

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[7] It should be noted that Fangers later work (Fanger, 1972) did not include this refinement.

[8] Data from Kansas State University by Rohles and Nevins (Rohles & Nevins, 1971)

thermal performance research in Australia in the period 1946-74 can also be characterised as a period which lacked strategic directions, where efforts were duplicated, and where lack of sufficient funds wasted opportunities and decreased the effectiveness of the notable work that was undertaken.

The two assumptions, first, that the climate *should* determine the design of buildings, and secondly, that people's preferred indoor environment is independent of climate and other contextual influences, can be seen to be at the heart of much of the thermal performance research in Australia. These beliefs to a large extent continue to be influential today. Energy *per se* and general environmental issues were not considered central to the scope of the problem and did not inform the discourse on design advice. Therefore the design advice for temperate Australia for this period was based on a different understanding of the problem than that which began to emerge during the mid-1970's. Since also the definition of the problem was to some extent assumed, and hence not discussed, or necessarily made explicit, the relationship of this design advice to later understandings of the problem is not always clear.

CHAPTER 3
DESIGN, ECONOMICS AND ENERGY

3.1 Introduction

This thesis takes the 1974 Williamson & Coldicutt paper as an exemplar of framing a response to the desire for energy-efficient housing in terms of the *solar-efficient* prototype. The characteristics of such a prototype as it has been developed and echoed in numerous publications were set out in Chapter 1. The purpose of this Chapter is to discuss its context, method and assumptions, given the background set out in Chapter 2, and to summarise the main findings.

The agenda for the paper was described as,

> *"The potential for solar energy usage in buildings as an alternative to other energy sources is significant but this potential will not be realised unless design is based on the view of the environment, the building and plant as a system. For the comparison of alternative designs, a statement of user requirements is essential. An optimum system may then be defined as satisfying these requirements at lowest total costs. Domestic buildings which may require both heating and cooling present a particular class of problem, but such buildings constitute the majority in Australia. Melbourne provides the opportunity for the development of a basic model which may be adapted to other regions. A popular project house and a modified thermally integrated version are compared on the basis of thermal performance both Summer and Winter by computer analyses. Initial costs and operating costs for each are compared and possible alternatives suggested for further evaluation."* (Williamson & Coldicutt, 1974)

The methodology employed was to use a thermal performance simulation computer program STEP[1] to undertake an evaluation of the energy consumption and cost effectiveness of a 'standard' AV Jennings house and to compare this with the performance of a modified 'solar' house. The evaluation involved a range of assumptions about, for example, climate, occupancy and air-conditioning plant operation. The possibilities able to be examined were constrained to some extent by the capabilities of the computer program being used for the exercise.

The exercise showed that given the various assumptions, and providing the computer model could be relied upon, the suggested modifications resulted in considerable cost and energy savings while maintaining thermal comfort conditions. The results were qualified because, although in principle the answers seemed reasonable, no attempt had been made to conduct an empirical validation of the program STEP at that time. The changes basically involved applying thermal insulation to the walls and ceiling (not common practice at the time), using massive construction (slab-on-ground floor,

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[1] The thermal performance simulation program was developed at CSIRO, Division of Building Research, Highett, Victoria

cavity brick external walls and solid brick internal walls, again not common in Melbourne at the time), and careful orientation with a large north facing glass area which was well shaded (by a deciduous vine) in summer. A fundamental conception in framing the Solar House solution was the belief that any need for summer air-conditioning should be minimised. Two subsequent papers in 1977 from the Department of Architecture and Building, University of Melbourne, *Low Energy Cost-Effective Dwellings for Melbourne* (Coldicutt & White, 1977) and *Cost/Value Appraisal of Low Energy Housing* (Williamson & Robinson, 1977), further developed the prototype description.

The main objective of the paper was to demonstrate the technical and economic feasibility of a dwelling design and construction which would have the potential for reducing energy consumption compared with the then current housing, while at the same time providing an improved thermal environment within the dwellings. In the context of the Symposium on *Utilizing Solar Energy in Dwellings* at which the paper was presented the essential hypothesis being tested was that,

> *"An integrated environmental design approach which views the building itself as a solar collector and energy conservation device may eliminate the need for special systems or reduce the requirements for these so as to reduce the importance of the initial cost factor."*

Four ideas derived from the discourse of the time were central to the approach taken in the paper and therefore the outcome. First, and the starting point, was a statement of the need to *establish performance requirements* as a basis for designing.

> *"In comparing thermally integrated systems for domestic buildings, it is necessary to establish user requirements, recognising the unavoidably arbitrary nature of such a statement. But without a clear statement of performance standards, studies and comparisons can not lead to any useful conclusions; no rational discussion is possible. A statement of performance for such systems requires the consideration of three main factors; thermal comfort limits, the permissible frequency of occurrence of conditions outside the limits of comfort and the acceptability of the system (building and plant)."*

Secondly, the idea of an *integrated environmental design* (IED), which was promoted in the UK by the Electricity Council in the early 1970's, was introduced. The term seems to have been coined by Alex Hardy and Patrick O'Sullivan at the University of Newcastle-upon-Tyne, UK. By early 1974 the State Electricity Commission of Victoria (SECV) was advocating a mutated version of the UK concept. Although IED was introduced by the UK's Electricity Council (and SECV) essentially to achieve a greater market for office air-conditioning, in a wider sense it was taken to mean adopting a design approach which took a holistic view of the various environmental and functional components of a building. In practice this was synonymous with embracing a systems approach to building design. The combination of building form, construction and heating/cooling plant were taken as the system in the paper. The necessity of treating these particular elements together as a system had been highlighted by Reyner Banham in his well known book *The Architecture of the Well-Tempered Environment* (Banham, 1969). It was suggested that the best design solution, from a wider IED point of view, would be found by optimising the system being considered.

An optimised thermal system was considered in the paper as achieving minimum ownership costs. This third idea, that of accounting for the *total ownership (or life-cycle) costs* in a design, had been established by Stone (1960; 1967). Life-cycle cost analysis was advocated as one essential component in IED to distinguish between competing solutions. Terence Wyatt, a UK consulting engineer, in a paper published mid-way through 1973 entitled *Building Economics and Energy Conservation* (Wyatt, 1973), argued that the total cost of the entire system should be optimised and that optimising individual elements did not lead to the same results as far as energy conservation was concerned.

The final key idea included in the paper was that of using *computer analysis* to provide the data for decision-making. An understanding of the possibilities offered by the new techniques for building performance evaluation by computer simulation and the ways this could be integrated into the activity of designing was just beginning to emerge at the time. Without such tools being available the investigation as presented would have been almost impossible.

The following sections expand on these topics.

3.2 Design Methodology

The personality of modern architecture had its genesis in the 1850's in the writings ofViollet-le-Duc (1959). He proposed the rationalisation of the art of architecture into logical procedures based on the rules for scientific investigation espoused by Descartes. As explained by Viollet-le-Duc, the method for acquiring knowledge necessary for achieving the most satisfactory building design solutions should be based upon breaking down the problem into its simplest units, its component parts. Because one can perceive directly these simple units, he argued that one can re-assemble the whole structure in a logical fashion. The whole entity consisted of the sum of the parts, no more and no less. De Zurko (1957) argues that functionalism was firmly instituted with this scientific consciousness. For example, LeCorbusier in *Five Points Of New Architecture* suggests that,

> *"....in order to solve a problem scientifically you first have to identify the separate elements."* (Le Corbusier, 1927)

In the 1960's a variety of writers (Alexander,Asimov and Jones were prominent amongst them) attempted to describe and rationalise the process of design. By the early 1970's the notion of the performance concept had been introduced into the design methodology literature. It was viewed as a functional approach to designing, but divorced from the "dogma" of the Functionalist Movement, because different types of functioning and different types of evaluation of performance were admitted (Handler, 1970, p11). Two large international conferences, the first in Versailles, France (1971) and the second in Philadelphia, USA (1972), heard many authors proposing performance as "the new language of design". Their arguments were compelling and based upon three assertions found in the design methodology literature:

- **Design should be an activity directed towards the goal of fulfilling human needs** (Asimow, 1962)

Robert Sommer expressed concern over the perceived lack of concern for user needs in building design.

> *"Frank Lloyd Wright put forth the doctrine that form follows function, which became a useful antidote to endless ornamentation. Yet it is curious that most of the concern with functionalism has been focused upon form rather than function. It is as if the structure itself, harmony with the site, integrity of the materials, the cohesiveness of the separate units, has become the function. Relatively little emphasis is placed on the activities taking place inside the structure."* (Sommer, 1969, p3)

- **The quickening pace of industrialisation meant that no longer could building designers rely upon tradition and/or direct experience to ensure design solutions satisfied intended aims.**

New materials and components were being produced at an ever increasing rate. Principles which served the designer in the 19th and early 20th centuries as a stable body of knowledge about human use of buildings no longer sufficed. Buildings were no longer built by widely used methods but most buildings, or at least the majority of components, were manufactured. The ability of architects to adapt to this changing situation was questioned.

> *"At the same time that the problems increase in quantity, complexity, and difficulty, they also change faster than before. New materials are developed all the time, social patterns alter quickly, the culture itself is changing faster than it has ever changed before. In the past....the individual designer would stand to some extent upon the shoulders of his predecessors.....The intuitive resolution of contemporary design problems simply lies beyond a single individual's integrative grasp."* (Alexander, 1964, p4)

- **Urgent action was required because of the failure of building designers to understand their role at a systems level, eg. building, urban, global systems**

Energy and environmental problems were beginning to appear as concerns in the design of buildings during the early 1970's. Some commentators took an optimistic view and argued that humans have always demonstrated the ability to take corrective actions. They believed that technological advances would overcome perceived problems. The book by Fritz Schumacher, *Small is Beautiful* (1973), however, offered an opposing view in drawing attention to the connection between economic growth and the increasing sophistication of technology and as a consequence environmental degradation and problems with human isolation. As a solution he advocated a simpler way of life which took true account of humans as part of a global system. The report of the Club of Rome, *Limits to Growth* (Meadows, 1972), published during 1972 also helped focus on these issues with the conclusion that,

> *"If the present growth trends in world population, industrialisation, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years."* (Meadows, 1972, p23)

It was believed by many that the benefits and cost implications of building design decisions, in the widest sense, were poorly understood by designers. There was seen a need to develop a design evaluation methodology which would systematically and efficiently lead to high performance solutions (Building Performance Research Unit, 1972).

The performance concept, the essential aspects of which were adopted in the 1974 paper, offered an approach which appeared to allow the designer to address these concerns.

3.2.1 The Performance Concept

The performance concept developed as an application of systems thinking to building design. A system is defined as an *entity*, real or conceptual, which may be conceived as comprising an input of some form, a process which acts to transform that input, and a resulting output. ABACUS (Building Performance Research Unit, 1972) suggested that a building could be considered as several systems, eg. economic, thermal, constructional etc. The first step in designing a system consisted of determining the required functional results as a number of performance requirements. The performance requirements were to be determined directly from a consideration of the "users" of the proposed building, the "users" being understood as consisting possibly at many different levels, eg. building users, building owners, the community, etc.

The "output" of the system which results from a given set of inputs could then be evaluated against the performance requirements. Because no nexus was established between the performance requirements and the system "output", the logic was essentially deductive and all possible designs could be conjectured and evaluated against the established requirements. A formal definition of the performance concept was accepted as,

> *"an attempt to provide a framework within which it is possible to state the desired attributes of a material, component or system in order to fulfil the requirements of the intended user without regard to the specific means to be employed in achieving the results."* (Wright, 1971)

In operation the performance concept centred on the idea that products, devices, systems or services can be described and their performances specified in terms of user's requirements without regard to their physical characteristics, design or the method of their creation. The key to the application of the performance concept was the identification of significant criteria which characterised the performance expected and the subsequent generation of methodologies for measuring how products, processes or systems met these criteria. The *performance requirements* were identified as qualitative statements describing goals of overall design outcomes or products and sub-systems within the solution. The characteristics by which a solution could be defined and by which evaluation could be made were termed the performance criteria. The *performance criteria* provided quantitative statements of the desired attributes of a final design outcome. *Evaluation techniques* enabled the scoring of candidate solutions to rank their ability to satisfy these criteria. (Haider & Khachaturian, 1972)

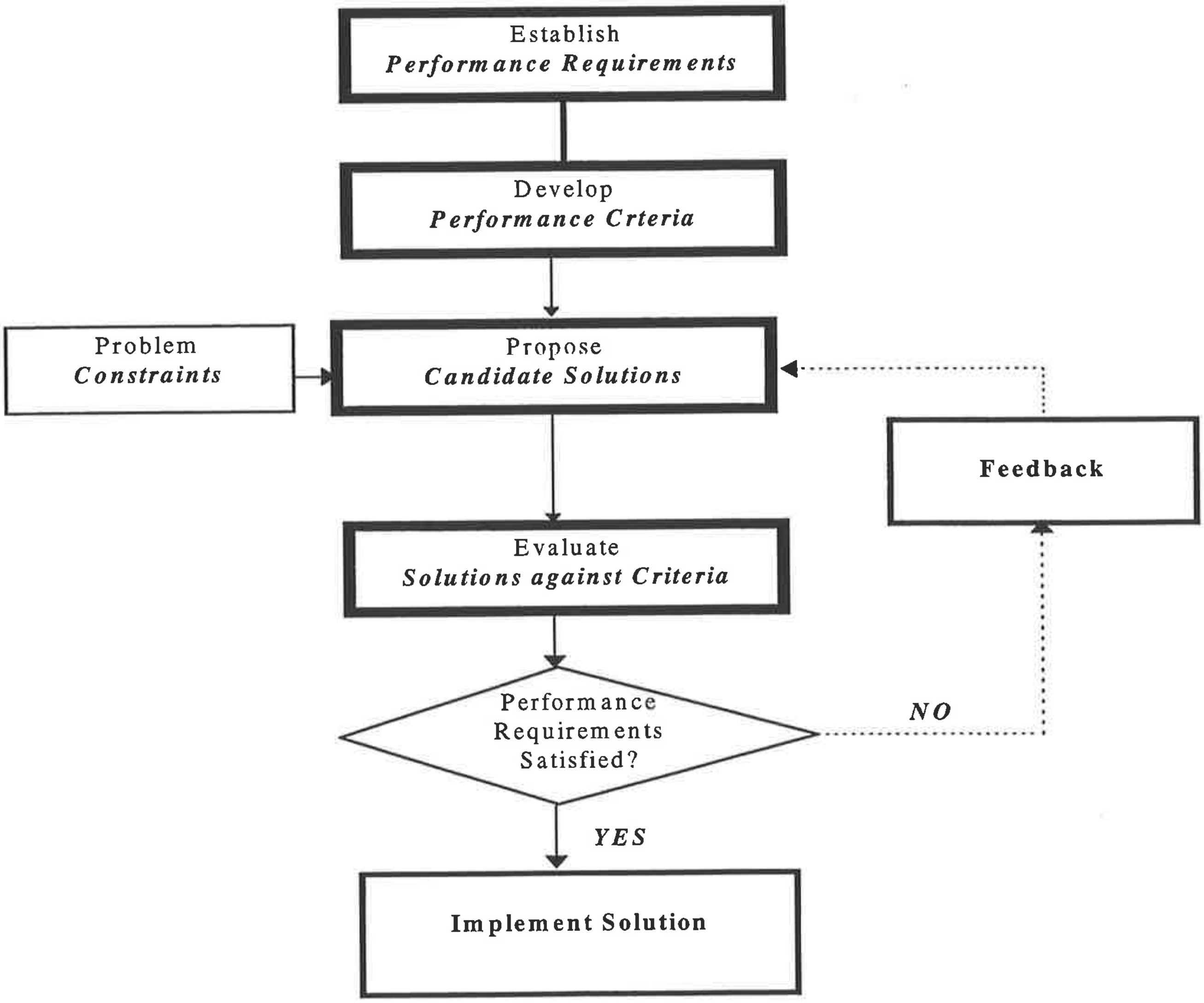


Figure 3.1: Performance Concept Evaluation Process

3.3 Design Performance Requirements

3.3.1 Energy Conservation

The problem of energy in the global system was brought into sharp focus by the Arab oil embargo of October 1973 and the rapid increase of OPEC oil prices. A growing public awareness of an "energy crisis" was just beginning to dawn. At times, however, the message was delivered with somewhat exaggerated claims. For example, the opening sentence in an otherwise valuable paper by Wyatt claims,

> *"It becomes increasingly clear that we of this generation are likely to consume in our lifetimes the entire stock of our world's most readily available natural resources, particularly those which yield fuel and chemical energy."* (Wyatt, 1973)

Information on the amount of energy used in the construction and operation of buildings began to appear in the literature. Building designers were encouraged to consider measures to reduce this consumption. Overseas Government authorities introduced regulations, provided incentives and distributed information (Beale, 1978). Professional organisations in the UK and US provided design guidelines and information which emphasised the need for energy conservation (see, for example, the edition of RIBA Journal 85(6), June 1978).

In Australia the crisis was seen essentially as a mismatch between conventional sources of energy and the growing demand for energy. The development of solar energy as an alternative resource was viewed by many as a realistic option for overcoming the shortfall. The 1973 Annual Report of CSIRO, DME explained this aim.

> *"It is well recognised that Australia's remaining fossil fuel is unlikely to last more than a few decades......The estimated life of the remaining oil is eight years and natural gas fifty years......The cost of electricity and gas are expected to rise, so there is an urgent need for an alternative energy resource to reduce Australia's dependence on imported fuels and extend the life of our main remaining resources..... The exploitation of solar energy on a competitive basis to complement conventional fuels is one way of doing this......"* (Division of Mechanical Engineering-CSIRO, 1976, p4)

Replacing energy consumed from a *non-renewable* supply in building construction and operation with a *renewable* source was viewed in the context of the time as an important design aim. However, recognising the limited altruism displayed by most building developers and home owners, the performance requirement that a design option should achieve a lower cost (compared to a "conventional" solution) was seen as a necessary component to realising energy conservation in the general housing industry.

3.3.2 Life-cycle costs (Minimum Ownership Costs)

Life-cycle costing quantifies what many designers take into account implicitly in their selection of design concepts, materials, etc, that is, a balance between initial costs and reliability, serviceability, maintenance, etc, as reflected in the on-going costs. The technique of life-cycle cost analysis considers total relevant costs over the life of a system which occur at different times, including costs of acquisition, maintenance, operation, and where applicable disposal, and expresses these as equivalent costs at a common time.

The major steps in performing life-cycle cost analysis are,

- Identify various alternative solutions
- Identify relevant cost items for each alternative

- Determine the amounts and timing of the cash flows
- Calculate the life-cycle costs using discounting technique

In the 1974 paper the life-cycle costing is given as the present worth of all costs and calculated as,

$$C_T = B + P + E * \frac{(1+i)^n - 1}{i(1+i)^n} + \sum M_i * P_i + \sum R_i * P_i' \text{ ....} \qquad \text{Equation 3.1}$$

where	C_T	total present value of costs
	B	initial costs of building
	P	initial costs of plant (heating & cooling equipment)
	E	annual energy costs for heating and cooling
	i	appropriate discount rate for fuel
	n	assumed period for life-cycle calculation (life of asset)
	M	annual maintenance costs for plant and relevant building items
	R	replacement costs for plant and relevant building items
	P_i	appropriate present value factors for uniform series payments
	P'_i	appropriate present value factors for once-off payments

The main design selection criteria established was to minimise C_T.

Life-cycle cost analysis also recognises that in the selection of any alternatives the following issues influence the final decision,

- relative initial cost differences between alternatives
- the likelihood of future relative price movements
- externalities and non-quantifiable benefits and costs
- aesthetic and/or moral considerations

These issues were in part considered in the 1974 paper.

3.3.3 Thermal Comfort

Conventional practice suggested that the performance requirement for an acceptable thermal environment was based on some notion of a state of thermal comfort, a condition which it was assumed people desire and which they would, under normal circumstances, take action to achieve. Human thermal comfort was defined for many years by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) as *"that state of mind which expresses satisfaction with the thermal environment"* (ASHRAE, 1974)

Early studies on thermal comfort were undertaken by heating and ventilating engineers (see, for example, work in the US by Houghton & Yagloglou (1923); Winslow, Herrington, & Gagge (1937; 1938) These initial studies were generally laboratory based, often with only a small number of subjects, involving experiments based on measuring the energy exchanges between the human body and "his" (usually male) environment and obtaining a simultaneous "subjective" verbal reaction to the physical conditions, eg hot, slightly warm, comfortable, uncomfortable, cold etc. Although Houghton and Yagloglou developed the notion of a thermal comfort zone (a range of air conditions plotted on a psychrometric chart) in which a majority of people expressed a sensation of neutrality, the emphasis was usually on discovering a "preferred" temperature which could be used as the basis for air-conditioning design and thermostat set points. An exception to the laboratory based experiments was the early work of Bedford in the UK who studied the thermal sensation assessments of factory workers and related their impressions on a seven point scale of warmth to simultaneous environmental measurements, thus enabling a numerical treatment of the findings (Bedford, 1936).

Into the 1960's and '70's many scientists, engineers and others continued to maintain that comfort conditions could be determined by scientific experimentation. During this period experimenters, most notably at the John B. Pierce Foundation Laboratory (Gagge *et al.*), at the Institute for Environmental Research at Kansas State University (Rohles, Nevins *et al.*) and the Technical University of Denmark (Fanger *et al.*), refined and extended the laboratory based experimental techniques to larger numbers of subjects. The notions of a stimulus/response mechanism were applied to this type of experiment during the 1960s (Stevens, Marks, & Gagge, 1969). These various investigations purported to demonstrate that the thermal sensation responses concerning the environment showed consistent relationships to measurable physiological mechanisms to the exclusion of other influences, for example, social customs.

The work of Ole Fanger (Fanger, 1972) and his equation for the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) is perhaps the best known outcome of this type of comfort research. Fanger showed that given a set of environmental variables (dry bulb temperature, mean radiant temperature, vapour pressure and relative wind speed) the predicted mean vote of a population expressed on a 7-point thermal sensation scale may be calculated, compatible with an assumed metabolic rate and clothing level. In 1973 Fanger visited The University of Melbourne and presented a seminar on his findings. Although some questioned the data analysis methodology (the assumption of equal intervals for the sensation scale, using mean temperature values, etc) employed to derive his conclusions, the PMV technique was generally perceived as a significant breakthrough in assessing the thermal environment, the only drawback being that its rapid calculation was not possible. Only in the late 1970's was the calculation computerised.

A different approach to assessing a satisfactory thermal environment, and in particular for addressing requirements related to free-running buildings, had been available to designers for some time prior to 1974. The idea, developed by Victor and Aladar Olgyay, was termed a bioclimatic chart and followed from the argument that in this case the designer was interested in knowing, subject to climate effects and human needs, the widest possible range of conditions in which thermal comfort would be possible (Olgyay & Olgyay, 1954; 1963). An example Olgyay Bioclimatic Chart is shown in Figure 3.2.

The Olgyay chart has two axes - dry bulb temperature and relative humidity. Using different combinations of these factors, a basic comfort zone is defined. However, the chart also shows how this relatively narrow comfort range may be extended by taking into account the effects of radiation (eg. sunshine) and air movement (wind). The chart is limited to a given metabolic rate and clothing level. The thermal comfort requirements shown in Figure 2 of the Paper employed a similar graphical presentation but used environmental temperature and relative humidity as the axes. The comfort zone limits were derived, with some transformation to environmental temperature, from the work of MacFarlane, and MacPherson & Hindmarsh as being applicable for Australian temperate climate conditions (MacFarlane, 1958; Hindmarsh & MacPherson, 1962). The air movement extensions were derived from a compilation of the work of Drysdale, and Olgyay & Olgyay (Drysdale, 1951; Olgyay & Olgyay, 1963).

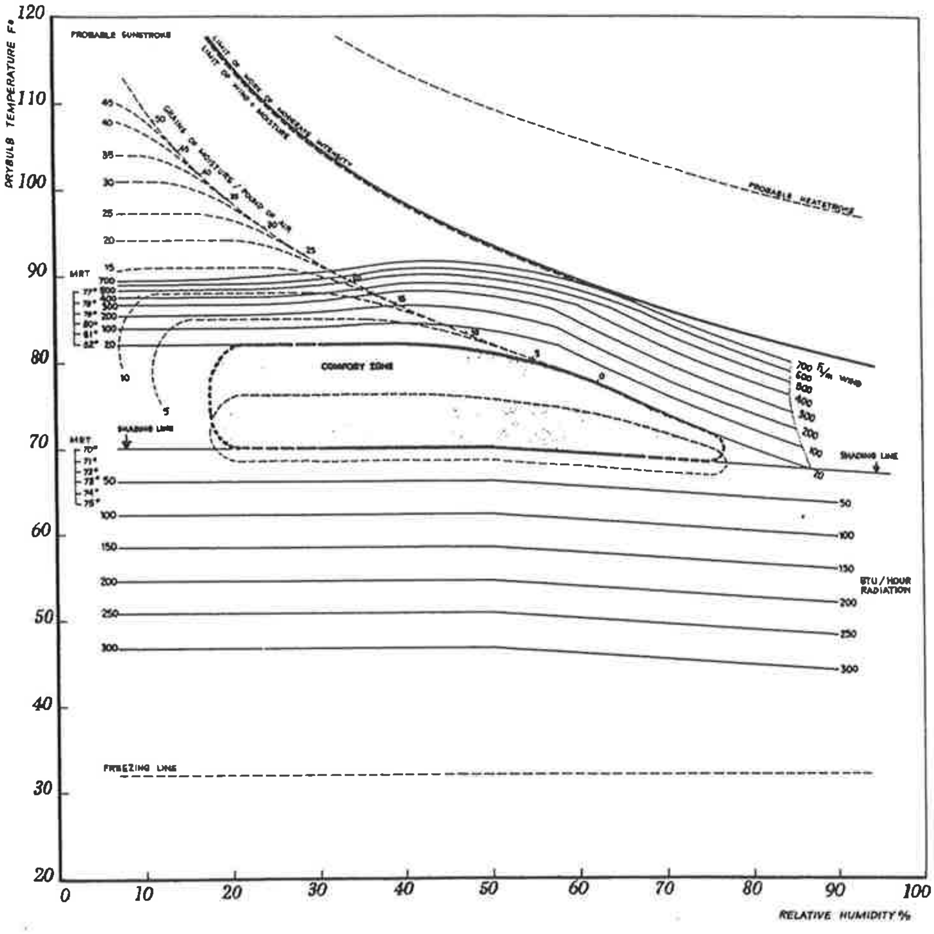


Figure 3.2: Olgyay Bioclimatic Chart

3.3.4 Frequency of Occurrence Outside Comfort Zone

The thermal comfort limits for dwelling living and sleeping zones used in the paper corresponded approximately to the mean preferred temperature from the research described above. Little was known however, about the tolerance of conditions outside the comfort limits or the likelihood of people taking action to ameliorate the situation should the limit of acceptability be exceeded, apart from information on maximum tolerable temperatures. The cost implications of assumptions concerning the frequency of occurrence of excessive conditions was appreciated. Anecdotal evidence suggested that as air-conditioning systems became a realistic cost option their installation in existing dwellings was in response to people experiencing only relatively low levels of discomfort. A conservative limit of tolerance was suggested of four days per annum with conditions outside the limits of the comfort zone. Given the computer simulation capabilities at the time the estimation of this quantity was not possible.

3.3.5 Design Acceptability

Again very little was known about the acceptability of design options which would directly influence thermal performance, such as the form of housing, distribution of windows, etc, although the importance of aesthetics, custom and fashion were acknowledged. The choice for the typical house of a popular house model from a large project builder (AV Jennings) was done to account, in part, for the acceptability requirement. The effect of the modifications on acceptability was unknown, but advice from AV Jennings indicated no significant impact. The importance of providing subdivisions with layouts suitable to ensure the necessary solar access en-mass was highlighted as a planning requirement.

3.4 Performance Evaluation

An essential element of the performance approach is a tool for the evaluation of design proposals. Hand calculations provided only limited, mainly steady-state, capabilities for providing data for a comprehensive performance evaluation. Computer-orientated simulation of thermal performance offered the possibility for determining dynamic behaviour, heating and cooling loads, and indoor space temperatures in response to actual climatic conditions. By the early 1970's the CSIRO, Division of Building Research had demonstrated a leading international role in developing such tools but the programs were at that stage still relatively crude models of the total thermal performance process.

3.4.1 Computer Simulation

Analysis of design proposals for the 1974 paper were performed using two computer programs. STEP (from the CSIRO, DBR, using the response factor calculation technique), and TEMPLOU (a small program developed at the School of Architecture and Building at the University of Melbourne). TEMPLOU was written to estimate summertime temperatures in unconditioned buildings and was based on the computation method outlined by Loudon (1968). The main findings were based on output from STEP, with TEMPLOU being used to test the implications of summer performance with different design options. These latter investigations were not reported in detail in the Paper.

A particular limitation at the time was the lack of long periods of climate data which could be used as input to the programs. As a result, only critical and intermediate three day periods (summer and winter) were used in the simulations, with annual heating and cooling loads being extrapolated from these short periods.

3.5 Results

The results achieved from the thermal performance investigations of a building depend on the many assumptions made for the analysis. Although many of the assumptions and performance constraints are spelt out in the 1974 paper many others must either be inferred or guessed. A summary of the more important assumptions are:

- House occupied by a generic average middle class family of 2 adults and 2 children; some awareness of energy issues assumed; energy conservation a presumed goal
- Continuous heating and cooling as appropriate with thermostat settings of 20°C for winter and 24°C for summer with a zero thermostat band width in both cases
- Constant 2 air changes per hour (ACH) ventilation rate, except 30ACH provided by exhaust fans on summer nights in modified house
- 70% efficiency for gas heater, a coefficient of performance (CoP) 1.5 for reverse cycle air-conditioning, evaporative cooler effectiveness unknown
- Electricity Costs Tariff (normal) - 1.9 cents/kWh, Gas Costs Heating - 0.16 cents/MJ
- Typical and modified house cost items as appropriate and heating and cooling plant costs supplied by AV Jennings

Three design options were included in the analysis, systems A,B and C. The differences are outlined in Table 3.1.

Table 3.1: Design Options Used in Analysis

	System A Typical House	**System B** Typical House - Modified	**System C** Improved "Solar" House
Roof/Ceiling	Tiled roof Ceiling plasterboard, no insulation	As for system A	Tiled roof, Reflective Foil Laminate (RFL) insulation Ceiling plasterboard, 50mm of mineral fibre insulation
Walls	External- brick veneer, RFL Internal - plasterboard of timber studs	As for system A	External, cavity brick ureaformaldehyde insulation Internal, brick
Floor	Suspended timber floor, coverings unknown	As for system A	Concrete slab-on-ground, quarry tiles to living area, carpet in sleeping areas.
Windows	Single glazed	As for system A	Improved north distribution, double glazed
Shading	Winter 450mm eaves, summer good solar control	As for system A	Winter no shading, summer deciduous vine on north, good control on other windows
Plant	Gas ducted heating, 2 zones Whole house evaporative cooling	Reverse cycle A/C, 2 zones	Gas heating, living zone only Fans

The estimated heating and cooling loads are shown in Table 3.2. Also shown for comparison are similar estimates from later papers, but based on computer simulation of complete winter and summer seasons.

Table 3.2: Annual Energy Loads and Consumption Estimates

Plant System	*Heating*	*Cooling*
Williamson & Coldicutt (1974)		
System A	*56 GJ continuous* *@Eff.=70%: 80 GJ*	*Evap. cooling* *1260 hrs of operation*
System B	*57 GJ* *@CoP=1.5: 38 GJ*	*27 GJ continuous* *@CoP=2: 13 GJ*
System C	*21 GJ* *@Eff.=70%: 30 GJ*	*Fans only* *1316 hrs*
Ballantyne (1975)*		
Brick Veneer (BV) *no wall insulation*	*64.3 GJ continuous* [illegible]	*22.7 GJ continuous*
BV *50mm ceiling insulation*	*47.2 GJ continuous*	*14.2 GJ continuous*
BV *100mm ceiling insulation*	*43.7 GJ continuous*	*12.6 GJ continuous*
Walsh (1975)**		
BV *no wall insulation*	*52.1 GJ continuous* *29.9 GJ intermittent*	*11.3 GJ continuous*
BV *with RFL in walls*	*31.9 GJ continuous* *20.8 GJ intermittent*	*8.6 GJ continuous*
Brick Cavity *no wall insulation*	*40.7 GJ continuous* *28.6 GJ intermittent*	*6.4 GJ continuous*
Williamson & Robinson (1977)***		
Typical	*43.0 GJ*	*7.0 GJ*
As above *but with insulation & shading*	*24.3 GJ*	*5.7 GJ*
Solar House	*18.0 GJ* 5,000 kWh	--

Note: * *heating to 20°C and cooling to 23°C*
** *intermittent heating is applied 0600-0900 and 1600-2200 whole house*
*** *heating and cooling applied 0700-2200 living area and 2300-0600 bedroom area.*

The present worth values estimated for each design alternative, shown in Table 3.3, clearly demonstrate the life-cycle cost advantages of the modified design, system C.

Table 3.3: Cost Comparison of Systems - Present Worth Values

System	House $	Plant $	Operation and Maintenance $		Replacement $		TOTALS $	
			5%	10%	5%	10%	5%	10%
A	0	2300	3000	1800	670	340	6000	4400
B	0	2200	5000	3000	670	340	7900	5500
C	1100	700	1000	600	80	40	2800	2400

3.6 Summary

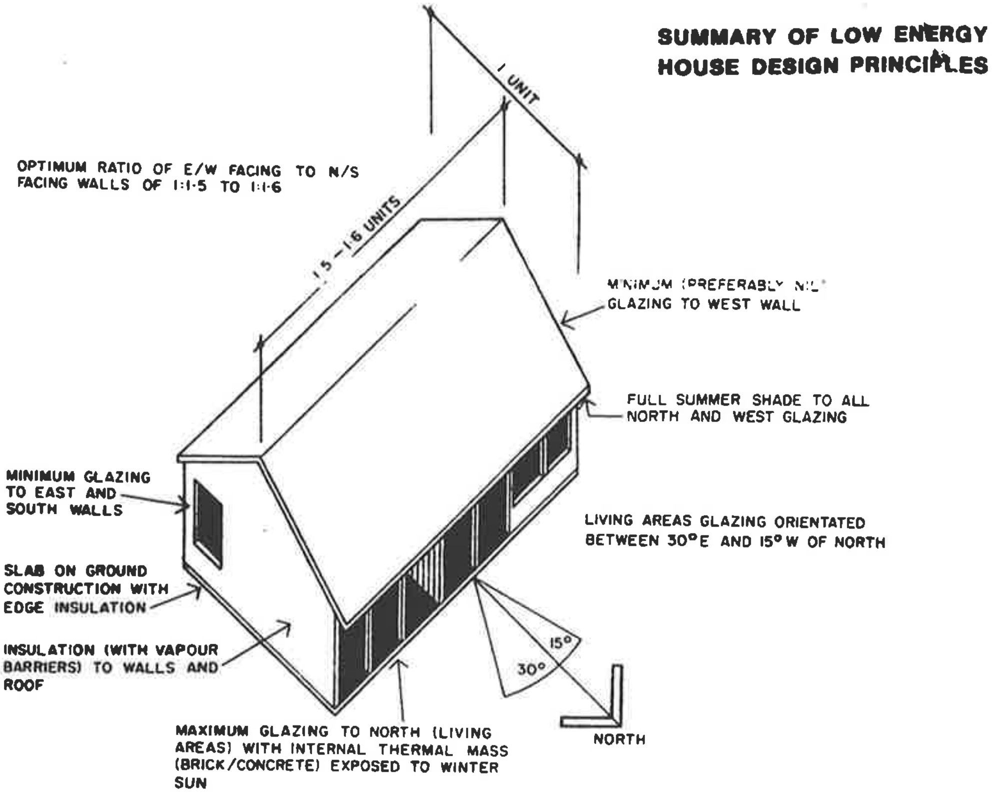
Using a systems approach embodied in an integrated environmental design concept, the 1974 paper analysed a small number (3) of building/plant options and concluded on the basis of computer simulation that a "solar house" proposal offered the potential for the lowest life-cycle costs and reduced energy consumption. The features incorporated into the "solar house" design were,

- heavyweight full brick construction and a concrete slab-on-ground floor
- thermal insulation applied to ceiling and external walls
- large north facing, solar collecting windows, no east or west windows
- good shading in summer with deciduous vine covered pergola
- reduced (compared with contemporary practices) infiltration in winter and good ventilation in summer

The analysis was confined to the Melbourne location although the paper implied that the solar house solution would be transferable to other temperate climate locations. This was not tested nor were other potentially satisfactory building/plant options examined.

The paper illustrates the changes in the discourse on the thermal performance design problem and an expansion in the scope to include explicit considerations of energy, life-cycle costs and the integration of these requirements into the overall solution. Numerous publications, from North America and Europe, became available in the mid-1970's which espoused advantages for "solar house" design solutions. The discourse in Australia captured these ideas in the notion of low energy design; energy-efficient design was not part of the language until the late 1980's.

The first comprehensive design guidelines for an Australian temperate region, setting out *Low Energy Design Principles,* appeared in the ACT in 1977 (NCDC, 1977; 1977, September). The nature of this design advice (see Figure 3.3) effectively established the *solar-efficient* prototype as the dominant concept for energy-efficient design advice.



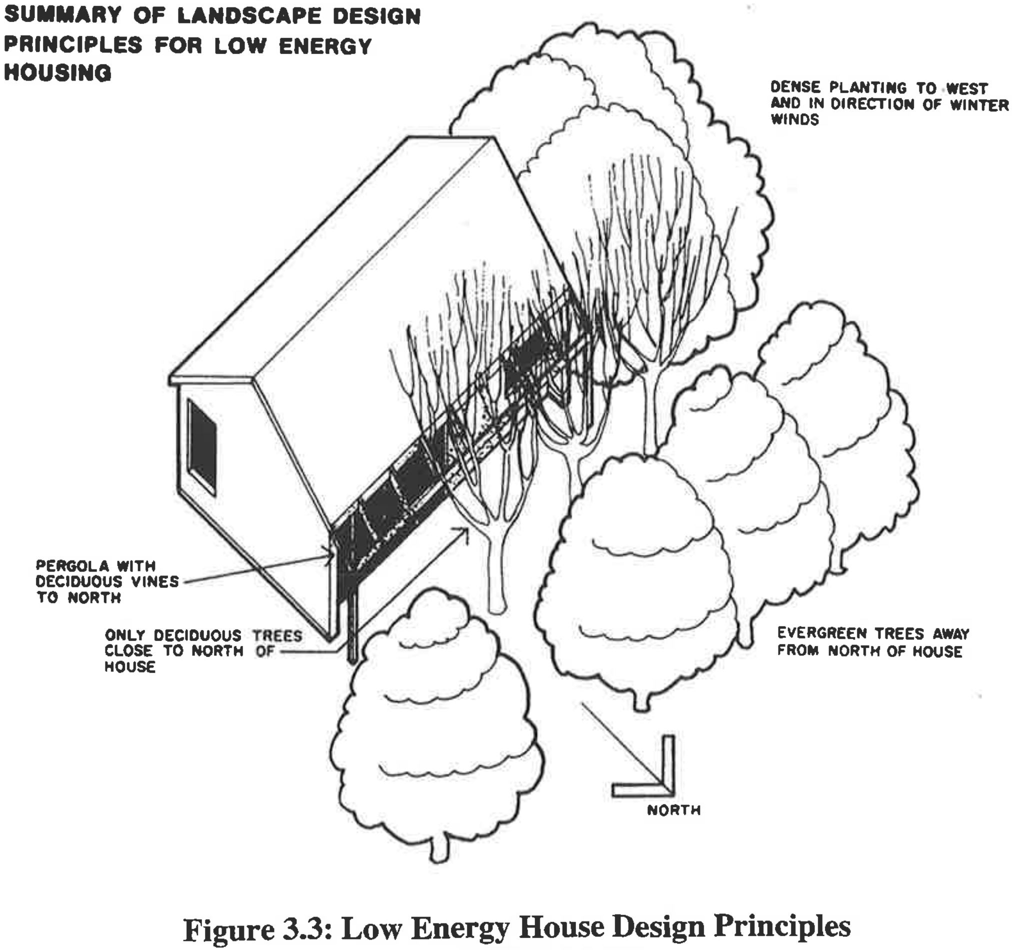


Figure 3.3: Low Energy House Design Principles
Source: (NCDC, 1977)

CHAPTER 4
NEW INSIGHTS 1975-1995

4.1 Introduction

The ends expressed as preferences, wants, requirements, needs, expectations and desires of all those involved in housing (or any intervention in the built environment), whether they be designers making decisions or people on whose behalf decisions are being made, together with the possible means of achieving a solution, combine to influence the perceived nature of problems, the way they are addressed, and therefore the final outcomes. If a designer believes, for example, that reducing energy consumption is important, but suspects that the building users may not share this belief, then solutions which minimise the users' control of say, lighting and air-conditioning systems, may be sought. Likewise the circumstances, customs, habits, routines, traditions and fads which a decision-maker imputes of a building user will influence a proposed design solution. If, for example, central heating is perceived to be beyond the financial resources of a user it will be dismissed as a possible solution to a heating problem. Establishing realistic performance requirements for a building which truly reflect the actual context in time, place and circumstance requires detailed knowledge of ends and means.

Information for the analysis of a dwelling design for a particular householder can be obtained directly by interrogation but analysis for an unknown or generic householder introduces special complications. An understanding by the designer of the range of possible requirements and means is necessary, and in the mid-1970's there was little of this information available other than that derived from personal experience and anecdotal evidence. For example, data for Australian locations on the magnitude of actual household energy consumption, household use patterns, thermal preferences and housing acceptability, did not exist. Nor was there any clear understanding amongst designers of the effect that changing construction factors such as window size and orientation or materials would have on performance. In the intervening period numbers of investigations and data collection programmes have been conducted throughout Australia with the aim of understanding some of these issues. This Chapter outlines some results of thermal performance investigations post 1974 in Australia and, where appropriate, overseas findings. No claim is made of a comprehensive coverage of all research work in the area. The survey emphasises work undertaken in the south-eastern temperate regions of Australia and is intended to illustrate the nature and approach taken to energy-efficient housing during the period.

4.2 Monitoring Experiments of Building Behaviour

Thermal performance research could be said to have blossomed in the late 1970s following an interest in energy conservation issues. Several organisations at Commonwealth and State Government levels provided public funding to undertake this research. Many of the projects involved monitoring the internal environment and energy consumption in real buildings in order to understand their behaviour and to provide background data for recommended improvements. Compared to earlier times this type of project became relatively easy following developments in electronic data collection equipment.

The Australian Housing Research Council (AHRC) established during the early years of the Whitlam Government (1972-75) was perhaps the first to encourage and fund this type of project. The AHRC, funded within the framework of the Commonwealth and State housing agreement, had the aim of improving existing techniques in building and the administration of controls. The Minister for Housing and Construction, the Rt.Hon. Les Johnson, in opening the inaugural meeting of the AHRC in November 1973 said,

> *"The aim of the Australian Government is to achieve national uniformity and harmony in regulations and standards. This must, however, allow for climatic and possibly other differences in various parts of our continent. But whilst technical and economic aspects are important, the overall objective to be pursued is the highest quality of the environment in our urban areas....."* (Commonwealth of Australia, 1974, p6)

Over a period of years the AHRC funded a number of projects that added to knowledge of the thermal performance of housing in Australia. Most, but not all, projects were concerned with investigations into public housing conditions. The first project funded in this area commenced in 1977 and was entitled "SOLARCH Experimental House Mark I" with project leader John Ballinger from The University of New South Wales. This project aimed to demonstrate that prefabricated housing was practical and that it could offer an acceptable thermal environment in Australia's hot-arid regions. The project involved building and extensively monitoring a prefabricated family sized dwelling at Fowlers Gap, NSW. The main contribution of this project probably lay in the knowledge gained on the problems and pitfalls concerning monitoring a building. As stated in final report of the project,

> *"In the beginning of this project it was hoped that a guideline document for the design of arid-zone housing would result. At this stage we feel that a considerable amount is known about the behaviour of the SOLARCH House, but the information on its own is not adequate to make future predictions......the results of these studies yielded useful results but also showed opportunities for further investigations. Such work will be continued in 1983 and 1984 in conjunction with work on the Bonnyrigg Solar Village in Sydney."* (Ballinger, 1982, p20)

The Bonnyrigg Solar Village (Ballinger, 1985) was an ambitious project involving the development, construction and long term monitoring of 12 energy efficient houses and 3 standard reference houses. Monitoring of temperatures, energy consumption and climatic data was undertaken over a 3 year period including approximately 2 years when the houses were occupied. The project's overall aim was to provide a large scale public demonstration of the principles of passive solar energy efficient housing as well as providing data for ongoing studies of thermal performance behaviour. The project was funded jointly by the national Energy Research Development and Demonstration Committee (NERDDC), the Housing Commission of NSW, the Energy Authority of NSW and the University of NSW. The project received extensive media publicity and conducted a number of open days which attracted a large number of visitors. Although massive amounts of experimental data were collected only a portion was ever analysed and this only in relatively simple terms. The lack of a comprehensive analysis plan within the project budget prevented greater use being made of the information. Analysis of internal temperature data during the unoccupied period showed that certain constructions produced more favourable conditions. When the dwellings were occupied the results were far less unambiguous, pointing to the "user" as an important factor in determining energy efficiency.

Two other projects (Projects 57 & 58) funded by the AHRC and conducted at the Faculty of Architecture and Building of the University of Melbourne systematically analysed the performance of public housing units in Victoria, Tasmania and Queensland (Coldicutt *et al.*, 1978b; Coldicutt *et al.*, 1985). Both projects used computer simulation methodology to examine the energy consumption and life-cycle costs of a large range of dwelling types and construction options. The computer program TEMPAL used for the analysis was "validated" during these projects by comparing its predictions with temperature measurements taken in a series of dwellings in the different climates. The simulation results suggested that relatively simple changes to dwelling design and construction could result in improvements to internal conditions and reductions in energy consumption and costs.

In South Australia the State Energy Advisory Committee (SENRAC) provided funds for a project which compared the relative behaviour of evaporative cooling and refrigerative air-conditioning for dwellings in South Australia (Williamson & Coldicutt, 1986). In stage I of this project the thermal performance of two almost identical unoccupied houses was monitored over a two and a half month summer period, 1983-84. Data was collected regarding cooling system performance, internal conditions and the external weather. This data was used, in part, to confirm the cooling system models incorporated into the TEMPAL computer program. Stage II of the project involved extensive simulation of dwelling/cooling system combinations for the range of climates found in South Australia. The findings were based upon the multiple criteria of thermal discomfort, energy consumption, water consumption and life-cycle costs.

During 1977 the CSIRO Division of Building and the Division of Mechanical Engineering at Highett in Melbourne combined to build and study a low energy consumption house (the LECH). The project was one of the most widely publicised projects of the time. The intention of the project was to provide information on the extent to which energy could be saved by improved building design, and on the issues of integrating solar energy equipment into the construction and subsequent operation of a house. The house was a modified version of a current model (the *Berkshire*) from the project builder Jennings Industries Limited (compare with the 1974 paper). The main variations to the conventional design were,

- both walls and ceilings were well insulated
- the building orientation and window placement, together with a floor of high thermal capacity provided for "passive" solar energy use
- two "active" solar systems provided domestic hot water and space heating. The space heating was provided by an air-based system using an under-floor rock storage.

The house was fully instrumented and measurements taken for a period of around two years with computer controlled virtual occupants. The LECH results were compared with the energy consumption from 22 comparable houses of the Berkshire model built in Melbourne suburban areas. Despite the commitment of resources to this major research undertaking only four relatively minor papers were every presented outlining the results (Walsh, 1979; Welch, 1980; Wooldridge and Welch, 1980; Welch, 1983). After the first winter's operation Wooldridge and Welch reported that,

> *"The LECH....built of conventional materials and building techniques, consistently required lower energy input than the houses of the survey, whilst maintaining a high level of occupancy comfort."* (Wooldridge and Welch, 1980)

4.3 Simulation Experiments

A monitoring experiment on its own has the severe limitation that the results cannot readily be generalised or extended to other situations such as changes in the building, operating conditions or location. The rapid advances in computing facilities and techniques provided the opportunity to conduct simulation experiments. Investigations reported in the 1974 Williamson & Coldicutt paper were an early version of such an experiment.

The most comprehensive simulation investigation of the thermal performance of Australian housing was conducted at the CSIRO, Division of Building Research, by Walsh, Gurr and Ballantyne and entitled *A Comparison of the Thermal Performance of Heavyweight and Lightweight Construction in Australian Dwellings* (Walsh *et al.*, 1982). Simulations were performed using the computer program ZSTEP of a dwelling of rectangular plan in seven localities in Australia: Alice Springs, Brisbane, Darwin, Melbourne, Perth, Wagga Wagga, and Williamtown (NSW). Some sixteen variations of brick veneer construction with a timber floor and cavity brick construction with concrete slab-on-ground floor were compared in the study. Calculations were made of temperatures when no heating or cooling was applied and heating and cooling loads were determined for three heating and cooling regimes. The same thermostat temperatures were used in each location, 20°C for heating and 26°C for cooling.

The experiment produced a raft of findings which showed the contextual nature of the conclusions regarding favoured construction types for the study dwellings. For example, the effect of a heating regime was found to be important in determining the relative merits of brick cavity and brick veneer construction. The effects of the heating regime were found to be interwoven with climate in a complex fashion. A continuous regime favoured cavity brick construction, while an intermittent regime favoured either construction, depending on climate.

4.4 National Evaluation of Energy Efficient Houses for Australia

A project, entitled *A National Evaluation of Energy Efficient Houses for Australia* (described as the NEEHA Project) was a joint investigation with the SOLARCH group in the University of New South Wales, the Department of Architecture, University of Adelaide, and School of Architecture and Planning, Curtain University of Technology, Western Australia (Ballinger *et al.*, 1991) and is probably the most comprehensive investigation of the thermal performance of dwellings undertaken so far in Australia.

The research project was established and funded jointly by the Energy Research Development Corporation (ERDC) and State government energy research authorities. It commenced in 1989 and extended over a 2 year period.

The project was instigated to assess the performance of existing Australian "energy-efficient" houses compared with a sample of "standard" houses. The "energy-efficient" sample consisted mainly of houses about which it was known that claims concerning improved thermal design had been made. The "standard" sample was established from people who responded to newspaper advertisements which sought assistance for a "research project studying the suitability of housing for the climate". In total 146 houses and households in the four city-regions of Australia - Adelaide, Sydney, Melbourne and Perth were studied. Approximately half the houses were "energy-efficient" designs and the other half were houses of "standard" design. The research programme sought to determine whether relationships existed between factors such as user evaluations of thermal comfort, lifestyle, quality/amenity, and both design characteristics and energy consumption.

The methodologies used in the NEEHA project included a household interview and a physical design checklist, seasonal questionnaires, and an electronic *Environment Response Logger* which recorded both indoor climate conditions and allowed input of householder thermal sensations and other factors.

A Household Interview was conducted in each house at the beginning of the study period. The interview was designed to be in part open-ended and in part structured. The information sought from the interviewees fell into the following categories:

- motivations for buying or building the house
- energy literacy and consciousness of building/climate related design issues
- value and importance attributed to a range of thermal comfort, thermal preference and lifestyle quality factors
- preferences relating to sunlight and daylight
- daily and seasonal activities involving the running of the house
- satisfaction with heating and cooling appliances
- satisfaction with the house in relation to climate and energy efficiency
- livability or pleasantness of the house
- intentions for the future
- background information including socio-economic data and acclimatization.

At the time of the interview data was also collected in the form of a Physical Design Checklist which related to the construction of the house, its form and orientation, the heating and cooling appliances and special design features, eg. solar collectors, etc.

In addition to the main interview, seasonal questionnaires were administered to elicit evaluations which might change according to the time of year or season. The information derived from the questionnaires related to the following topics:

- evaluations of the thermal transience of the house
- rooms heated or cooled and frequency
- time spent maintaining thermal comfort
- the situation and preferences regarding sunlight penetration
- thermal comfort and amenity satisfaction

The questionnaires were administered at three seasons to each household, summer, winter and a mid-season (autumn or spring) depending on the location.

The *Environment Response Logger* was an electronic instrument designed to record subjective thermal sensation responses and objective measures of indoor climate conditions. The householders entered information in five categories, thermal sensation, thermal preference, clothing, activity and perceived air movement. The thermal sensation and preference scales displayed on the *Loggers* are shown below. When respondents completed a "vote" the device recorded the prevailing dry bulb temperature and relative humidity and in addition the date and time. The instrument also recorded automatically the temperature and relative humidity at three hourly intervals. Data was stored on a removable RAM memory module for down-loading to a computer for analysis. More than 120,000 "votes" were collected during the project providing a substantial data base of thermal comfort data.

How do you feel?

COLD	COOL	SLIGHTLY COOL	NEITHER COOL NOT WARM	SLIGHTLY WARM	WARM	HOT
1	2	3	4	5	6	7

How would you like to be feeling?

COOLER	NO DIFFERENT	WARMER
1	2	3

Note: Numerical scales not shown on Loggers but used in subsequent analysis of data.

4.5 Household Energy Use

In 1974 there was a paucity of information on typical household energy consumption. In reviewing documents dealing with energy and energy conservation, there is a remarkable absence of concrete energy consumption figures. An example of the lack of data is seen in a 1977 inquiry of the Victorian Government instigated by its Conservation of Resources Committee of Parliament to investigate the extent of Victoria's energy resources and means of conserving them. The first report of this Committee outlined the energy supplies available in Victoria. The second report dealt specifically with issues of building design, techniques and standards aimed at reducing energy consumption (Conservation of Resources Committee, 1978). Although cost figures supplied by electricity and gas authorities are detailed in the report, actual energy consumption statistics are not included. Gas space heating is quoted at $71.40 per annum and electric heating at $51 per annum. A finding of the Committee was that more detailed energy consumption figures were required.

In 1975 the Council of The Institution of Engineers, Australia, established a Task Force on Energy. Reports of working groups of this Task Force were presented to the *Conference on Energy 1977: Towards an Energy Policy for Australia.* Working Party 12 titled *Thermal Economy in Buildings* gave as a recommendation,

> *"There is a paucity of data relating to the detailed use of energy in buildings......It is recommended that the Australian Government be encouraged to coordinate the collection and assembly of detailed data......."* (Rawlings, 1977)

Another example illustrating the lack of data can be seen in the Proceedings of a conference held in Sydney, March 1978, entitled *Energy Conservation in the Built Environment.* More than 250 delegates attended the conference. Nineteen papers were presented over two days and covered many topics relating to energy use for transport and buildings. Many papers detailed the percentage energy use in the various sectors. A consensus was that buildings (institutional, commercial and residential) accounted for around 20% of total primary energy consumption in Australia. Although many papers dealt specifically with domestic energy use and consumption not a single paper presented statistical information on household energy consumption.

4.5.1 Overall Delivered Energy

This section gives details of household energy consumption data which began to emerge during the early 1980's.

An early project conducted during 1981 which gathered actual energy data was *Energy Requirements, Energy Use and User Satisfaction in Victorian Public Housing* funded through the Australian Housing Research Council Project (Coldicutt *et al.*, no date). Some data was collected on household energy consumption for the period 1978-1980. Houses in the Melbourne suburb of Paterson Lakes and to the east of Melbourne, the Gippsland town of Traralgon, were included in the study. All of the houses were designed by the Ministry of Housing with floor areas of approximately 100m^2. A summary of average annual energy consumption data from this research is shown in Table 4.1. The research found that the energy use for space heating was related to the area of house heated and the hours of heater use, and that these in turn were related to the type of heater installed, eg. direct electric, off-peak electric or gas.

Table 4.1: Energy Consumption Data, Melbourne & Traralgon 1978-80

Location	**Annual Energy Use**
Paterson Lakes	
Gas/Electric Households	
Gas	75GJ[1]
Electricity	8-12GJ
TOTAL	**83-87GJ**
All electric households	
TOTAL	**39GJ[2]**
Traralgon	
All electric households	
TOTAL	**47GJ**

Notes: *1. Main space heating - approximately 40GJ (p 61)*
2. Main direct heating - approximately 8GJ (p 60)

The first Australian Bureau of Statistics (ABS) national household energy survey was conducted in 1982-83 (ABS, 1984). State-based domestic appliance and energy usage surveys were conducted a few years earlier during 1978-79 in Tasmania and South Australia as pilot projects (ABS, 1978, June); ABS, 1979, April). Further national surveys were undertaken in 1985-86 and 1989-90. Analysis of these data by the Australian Bureau of Agricultural and Resource Economics (ABARE) indicates that average household energy consumption during the period 1982-83 to 1989-90 remained relatively constant at approximately 59 GJ per household. The ABARE estimated that dwelling energy consumption per person in 1975-76 was approximately 18.5 GJ and also showed that, following a small drop during the mid-1980's, this figure rose in 1989-90 to 19.2 GJ (ABARE, 1991). A more recent analysis of nationwide residential energy statistics suggests that in the period 1973-74 to 1981-82 average energy consumption per person was 18.16 GJ and in the period 1982-83 to 1990-91 increased to 18.38 GJ (Wilson *et al.*, 1993). These figures show that, despite substantial promotional efforts by Governments, energy conservation gains represented by a decrease in consumption in the residential sector have been non-existent. In commentary Wilson *et al.* say the figures are,

> *".....consistent with the widespread view that the residential sector is among the least responsive to energy efficiency changes, as a result of a combination of factors including the relatively low share of energy costs in the total household expenditure, the lack of disaggregated metering information, and the splitting of investment decisions between tenants, owners and contractors. It may also be that consumers have a relatively fixed energy 'budget', within which any savings from one form of energy (eg, lighting) are offset by increased expenditure on another, such as heating."* (Wilson *et al.*, 1993, p40)

A further confounding factor during this period (1975-1995), the influence of which cannot easily be extracted from the statistics, is the increasing penetration of household energy consuming devices, for example, air conditioners, central heating and dishwashers.

Other data collected in national expenditure surveys showed that average Australia-wide household expenditure on fuel and power displayed a small increase from 2.25% of total expenditure in 1974-75 to 2.56% in 1988-89. During the same period, however, lower income households showed an increase in fuel and power expenditure greater than the average. At the second decile income level (i.e. households in the lowest 20% of household income) the average expenditure on household fuel and power increased during the period from 2.48% of weekly expenditure to 3.67% (ABS, 1990).

A report in 1983, *Energy Use and Conservation in Buildings* (Roennfeldt *et al.*, 1983, May) gives values for "Indicative average household energy consumption by State" for 1972-74 and 1980-81 as shown in Table 4.2. Although the source of these figures is quoted as Department of National Development and Energy and the Australian Bureau of Statistics, details of their derivation are not discussed. A footnote says "simple average of total final energy (residential) divided by number of households". The energy reduction in the period is attributed to a trend away from oil and towards natural gas. The report states "There is a marginal decline in average annual energy consumption per household in all States, possibly reflecting a combination of lower energy usage overall and an improvement in end-use efficiency in moving away from oil to electricity and natural gas".

Table 4.2 also shows the energy consumption figures derived from the ABS 1985-86, National Energy Survey. Although the differences between the Roennfeldt and ABS values could be explained by a marked reduction in energy consumption, the variations are probably due to either errors or (more likely) different assumptions, particularly in the Roennfeldt statistics. One difference, for example, could be explained by the possible inclusion of consumption estimates for other fuels such as wood and kerosene, not included in the ABS values.

Table 4.2: Average Annual Household Energy Consumption by State Given by Different Sources

State	GJ/Household		
	1972-74[1]	1980-81[1]	1985-86[2]
Tasmania	101.1	94.4	34.2
Victoria	85.7	82.4	59.0
South Australia	51.6	48.2	34.6
New South Wales	48.4	47.8	29.3
Western Australia	58.3	52.3	23.2

Sources: 1) *Roennfeldt* et al., *1983,May, p 321, Table V*
2) *ABS, 1988*

Table 4.3 below shows some of the variations in annual energy consumption due to various factors.

Table 4.3: Annual Average Household Reticulated Energy Consumption (GJ)

Type of Dwelling/Fuel Type	Location		
	Victoria (Melbourne)	ACT	Sth Aust (Adelaide)
Average of Total Private Households	59.0 (65.8)	41.0	34.6 (37.0)
Households with 8 to 9 Rooms	68.9-75.3	42.7-46.6	40.0-43.1
Households by Composition 2 adults & 1 or 2 children	71.2 (79.0)	43.8	41.4 (44.6)
All Private Households, Type of Energy Used			
- Electricity Only	(27.1)	40.8	(27.5)
- Electricity & Gas Only	(73.2)	61.2	(42.3)

Notes: *1) Source ABS, 1988*
2) Reticulated Energy includes electricity and gas only
3) Figures in brackets are for Capital city

The order of magnitude of the overall energy consumption figures are verified by data collected as part of the NEEHA Project (Ballinger *et al.*, 1991). Table 4.4 shows the average annual energy consumption derived from supply authority records over a two year period prior to the study. The total sample is divided into Standard and Energy Efficient sub-samples. It was not possible to apportion energy consumption to end-use categories. In Adelaide the energy reduction for the "energy-efficient" sample is around 34% while in Sydney the results show that the "energy efficient" sample is achieving an energy consumption reduction of around 19% . In Melbourne and Perth the study produced the confounding results that the "energy efficient" samples were consuming more energy than the "standard" samples. The reasons for these results were not clear but the obvious conclusion which can be made is that an "Energy Efficient House" does not necessarily mean reduced energy consumption: the occupants may be achieving a higher level of amenity for a given energy input.

Table 4.4: Energy Consumption - NEEHA Project Average Annual Energy Consumption (GJ) (Electricity and Gas only)

Location	Melbourne	Sydney	Adelaide	Perth
Standard Houses Average	54.4	43.6	44.3	17.8
Energy Efficient Houses Average	64.7	35.0	29.1	26.5

Source: ***Williamson et al., 1993, March***

4.5.2 Heating and Cooling Energy

Energy consumption statistics are notoriously difficult to interpret in a meaningful way. Generally only electricity and gas consumption is measured, therefore fuels such as wood, oil and solar are not taken into account in presenting the data. Data presented in the following Tables must be understood in this light.

Table 4.5 combines several sources which give information on estimated average total household energy consumption attributable to different end uses.

Table 4.5: Estimated Percentage of Energy Budget in Different Areas of Domestic Use Period 1977-79

State		Space heating or cooling	Water Heating	Other Uses
Victoria	Rawlings[1] Roennfeldt[2]	35 (50)	35 (25)	30 (25)
ACT[3]		61	20.3	18.7
South Australia	ABS[4] Roennfeldt[2]	32.2 (35)	30.3 (30)	37.5 (35)

Sources:
1) *Rawlings, 1977*
2) *Roennfeldt et al., 1983,May*
3) *National Capital Development Commission, 1977, p11*
4) *ABS, 1979, April, p13*

Using data from Tables 4.3 and 4.5 above, estimated values for average household energy consumption related to the end uses heating and cooling for the three city regions Melbourne, Canberra and Adelaide, in the period 1975-80, is shown in Table 4.6. It should be noted that the values for Melbourne are much less than the figures calculated in the 1974 Williamson & Coldicutt paper for the "typical" hypothetical house System A (see Table 3.2).

Table 4.6: Estimated Heating and Cooling Energy Consumption in an Average Household

City	Space heating or cooling, GJ
Melbourne	26-35
Canberra	30-38
Adelaide	13-18

Note: The range shown attempts to reflect the variables of household size and composition, fuel type mix, plant efficiencies etc.

4.5.3 Relation to Climate

As discussed in Section 2.3.1 conventional wisdom suggests climate is a principle determining factor in building performance and by implication (and scientific estimates) building energy consumption for heating and cooling energy consumption.

The diagram, Figure 4.1, appears to support this assumption. The graph was first published in a paper presented at the *Conference on Energy 1977: Towards an Energy Policy for Australia*, conducted by The Institution of Engineers, Australia (Rawlings, 1977). Clearly the graph includes per capita *domestic and commercial primary energy* consumption. The source of the data is not stated, but given the paucity of data at the time it was most probably based on theoretical estimates.

By several transformations, Figures 4.2a, 4.2b and 4.2c, the same graph was interpreted as showing a direct relationship between household *heating* energy requirements and the severity of the climate expressed in terms of Heating Kelvin Hours thereby reinforcing the conventional wisdom.

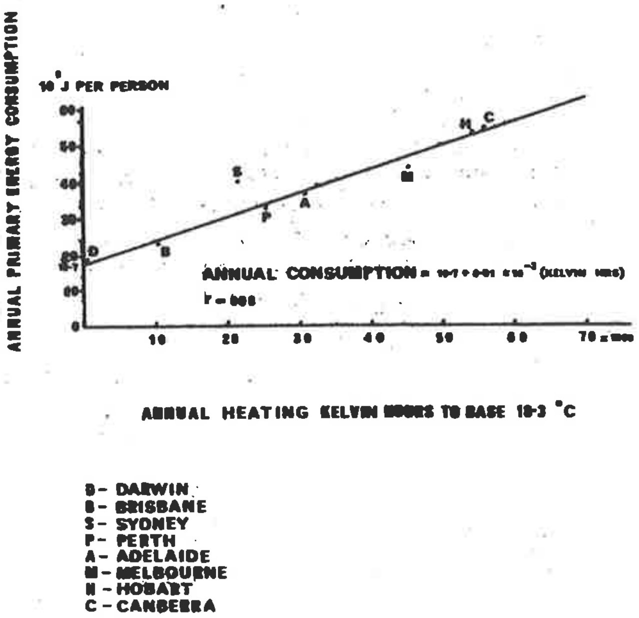


Figure 4 Domestic and commercial primary per capita energy consumption for Australian capital cities. Energy covers cooking, lighting, domestic hot water and heating and cooling requirements

Figure 4.1: Energy Consumption vs Climate, Rawlings et al., July 1977

Source: Rawlings, 1977

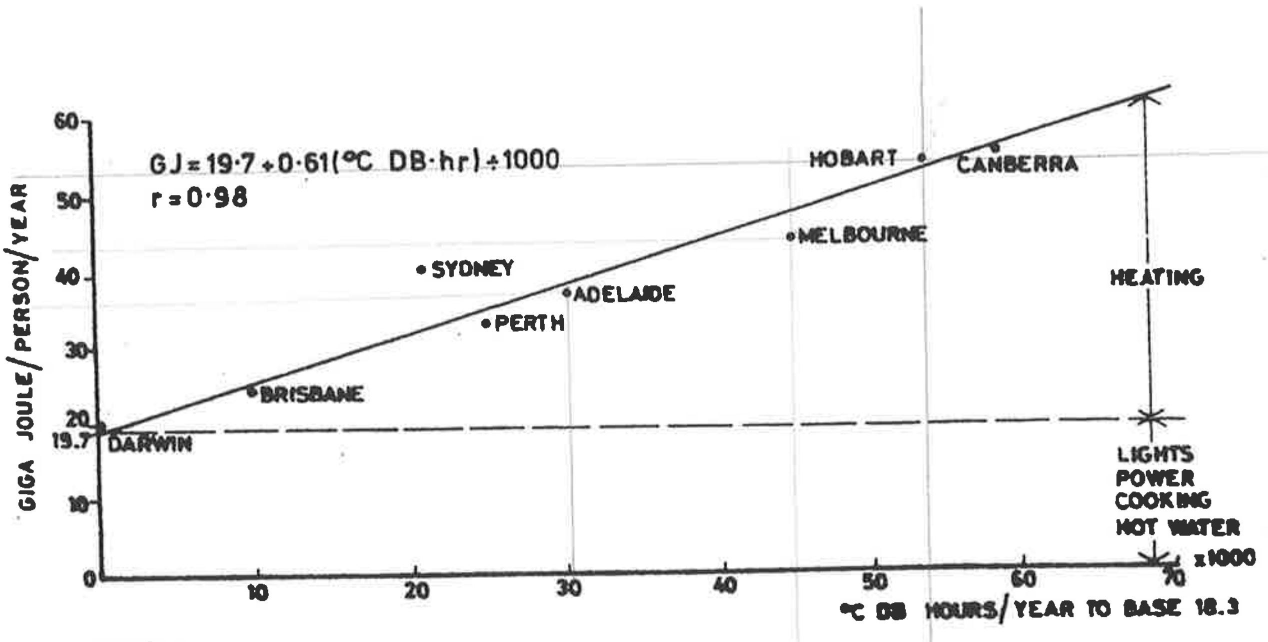


FIG.1
ENERGY CONSUMPTION PER PERSON IN BUILT ENVIRONMENT VERSUS DEGREE HOURS BASE 18·3°C

Figure 4.2a: Energy Consumption vs Climate, NCDC, 1977
Source: NCDC, 1977, p3

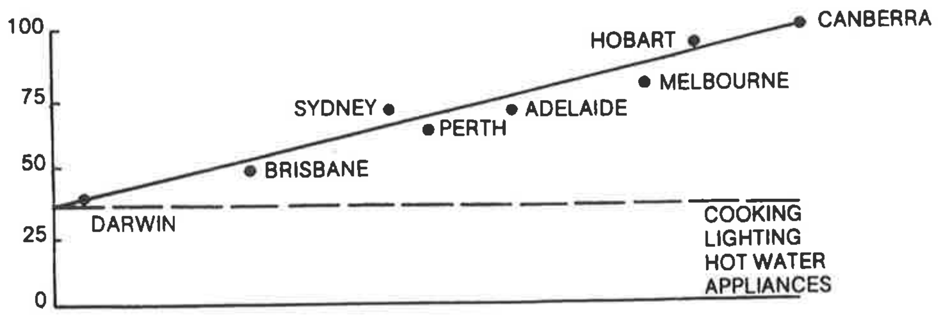


Fig.2 CAPITAL CITY SPACE HEATING REQUIREMENTS

Figure 4.2b: Energy Consumption vs Climate, NCDC, September 1977
Source: NCDC, 1977,September

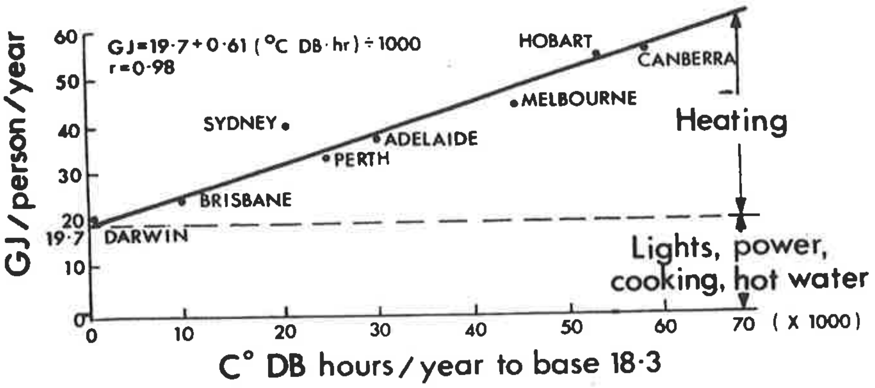


Fig. 5. Energy consumption per person in built environment for some Australian cities.

Figure 4.2c: Energy Consumption vs Climate, Kalma and Millington, 1978
Source: Kalma and Millington, 1978

Using the ABS 1985-86 household energy consumption and income data (ABS, 1988; 1990) and representing the severity of a climate as the sum of Heating and Cooling Degree Days,[10] a somewhat different picture emerges as shown in Figures 4.3 to 4.5.

Household energy consumption per household is complicated by the mix of gas and electricity as fuels, each with different efficiency ratings and likely usage patterns and by the mix of household types, separate houses, townhouses, etc. Figure 4.3 shows the average annual energy consumption for separate houses. Data is shown for all such households, that is, those with both electricity and reticulated gas supplied and for those households with electricity only. The high penetration of gas usage in Melbourne is evident in the Figure 4.3. Figure 4.4 shows the energy consumption per person and Figure 4.5 shows the energy costs per household.

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[10] Analysis has shown that using a heating base of 18°C and a cooling base of 24°C produces the highest correlation coefficients

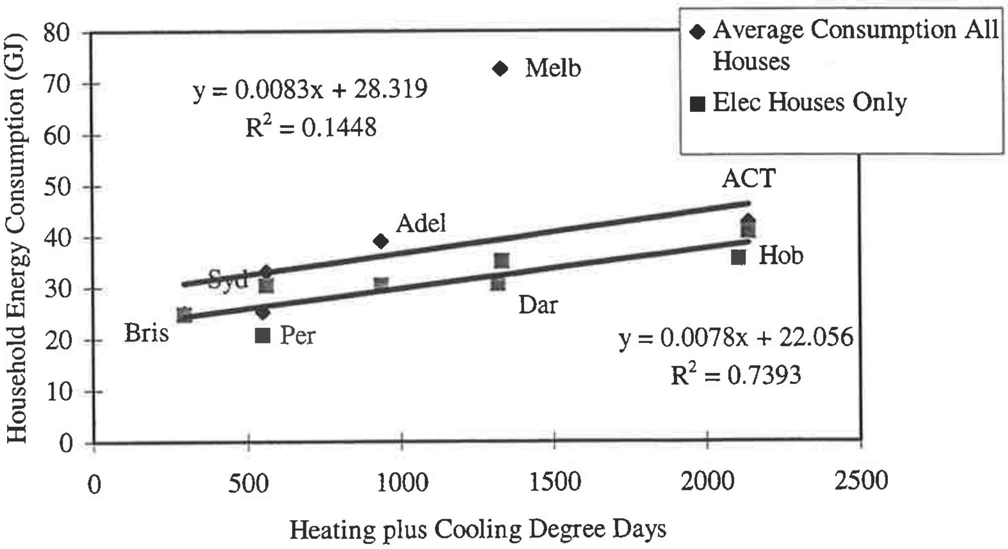

Figure 4.3: Average Household Annual Energy Consumption , Separate Houses Only
Note: Heating Degree Days at base 18°C and Cooling Degree Days at Base 24°C

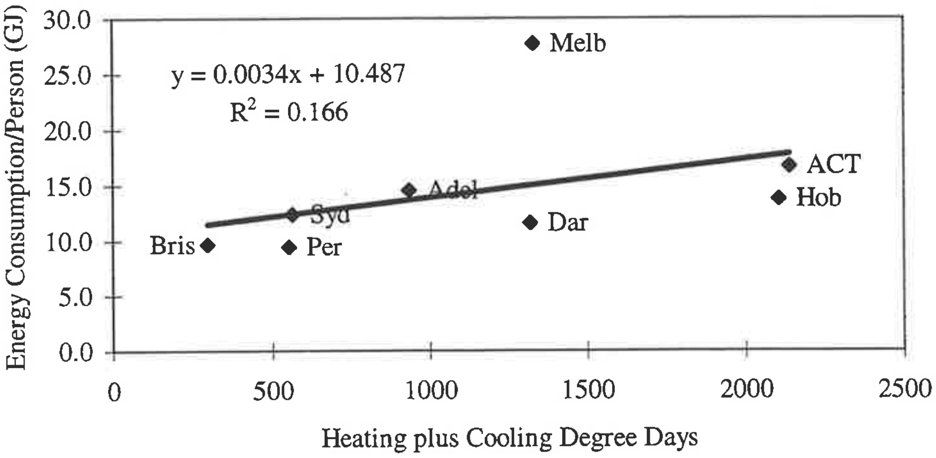

Figure 4.4: Average Annual Energy Consumption per Person, Separate Houses Only
Note: Heating Degree Days at base 18°C and Cooling Degree Days at Base 24°C

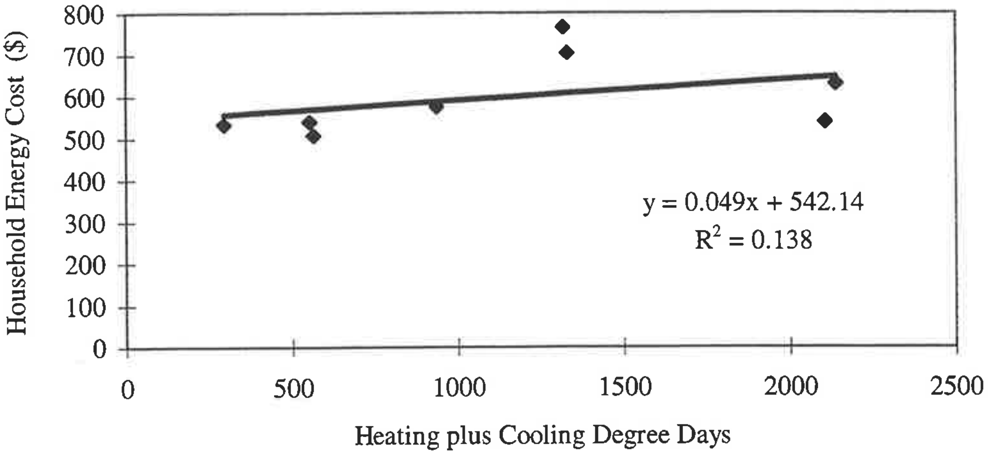

Figure 4.5: Average Annual Household Energy Cost, All Houses
Note: Heating Degree Days at base 18°C and Cooling Degree Days at Base 24°C

In all cases shown above the relationship with the climate index is very poor. The energy consumption for households without reticulated gas supply, that is, households with only electricity, indicates a slightly stronger correlation with the climate index but even this is relatively weak at R^2=0.74. If we convert data of Figure 4.1 to the climate index based on heating and cooling and compare the results with Figure 4.4, we find that the former suggests a relationship to climate more than four times stronger than the more recent statistics reveal. A simple direct and strong relationship between energy consumption and climate severity is not demonstrated, indicating that other factors have a major influence. However, theoretical estimates of energy consumption often show a very different relationship with the climate. This can be seen be examining the data base of household heating and cooling energy consumption produced by Isaacs using the CSIRO program CHEETAH during the development of the Australian National House Energy Rating Scheme-NatHERS (Isaacs, 1996). Computer simulation estimates of the average NatHERS heating and cooling consumption derived from over 450 house type variations for each location are shown in Figure 4.6. The estimates are based upon "standard" assumptions regarding user patterns of heating and cooling behaviour and thermostat settings. A heating efficiency of 1.0 is assumed and the CoP for cooling is taken as 2.6 to convert energy load estimates to delivered energy figures.

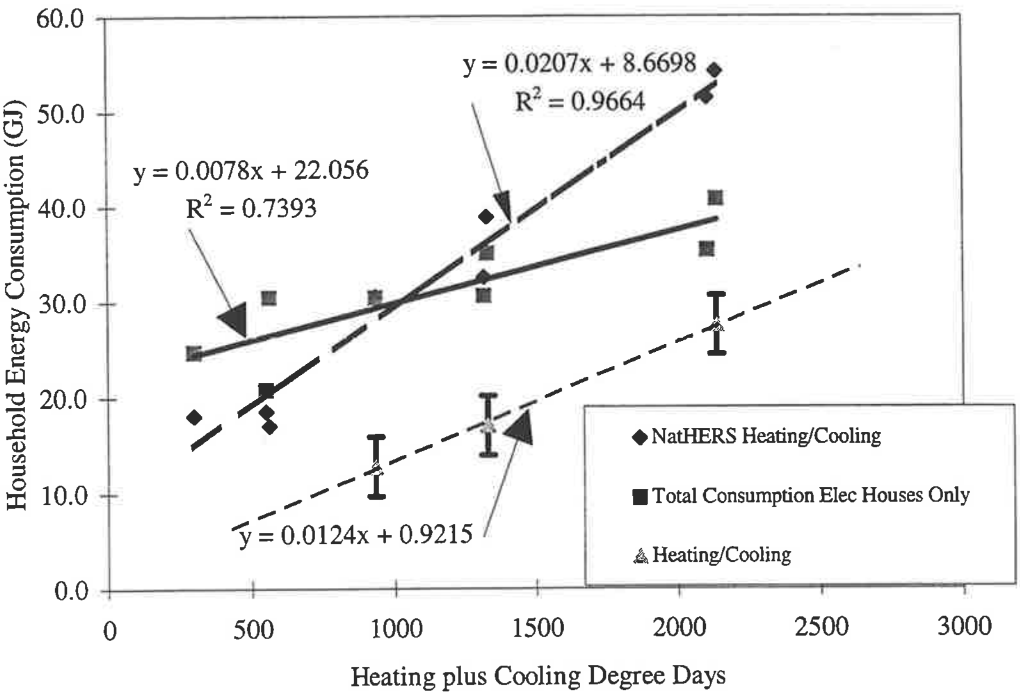

Figure 4.6: Annual Household Energy Consumption (All Electric Houses Only) Compared with Estimated and Calculated (NatHERS) Heating and Cooling Consumption
Note: Heating Degree Days at base 18°C and Cooling Degree Days at Base 24°C

The NatHERS energy estimates can be compared to actual average heating/cooling consumption derived from the total energy consumption data and the proportion attributable to heating and cooling (see Table 4.5)[11]. The results show that compared with "average" heating and cooling consumption the computer predictions over-estimate consumption in all climates by a significant amount. The relationship between climate severity and heating/cooling energy consumption represented by the slope of the line shows that the NatHERS values exaggerate the effect of climate by a factor of 1.5. This result echoes the 1948 findings from the UK reported in Chapter 2 and suggest that there is a complex relationship between climate and household energy consumption not adequately accounted for in a simple model of behaviour. We could hypothesise that factors such as dwelling/plant practices and use patterns, financial considerations (fuel expenditure elasticity), social and cultural aspects, etc., act to decrease the influence of climate as a main determining factor of household energy consumption. The data suggests that policy and design decisions based on simple conventional assumptions may lead to incorrect answers.

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[11] The accuracy of the heating/cooling consumption estimated in this manner may be assessed by considering the results for the ACT where all electric houses account for 43% of all houses. The derived relationship predicts a total annual energy consumption of 38.7GJ with a constant, climate independent, component of approximately 22GJ. If the entire marginal component was attributed to heating/cooling requirements this use would then account for 57% of the total usage. This figure accords well with measurements of the heating/cooling component in the ACT (see Table 4.5) which shows the percentage to be around 61%.

4.6 Thermal Preferences

The notion of *thermal preferences* has been introduced to provide designers with an understanding of the many complex issues involved in designing a house (Williamson *et al.*, 1989). This notion recognises that built environment decision-making typically involves a multitude of human requirements, some of which conflict, many of which cannot be precisely known, and most or all of which are at least to some extent context dependent. *Thermal preferences* are concerned with identifying the human requirements which influence the thermal design of a building and over which a designer has some control. Several research projects can be identified as providing valuable information related to this issue.

4.6.1 Attitudes Surveys

Perhaps the first researcher in Australia to conduct surveys of occupant attitudes to climate and comfort was Ann Marshall, in the Department of Geography, The University of Adelaide. Her work, which began in the mid-1950's, went largely unnoticed by researchers in the building thermal performance area because it operated within the discourse of geography . An early survey of Marshall's aimed to,

> *"...discover different degrees of suitability of houses for the most usual resident in summer. "Suitability" in this sense means suitability as a shelter, to modify the outside variations of temperature, and provide indoor conditions as comfortable as possible. Whatever, other functions a house serves, from the need for privacy to the desire for social esteem, this function of shelter must be regarded as primary."*
> (Marshall, 1958, p. 24)

The experiment in this study was "designed to show differences in comfort due to house design or house orientation, or both", with the results showing "uncompromisingly the differences between individuals" (Marshall, 1958, p.27). Marshall was perhaps ahead of the time when in 1973 she suggested,

> *"We can keep houses cooler in summer and warmer in winter by insulation, especially ceiling insulation. We can decrease heat gain by using white reflective surfaces and increase it by dark absorbing surfaces. We can orient the house so that the valuable winter sunlight penetrates into rooms where it can do most good, and exclude the sunlight in summer by efficient forms of outside screening. We can accept the fact that glass creates problems in both* summer *and winter, and use glass areas in a way appropriate to the climate. A building based on these considerations would be a comfortable shelter without a wasteful use of energy for heating and cooling."*
> (Marshall, 1973, p.255)

The attitude survey techniques of Marshall were developed by Jill Kerby (1975, 1979a) in a study concerned with an investigation of the relationship between climatic suitability, indoor comfort and household energy consumption[12].

Several surveys conducted post-1974 in Australia aimed at discovering the attitudes of home owners and builders to the idea of energy-efficient (or low energy) housing. David Crossley was one of the first researchers to conduct such surveys. His work involved gaining data to form an understanding of public attitudes, knowledge and behaviour regarding energy conservation and energy use. He found that barriers to energy conservation practices could be categorised as relating to personal disposition, living situation, economic costs, social costs, inadequate information and structural factors (Crossley, 1980; 1981). These findings were confirmed by a research project commissioned by the South Australian Department of Mines and Energy in 1983 entitled, *Implementation Strategy for Low Energy Housing in South Australia* (SADME, 1983) which used a variety of approaches to study factors affecting dwelling choice. Consumer awareness and attitudes to low energy housing issues were summarised as,

> *"[C]onsumer awareness was felt to be deficient in three main areas; the true cost of energy, the nature of low energy design and the importance of personal behaviour as a means of reducing household energy consumption. Regarding the nature of low energy design, it was felt that many people identified it with non-conventional looking housing and related it to the counter culture movement."* (SADME, 1983, p28)

The study found that only a *minority* of house occupants placed top priority on thermal performance or energy related matters and pointed to the inadequacies of the then current efforts to promote the notion of low energy housing. Since at the time the main recommendations for low energy house design revolved around the rules-of-thumb associated with the *solar-efficient* prototype the findings suggest a possible mismatch between these recommended design strategies and the preferences of the majority of house owners and builders. The report concluded among other things that:

> *"...most consumers regard factors such as cost, appearance and style of house and residential amenity as considerably more important house selection criteria than energy saving factors."* (SADME, 1983, p49)

Similar results were found in the NEEHA project (Ballinger *et al.*, 1991). When respondents were asked the question "*When you where last looking for a place to live, what was it that made you choose to build this house?*" the reasons given (Table 4.7) show that energy-efficiency is not a major factor. These findings highlight the importance of taking into account when giving design information, those issues of primary concern which affect the energy-efficiency of a dwelling.

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[12] This work, undertaken by Jill Kerby as part of her PhD research, was supervised by Ann Marshall.

Table 4.7: Reasons Given for Choosing House (% of responses)

	Adelaide	Sydney	Melbourne	Perth
Neighbourhood	57	75	80	33
Spatial qualities-room size, layout, design	57	75	70	21
Convenience-location, city, transport, work	57	75	30	54
Site considerations	57	25	30	83
Price/Cost/Value	42	50	59	38
Pleasant views	42	25	10	8
Local amenity	29	25	70	37
Inward looking privacy/security	0	50	30	0
Daylight qualities	0	25	60	21

Source: Ballinger* et al., *1991

Having chosen a house, householders often carry out alterations to improve the thermal performance, one of the main measures being the installation of thermal insulation. Data from a recent ABS survey (ABS, 1994) presented in Figure 4.8 shows the penetration rate of thermal insulation by selected States is high despite there being no mandatory requirement, other than in Victoria[13], at the time of the survey.

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[13] Mandatory thermal insulation was introduced into the building regulations in Victoria in 1992.

Table 4.8: Insulation Installed (% of dwellings)

Whether/Where Installed	Victoria	SA	NSW	WA
Roof/ceiling	68.5	70.3	43.0	51.5
Walls	19.1	17.7	11.6	3.3
Floor	0.5	0.2	0.3	**
Other	0.1	0.3	0.1	0.3
Not insulated	30.5	27.8	55.5	48.0

Source: ABS, 1994. p22

A number of studies over recent years have been concerned with assessing the effectiveness of thermal insulation. In a study undertaken by Kerby (1979a), the effectiveness of thermal insulation was one of the factors considered. This study reported the confounding result that households with insulation consumed 12% (11GJ) more primary energy than households with uninsulated dwellings. A subsequent analysis (Kerby, 1979b) of the data revealed that insulated dwellings were associated with:

- the presence of space heating and/or air-conditioning
- larger dwelling size
- a greater number of occupants
- higher incomes
- a higher satisfaction with thermal comfort.

The South Australian Department of Mines and Energy commissioned a study (Cloher, 1981) aimed at determining the effectiveness of thermal insulation in dwellings. This study sought to determine the extent of energy savings and/or improved levels of thermal comfort resulting from the installation of insulation for dwellings within metropolitan Adelaide and the Adelaide Hills area. Again insulated dwellings on average showed higher energy consumption. Despite the difficulties of analysis the study was able to conclude that of the households surveyed,

1. about 10% of households decreased energy consumption after insulation without increasing comfort levels.

2. about 55% of households either decreased or kept constant energy consumption and at the same time increased comfort levels with little or no additional expenditure on other comfort-inducing aids.

3. about 28% of households increased both energy consumption and thermal comfort levels.

This study also sought information on consumer attitudes to the installation of thermal insulation. Householders were asked their reasons for installing insulation. The results are shown in Table 4.9.

Table 4.9: Reasons Given for Installing Insulation (% of households surveyed)

Reasons for Installation	**Primary**	**Secondary**
Summer heat	68	13
Winter cold	15	38
To reduce heat/cooling bills	10	17
Energy Savings	0.3	0.6
Don't know	0.1	0.4
Other	0.1	0.3

Source : Cloher, 1981, p60

The report stated that :

> *About 33% of householders had not considered (financial) savings, 9% had expected no savings while 44% thought there might be some savings but were vague about the extent of such savings....It is clear from the survey that the majority of householders are uncertain (and possibly unconcerned) about the amount they spend on domestic fuel....Most householders value thermal comfort much more highly than reduced fuel bills.*

A later study commissioned to investigate an implementation strategy for low energy housing in South Australia (SADME, 1983) found that 85% of respondents to a survey were aware of the energy saving benefits of ceiling insulation and 60% of wall insulation.

In the same ABS survey (ABS, 1994) quoted above, respondents were asked the main reason for installing thermal insulation in their dwelling. The results for some States and the country as a whole are shown in Table 4.10.

Table 4.10: Reasons for Installing Thermal Insulation (% of responses)

Reason	**Victoria**	**Sth Aust.**	**ACT**	**Australia**
Achieve Comfort	66.0	78.6	63.5	76.4
Save on energy bills	25.6	16.2	21.6	16.3
Reduce energy use	6.7	4.1	12.9	4.9
Other	1.8	1.1	2.1	2.4

Source: ABS, 1994, p22, Table 2.2

These results clearly indicate that when people undertake thermal performance improvements to their dwelling the main motivation appears to be a desire to improve comfort.

4.6.2 Housing Acceptability

The 1974 Williamson & Coldicutt paper refers to appearance, initial cost, minimum attention to building operation and matters of aesthetics, custom and fashion as being components which relate to the endorsement of an energy-efficient design solution by potential householders. These and other considerations of the general acceptability of energy-efficient housing have been the subject of various research investigations.

The new housing market in each State of Australia is dominated by a small number of project builders. The products they supply meet market expectations as influenced by advertising, fashion, etc, but also satisfy the demands of marketability, buildability (taking into account the available expertise and materials) and cost constraints. There is no doubt that thermal considerations do not figure high in design or house selection priorities. This view is reinforced in a survey by Pradhan (1993) of sales representatives from the leading project builders in Adelaide who suggested that energy-efficiency issues were rarely considered by clients in the choice of their house or in the choice of options which may be offered by the builder. Despite this assessment, the sales representatives indicated that the majority of people took up the option to have thermal insulation installed in the walls and ceiling[14].

The *solar-efficient* prototype dwelling implies a particular form. It suggests, for example, the positioning of sleeping areas towards the south and minimum glazing in the east, west and south orientations, together with heavy shading to the east and west facades. Many rooms in such a house could be poorly daylit, and could use extra energy for artificial lighting. The prototype design strategies assume, among other things, that people do not put a high priotity on sun penetration into bedrooms during the winter period. This issue was raised in questions asked as part of the NEEHA Project to ascertain the acceptability of such a design (Ballinger *et al.*, 1991).

Figures 4.8 and 4.9 show the results of questions relating to the desirability of having direct winter sun in living rooms and bedrooms.

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[14] Several builders indicated that they offered thermal insulation as a no-cost option in order the attract clients.

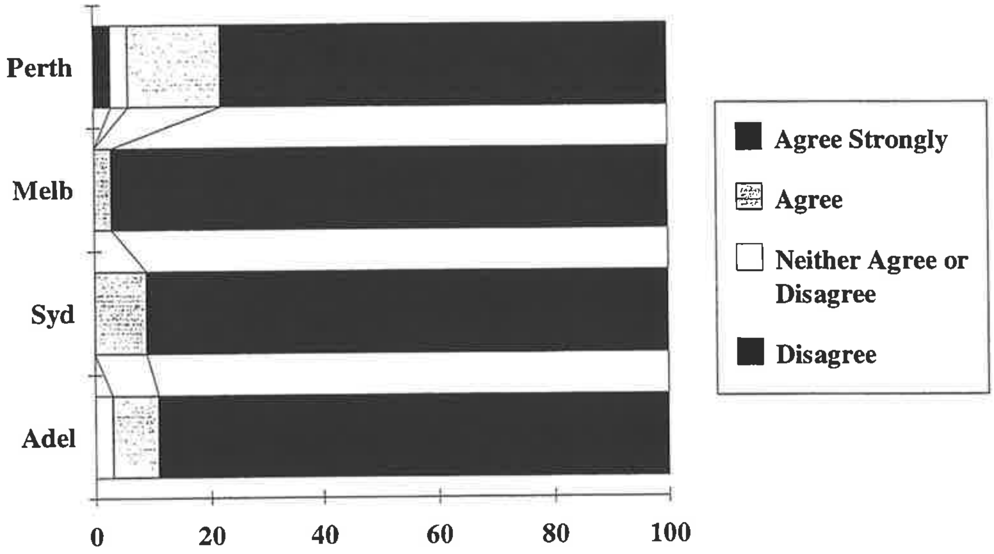

Figure 4.8: Winter Sun in Living Rooms (% Responses)
Q3a "Could you indicate the extent to which you agree or disagree with the statement 'Living areas should receive some direct sunlight in winter'"

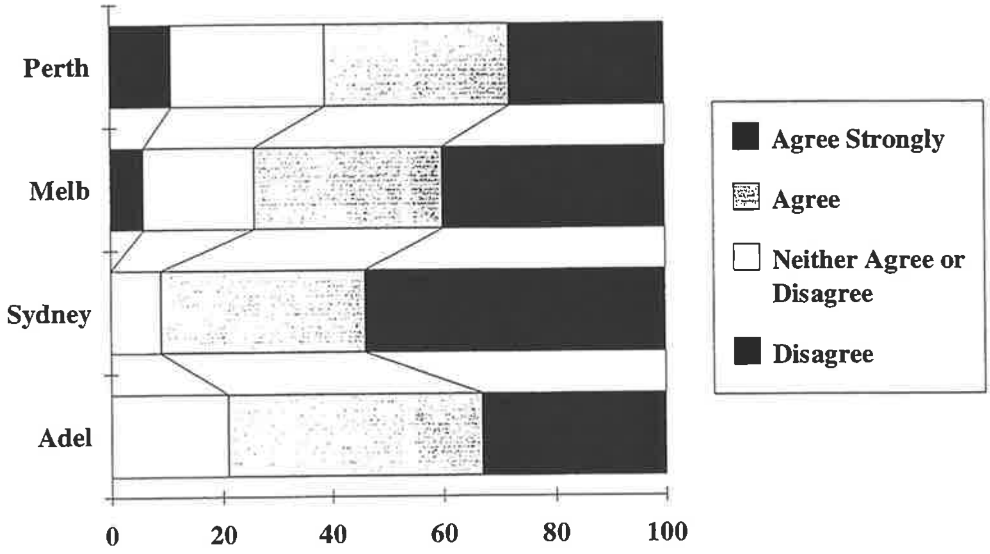

Figure 4.9: Winter Sun in Bedrooms (% Responses)
Q3b "Could you indicate the extent to which you agree or disagree with the statement 'Bedroom areas should receive some direct sunlight in winter'"

Although a stronger preference appears for winter sun in living areas, the majority of people in each location agreed that there should be at least some sun entering bedrooms during winter.

We can compare preferences with actual performance. Table 4.11 shows ABS survey results for rooms receiving winter sun.

Table 4.11: Rooms in Dwellings Receiving Winter Sunlight (% of cases)

Rooms in sunlight	WA	Victoria	NSW	SA	Australia
Lounge/living/family	50.9	60.6	57.3	49.0	56.4
Bedroom(s)	48.6	52.7	58.6	45.1	55.4
Kitchen/dining	28.1	37.4	38.1	31.4	36.5
Laundry/bathroom	8.3	8.2	12,5	7.4	10.5
Other	3.0	2.5	4.7	3.1	3.8
No Winter Sunlight	***15.9***	***8.8***	***10.1***	***18.2***	***11.0***
Don't know	1.5	2.0	2.1	2.0	1.8

Source: ABS, 1994, p32, Table 2.11

Both the preference expressed for winter sunlight in bedrooms and the current actual performance would be impossible to achieve with the *solar-efficient* prototype design recommendation of a zoned planning arrangement with the living areas to the north and bedroom areas to the south.

Another important aspect of acceptability relates to the concept of design times, that is, the time of year and the time of day which causes the main performance concerns related to thermal performance issues. Design times are important because a householder who perceives some inadequacy in performance may at some stage seek to improve the situation by installing more energy consuming devices such as air-conditioning. A question in the NEEHA project asked the respondents,

> *"If you were choosing a house that would be suitable for the climate where you live, you might want to consider what it would be like inside the house. Indicate (on a 10-point scale) how important it would take to the following various times (shown) into consideration."*

The results are shown in Figure 4.10. Although all times were registered as important, slightly more weight was given in each location to "Hot summer nights in bed" and "Hot summer evenings" indicating the special importance which should identified with maintaining comfortable sleeping conditions on hot evenings. Dwelling design solutions which do not satisfy the requirements for comfort at these critical times are likely to be perceived by the occupants as flawed.

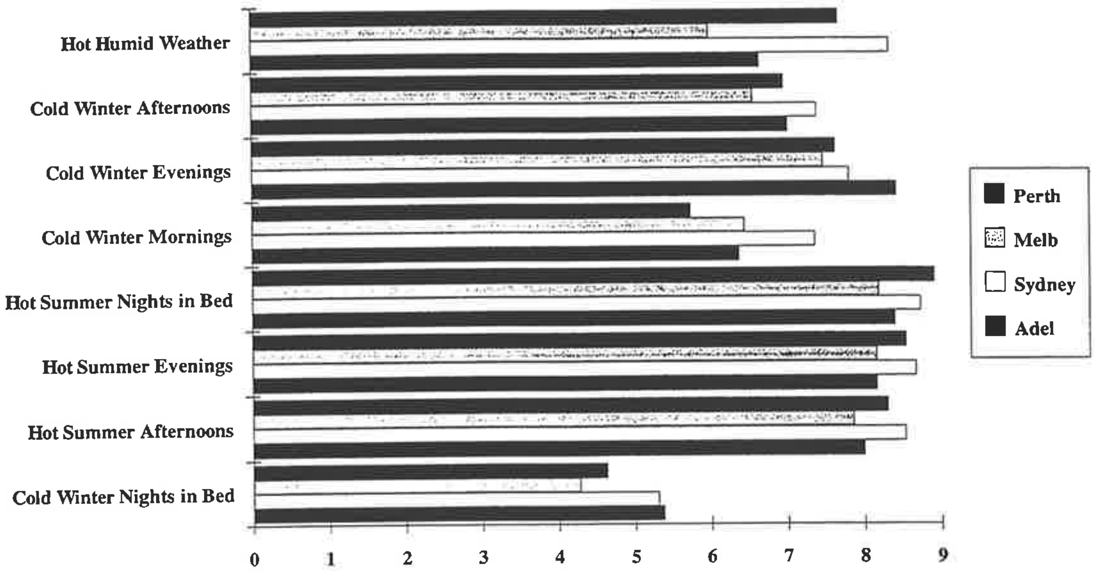

Figure 4.10: Design Times Question (% Responses)

4.7 Thermal Comfort

Most of the research in the field of thermal comfort may be classified into two broad groups, according to the range of factors studied and the methodology adopted.

First *laboratory based* (or climate chamber) methods tend to emphasise the effect of the physical environment on human thermal comfort, to the exclusion of other factors such as habit or cultural background. The effective temperature scale *ET* (Houghton & Yagloglou, 1923), the rational effective temperature scale *ET** (Gagge *et al.*, 1971) together with *TSENS* and *DISC* (Gagge *et al.*, 1986) are indices of thermal comfort which are outcomes of laboratory investigations. Probably the best known and most widely accepted comprehensive thermal comfort index is Predicted Mean Vote (PMV) developed by Fanger (1972). For a given set of environmental variables the mean vote of a population expressed on a 7-point thermal sensation scale may be calculated, compatible with metabolic rate and clothing levels. The international standard ISO 7730 *Moderate Thermal Environments - Determination of the PMV and PPD indices and the specification of the conditions for thermal comfort* (ISO-International Organisation for Standardisation, 1984) is based upon this relationship and is predicated on the belief that thermal comfort is a universal phenomenon unrelated to the context.

A major criticism of models for predicting thermal comfort which are based solely on laboratory investigations is that field surveys have shown consistently that people adapt to their surroundings and accept conditions that would appear to lie outside the established comfort range. Researchers undertaking *field studies* assert the importance of environmental factors and claim that in practice, people are comfortable in a wide range of environments as they respond to the complex situations encountered in their daily life. This does not mean that, given the opportunity, they would not "vote" for a comfort temperature in accordance to that predicted by the models. It only means that in complex real-life situations, behaviour patterns are modified so that comfort may be maintained at temperatures close to those to which people are actually exposed.

The work of Michael Humphreys in 1975 drew attention to this issue when he presented an analysis of 36 field surveys, totalling over 200,000 observations, conducted by other researchers into the question of human thermal comfort (Humphreys, 1975). He found a very strong relationship between the neutral temperature[15] indicated by respondents in free-running buildings and the outdoor mean temperature. The work of Auliciems in Australia (Auliciems, 1983) confirmed this type of relationship.

The criticism of field studies is that they are generally not able to measure the variables with the same accuracy as the laboratory methods, thus throwing some doubt on their findings. Many claim that within the bounds of experimental error the results are the same.

4.7.1 Thermal Neutrality

Neither of the approaches discussed above for predicting the comfort conditions for a given population in a given environment question the desirability and the necessity of providing thermal comfort under all situations and at all times. They merely seek to determine what the desired conditions might be. Williamson *et al.* (1989) raised the possibility that,

> *"thermal neutrality cannot be assumed to be a goal in all built environments. And, even where it is found to be a relevant goal, it cannot be assumed that the costs of providing thermal neutrality will be considered justified by the occupants and/or by those who pay the building's construction and running costs. Further, it cannot be assumed that the non-monetary costs of providing thermal neutrality will be considered justified: plant noise, perceived health risks, and loss of close relationship with outdoors are examples of possible non-monetary costs which may be associated with the provision of thermal neutrality by air-conditioning plant".*

Taking all four locations in the NEEHA Project together, the following Table 4.12 (see Section 4.4 for scale descriptions) shows the cross-tabulation to the questions on the *Environment Response Logger* panel "How do you feel?" and "How would you like to feel?". The response to the former question is referred to as the VOTE and the latter as HOW.

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[15] Neutral temperature is that temperature at which 50% of a sample population will indicate on a 7-point thermal sensation scale as in the range 1-4 and 50% in the range 4--7. It is usually considered synonymous with comfort temperature.

Table 4.12: Cross-tabulation of Vote vs How (% of total votes)

	Standard houses/all			
VOTE	HOW			
	1	2	3	TOTAL
1	0.1	0.0	1.0	**1.0**
2	0.0	0.3	3.1	**3.4**
3	0.2	5.7	13.3	**19.2**
4	0.6	49.3	1.5	**51.4**
5	5.3	10.8	0.9	**16.9**
6	2.6	4.1	0.1	**6.9**
7	0.8	0.3	0.1	**1.2**
TOTAL	9.6	70.5	19.9	100.0

	Energy Efficient houses/all			
VOTE	HOW			
	1	2	3	TOTAL
1	0.0	0.0	0.4	**0.4**
2	0.1	0.5	2.0	**2.6**
3	0.3	6.1	8.5	**15.0**
4	0.5	53.1	1.8	**55.4**
5	3.6	12.7	0.5	**16.8**
6	1.9	7.0	0.1	**9.0**
7	0.5	0.1	0.1	**0.6**
TOTAL	6.8	79.6	13.5	100.0

This cross-tabulation shows that people do not always equate not wanting to feel any different ("no different") with "neither cool nor warm." Taking both samples together a significant number of people (23.8%) voted either "slightly cool" or "slightly warm", and even "warm" and "cool", together with a corresponding "no different" indicating their preference was not thermal neutrality. Anecdotal evidence gained during the project interviews with householders suggested that one explanation is that when people are operating heating or cooling appliances they wish to "feel" the effect. The inherent methodological assumption that the desired state is one of thermal neutrality cannot account for this behaviour.

Taking the total sample of houses studied, less than 10% of votes fall outside the three central thermal sensation vote categories indicating that occupants generally have a high level of thermal satisfaction with their dwellings.

4.7.2 Acceptable Thermal Conditions

There is now a large body of evidence which suggests that the predictions of the principal theoretical heat-exchange models of thermal comfort show significant discrepancies compared to the findings from field studies, putting in doubt estimates of thermal acceptability based on these models. The main contention is that the models do not adequately account for various contextual factors, in particular the apparent changes in preferred environmental conditions as a function of the varying external conditions. Humphreys (1978) has suggested, for example, that for free-running buildings the neutral or comfort temperature is related to the mean monthly external temperature by the expression,

$$T_n = 0.534\,T_m + 11.9 \quad \ldots\ldots\ldots\ldots(R^2=0.95). \qquad \text{Equation 4.1}$$

where T_n is the neutral temperature in deg C,

T_m is the mean outdoor temperature defined as $(T_{ave\ max} + T_{ave\ min})/2$.

In the same study Humphreys found a similar but weaker relationship for climate controlled buildings and this he suggested was best described as an exponential equation,

$$T_n = 23.9 + 0.295(T_m - 22)\, e^{-\left(\frac{(T_m - 22)}{(24\times\sqrt{2})}\right)^2} \quad \ldots\ldots\ldots\ldots(R^2=0.52) \qquad \text{Equation 4.2}$$

(This relationship applies to the range -24°C<T_m<23°C)

The equations 4.1 and 4.2 are plotted in Figure 4.12.

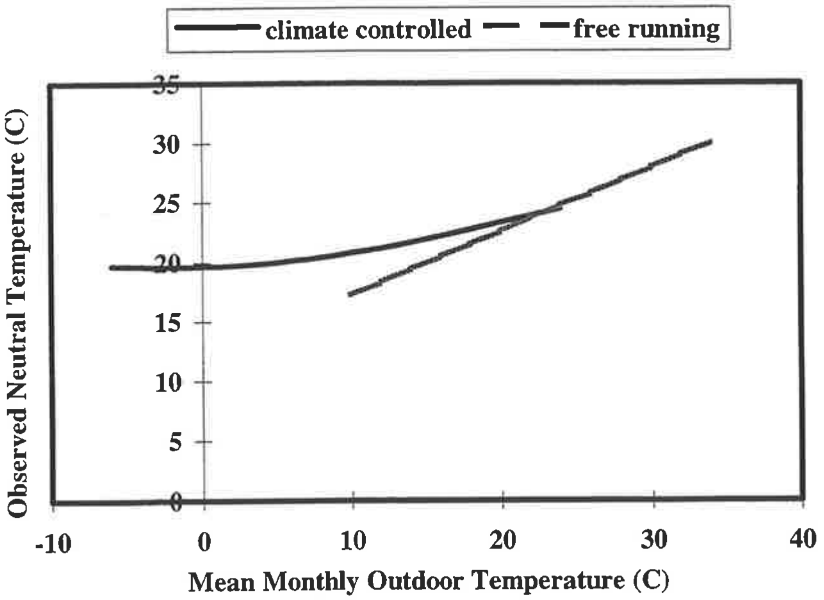

Figure 4.12: Preferred Temperatures
Source: Derived from Humphreys, 1978

Humphreys (1981) also showed that a quadratic expression (Eq. 4.3) which includes both the mean external temperature and the hottest month of the year provided a reasonable predictor of the indoor comfort temperature.

$$T_n = 0.0065\,T_m^2 + 0.32\,T_h + 12.4 \quad \ldots\ldots\ldots\ldots(R^2=0.59). \qquad \text{Equation 4.3}$$

(This relationship applies to the range -24°C<T_m<23°C, 18°C<T_h<30°C)

Equation 4.2 was felt to better represent the anticipated trends beyond the data limits.

The implication suggested from this data is that, in warm to hot climates (T_m>23°C), people in free-running or naturally ventilated buildings tolerate higher temperatures compared with people in air-conditioned buildings. In cold climates the opposite is true. Houses in mild temperate climates with intermittent heating and/or cooling can be considered as essentially displaying free-running behaviour.

In a more recent study Busch (1992) supports this suggestion. He found that the neutral temperature observed in air-conditioned office buildings in Thailand was lower when compared with those found in naturally ventilated buildings where the occupants preferred considerably higher neutral temperatures, 24.5°C compared with 28.5°C. DeDear *et al.* (1991) found a similar result in Singapore; a neutral temperature of 24.3°C for air-conditioned buildings and 28.5°C for ventilated apartment blocks. Results from both these studies for the naturally ventilated buildings indicate comfort temperatures well above ISO7730 predictions to achieve a PPD of around 5%. Using a range of indicative input variables the ISO7730 comfort temperature would be in the range 22.5°C-24.6°C.

Auliciems (1983) has used Australian field studies in combination with selected Humphreys' data to provide several modified equations which are based on combined data from free-running and climate-controlled buildings.

$$T_n = 0.31 T_m + 17.6 \quad \text{..............} \quad \text{Equation 4.4}$$

or

$$T_n = 0.73 \overline{T}_i + 5.41 \quad \text{...........} \quad \text{Equation 4.5}$$

where $\overline{T}_i$ is the mean indoor temperature.

As an alternative to formulas 4.4 and 4.5, using both internal and external temperatures as the independent variables he found that,

$$T_n = 0.48 \overline{T}_i + 0.14 \overline{T}_m + 9.22 \quad \text{...............} \quad \text{Equation 4.6}$$

An analysis of mean internal temperatures measured during the NEEHA Project is shown in Figure 4.14 (Riordan, 1992). Here the temperature data is binned by house, and plotted against the mean monthly external temperature. The regression line of best fit (R^2=0.69) is given by,

$$T_i = 0.58 T_m + 10.5 \quad \text{.............} \quad \text{Equation 4.7}$$

The neutral temperature was found to provide a good correlation with the mean external temperature (R2=0.89),

$$T_n = 0.537\,T_m + 11.0 \quad \ldots\ldots\ldots\ldots \quad \text{Equation 4.8}$$

The similarity between equations 4.7 and 4.8 suggests that the conditions which people express as neutral are on average those conditions which occur inside their houses. The spread of internal temperatures about the trend line in Figure 4.14, however, throws some doubt on the sense of considering only the central values.

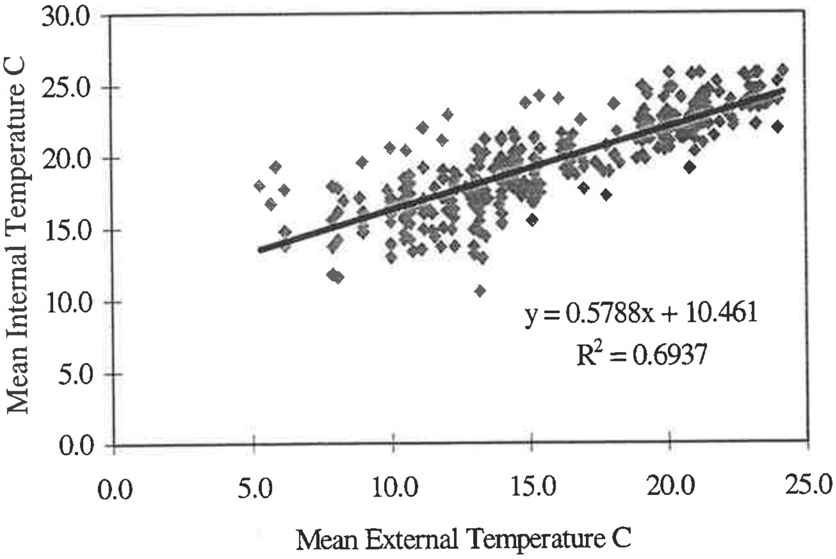

Figure 4.14: NEEHA Project - Mean Internal vs External Temperatures

A recent study by Nicol *et al.* in Pakistan (Nicol *et al.*, 1994) found that the temperature which people find comfortable in summer in buildings without conditioning is given with reasonable accuracy by the equation,

$$T_c = 0.534\,T_m + 12.1 \quad \text{for } 20^{\circ}\text{C} < T_m < 35^{\circ}\text{C} \quad \ldots\ldots \quad \text{Equation 4.9}$$

In winter (9°C<T_m<20°C) in heated and partly heated buildings the preferred conditions are about 2.4°C higher.

For buildings with climate control the study found that T_c was given by,

$$T_c = 0.38\,T_m + 17.0 \quad \ldots\ldots\ldots\ldots\ldots \quad \text{Equation 4.10}$$

The correspondence between Humphreys (Eq.4.1), Auliciems (Eq.4.4), Nicol (Eq.4.9 & 4.10) and Riordan (Eq.4.8) predictions for the neutral temperature is shown in Figure 4.15.

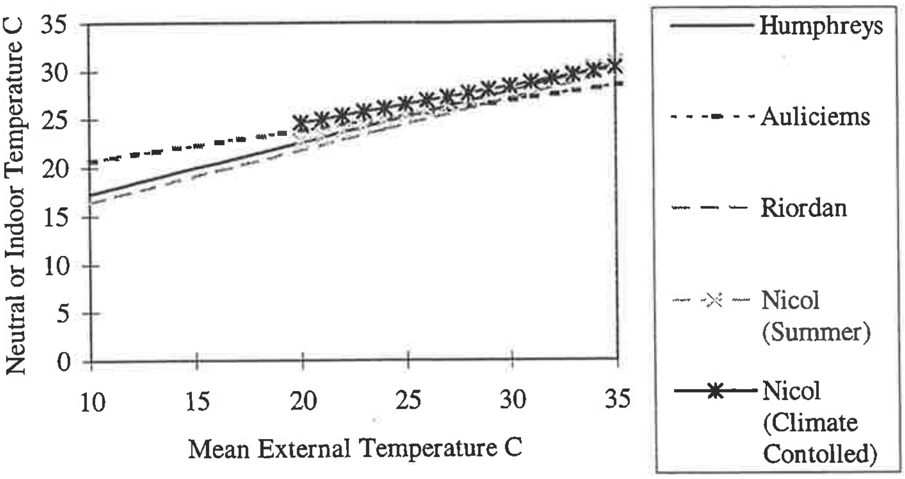

Figure 4.15: Predictions of Neutral Temperatures as a Function of Mean External Temperature

4.7.3 Adaptive Models

Contemporary thermal comfort studies are attempting to address the contextual nature of the thermal environment requirements. Humphreys (1995) has suggested the development of an adaptive model which would include factors to modify an accepted thermal index to account for contextual aspects. Figure 4.16 suggests how such a model could be constructed.

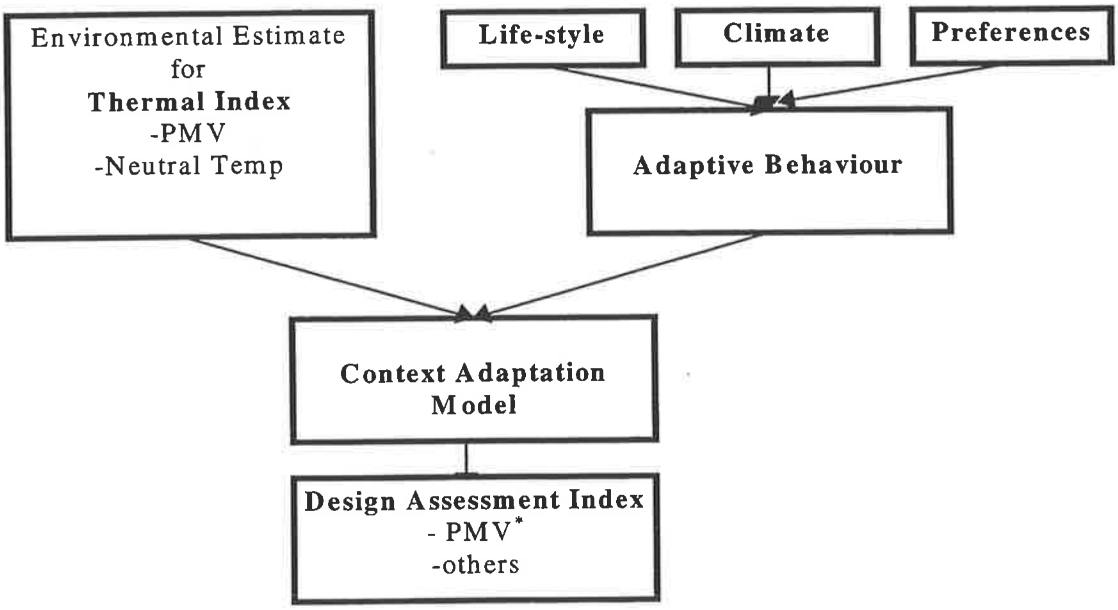

Figure 4.16: Adaptive Model Construction

Williamson *et al.* (1994) have shown that a more comprehensive design assessment index may be developed using the PMV concept. Estimates of actual mean vote (AMV) found in field studies may be derived from the estimated PMV with good accuracy. As shown in Figure 4.17 analysis of field study comfort data shows that a strong relationship (R^2=0.87) can be derived relating the difference [PMV-AMV] to the mean external temperature. The data is derived from comfort surveys in Australia (Williamson et al., 1989; Williamson *et al.*, 1991; Ballinger *et al.*, 1991), with additional limited data from Papua-New Guinea (Ballantyne *et al.*, 1979), the UK (Oseland, 1994), Uganda (Olweny, 1996) and Pakistan (Nicol *et al.*, 1994).

Figure 4.17 also shows a ±0.5 [PMV-AMV] error band indicating that most of the data falls within these limits. An interesting departure from the general trend is data collected in Pakistan during winter by Nicol *et al.* (1994). This data highlights the need to consider the contextual factors (in this case, possibly cultural factors) when suggesting appropriate thermal comfort levels.

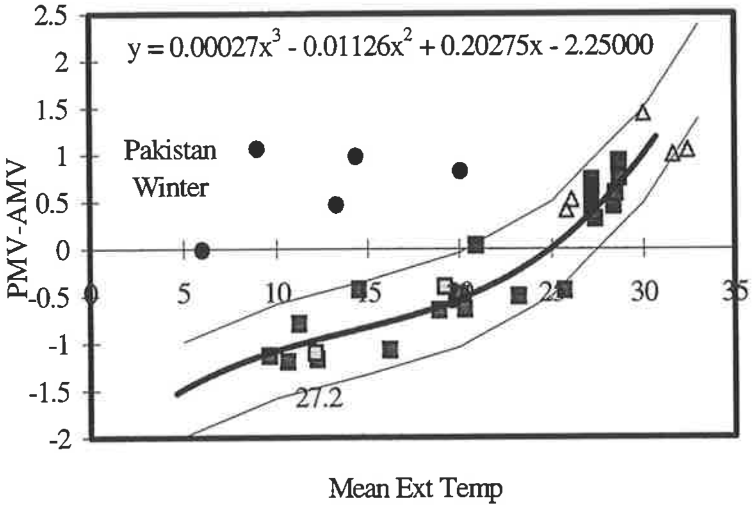

Figure 4.17: Adaptive Comfort Model: PMV-AMV vs Mean External Temperature

4.8 Heater and Cooler Use

The types of heaters and coolers normally installed in dwellings and their use patterns have a significant influence on energy consumption. Despite the importance in producing accurate energy predictions of having detailed knowledge on these issues, relevant data in a range of locations is difficult to obtain. The following sections present some data derived from the ABS, the NEEHA Project and market survey data from the Electricity Trust of South Australia (ETSA).

4.8.1 Types of Heaters and Coolers

Data relating to the penetration of heating and cooling devices in South Australia and Victoria are shown in Table 4.13.

Table 4.13: Penetration of Heating and Cooling Appliances in Households, SA & Victoria (% of households)

Year	1985-86 SA	1989 SA	1991 SA	1994(3) SA	1994(3) VICT
Main Heating					
Electric	38	37(1)	37	36	12
Gas	27	31	31	32	71
Wood/Solid Fuel	21	21	22	19	14
Oil	9	7	2	4	1
Other	*	2	*	2	*
No heating	*	2	*	6	1
Total	95	100	92	93	98
Air Conditioning					
Evaporative	13	13(2)	na	15	6
Refrigerative/Reverse Cycle	50	54	na	48	30
Total	63	67	68	63	36
Ceiling Fan	na	na	33	na	na

*Sources : **1985/86-ABS, 1987, 1991; (1)1989-ABS, 1990B;(2)1989-ETSA Residential Survey 1992, (unpublished), (3) ABS, 1994, Tables 3.1, 4.5 & 4.8***

A cross correlation of the likely heater and cooler options derived from several sources of data is shown in Table 4.14 indicating a significant number in each category.

Table 4.14 : Heater/Cooler Options - % of likely combinations Adelaide

		C1/fan	C2/evap	C3/rcac	C4/none
		30%	20%	40%	10%
H1/gas	35%	10.5	7	14	3.5
H2/portelec	25%	7.5	5	10	2.5
H3/rcac	15%	4.5	3	6	1.5
H4/slowcomb	25%	7.5	5	10	2.5

Source: ETSA, 1992

4.8.2 Areas of House Heated and Cooled

Information on the range of plant use is limited. The few studies available show a wide variation in household practices. For one of the coldest areas in the country, a study of 142 households in Tasmanian public housing showed approximately 13% of households heated only the living room, and approximately 40% heated the whole house (Coldicutt *et al.*, undated, p64). A survey in South Australia by the Electrical Trust of South Australia (ETSA), showed a wide range of rooms and areas of dwellings heated and cooled (ETSA, 1992). Data from this survey shown in Appendix E indicates that for dwellings in Adelaide 77% of house occupants heat up to three rooms and 87% cooled up to six main rooms. The NEEHA study (Ballinger *et al.*, 1991) also found a wide range in application and use patterns. Figs 4.18 & 4.19 show the range of rooms heated and cooled.

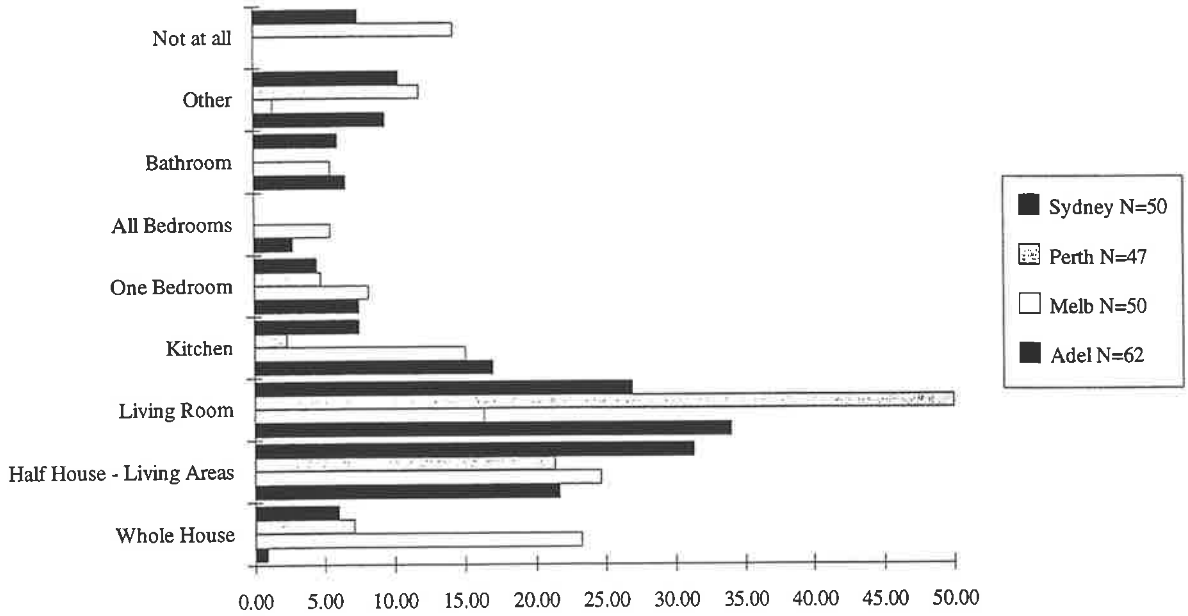

Figure 4.18: % of Responses
"At this time of the year (winter), which rooms in your house do you usually heat?"

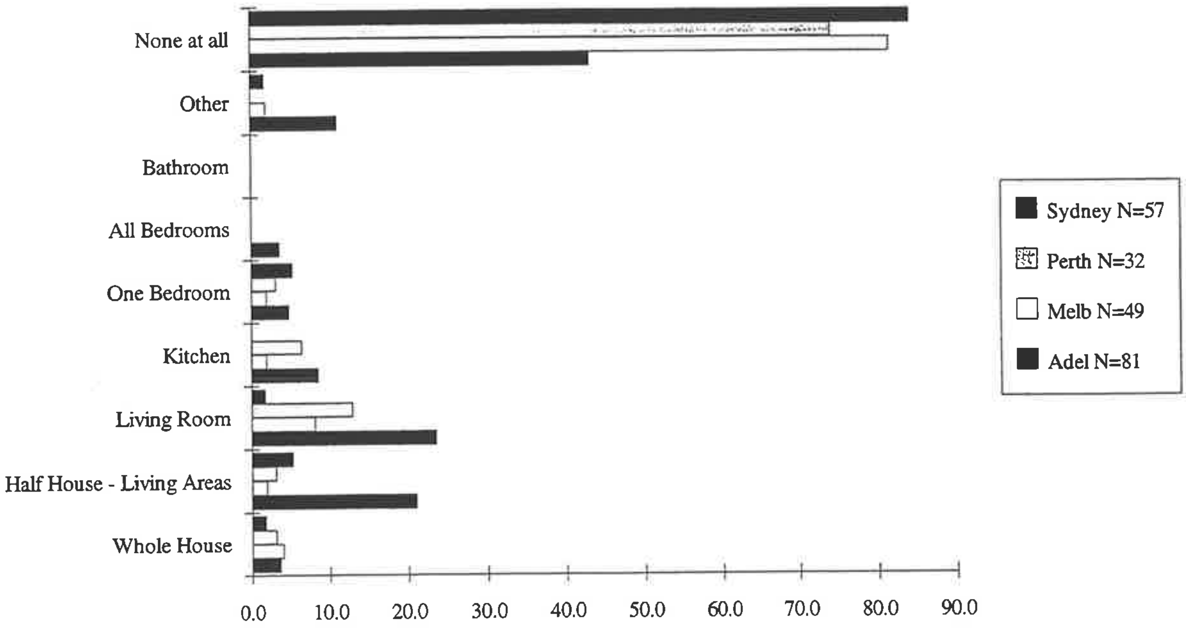

Figure 4.19: % of Responses
"At this time of the year (summer), which rooms in your house are cooled by an evaporative or refrigerative air-conditioner?"

4.8.3 Times of Heater and Cooler Use

For a sample of households in Tasmanian public housing, use patterns of the main heater ranged form "short periods of the day" and "special occasions" to use all day. The commonest use pattern was mornings and evenings (Coldicutt *et al.*, undated, p73).

In the NEEHA Project heating was mostly described in all locations as being used "evenings before bedtime" and where cooling was installed the use was mostly described as "in afternoons". Figs 4.20 & 4.21 show the full responses for the times of day and night when heating and cooling is usually used.

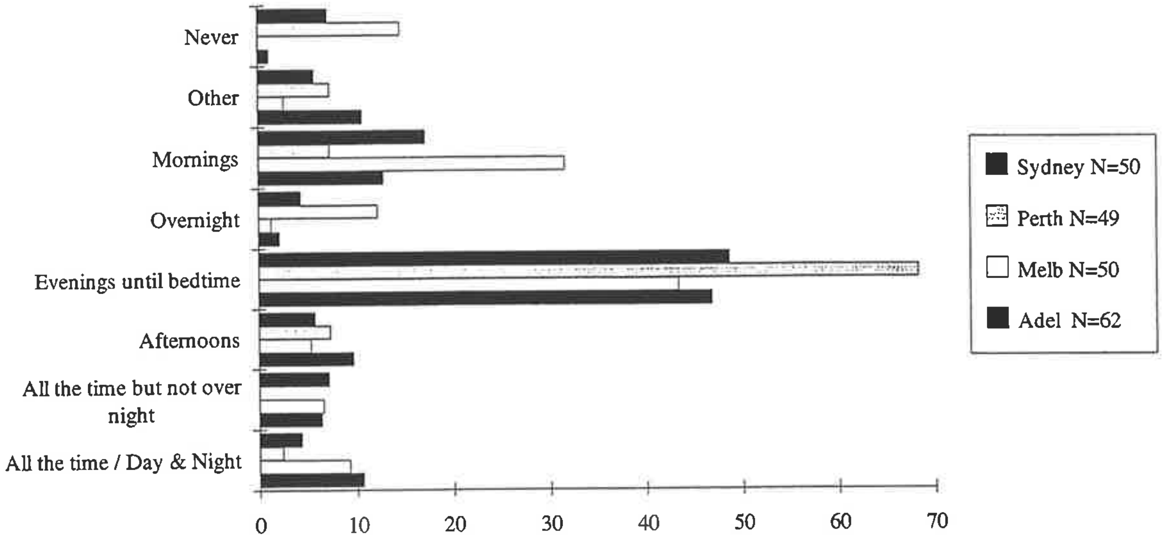

Figure 4.20: % of Responses
"At which of the following times of the day or night do you usually use heaters at this time of the year (winter)?"

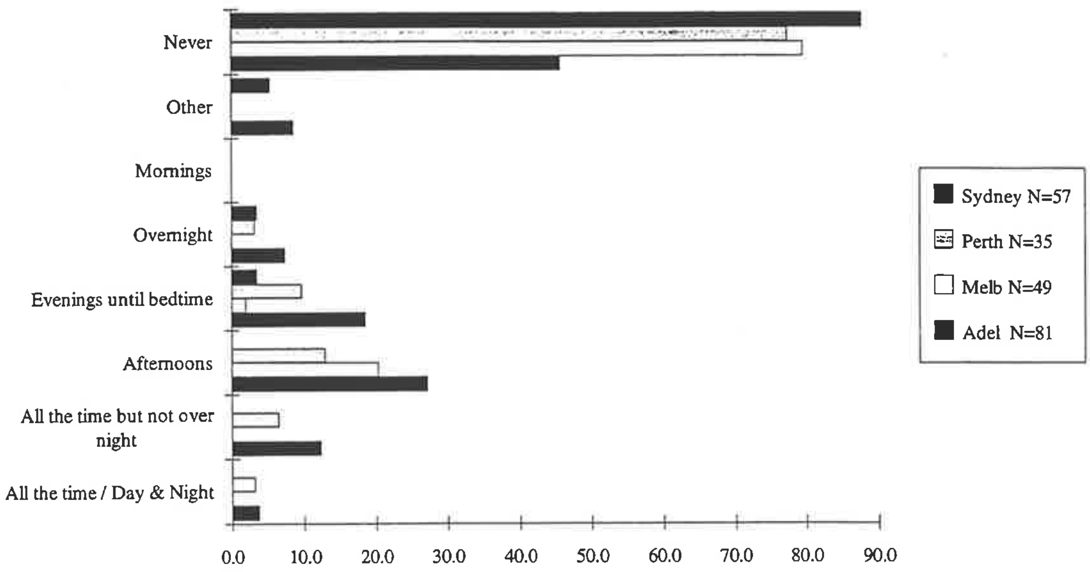

Figure 4.21: % of Responses
"At which of the following times of the day or night do you usually use *an air-conditioner at this time of the year (summer)?"*

The ETSA data shown in Appendix E indicate that for Adelaide, the majority of households use a heater over 20 days per month during winter with the most common period of operation being 1-3 hours during the daytime and 4-6 hours during the night time. Data for cooler operation during summer shows that the average usage is around 5-12 days per month, with use on an average day being less than 4 hours and on a hot day around 4-8 hours. Similar detailed data could not be obtained for other locations.

4.8.4 Thermostat Settings

The least adequate data on which to base computer simulation energy predictions are those concerning thermostat settings, as no comprehensive work has been conducted in Australia (or almost anywhere else) to determine thermostat settings used in practice by householders. The problem is complicated by the fact that most plants are manually operated and without proper thermostat control. A normal assumption for thermal performance design evaluation is that thermostat settings (or equivalent operating temperatures when appliances do not have a thermostat) correspond to some theoretical thermal comfort or thermal neutral condition. Such a condition may be derived from standards such as ISO 7730 (ISO-International Organization for Standardization, 1984). The work of Humphreys and Auliciems described above may also be used to allow for the context of the external climate in an attempt to account for peoples' apparent changes in preferred temperature as a function of external temperature. However, the spread of results about the central trend line shown in the analysis of the NEEHA Project data by Riordan (1992), presented in Figure 4.14 above, suggests a great variability in household use patterns around a central trend.

In a further examination of NEEHA Project data using a Probit regression technique as described by Ballantyne *et al.* (1977) and binning data by location and season, Riordan (1992) found that the "Neutral/Slightly Warm" and the "Slightly Cool/Neutral" 50th percentile thermal sensation vote transition temperatures[16] are related to the mean external temperature for the variety of climates and seasons studied. These results may be used to infer a thermostat-like setting at which people will initiate a cooling or heating event. We can derive from ISO7730 (p3, Table1) that a shift from a comfort condition of approximately a 0.5 vote interval will result in a 10% predicted percentage dissatisfied (PPD). Adopting this as an evaluation criteria, an internal temperature mid-point between the neutral temperature and the 50th percential "Neutral/Slightly Warm" could be regarded as a mean cooling commencement temperature. By the same logic, the mid-point between the neutral temperature and the 50th percentile "Slightly Cool/Neutral" temperature, could be regarded as a mean heating commencement temperature. A limitation to these notions is, however, clear from the results in the thermal sensation and preference cross tabulations presented above (Table 4.12), because people indicated that they sometimes wanted to be other than "neutral". A further limitation, of course, is that we do not know from any of this data what will happen after heating or cooling have commenced.

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[16] The 50th percentile thermal sensation vote transition temperatures correspond to the temperatures when 50% of people will have changed their vote from neutral to slightly warm or neutral to slightly cool.

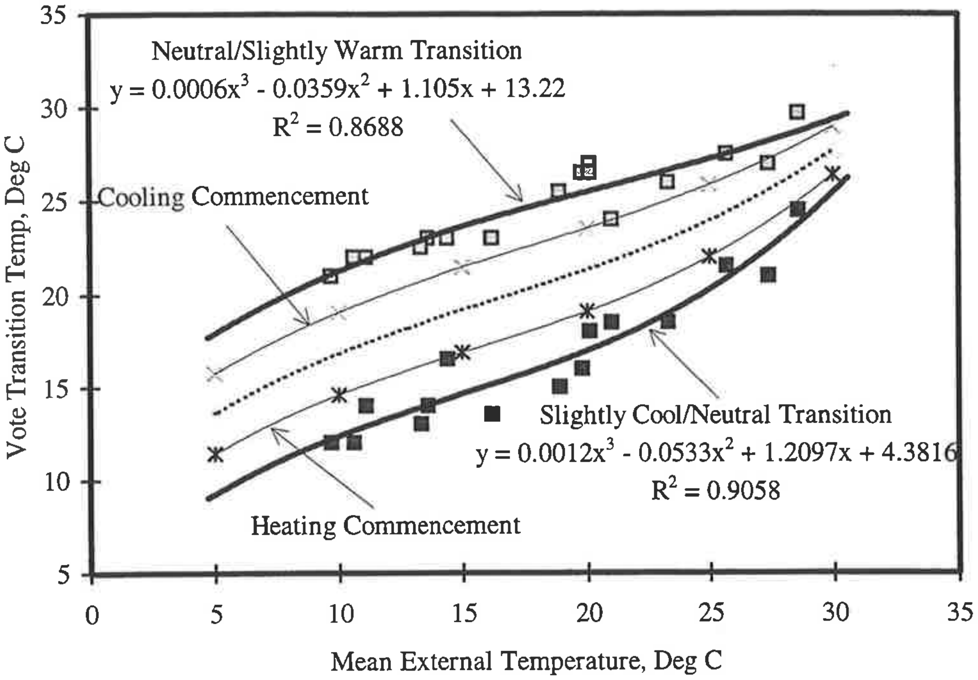

Figure 4.22: Thermal sensation 50th%ile vote transition temperatures vs mean external temperature from NEEHA Project.
Source: Riordan (1992)

Although the trendlines in Figure 4.22 are shown as cubic relationships, with sufficient accuracy the transition lines and heating/cooling initiation lines may be represented by linear equations with the *cooling initiation* line as,

$$T_{tc} = 0.50\,T_m + 13.6 \quad \ldots\ldots\ldots\ldots \quad \text{Equation 4.11}$$

and the *heating initiation* line as,

$$T_{th} = 0.57\,T_m + 8.5 \quad \ldots\ldots\ldots\ldots \quad \text{Equation 4.12}$$

A thermostat/behavioural model can be proposed as a logical expression,

if($T_i > T_{tc}$ then cooling and $T_i = T_n$)

else

if($T_i < T_{th}$ then heating and $T_i = T_n$)

4.9 Summary

Data obtained over the last ten to fifteen years has enhanced our knowledge of the scope of the problem of energy-efficient housing in the temperate regions of Australia. Our understanding of household and personal requirements with respect to factors such as thermal preferences, thermal comfort and household use patterns has improved. The focus of higher goals has changed with more emphasis now on environmental issues as opposed to energy reduction *per se*. Perceptions of the means of implementing energy-efficiency have also changed with differences in dwelling construction methods and practices. Thermal insulation (to ceilings at least) is now accepted not as an add-on extra but as a standard element in construction; concrete slab-on-ground has replaced suspended timber flooring as the most usual construction technique; more attention is given to providing shading around houses; and finally, the relative price of unit air-conditioning appliances and ceiling fans has fallen, with a corresponding increase in their penetration rates.

The data presented above demonstrates that there is a large variety of factors which influence the thermal performance, and therefore energy-efficiency, of a dwelling.

Because any design situation is contextual, detailed knowledge is required:

- to enable clear ordering of priorities
- to make trade-offs explicit, and
- to permit correct calibration of simulation models for testing design options

The issue of appropriate and reliable tools for design evaluation is the subject of the following Chapter.

Based on the data presented in this Chapter, Tables 4.14 and 4.15 set out four combinations of appliance type and household use patterns, in Adelaide and Melbourne, for both heating and cooling. Collectively this data is representative of the present situation in these cities and form the input data used in the computer simulations described in Chapter 7.

Table 4.15a: Recommendations for Thermal Modelling Household Use Patterns, Adelaide

Cooling	**Option C1**	**Option C2**	**Option C3**	**Option C4**
Type of Appliance Capacity/Output	*Fan* 5*60-100Watts	*Evaporative Cooler* *Effectiveness 75%* 300-1500Watts	*RC or Refrigerative Air-conditioner* ½-2½HP, COP ~2.6	*No cooling*
Hours of Operation Rooms of House	4pm - 11pm (living) 10pm - 4am (bedrooms) Whole house at times (see above)	12am - 23pm (living)am 11pm - 6am (bedrooms)	5pm - 11pm (living) 9pm - 2am (bedrooms)	
Thermostat settings	na	24^{O}C ±2 Adelaide	22^{O}C ±2 Adelaide	

Heating	**Option H1**	**Option H2**	**Option H3**	**Option H4**
Type of Appliance Capacity/Output	*Gas* Input 22-40MJ Efficiency 70-80%	*Electric Portable* 3*2.4kW	*Reverse cycle* *Air-conditioner* ½-2½HP, COP ~3.0	*Slow combustion* 4 -5 refuels/day
Hours of Operation Rooms of House	BV, BCu, BCi 7 - 9am & 5 - 11pm (living) 8 - 11pm (bedrooms) LW 7 - 12am & 3 - 11pm (living) 5 - 11pm (bedrooms)	BV, BCu, BCi 7 - 9am & 5 - 11pm (living) 8 - 11pm (bedrooms) LW 7 - 12am & 3 - 11pm (living) 5 - 11pm (bedrooms)	BV, BCu, BCi 7 - 9am & 5 - 11pm (living) 8 - 11pm (bedrooms) LW 7 - 12am & 3 - 11pm (living) 5 - 11pm (bedrooms)	Continuous Wholehouse
Thermostat settings	18^{O}C ±2	18^{O}C ±2	18^{O}C ±2	na

Table 4.15b: Recommendations for Thermal Modelling Household Use Patterns, Melbourne

Cooling	**Option C1**	**Option C2**	**Option C3**	**Option C4**
Type of Appliance Capacity/Output	*Fan* 5*60-100Watts	*Evaporative Cooler* *Effectiveness 75%* 300-1500Watts	*RC or Refrigerative Air-conditioner* ½-2½HP, COP ~2.6	*No cooling*
Hours of Operation Extent - Rooms of House	4pm - 11pm (living) 10pm - 4am (bedrooms) Whole house at times (see above)	12am - 11pm (living) 23pm - 6am (bedrooms)	5pm - 11pm (living) 9pm - 2am (bedrooms)	
Thermostat settings	na	24°C ±2 Melbourne	22°C ±2 Melbourne	

Heating	**Option H1**	**Option H2**	**Option H3**	**Option H4**
Type of Appliance Capacity/Output	*Gas* Input 22-40MJ Efficiency 70-80%	*Electric Portable* 3*2.4kW	*Reverse cycle* *Air-conditioner* ½-2½HP, COP ~3.0	*Slow combustion* 5-7 refuels/day
Hours of Operation Rooms of House	BV, Bcu, BCi 7 - 9am & 5 - 11pm (living) 8 - 11pm (bedrooms) LW 7 - 10am & 12am- 11pm (living) 7 - 11pm (bedrooms	BV, Bcu, BCi 7 - 9am & 5 - 11pm (living) 8 - 11pm (bedrooms) LW 7 - 10am & 12am- 11pm (living) 7 - 11pm (bedrooms	BV, Bcu, BCi 7 - 9am & 5 - 11pm (living) 8 - 11pm (bedrooms) LW 7 - 10am & 12am- 11pm (living) 7 - 11pm (bedrooms	Continuous Wholehouse
Thermostat settings	17°C ±2	17°C ±2	17°C ±2	na

CHAPTER 5
DESIGN EVALUATION

5.1 Introduction

Since the mid-1970's energy and thermal performance analysis computer programs have been employed for the quantitative evaluation of existing and proposed buildings. Earlier attempts at the thermal performance simulation of buildings were relatively crude. It was necessary to make many assumptions and to introduce many simplifications in order to make the problem manageable in terms of input requirements, computational capacity, and reasonable computer run times. Early programs operated on either estimated or very limited climatic data, especially radiation data. Although some checking was usually made between the program predictions and measurements in the field, comprehensive confirmation or validation was not really possible because of the immensity of such a task using more or less manual techniques for recording and manipulating the data. Program simplifications often rendered the simulation technique irrelevant to a particular design problem, for example, because of limitations in permissible geometric description of a building, or lack of reality in dealing with features such as shading. The older programs (and to a lesser extent present programs) were often irrelevant to on-the-job designers because of the time and knowledge required to provide the necessary input data.

Present thermal simulation models are based upon established computational techniques and incorporate features which allow reasonable representations of the realities of most of the thermal system. However, two areas not often adequately dealt with, even in some of the more advanced simulation tools, are the shading of the building surfaces and windows, and the heat flow through slab-on-ground and suspended floor constructions. Both these aspects have important implications for accurate simulation of buildings in temperate climate locations. In addition, while the descriptive power of these programs continues to be enhanced the problem of confirming their adequacy for particular uses remains a contentious issue.

The comparative analysis of dwelling designs carried out as part of this thesis (see Chapter 7) uses the thermal simulation program *EnCom2*. *EnCom2* is based on the same computational technique as an earlier well known Australian program TEMPAL[16]. Heat flow calculations through opaque elements in *EnCom2* uses the 'Advancing Mean Technique' developed by Alan Coldicutt (Coldicutt, 1976). An expanded description of the mathematical basis of this technique is given in Appendix B. For this thesis *EnCom2* has been improved in order to provide greater confidence in

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[16] The program TEMPAL was developed by A & B Coldicutt at the Department of Architecture and Building, The University of Melbourne.

the results. The enhancements include, better heat flow algorithms incorporating the most up-to-date estimates for external film coefficients, improved shading calculations, the provision of non-isotropic sky conditions and enhanced occupant models. This Chapter deals with some of the more important features introduced into *EnCom2* related to these issues, as well as measures to ensure the validity of the program results.

5.2 Shading

Even some of the most advanced thermal/energy simulation computer programs fail to treat in a comprehensive manner the effects of shading on the thermal performance of a building. In general shading may be caused by installed shading devices, self-shading by the building or the shading afforded by adjacent or distant objects such as other buildings or trees. Studies conducted to test the influence of shading on estimates of heating and cooling loads report significant sensitivity (see Pletzer, *et al.*, 1988; El-Refaie, 1987).

If shading is not treated comprehensively inaccuracies can be introduced, and restrictions imposed on the building analysis because of limitations of the shading algorithm incorporated into a program will mean incompleteness. With such shortcomings the usefulness of a simulation tool to a designer is reduced and may result in it being irrelevant.

The difficulty of dealing with the shading problem is highlighted in the following quotation,

> *"Rigorous calculations of the solar cooling load due to windows is difficult due to the ever-changing position of the sun and the resulting movement of the area where the sun's rays strike the interior surfaces of a space........When external shading devices are added, the problem is further complicated."* (McQuiston and Spitler, 1992, p8.5)

5.2.1 Background

Shading design-aids in various forms have been available to building designers since WWII. Some examples of these aids are detailed below.

Sun Path Diagrams

These show a planar projection of the sun's path for a particular latitude. The earliest publication employing this technique appears to be by R.O.Phillips in May 1948 at the Commonwealth Experimental Building Station in Sydney (Phillips, 1948). The preface to this document says,

> *"There is little doubt that architects, town-planners, and the public generally are becoming increasingly conscious of the need for designing buildings for sunlight, whether for maximum penetration in cold climates, or adequate shading for hot conditions. However desirable this may be, information available on the subject has not proved adequate for most designers to give it the attention which it deserves."*

Phillips provided stereographic projection sun path diagrams to cover the principal cities in Australia, New Zealand and New Guinea.

Other forms of projection have also been produced such as orthographic and equidistant projections (Olgyay and Olgyay, 1963; Markus and Morris, 1980). Used in conjunction with shadow angle protractors these enable the calculation of shading and shadow patterns. Overlays are also available which, used in conjunction with these sun path diagrams, allow an estimate at each hour of the incident solar irradiance (direct, diffuse and ground reflected), for clear sky conditions on surfaces of different orientations and slopes (see for example, Markus and Morris, 1980). Etzion (1991) has developed a technique based on these charts which enables the rapid estimation of the proportion of a window or surface shaded by horizontal or vertical projection.

Shadow path, 'flagpole' or sun-dial diagrams.

These are similar in operation to the sun path diagrams described above. The shadow of a gnomon of known height is constructed on a horizontal plane thus enabling the shadowing of any object to be estimated (Pilkington Environment Advisory Service, 1969). In conjunction with these shadow path diagrams, techniques are also available for estimating hourly solar heat loads for a defined sky condition (Coldicutt *et al.*, 1977).

Tabulated/graphical radiation values

ASHRAE developed tables of clear sky hourly solar heat gain values for eight degree intervals of latitude, seventeen different window orientations and for each month of the year. Shading coefficients provide a correction to these values for the actual glazing system and facade designs (ASHRAE, 1989). In Australia, Spencer developed a comprehensive set of Solar Tables for the capital cities which give solar heat gains through windows under clear sky conditions. The effect of horizontal sunbreaks for radiation received on a vertical surface is also shown in the tables (Spencer, 1974).

Each of these techniques is based on manual application and generally applies to relatively simple sun-shading devices such as horizontal or vertical projections from the building. They deal, with some exceptions, only with shading of the direct component of solar radiation.

A computer estimation of shading has the potential to be comprehensive and capable of incorporating any possible configuration of obstruction (opaque and partly transmitting) to solar radiation, handle direct, sky and reflected components and should not have limitations in respect to geometry, orientation or latitude.

5.2.2 Computer Calculation Methods

Several methods for estimating the effects of shading for building energy performance and load calculations by computer can be found in the literature. An early paper by Ballantyne and Spencer (1969) sets out a method for estimating the effects of horizontal sun breaks of infinite length considering direct, diffuse and reflected radiation components. The method outlined in this paper formed the basis for shading calculations use in the production of the Spencer Tables (Spencer, 1974) and was also incorporated into CSIRO thermal calculation programs (Z)STEP and TEMPER[17]. Delsante and Spencer (1994) have recently provided improvements and extensions to these formulations to deal with finite projections and have incorporated them into the CHEETAH[18] program.

McCluney (1990) has provided a brief background to computer shading calculations and presents a technique for dealing with horizontal awnings. This technique has now been incorporated into a program AWNSHADE (McCluney, 1995).

5.2.3 Shading Calculation with Ray-tracing

All the techniques discussed above have limitations in terms of building and shading device configuration and geometry. Given the importance of shading considerations to simulation accuracy, a general method for estimating the influence of shading on both the opaque and diathermic portions of the exterior surfaces of a building has been developed by the author. The method can take into account building surfaces of any slope and azimuth and all configurations of obstructions. It accounts for total solar radiation (direct, diffuse and reflected components) which reaches a building surface or which may be transmitted through a window.

The approach involves a ray-tracing type technique. A wall or window is divided into a grid and rays emanate from these grid points. The grid coarseness can be altered to suite particular applications. Obstructions are described as planar polygons defined by Cartesian coordinates. Simplified input descriptions are provided for "standard" horizontal and vertical shading devices.

A ray from a grid point intercepts an obstruction, and is therefore "shaded", when the point of intersection between the ray and the plane falls within this polygon. A Monte Carlo technique is employed to reduce the computation time. Direct solar beam rays are calculated at given time intervals. View factors are estimated for the sky, ground and obstructions. The Perez model for a non-isotropic sky is incorporated into the diffuse irradiance calculations (Perez, 1987). The partial transmission of solar radiation through obstructions (eg. trees, shade cloth etc.) can be calculated.

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[17] See Chapter 2 for description of these programs.

[18] CHEETAH from CSIRO, DBR is a user friendly program with the ZSTEP computational engine.

Reflections from obstructions are taken into account as well as partial shading of the ground caused by the building itself or by the obstructions. The mathematical basis for the technique is given in Appendix B.

A computer program *Shading* has been written which utilises this method. At each hour the program calculates direct radiation shading factors together with view factors for the sky, obstructions and the ground. The results are used as input to the modified *EnCom2* program. *Shading* may also be used as a stand alone tool to provide information to designers on the effectiveness of shading devices.

5.3 Ground Heat Flow Through Concrete Slab-on-Ground

Heat flow to the ground is one of the more contentious issues in thermal performance modelling. A possible error in the TEMPAL program ground heat flow model was first raised in a report by the Gas and Fuel Corporation of Victoria & Sustainable Solutions (1992). This report detailed a study comparing heating and cooling load estimates from the programs CHEETAH and TEMPAL. They reported a good match in all cases except those involving slab-on-ground construction, the errors probably being caused by incorrect asumptions regarding the 1m depth ground temperature. Because a substantial portion of houses in Australia are constructed using the slab-on-ground technique it is important to ensure that the algorithms are providing credible results. The following describes the 'new' ground temperature model embedded in the *EnCom2* program.

5.3.1 Estimating the Ground Temperature

The model of heat flow in a concrete slab-on-ground adopted in *EnCom2* uses the "Advancing Mean"algorithm and divides the slab area into two components: a core, or central section, and the slab edge section. Heat flow from the core is calculated to a sink taken at a depth of 1m below the bottom of the slab. Heat flow from the edge is assumed to flow partly to the earth and partly to the external surface at air temperature.

Estimating the temperature at the 1m depth is critical for application of the method yet little is known experimentally of the likely values. The following outlines the modified *EnCom2* ground temperature calculation procedures.

T_{g_t}, the ground temperature at a depth of 1m, may be estimated from,

$$T_{g_t} = \overline{T}_{g_t} + \widetilde{T}_{g_t} \quad \text{.........} \quad \text{Equation 5.1}$$

Where $\overline{T}_{g_t}$ is the annual mean temperature and $\tilde{T}_{g_t}$ is the annual harmonic temperature swing (ie the temperature variation from the mean).

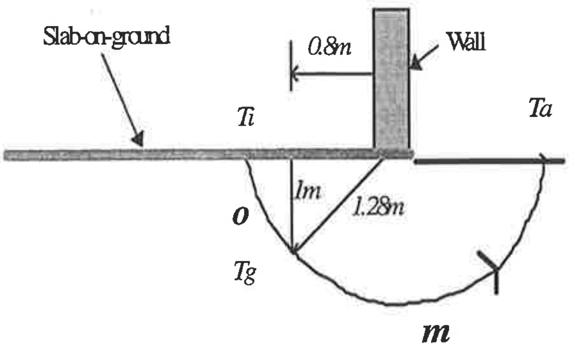

Figure 5.1: Assumed Heat Flow Geometry Under Slab
Note: subscript o refers to core section of path and m the edge section.

Temperature transition from T_i, the internal temperature to T_a, the external air temperature is assumed to take place on a heat flow path described by the locus of a semi-circle of path length ~4.0m, corresponding to a radius of 1.28m. This semi-circle is constructed by making the assumption that the isotherm at a depth of 1m is parallel to the underside of the slab until a point approximately 1m from the external face of the wall. This assumption is derived from an examination of detailed heat flow measurements taken of a series of slab-on-ground installations (Bareither *et al.*, 1948).

$\overline{T}_{g_t}$ and $\tilde{T}_{g_t}$ are calculated following the method suggested by Delsante (1990). The mean temperature component is derived from,

$$\overline{T}_{g_t} = \frac{U_o \overline{T}_{i_t} + U_m \overline{T}_{a_t}}{U_o + U_m} \quad \text{............} \quad \text{Equation 5.2}$$

where $\overline{T}_{a_t} = \sum_{a=1}^{12} T'_{a_t} \big/ 12$ and $\overline{T}_{i_t} = \sum_{i=1}^{12} T'_{i_t} \big/ 12$; T'_{a_t} and T'_{i_t} are the mean monthly external and internal temperatures respectively.

The harmonic temperature component is derived from,

$$\tilde{T}_{g_t} = \frac{\Gamma_o \tilde{T}_{i_t} + \Gamma_m \tilde{T}_{a_t}}{Y_o + Y_m} \quad \text{.............} \quad \text{Equation 5.3}$$

where $\tilde{T}_{a_t} = T'_{a_t} - \bar{T}_{a_t}$ and $\tilde{T}_{i_t} = T'_{i_t} - \bar{T}_{i_t}$

5.3.2 Verification of Ground Temperature Model

Measurements taken by Spooner and quoted in Delsante (1990) offer the opportunity to verify the ground temperature model. Spooner provides measurements over a 24 month period for external and internal temperatures and the temperature at 1m depth for a building with an insulated concrete slab-on-ground floor. Using information on the thermal properties of the ground given in Delsante, the following annual harmonic transfer functions have been derived.

Table 5.1: Annual Harmonic Transfer Functions

Component	**U-value**	**Transfer Modulus** Γ	**Lag (days)**	**Internal Admittance** Y	**Lead (days)**
Core insulation, concrete slab, and 1m soil ρ=2100 kg/m3 * k=1.4 c=810	0.31	0.29	34.1	0.62	4 6.3
Edge of slab, path length 2.9m	0.47	0.46	20.3	0.61	32.6

Note: * Assumed values only, actual values not measured. The transfer functions are calculated using a computer program HEATRANT developed by the author.

Figure 5.2 shows the measured external, internal and 1m depth ground temperatures compared with the estimated ground temperature. The mean error in this case is 0.62°C.

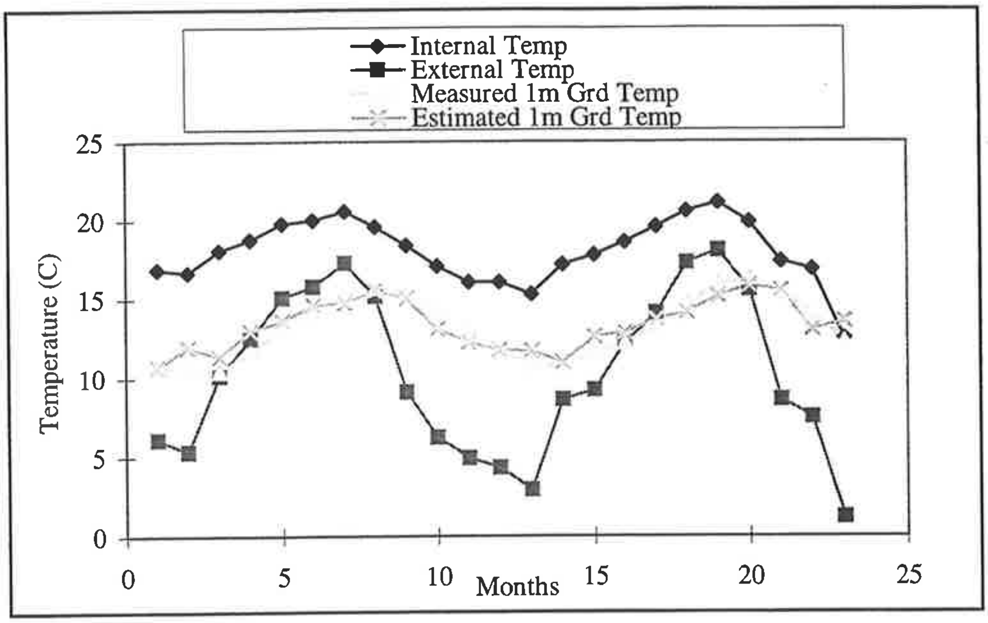

Figure 5.2: Estimated 1m Ground Temperature vs Measured Values
Note: Measured values derived from Spooner and given in Delsante (1990).

The result gives some confidence that the proposed ground temperature model is sufficient to provide reasonable estimates of the 1m deep ground temperature. This model has been incorporated into the *EnCom2* program.

5.4 Validation of Thermal Performance Computer Programs

The purpose in conducting a thermal analysis of a building using a computer program is to predict some aspect of a building's thermal sub-system in order to provide information for decision-making. These programs are based on models which may be considered as representations of part of a building's performance. Models may be defined as a construction of relationships and interdependencies of theories concerning real world processes. Models may be physical, mathematical or conceptual. More specifically, a computer simulation model involves the use of a computer-based numerical technique to relate variables and parameters. The variables may be exogenous variables which are independent (eg. external dry bulb temperature supplied as input data, input related to building users such as heat loads, plant use etc.) or endogenous variables which depend on the model (eg. surface conductance). Parameters are quantities described by input data which influence the determination of the endogenous variables within the model (eg glass transmission properties).

Ideally, any model used for reliable decision-making would accurately represent the real system. The very nature of models generally means however that many aspects of reality that in fact affect behaviour have been excluded because they have been deemed by the model builder to be unimportant. Validation is seen as being concerned with examining the correspondence between reality (or at least a sub-system of reality) and the model predictions.

Various philosophical positions and methodological techniques have been proposed towards the issue of computer model validation. Thirty years ago Naylor and Finger (1967) stated that,

> *"..the reason for avoiding the subject of verification stems from the fact that the problem of verifying or validating computer models remains today the most elusive of all the unresolved methodological problems associated with computer simulation techniques."*

This problem still exists despite numerous studies to develop appropriate methodologies.

In a formative work Judkoff *et al.* (1983) discuss three methodological approaches which may be applied to the validation of building thermal analysis programs. These are;

(a) comparative studies, involving the direct comparison of an analysis of the same cases by different programs,

(b) analytical verification, in which simple test cases are defined to examine the behaviour of particular components of a program, eg. heat-transfer mechanisms.

(c) empirical validation, where a real building or test cell is monitored and the calculated results compared to the measured results.

Earlier attempts to standardise validation techniques centred around two of these techniques, empirical validation (Judkoff *et al.*, 1983; Bloomfield, 1985; Eppel *et al.*, 1993) and intermodal comparison (Judkoff & Neymark, 1993). Using empirical validation the output of a simulation program is compared with the results of measured data from real (or simplified) buildings. Intermodal validation involves the comparison of the results of one program with the output from one or more other programs. Lomas (1994) provided a good summary of the state-of-the-art of thermal performance simulation validation in the mid-1990's.

Despite the advances in validation methodology, inadequacies can still be identified with the suggested techniques such as:

a) No attempt is made to take into account the severity of the validation test, that is, how different the variable being validated (for example, internal temperature) might be from the variables providing input to the model. (A single input variable, for example external temperature, may be a better predictor than the model).

b) None of the tests give a single measure of the success (or otherwise) of the test and it is left largely to the judgement of the validator to determine adequacy or otherwise.

c) Isolation of sources of error remains a difficulty, although the BESTEST (Judkoff and Neymark, 1993) procedure provides some assistance in this area.

d) Tests cannot be used easily for internal validation and/or algorithm "tuning".

e) Several key building elements (for example, concrete slab-on-ground) and climate effects (for example, shading) are not adequately tested by any of the standard validation procedures.

f) Little data relates to free-running situations, which is the normal condition in temperate climates.

Williamson (1995, presented in full as Appendix B3) outlines a technique which overcomes these inadequacies and which can be employed as part of an empirical validation methodology to establish the accuracy of simulation predictions. The technique, termed the *Confirmation Technique*, is particularly suited to evaluation under free-running or intermittent heating/cooling conditions.

Evidence presented in this paper (an overall *Degree of Confirmation D′* = 0.87 and the evidence from Figure 5.1) provides assurance that the *EnCom2* program is sufficiently accurate for design decision making.

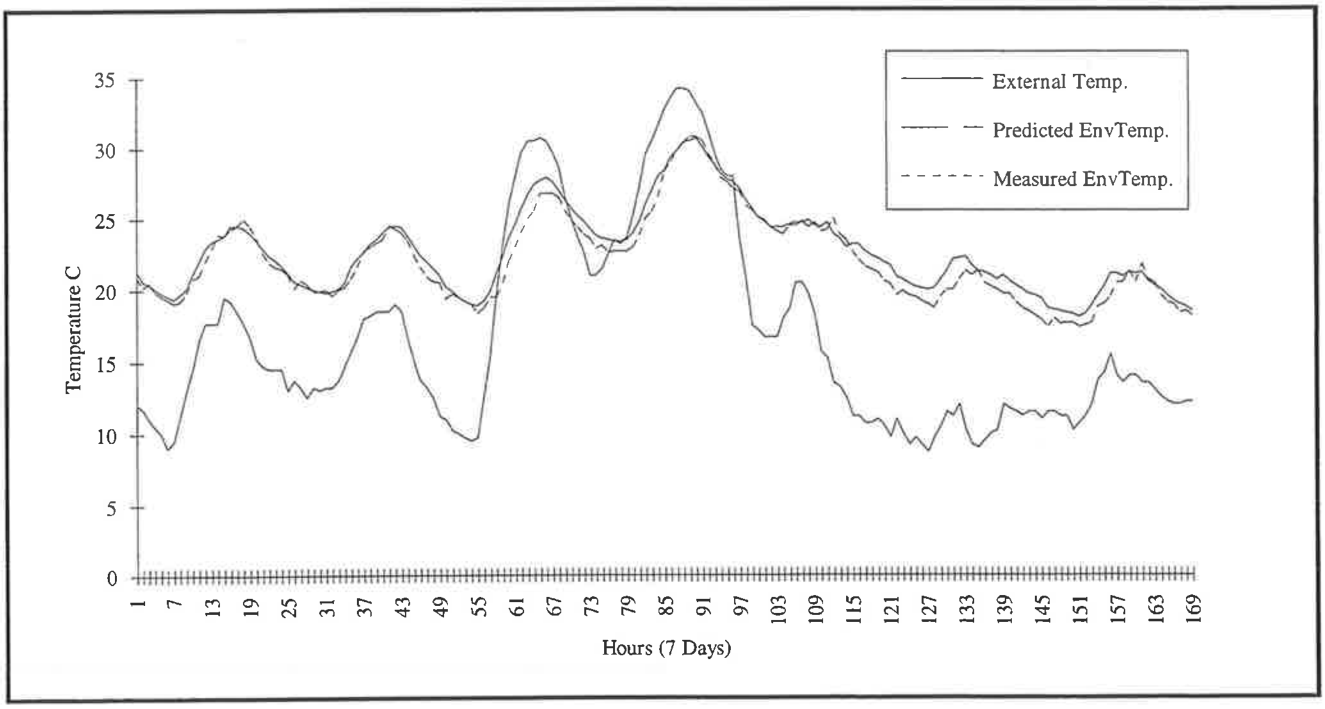

Figure 5.3: Comparison of Measured and *Encom2* Predicted Environmental Temperatures[19]

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[19] The data used in this validation exercise were derived by the author from monitoring external climate and internal conditions (environmental temperatures and Wet Bulb temperatures) at the CSIRO, Low Energy Consumption House (LECH), Highett, Melbourne between August to November 1988. The 7 days used for the validation relates to a free-running period. The working drawings which showed the detailed construction of the building elements of the LECH were obtained from the CSIRO. The thermal properties of building elements used in the simulations were taken from Coldicutt (1989). The rockbed floor storage system of the LECH was not operating during

5.5 Summary

This Chapter has dealt with several aspects of thermal performance simulation aimed at reducing uncertainty and inaccuracy in the numerical calculation process. The shading calculation technique with ray-tracing enables the full range of shading devices and obstructions to be considered; and a proposed ground temperature model shows a good match to measured values. Both measures have been incorporated into the simulation program *Encom2*. Empirical validation of this program using the *Confirmation Technique* gives confidence in the simulation results, especially for essentially free-running buildings. This work establishes *EnCom2* as an appropriate tool for simulations addressing the hypothesis of this thesis.

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these tests and was modelled as a simple concrete slab-on -ground element. The temperature measurements at the bottom of the rockbed were considered to be the ground temperature. Ventilation measurements were not included in the data gathered during these tests. Comprehensive measurements of the whole LECH house air change rates by the tracer gas decay technique were conducted over a number of years by the CSIRO. The *EnCom2* ventilation input parameters were derived from this data. Although zoned operation is assumed for the simulations the errors introduced are thought to be small.

CHAPTER 6
(RE)FRAMING THE ISSUES

6.1 Introduction

When an attempt is made to communicate some message, the way in which it is said, what is chosen to be included or excluded, intentionally and unintentionally, considered and unconsidered, and the assumptions, both explicit and implicit, all influence the perception of the message by those for whom it is intended. If a message is interpreted without taking full cognisance of underlying assumptions then it can be assumed that there is a failure to communicate.

This Chapter presents a rationale for assessing the nature, use and appropriateness of knowledge used in the design process. The notion of an ignorance-based design approach is introduced[18]. This approach, based on a taxonomy of ignorance suggested by Smithson (1988), allows an assessment of knowledge applicable to a design situation in a context of uncertainty, where the problem definition and available information may be vague, probabilistic, incomplete, ambiguous, unreliable, non-specific or absent. The approach makes a useful distinction between knowledge which is irrelevant to a particular design situation and knowledge which is in error. Recognising people's limited knowledge about building design the concept aims at improving the appropriateness of information made available to designers and others. Although this discussion is centred on the notion of energy-efficient housing, the wider concern is with the nature of applicable knowledge in building science, and especially with the limits of applicability of those branches of knowledge which emphasise limiting inaccuracy and uncertainty.

The content and interpretations of the 1974 Williamson & Coldicutt paper are discussed to illustrate an ignorance-based analysis.

6.2 Defining the problem: design requirements, means and contexts

The purposeful nature of building design can be considered in terms of the ends of all the various people involved and the means by which these requirements can and should be addressed. Ends may be considered as states or processes experienced by humans. Few of these can meaningfully be described as states or processes which buildings *must* necessarily provide for humans. Required

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[18] This Chapter is an adaptation of a paper by Coldicutt, S. and Williamson, T.J. (1991) *An Ignorance-Based Approach To Fenestration And Shading Design*. The original adaptation of the Ignorance-based Approach to a consideration of design information by Susan Coldicutt is acknowledged. Subsequent papers Coldicutt, 1992 and Coldicutt and Williamson, 1993 have been published.

states or processes, which can be designated as design requirements, must therefore be understood in a relative and contextual sense. Design requirements may include broad goals of the various stakeholders involved in the overall processes of providing housing, down to the individual requirements of a householder related to the design of a specific house. Requirements can also be expressed as a composite description of a desired outcome; "energy-efficient housing" is an example. A contextual approach becomes even more necessary when the requirements are combined in such a manner.

Design means are concerned with the way by which the design requirements are realised in the material world. They can include, but are not limited to, *mechanism-means* which cause or allow an action to achieve some requirement (for example, air movement and sun penetration into a space) *object-means* (materials, components and the like) and *assessment-means* for anticipating the outcomes of design decisions (manual design aids, computer simulation).

In conceptualising the problem it must be recognised that the design requirements and design means can only be understood in relation to each other.

Mechanisms do not *act* without the involvement of an agent (for example, heat, or the force of gravity), objects do not *perform* unless subjected to some process (for example, the effects of sunlight), and neither do they *function* except in relation to the requirements of some subject, be it animate or inanimate. Likewise requirements cannot be understood as pure abstraction, as they gain their meaning by interpretation of the consequences in relation to a completed and functioning design: for example, a requirement such as thermal comfort can be understood only in the context of particular subjects and the design means by which it might be achieved, or fail to be achieved (for example, clothing, an open window). Assessment methods and techniques to *evaluate* design proposals can be misleading and even dangerous unless they relate to the particular physical and societal context of the problem; imagine calculating the effects of wind loading on a building using incorrect terrain assumptions, or estimating CO_2 emissions for household heating based on burning gas as a fuel, when electricity from a coal fired power station is the main energy source in an area.

A lack of awareness of the essential inter-relatedness of design requirements and the design means in issues such as thermal comfort, allows misleading concepts to flourish. An example is the idea that preferred internal conditions can be determined without consideration of the social and economic context. The largely unsuccessful promotion of energy-efficient housing in Australia shows how a prescriptive approach on its own will not work and must be accompanied by consideration of householder goals or needs.

An essential step to improving the implementation of energy-efficient housing is to improve knowledge available to decision-makers. To be successful this must be based on an understanding of their inherent requirements and the means for achieving them.

Such ventures do not start with a blank slate. Intentional subjects (decision-makers, designers and others) who act in a context, and who have some attitudes, beliefs, knowledge and understanding about the problem and the context can be assumed. In general it can also be assumed that passive subjects (the householders, users, the community and others) exist who will be affected in some way by the design.

A realistic starting point for improving knowledge is to assume that each problem is unique. This assumption marks a clear distinction between design problems and many other sorts of problems, such as that of gaining scientific information about the sun. While it may be that some design problems are very similar to each other in all respects (requirements, means, subjects, and contexts) at the very least each is unique in space and time, and in requiring a unique decision. Such an assumption forces a clear recognition that generic solutions and prototypes are most likely sub-sets of a range of possibilities.

The implications which follow are that on the one hand, it is necessary to address particular decision-maker's requirements, means and contexts in such a way that they are applicable to unique design problems, and on the other hand, it is necessary to be able to identify and address common issues which occur, say, in particular contexts. Since, however, contexts are indefinitely broad and indefinitely multi-dimensional, and designers bring indefinitely broad and multi-dimensional understandings to bear on these unique problems, there is a need to find some simplifying assumptions or techniques. To start with, key aspects of the contexts of designs can be acknowledged. At the very least, this entails, for our society in Australia:

- acceptance of the existence of the current organisational structures within which buildings are produced, and the roles of various decision-makers within these;
- acceptance of "market forces" as an existing powerful means of deciding how to allocate the limited resources which are used in and for buildings;
- acceptance of the existence within our culture of an understanding that a dwelling is potentially a highly meaningful object.

The acceptance of the existence of these current situations does not mean that those involved cannot or should not seek to change them, but rather that they are acknowledged as a starting point.

Finally, in dealing with the design means for addressing problems, it can be accepted that the range will be limited to those which would be considered as commonly adopted.

6.3 Requirements and means for energy-efficient housing

Since a unique set of requirements may be relevant to each design problem, and these requirements establish the criteria by which solutions will be assessed, it is useful to look at the scope of design requirements which might be relevant to energy-efficient housing design. In doing so it will be inevitably found that, to some extent, it is necessary to use concepts which can also be referred to as means; so it is a matter of emphasising the requirements here. Means will be addressed more specifically later.

Acceptance of the existence of market forces and of the culturally-based meaningfulness of, for example, fenestration and shading devices implies a number of requirements. Among others, the end *efficiency* underlies the acceptance of market forces: it is implied that the material and other input to the fenestration and shading should be used to give as high an 'output' as possible, where that output is the satisfaction of the various requirements which are sought to be addressed. The culturally-based meaningfulness of fenestration and shading implies addressing some requirements which can only be understood as culturally-based: they must be interpreted in relation to the particular, ever-changing, cultural and historical context.

The design requirements which receive almost exclusive attention in relation to energy-efficient housing are, thermal comfort and operational energy conservation.

The following table however, illustrates the potentially broad scope of goals and requirements which may relate to both the process and the product of achieving energy-efficiency in housing[7]

HIGHER GOALS

Environmental Protection
- greenhouse gas emission

Social Justice
- access to housing
- household expenditure
- appropriate interventions
- access to resources

Broad Economic Issues
- economic sustainability
- balance of payments
- public expenditure

Urban Quality
- solar access
- development density

Altruistic
- save non-renewable resources

PROCESS RELATED GOALS

Market Issues
- sharing information and technologies
- effective policies and management strategies
- development of interventions
- financial viability

Human Issues
- involvement of players and stakeholders
- comprehension
- appropriate technologies
- life-style preferences
- cost

PRODUCT RELATED REQUIREMENTS

Energy Issues

- end-use efficiency
- energy conservation
- load management
- interfuel substitution

Human Issues
- thermal comfort
- health/safety
- thermal preferences
- cost-effectiveness

Many of the goals and requirements when considered together may be in conflict, for example:

- achieving operational energy conservation may not achieve a reduction in greenhouse gas emissions,
- insisting on strict thermal comfort requirements may not match a requirement for cost-effectiveness,
- ensuring solar access may mean high development densities are not possible,
- satisfying certain life-style preferences, say for high security windows, may mean air-conditioning is necessary to meet thermal comfort requirements, thereby not achieving a requirement for energy conservation,
- issues such as overlooking, privacy and the appearance of a building may limit possible design solutions and limit fulfilment of achieving energy-efficiency.

This begins to show the complexity of the goals and requirements involved. It is only in relation to a particular design problem that any of these goals and requirements can be deemed to be irrelevant or unimportant, and thereby the scope of the problem reduced.

Since many of the goals and requirements are concrete in nature, undertaking some form of computational prediction is the only way to ensure that they are likely to be satisfied. Therefore those requirements which are amenable to numerical prediction should be understood in some detail. Many of these are however somewhat abstract in nature. For example, people's requirements for heating and cooling can in many circumstances be seen generally as centring around 'comfort' or 'neutrality', but a wide range of environmental conditions are accepted in various contexts; people do not require thermal neutrality for every minute of their lives. It is also known that the requirements for heating and cooling can vary greatly with context, the social and economic situation, and are influenced to a greater or lesser extent by adaptation. To specify acceptable limits for predictions it is necessary to take all these influences, and more, into account.

Examination of both mechanism-means and object-means leads to a similar conclusion. Although it is possible to describe various attributes of the many *mechanism-means* and *object-means* which may be relevant (for example, heat and mass flow processes, building materials, heating and cooling equipment, furnishings and many more, in their many and various forms and in addition the technological advances and innovations which may be possible), these in most ways are context-specific and open in scope.

If these are to be narrowed down, there is a need to do so in a way which is relevant to the particular design problem. Since total familiarity with each particular design problem is not possible, then it is difficult to know how to narrow down and simplify the requirements and means. In order to chart paths through the enormous scope of potentially relevant knowledge, it is useful to examine the obscure border-region between knowledge and ignorance.

6.4 Ignorance

Smithson defines ignorance as follows:

> *"A working definition of ignorance ... is ... 'A is ignorant from B's point of view if A fails to agree with or show awareness of ideas which B defines as actually or potentially valid'" (Smithson, 1988).*

This definition draws attention to the importance of point of view, a concept which helps us to relate ignorance to a design problem and to the purposefulness of designers, occupants, and other stakeholders. In this definition A could be a designer while B could be any of the stakeholders in the provision of energy-efficient housing (users, builders, finance lending institutions, society, energy supply authorities, etc).

To Smithson's definition a further aspect can be added,

"A (a designer) is ignorant from B's (the provider of information) point of view if A fails to show awareness *of limitations* of ideas which B defines as actually or potentially applying"

Ignorance can be divided into two main types - ignorance-in-kind, and ignorance-in-degree, as is shown Figure 6.1 below.

Ignorance can be further divided into error and irrelevance, where irrelevance is 'a declaration of irrelevance' (Smithson, 1988, p7) and error is 'an erroneous cognitive state' (Smithson, 1988, p7). Error can be further subdivided into distortion and incompleteness, giving the four types of ignorance shown at the bottom of the diagram:

- *confusion* (distortion, an error in kind)
- *absence* (incompleteness, an error in kind)
- *inaccuracy* (distortion, an error in degree)
- *uncertainty* (incompleteness, an error in degree)

These, plus *irrelevance*, are the types of ignorance that are important to consider in relation to energy-efficient housing. In this context irrelevance can be either in kind or in degree. Ignorance can apply to content, such as information, and to processes, such as methods of calculation.

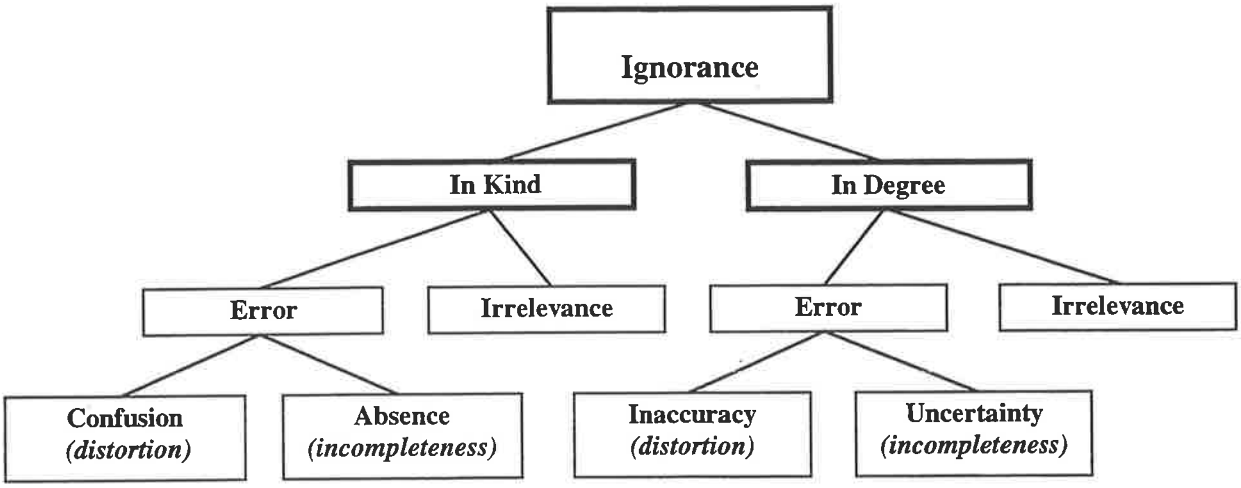

Figure 6.1: A Taxonomy of Ignorance

6.4.1 Ignorance-in-Kind

In applying knowledge in design, the priority given to issues has to do with the scope and nature of the design problem flowing from the goals and requirements. It is in connection with this that ignorance-in-kind needs to be considered. An inappropriate definition of the design problem is either an error in kind, involving either confused definitions of the problem or absence of inclusion of key aspects, or it is an irrelevance in kind (or lack of relevance), involving the declaration by one person of processes or content to be irrelevant to the problem, when some other concerned person holds them to be relevant. If ignorance-in-kind is not addressed adequately it is likely that solutions to the design problem as understood will be incidental to the *actual* design problem.

Ignorance-in-kind can be minimised by any approach which tests the scope of the problem, with the aim of first showing all kinds of possible goals, requirements and means, so that the problem as first understood can then be re-defined to address the actual design problem. Since designers can never know that they have discovered the actual design problem, this attempt to minimise ignorance-in-kind will be an exploratory, perhaps inspired, but also a pragmatic process, in which experience, hermeneutic reflection (Gadamer, 1977), and creative approaches, involving, if possible, a range of people concerned with the problem, contribute to an expanded and deeper understanding of the design problem. Out of this process an adequate interpretation of the design problem can emerge, as constrained by the pragmatic situation, such as limited time (for examples and discussion see Brookfield, 1987; Schon, 1983).

Since this process must relate to the specific design problem it cannot be undertaken out of context. The best that can be hoped for is that generic design problems be addressed in ways that are useful to the on-the-job designers. Requirements and means can be suggested for consideration, as well as the provision of detailed information about relationships between requirements, related criteria and means. Attempts can also be made to dispel misconceptions, but in doing so care must be taken not to constrain the on-the-job designer's interpretation of the unique, context-specific building design problem. In practice, many aspects of problem-definition about buildings are made in regulations which aim to safeguard, among other things, the health and safety of building occupants. Regulations and non-mandatory design standards and codes of practice help to reduce problem definition. This to some extent removes the problem definition task from the particular design decision-maker, but it also removes the theoretical question of whether these regulations are an appropriate means of achieving societies' requirements.

Because an unknowable large range and variety of requirements and means may be relevant to a particular design situation, ignorance-in-kind should not be built into any information that is provided.

6.4.2 Ignorance-in-Degree

Having examined ignorance-in-kind to see if they are addressing the right problem, designers can seek to minimise ignorance-in-degree. To do this it necessary for the content of requirements and means to be expressed by some form of unambiguous scale of measurement. Three levels of categorisation are possible, and their order of preference is:

- a ratio/interval (or absolute numerical) scale. A ratio scale tells us that one unit has so many times as much of a property as does another unit. An interval scale tells us that one unit differs by a certain amount of the property from another unit. A house in which 40GJ of energy is used for heating can be said to use twice as much energy as one in which 20GJ is used. Cost in dollars is another example of a ratio scale. Temperature in degrees centigrade, however, is an interval scale. A temperature of 40°C is not twice as hot as a temperature of 20°C. A statistical description of limits of acceptability (for example, a given temperature should not be exceeded on more than 5% of time) is an expression in a ratio scale.
- an ordinal scale, which tells us that one unit has more of a property than another, for example, a 4 Star Energy Rating for an appliance implies it is better than one with 3 stars.
- failing these, it would be useful to have at least some sort of nominal classification which tells us what class a unit would fall into if designers are to talk meaningfully about ignorance-in-degree. The classification of an environment as comfortable-4, slightly uncomfortable-5, etc., is an example of the use of an ordinal scale.

If the ends or means that are sought to be addressed do not even lend themselves to unambiguous categorisation, it is difficult or impossible to minimise ignorance-in-degree since there will be no way of describing it. Ends which relate to culturally-specific meanings tend to fall into this group.

Depending on the requirements and means which designers seek to address, they may be able to use numerical techniques, such as manual or computer calculations, or design charts, nomograms etc. which are based on such calculations, to seek to minimise inaccuracy and uncertainty. There is, however, potential for inaccuracy and uncertainty regarding any ends and means. Two main causes are the need to make assumptions about the future and limitations inherent in the quantification of data. These affect all our information about natural and cultural environments, our information about building materials and appliances, about costs, and about peoples' goals. While at least some of the potential for ignorance-in-degree can be appreciated, and sought to be minimised by techniques such as sensitivity analysis, the stumbling block in practice is often the difficulty of communicating this to potential users, with the result that users interpret the information as accurate and certain information.

A further area for possible ignorance-in-degree relates to the results from different numerical techniques, for example, thermal performance simulation programs. Software developers generally intend that their program results fulfil the requirements of a ratio scale, and users assume that this is the case and treat the results as such. Software validation using empirical data is an attempt to demonstrate that this assumption is true. However, given that most thermal performance software includes features which are beyond empirical validation data sets, the potential for error is great. When comparing a number of reputable computer programs several validation exercises have shown that unexplainable differences in the calculation of heating and cooling loads can be as much as ±33% from the average value for high-mass buildings with the typical average variation over all building types being around ±21% (see for example, Judkoff & Neymark, 1993). Also, comparing the results from one analysis tool with another is questionable since they do not necessarily form comparable ordinal scales. Add to this the fact that variations in assumptions and operation by the simulation package users is known to produce substantial variations, the use of such tools must be treated with caution. The appropriate use of computer simulation programs is discussed further in Section 6.6.

6.5 Design in the Real World

If the on-the-job designer's analysis of the scope of the problem shows that the scope is so broad that much ignorance-in-kind remains likely, given the realities of what one can expect design decision-makers to find out about each design problem, and the realities of the world (such as price changes, and the indiscernible nature of the future), it may be irrelevant for a designer even to consider an approach which seeks to minimise ignorance-in-degree: a designer may conclude that the rigour of, for example, a time-consuming computer design aid, would be irrelevant to a design problem, and that the scarce resources of time could be applied more usefully in other ways. It must be emphasised that it is not primarily a question of whether computer programs or other aids can model the extensive information on ends and/or means adequately, but whether the designers of energy-efficient housing can and should obtain the real-world input which covers all requirements and means established as potentially relevant to the design problem. Since ends and means need to be established in relation to each other, designers may need to find out about all potentially relevant ones even if, in doing so, it is discovered that some are not relevant to the particular design problem.

This line of thinking can of course result in an error-in-kind by absence from the point of view of other stakeholders. Where this occurs public intervention in the form of regulations which specify either mandatory requirements or means may be required to ensure that designers deal with the particular issue. In such a case the goals and requirements which are addressed should be clearly described to reduce ignorance-in-kind and be based on transparent scientific principles to minimise ignorance-in-degree.

6.6 Appropriate Use of Simulation

In Chapter 5 it is suggested that overall we can have some confidence that the error-in-degree has been reduced for the *EnCom2* software package, however a question still remains. How should such programs be used for design evaluation? Should, for example, it be assumed that the predictions of energy consumption, temperatures etc. form true ratio/interval scales and use the results in an absolute sense to calculate information such as life-cycle costs?

Design evaluation using computer program simulation cannot be considered an exact science and its use must reflect this fact. There are significant possibilities of the introduction of ignorance-in-kind as well as ignorance-in-degree. Ignorance-in-kind can be reduced by a software developer clearly stating the computation assumptions and limitations of a program package. Ignorance-in-degree, in particular error, is more difficult to eliminate as, in part, this may result from operator variations and mistakes. Given these circumstances, computer simulation results should be employed only to order design proposals against appropriate criteria, for example, energy consumption, comfort conditions, life-cycle costs.

The major steps in performing such design evaluations would be:

1. Specify the requirements and means applicable to the problem.
2. Identify various alternative solutions.
3. Identify appropriate evaluation indices related to requirements (and means) eg. energy consumption (MJ), comfort (PMV).
4. Undertake simulations to estimate index values for each alternative, including sensitivity analysis to determine the influence of major assumptions.
5. Compare the solutions on an ordinal scale for each design requirement. Where multiple criteria are used, the ordering of solutions against each criteria may be different. For example, one solution may result in minimum CO_2 emission while another has a minimum life-cycle cost.

Where potentially more than one computer program could be used to evaluate the same or similar buildings such as in a House Energy Rating Scheme (HERS), the methodology must account for the possible (and probable) differences between program results. Using simulations results in the form of ratio/interval (or absolute) scales would not satisfy this objective. Expressing simulation results on an ordinal scale constructed as a ratio of the target building results to those of a reference building would overcome the problem. This technique would also lessen the influence of systematic program and operator differences between two simulation packages.

6.7 An Ignorance Evaluation of the 1974 Williamson & Coldicutt Paper

An ignorance evaluation of the 1974 Williamson & Coldicutt paper provides an indication of the way in which this kind of analysis can highlight sources of error. This analysis can be undertaken from two aspects: first, from the point of view of the content of the paper (or what it does not contain) and secondly, from the view of how aspects of the paper have been interpreted.

6.7.1 Content of the Paper

Errors in Kind

The paper introduces confusion in that the context of the problem is not made adequately clear. Statements like "Melbourne tends to be the most difficult region......hence, a basic model developed would serve as a useful one for adaptation to the other regions" plays down the importance of the contextual elements of climate, household preferences, the availability of different fuel types, etc. In addition, assumptions such as ".... the need for a reappraisal of the basis on which we develop sites for housing." and "Where higher initial costs are involved there will be the need for special provision from lending authorities with Government support", ignore the social and institutional context of the design solution.

Absence is apparent in the omission of certain thermal preferences as being important requirements in developing a suitable design solution, for example, the strong preference for sunlight in bedrooms.

Errors in Degree

Inaccuracy is inherent in the methodology used to estimate the heating and cooling energy consumption and summertime temperatures. The STEP program had several inadequacies at the time for the enterprise being undertaken. The program placed severe limitations on building form, user patterns, etc., which could be assumed for the design. Finally there was insufficient data at the time (for example, actual energy consumption statistics) for a detailed calibration of the simulation tool.

Uncertainty is indicated by numbers of simplifying assumptions introduced in order to operate the simulation tool. Using double-glazing as a substitute for curtains is an example.

6.7.2 Interpretations of the Paper

Errors in Kind

Almost all references and citations to the paper describe the mechanism-means and object-means employed in the "Improved House" design solution; some mention the requirement which relates to thermal comfort but all other requirements and contextual aspects mentioned in the paper are generally neglected. These interpretations are essentially errors in kind, confusing the nature of the means proposed as a general solution to a low-energy (energy-efficient) house.

Errors in Degree

Errors in degree, including the inaccuracies of the methodology and the uncertainties described above, are not discussed in references to the results in the paper by others. This indicates ignorance and a naive acceptance of the "scientific method", in particular the belief that results which are derived from computer simulation are inherently correct.

6.8 Summary

The aim of this Chapter has been to position the applicability of design knowledge, in particular, knowledge concerning energy-efficient housing, in the total design process. By applying the ignorance concept, the limitations of such knowledge to a designer or decision-maker are highlighted.

Applying the analysis to rules-of-thumb associated with the *solar-efficient* prototype we see that, because of the lack of clarity in the goals being addressed and the inability to deal with the inter-relatedness of design elements, there is likely to be a high level of built-in ignorance for those who attempt to use them in design. Furthermore, because design means such as heating and cooling plant are not included in the rules, there is likely to be a high level of irrelevance associated with the majority of goals which may be imputed by the designer. These points are explored further in the investigations described in Chapter 7.

CHAPTER 7
LIMITS OF THE PROTOTYPE

7.1 Introduction

The aim of this Chapter is to demonstrate, with a small range of typical examples, limits of the *solar-efficient* prototype rules-of-thumb approach for providing advice on the design of energy-efficient housing. The built-in ignorance inherent in such an approach is examined. The investigation takes into account present conditions, requirements, preferences and design knowledge which have been elaborated since the mid-1970's.

The analysis is constructed to test the thesis hypothesis, that *for the temperate climate regions of Australia the presentation of advice for energy-efficient house design in the form of rules-of-thumb associated with the concept of the solar-efficient prototype is inadequate and in many circumstances can direct designers away from more applicable solutions.*

To be generally valid the rules-of-thumb approach should yield consistent results measured against a number of major goals. Since the approach is largely acontextual it would be expected that the rank order of building variations would be similar for different climates and different plant configurations, etc. Also, because the approach makes no recognition of possible conflicting goals within the general heading of energy-efficiency it would be expected that, for example, a dwelling designed in strict conformity to the rules-of-thumb would yield the "best" results measured against any of the commonly cited energy-efficient goals. The rules-of-thumb solution should achieve, for example, the lowest or near-lowest delivered energy consumption, CO_2 emission rate and life-cycle cost to achieve "acceptable" comfort conditions. The extent to which this is not the case represents the weakness of the approach.

7.2 Performance Analysis

The analysis will involve the following steps.

1. Construct a computer model of a generic project house typical of those constructed in Adelaide and Melbourne and which represents current expectations. The dwelling will be considered in four variations as listed below.

- insulated brick veneer with concrete slab-on-ground (BV)
- lightweight timber framing with a suspended timber floor (LW)
- brick cavity construction with concrete slab-on-ground and ceiling insulation only (BCu)

- brick cavity construction with concrete slab-on-ground and wall and ceiling insulation (BCi)

A variety of heating and cooling plant - direct electric, reverse cycle (heating and cooling), gas heating, heat-pump (cooling only), evaporative and fan cooling will be considered. Appendix C sets out the details of input data and assumed dwelling operating conditions.

2. Using performance data derived from the simulation program *EnCom2*, calculate the performance (and costs) related to specified objectives for each construction/plant variation. Derive solution sets comprising the relative performances compared with a typical variation.

3. Assume a number of objective weightings.

4. Calculate the weighted benefits and weighted costs for each variation.

5. Apply multi-criteria analysis to determine an optimum set for each variation.

6. Rank solutions for three decision methods - *net benefit, benefit-cost ratio* and *best compromise*.

7. Compare results to advice based on the prototype rules-of-thumb.

The analysis is not intended to be exhaustive It is simply intended to include sufficient common variations of construction and plant type to test the research hypothesis by comparing the results of various solutions with those which follow the rules-of-thumb associated with the *solar-efficient* prototype. The principle assumptions being examined centre around four issues embedded in these rules-of-thumb. These are,

1. the implication that the rules hold, or at least do not mislead, for all relevant energy-efficient objectives and preferences.

2. the implication that heavyweight construction is always better than lightweight construction.

3. the absence of advice on heating and cooling plant, and therefore the implication that the rules hold true for all main types of plant(s).

4. the implication that the rules are relevant irrespective of the amount of solar access

Analysis of preference data presented in Chapter 4 has already provided insights into the applicability and likely adoption of other rules-of-thumb. The rule regarding zoning of living areas to the north (and hence the usual consequence, bedrooms to the south) is recognised to be not viable because of strong householder preferences requiring sunlight to bedrooms (see Section 4.6.2). The rule regarding thermal insulation of walls (masonry veneer and framed construction) and ceiling is assumed to be relatively non-controversial as suggested by the high penetration rates (see Table 4.8) despite the non-mandatory environment at the time of the survey and in spite of the evidence (see Section 4.6.1) which suggests that energy conservation is not always achieved. There is little comparable data, however, on attitudes and practices which relate to ventilation. In the performance analysis low winter infiltration rates are assumed, but not minimised to the extent of possibly creating air quality problems. Good summer ventilation is assumed to operate when this is advantageous. A similar unknown situation relates to the rule-of-thumb regarding shading. The little evidence available suggests householders accept that good summer shading will enhance performance. In the analysis with full solar access, the shading is limited to that provided by the usual eaves construction. The analysis set with restricted solar access allows for an arrangement of trees, fences and a carport typical on a suburban allotment.

7.2.1 Identifying Design Goals

The broad goals of energy-efficient housing (see Chapter 1) encompass several objectives which designers could be expected to address, either explicitly or implicitly, when undertaking the design of an energy-efficient dwelling. These are likely to include:

- low energy use (or the different but related aim of low energy cost). The energy use may be defined in terms of delivered energy, operational primary (non-renewable) energy or life-cycle energy use, including embodied energy. The related energy costs may be calculated in terms of life-cycle costs. The life-cycle costs will be expressed as the present value of the initial cost of construction and plant together with the discounted costs of fuel and maintenance over a given period of building operation. Acceptable initial costs of the thermal “improvements” would be determined by the occupants so as not to exceed a budget.

- acceptable thermal conditions (with "acceptability" defined by some notion of a thermal comfort “standard”).

- low peak plant operating loads.

- reduced greenhouse gas production measured by CO_2 production.

The potential conflicts between even these four aims are unlikely to be resolved in the general case, as the resolution of the conflicts varies in practice according to context-specific and problem-specific factors. At the occupant level, these include personal preferences and a family's spending power. At the community level, these include the cost of energy and the desire to avoid building new power stations.

The explicit energy-efficient criteria chosen to be examined in this analysis are detailed below. In each case, a numeric variable is used to represent the performance of a design in relation to a goal.

Winter comfort

In both Adelaide and Melbourne cold winter afternoons and evenings (see Figure 4.11) were identified as main design times. Winter mornings were also important but to a lesser extent. Therefore, the criterion of winter discomfort chosen to be applied is the number of hours in the living zone of the dwelling for the hours 0700 to 2300 when the estimated PMV (using the PMV Adaptive Comfort Model, Figure 4.17) is less than 2.5, that is, in the categories “cool” and “cold”.

Summer comfort

?

Summer nights in bed are also identified in both locations as a main design time. The criterion used for summer discomfort is therefore taken as the number of hours in the sleeping zone of the dwelling between the hours 2200 and 0400 when the estimated PMV is greater than 5.5, that is, in the categories “warm” and “hot”.

Peak winter heating load

The estimated peak load requirements for heating plant are measured in kW.

Peak summer cooling load

The estimated peak load requirements for cooling plant are measured in kW.

Annual delivered energy consumption

The annual delivered energy consumption (GJ) is calculated from the energy loads estimated by the *EnCom2* program. The basic relationship between energy consumption and energy loads is,

$$DeliveredEnergyConsumption = HeatingLoad * \frac{1}{\xi_h} + CoolingLoad\,(orPowerConsumption) * \frac{1}{\xi_c}$$

where ξ_h and ξ_c are the Energy Utilisation Ratios (EUR) for the heating and cooling plant. A EUR is defined as,

$$\xi_i = \frac{PlantHeating \cdot or \cdot CoolingOutput\,(orPowerConsumption)}{TotalPlantEnergyInput}$$

Table 7.1 gives various EUR figures for typical heating and cooling plant. For evaporative cooling and fans the delivered energy consumption is calculated directly in *EnCom2*. A EUR for evaporative coolers of 0.9 allows for energy consumed in delivering the water to the dwelling. Annual delivered household energy consumption (for heating and cooling) is included as a criteria (and examined in the following discussion), firstly, it is understandable at the household level (Australian Bureau of Statistics figures related to this quantity), and secondly, it is the most usual measure included in Energy Rating Schemes.

Table 7.1: Typical EUR Values

Plant Type	**EUR**
Heating	
Gas, wall furnace	0.70
Gas, ducted	0.80
Direct electric, radiant or convective	1.0
Air-source heat pump, total	3.0
Ground coupled heat pump	5.0
Slow combustion stove	0.6
Cooling	
Air-source heat pump, total	2.6
Fan	1.0
Evaporative cooler	0.9
Ground loop heat pump	5.0

Source: South Australian Energy Information Centre, personal communication

Annual primary energy consumption

Primary energy consumption expresses the design implications for overall fossil fuel resource usage to supply heating and cooling. The conversion of delivered (or secondary energy) to primary energy is achieved by applying a primary/secondary energy ratio multiplier. Table 7.2 shows primary/secondary energy ratios suggested by various authors together with the "average" values used in this analysis.

Table 7.2: Primary Energy Factors

Source	**Fuel**	**Primary/secondary Energy Ratio**
Treloar, 1996	Gas Electricity	1.4 3.4
Gas & Fuel Corporation & Sustainable Solutions, 1992	Gas Electricity	1.07 4.15
Derived from, SA Office of Energy, 1993	Gas Electricity	1.13 3.11
Used in this analysis	***Adelaide*** Gas Electricity ***Melbourne*** Gas Electricity	 1.2 3.2 1.3 3.4

Life-cycle heating and cooling energy consumption

The life-cycle energy consumption is taken as the sum of the embodied energy contained in the dwelling and the delivered energy for heating and cooling. The embodied energy is calculated by the Pullen technique (Pullen, 1995). A sample spreadsheet is shown in Appendix D.

Life-cycle CO_2 emissions

Carbon dioxide (CO_2) is a principal contributor to greenhouse gas emissions (N.G.S.C., 1992). The CO_2 production (tonnes) is associated with both the embodied energy and the operational energy. The conversion from delivered energy to CO_2 emissions depends on the type and quality of fuel to be used. The delivered energy conversion factors used in this analysis are shown in Table 7.3.

Table 7.3: CO_2 Emission Factors

Fuel	CO_2 Production
South Australia	
Electricity	386 kg/GJ
Natural Gas	61.2 kg/GJ
Wood	96.3 kg/GJ
Victoria	
Electricity	273 kg/GJ
Natural Gas	60.7 kg/GJ
Wood	96.3 kg/GJ

Source: Personal communication, Alan Pears, Sustainable Solutions-Melbourne, June 1996.

Costs

Since for most people financial resources are limited, the cost implications of design decisions in terms of both initial and life-time costs are important. The total cost ($) is expressed in terms of life-cycle costs using an appropriate discount rate and period for amortization. In the following analysis the discount rate is 5% and the period 25 years.

7.2.2 Multiple Ends Decision-Making

The 1974 Williamson & Coldicutt paper simplified the decision-making process to a single objective, that of minimising the total (or life-cycle) costs, essentially assuming that the benefits of all examined solutions were identical. Where many ends are to be addressed explicitly it is likely that their description as individual attributes will be too cumbersome, and that the designer or the potential householder will not be able to recognise their applicability for ranking proposed real-world design solutions without an ordering procedure. Multiple-criteria decision techniques described by Cohon (1978) provide a method of dealing with this situation. Radford and Gero (1988a), D'Cruz (1984) and others have demonstrated their application to design problems. Figure 7.1 shows the boundary of a set of feasible solutions with two objectives Z1 and Z2 with a set of

Pareto optimal performances located around a surface S. Any solution on this surface, known as the Pareto optimal or noninferior set, may be considered the *best* solution depending on the *method* chosen for dealing with tradeoffs. Generally this *method* is not apparent; there is no one clearly most appropriate way to choose between design solutions which are members of the Pareto optimal set.

There are various methods of identifying designs which have performances which are members of the Pareto set (see for example, Cohon, (1978) and Radford & Gero, (1988)). With relatively small numbers of cases the set can be identified directly by exhaustive enumeration of all designs and their performances in the various objectives.

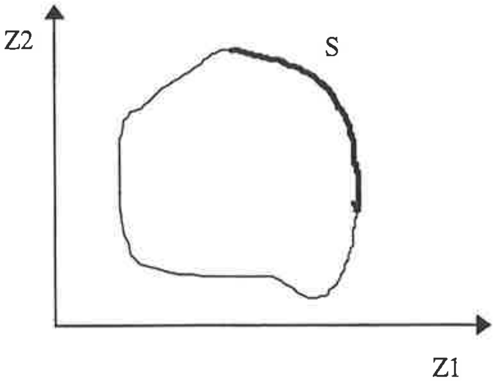

Figure 7.1: Surface of Optimal Performances for Two Criteria Z1 and Z2

The most common approach to choosing a solution from amongst the Pareto set is to convert the multiple-criteria problem into a single-criterion problem by forming a weighted sum of the criteria or objective functions for each solution such that,

$$\sum_{k=1}^{p} W_k Z_k(X) = R \quad \text{..........} \quad \text{Equation 7.1}$$

where, W_k are weights attached to each of p performance of objectives $Z_k(X)$.

Radford and Gero (1988b) describe this technique as "the Additive Composition Model". They state that,

> "*.....the weights are themselves meaningful because they state the preferences between objectives.*" (Radford & Gero, 1988b)

Equation 7.1 can be reformulated in terms of the familiar cost-benefit analysis model such that the net benefit of a solution A_j is given by,

$$\sum_{k=1}^{p} w_k B_k(A_j) - W_r C_j = [A_j] \quad \text{.........} \quad \text{Equation 7.2}$$

where, w_k are weights attached to each of p objectives perceived as a benefit $B_k(A_j)$ over j solutions, for example, reduced delivered energy consumption, reduced CO_2 emission etc.

C_j Life-cycle cost of solution j

and W_r expresses the relative weighing associated with the weighted benefits (W_b) and the life-cycle cost functions (W_c) for solution j.. $W_r = W_c/W_b$

In the following work the complete set of performances for the case study designs are generated, whether or not they lie amongst the Pareto set. Because only a relatively small number of variations are examined the Pareto sets are identified by inspection of a cost-benefit plot.

The weighting of performance measures and costs depends on the decision-maker's preferences related to the analysis objectives. It is not the purpose of this thesis to presume these preferences. Weightings for any personal decision-maker would probably be different from the weightings used, for example, by those developing a generic House Energy Rating scheme. Instead, the need here is to investigate how design decisions might be sensitive to different relative preferences and to compare the design solutions which might emerge with those that result from following the rules-of-thumb associated with the *solar-efficient* prototype house. Five weighting sets shown in Table 7.4 have been chosen arbitrarily in the range 0-100 to correspond to different overall assumptions concerning objectives as represented by house "types". These house "types" are used as case studies to explore the range of optimal solutions which are generated using the assumed weightings. The sensitivity of these weightings will be discussed later.

To provide a consistent method of measurement for the benefit and cost values they may conveniently be expressed as standardised values against a typical solution. In this way they represent a relative benefit and cost compared with a typical solution. Choosing an appropriate typical solution acknowledges the contextual and social dimension of the problem. Although better solutions may be found, the typical solution should be that which is deemed to be an adequate answer to the multi-criteria problem at a certain place and time. The typical solution will comprise a particular construction/plant variation for each location. The aim of energy-efficient design advice may be seen as providing information for "better" solutions relative to the typical solution.

Relative benefits for proposed solutions relative to the typical solution are expressed as,

$$B_k(A_j) = {K_{k_j}} / {K_{k_t}}$$ .... Equation 7.3

where K_{k_j} is the estimated performance measure k for the variation j

and K_{k_t} is the estimated performance measure k for a the typical solution

Consider, for example, that the chosen typical solution has a CO_2 emission value of 1.3 tonnes and a different construction/plant variation achieves an estimated CO_2 emission of 0.9 tonnes, then B_k for the proposed solution would be 1.44. This would indicate a positive relative benefit for this solution compared to the typical solution, that is, $B_j > 1$. In a similar way relative costs may be calculated by estimating the life-cycle costs expressed as the present value of all costs for the typical and other proposed solutions. In this case the relative costs would be,

$$C_j = {L_j} / {L_t}$$ .... Equation 7.4

where, L_j is the estimated life-cycle cost for the variation j

and L_t is the estimated life-cycle cost for the typical solution

A relative cost value $C_j < 1$ shows a relative cost advantage of solution j compared with the typical solution.

7.2.3 Decision Method

As stated above there is no *a priori* method for choosing amoung the solutions which comprise the Pareto set. For this work three decision methods are examined.

Net Benefit

In net benefit analysis we seek that solution for which A_j in Equation 7.2 is maximum.

It should be noted that this formulation is not sensitive to the classification of a project effect as a cost rather than a benefit, and *visa versa*. Thus, all cost objectives can be treated as negative benefits and all benefits as negative costs. The outcome will be the same however the division is made.

It is suggested that the net benefit technique is preferred when choosing between mutually exclusive projects (see, for example, Dasgupta & Pearce, 1972).

It must also be noted that for building design projects the need to ensure that the initial costs do not exceed a given budget is also a usual consideration. Where cost is not a consideration, solutions will be ranked in terms of their benefit performance.

Benefit-Cost Ratio

The *benefit-cost ratio* expressed as $\Sigma B/\Sigma C$ is often advocated in building performance literature as a legitimate decision rule. d'Have for example (1981) suggests that either $\Sigma B/\Sigma C$ or $\Sigma B/(\Sigma C)^2$ provide a suitable basis for ranking proposed solutions. The benefit-cost ratio of the weighted objectives may be expressed in terms of previously defined terms as,

$$\sum_{k=1}^{p} w_k B_k(A_j) \Big/ W_r C_j = [\alpha_j]_{\max} \qquad \text{.......... Equation 7.4}$$

where $W_r > 0$ and $C_j > 0$

In this case the ranking of solutions is not necessarily insensitive to the allocation of an objective as a benefit or a cost.

Best Compromise Solution

Where Z1* (cost) and Z2* (benefits) represent the best performances for criteria Z1 and Z2 then point R can be designated the ideal point. A *best comprise solution* may be determined as that which minimises the length of line RP, where P is a point on the Pareto surface corresponding to a particular solution.

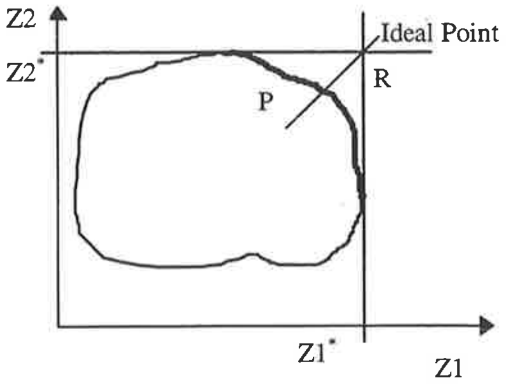

Figure 7.2: Best Compromise Solution for Two Criteria Z1 and Z2

The distance RP is calculated as,

$$\sqrt{([Z_1^* - Z_1(X)])^2 + ([Z_2^* - Z_2(X)])^2} = [d_{\min}] \quad \text{..........} \quad \text{Equation 7.5}$$

where, $Z_1 = W_r C_j$ and $Z_2 = \sum_{k=1}^{p} w_k B_k(A_j)$ are as described in Eq. 7.2.

Table 7.4: Performance Weightings

	Winter Comfort	Summer Comfort	Winter Load	Summer Load	Annual Delivered Energy	Annual Primary Energy	Life-cycle Energy	Life-cycle CO2 Emission	Costs Weighting Ratio Wr
Low Energy House	50	50	0	0	70	0	70	0	1
Ecological/Cost Conscious House	30	30	0	0	0	0	80	80	1.45
Energy Efficient House	50	50	10	10	70	50	70	70	1
The Balanced House	50	50	50	50	50	50	50	50	1
Energy-Efficient Prototype Rules-of-Thumb	60	60	0	0	60	0	0	0	0

Note: The reader is invited to explore further weightings using the Excel spreadsheet MC.xls on the enclosed PC disk. Some instructions for its use are shown in Appendix F.

7.2.4 Dwelling Details

The generic dwelling used in the analysis (details are given in Appendix C) is typical of a large range of project builders' models. A rectangular plan form has been chosen to match the house plans used in the 1974 Williamson & Coldicutt paper, but other common forms, L or T shape could have been chosen without invalidating the conclusions. In general the design allows for the degree of sun and daylight penetration levels in living and bedroom areas described in preference surveys as desirable (see Section 4.3.2). Because the positive value of thermal insulation seems to be accepted, walls and ceilings are considered insulated. Although acknowledging that the utility value for thermal insulation will vary with dwelling construction/plant variations, a constant level of insulation has been chosen for each location which is considered typical "best practice". The levels reflect the recommendations in Australian Standard AS2627 (Standards Association of Australia, 1983). A brick cavity construction variation without wall insulation has been included because of the present difficulty and cost in Australia of providing insulation to cavity brick walls.

Dwelling operation details have been chosen to represent a set of standard conditions for each location. Heating and cooling operations are determined by the control algorithm proposed in Section 4.5.4.

Two solar access conditions are employed for the analysis. The first is unrestricted solar access which is implied in the rules-of-thumb, and the second, the more usual case in practice, is restricted solar access caused by on-site building additions such as carports and garages, neighbouring constructions such as fences and buildings, and vegetation such as trees. A smaller range of construction/plant options are considered for the restricted solar access cases to confirm the trends deduced from the full solar access examples.

All building and plant costs are derived from Rawlinsons-Australian Construction Handbook 1996 (1996). Gas and electricity costs correspond to December 1996 tariffs for domestic consumption.

7.3 Performance Results

Tables 7.5 and 7.6 show the sample results for Adelaide and Melbourne respectively. Annual performance calculations were made using climate data for a reference year derived from the Australian Climate DataBase (ACADS-BSG). Run numbers 1-16 in both cases assume full solar access, while runs 17-27 for Adelaide and runs 17-25 for Melbourne are calculated on restricted solar access. The performance of each variation is standardised at the appropriate solar access condition against the "typical" variation which consists of brick veneer construction, concrete slab-on-ground with gas heating and refrigerative cooling.

The delivered energy totals show variations between construction/plant variations and between locations. The average ratio of difference for similar building/plant solutions between Adelaide and Melbourne attributable to climate is around 1.30, that is, typically the Melbourne results are 30% higher than the Adelaide results. Taking all results together and also including weightings for construction and plant penetration mixes, the results show that Melbourne dwellings overall consume around 42% more delivered energy. Using these weighted figures Figure 7.3 shows the results for the sum of heating and cooling delivered energy plotted against the climate index in the same way as Figure 4.6. Because the calculated results relate to well insulated new construction, whereas the Figure 4.6 values relate to all existing electric only dwellings, the correspondence between the two is as expected, that is, the net energy totals are less and the slope of the line is slightly flatter because of the increased insulation with climate severity. The results give some validation to analysis assumptions concerning dwelling user patterns.

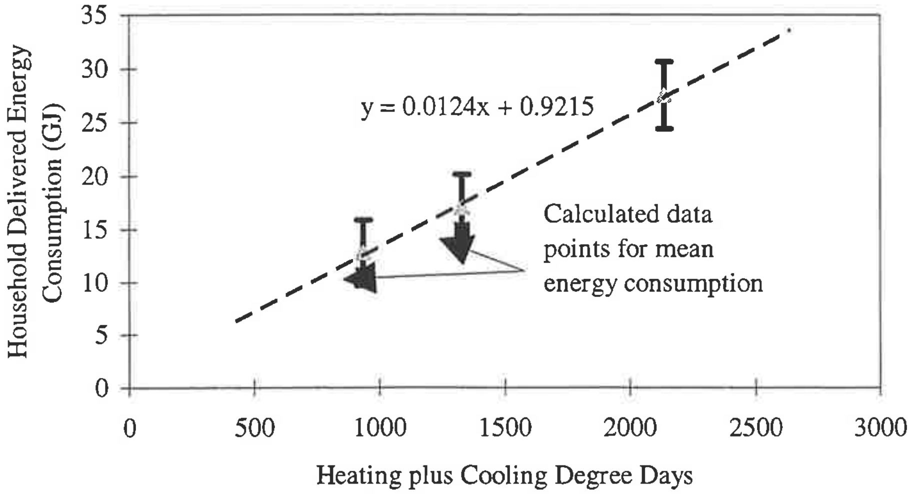

Figure 7.3: Calculated Weighted Heating/Cooling Energy Consumption vs Climate

Run Number	Description	Heating Load	Cooling Load or Power Consumption	Total Energy Load	Winter Discomfort, Z1(Hrs)	Summer Discomfort, Z2 (Hrs)	Peak Heat Load Input (kW)	Peak Cooling Load Input (kW)	Diff Capital/Construction Cost	Equipment Cost, Heating/Cooling	Annual Maintenance ($)	Heating Fuel Code, G,E,W	Cooling Code, C,F,E,N	Heating Efficiency	Cooling Efficiency	***Delivered Energy Total (GJ)***	Annual Heating Cost	Annual Cooling Cost	Annual Total Cost ($)	Annual Primary Energy Total (GJ)	Annual CO2 Production (Tonnes)	Embodied Energy (GJ)	Life-cycle Energy (GJ)	Embodied CO2 (Tonnes)	Life-cycle CO2 Production	Life-cycle Cost %-1	Life-cycle Cost %-2	Winter Comfort	Summer Comfort	Winter Load	Summer Load	Annual Delivered Energy	Annual Primary Energy	LC Energy	LC CO2	Benefits Summary Value	LLC %-1	***Weighted Costs***	***Weighted Benefits***	***Net Benefits***	***Net Benefit Rank***	***Ideal Point Distance***	***Best Comprise Rank***	***Benefit/Cost Ratio***	***Rank Benefit/Cost***
	Full Solar Access Examples																											*50*	*50*	*50*	*50*	*50*	*50*	*50*	*50*	*50*	*1*								
1	BV/conc slab, ins AS2627, Elec heating & cool	3.6	6.9	10.5	72	7	6	5	0	8895	200	e	c	1	2.40	6.48	119.2	95.2	214.4	20.72	1.77	666.3	990	60.0	148.34	$14,735	$12,656	1.00	1.01	1.00	1.00	1.24	0.74	1.08	0.78	0.98	0.93	46.5	49.0	2.5	*15*	*79.63*	*13*	*1.05*	*15*
2	LW const. timb fl, ceiling & walls ins., Elec heat & cool	8.1	7.3	15.4	106	6	6	4	-5530	8895	200	e	c	1	2.40	11.14	268.2	100.7	368.9	35.65	3.04	582.2	1139	53.0	205.07	$11,383	$8,529	0.68	1.18	1.00	1.25	0.72	0.43	0.94	0.56	0.84	0.72	36.0	42.2	6.3	*13*	*83.16*	*15*	*1.17*	*13*
3	BC/conc. slab, ceiling but no wall ins, Elec heat & cool	6.0	9.8	15.8	78	1	8	7	3652	8895	200	e	c	1	2.40	10.08	198.7	135.2	333.9	32.27	2.75	734.6	1239	65.5	203.14	$20,071	$17,393	0.92	7.06	0.75	0.71	0.80	0.48	0.86	0.57	1.52	1.27	63.4	75.9	12.5	*12*	*65.56*	*12*	*1.20*	*12*
4	BC/conc. slab, ceiling & wall ins, Elec heat & cool	3.1	8.8	11.9	17	1	6	6	5956	8895	200	e	c	1	2.40	6.77	102.6	121.4	224.1	21.65	1.85	747.7	1086	66.7	159.03	$20,828	$18,700	4.23	7.06	1.00	0.83	1.18	0.71	0.98	0.73	2.09	1.32	65.8	104.6	38.8	*6*	*51.13*	*5*	*1.59*	*7*
5	BV/conc slab, ins AS2627, Gas heat & cool	3.6	6.9	10.5	72	7	6	5	0	10095	250	g	c	0.7	2.40	8.02	61.7	95.2	156.9	15.37	1.10	666.3	1067	61.0	115.83	$15,830	$13,789	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	50.0	50.0	0.0	*16*	*80.04*	*14*	*1.00*	*16*
6	LW const. timb fl, ceiling & walls ins., Gas heat & cool	8.1	7.3	15.4	106	6	6	5	-5530	10095	250	g	c	0.7	2.40	14.61	138.9	100.7	239.6	23.62	1.53	592.8	1323	54.0	130.64	$11,465	$9,009	0.68	1.17	1.00	1.00	0.55	0.65	0.81	0.89	0.84	0.72	36.2	42.1	5.9	*14*	*83.33*	*16*	*1.16*	*14*
7	BC/conc. slab, ceiling but no wall ins, Gas heat & cool	6.0	9.8	15.8	78	1	8	5	3652	10095	250	g	c	0.7	2.40	12.65	102.9	135.2	238.1	23.35	1.64	745.2	1378	66.5	148.27	$20,626	$18,177	0.92	7.06	0.75	1.00	0.63	0.66	0.77	0.78	1.57	1.30	65.1	78.6	13.5	*11*	*64.89*	*9*	*1.21*	*11*
8	BC/conc. slab, ceiling & wall ins, Gas heat & RC cool	3.1	8.8	11.9	17	1	6	6	5956	10095	250	g	c	0.7	2.40	8.10	53.1	121.4	174.6	17.05	1.27	758.4	1163	67.7	131.18	$22,035	$19,905	4.23	7.06	1.00	0.83	0.99	0.90	0.92	0.88	2.10	1.39	69.6	105.1	35.5	*7*	*54.51*	*7*	*1.51*	*8*
9	BV/conc slab, ins AS2627, RC heat & cool	3.6	6.9	10.5	72	7	3	5	0	10665	250	rc	rc	3	2.60	3.85	39.7	87.9	127.6	12.33	0.72	676.9	870	61.0	97.20	$15,987	$14,093	1.00	1.00	2.00	1.00	2.08	1.25	1.23	1.19	1.34	1.01	50.5	67.2	16.7	*10*	*64.89*	*10*	*1.33*	*10*
10	LW const. timb fl, ceiling & walls ins.,RC heat & cool	8.1	7.3	15.4	106	6	3	5	-5530	10665	250	rc	rc	3	2.60	5.51	89.4	93.0	182.4	17.62	0.77	592.8	868	54.0	92.33	$11,229	$9,060	0.68	1.17	2.00	1.00	1.46	0.87	1.23	1.25	1.21	0.71	35.5	60.4	24.9	*9*	*65.43*	*11*	*1.70*	*6*
11	BC/conc. slab, ceiling but no wall ins, RC heat & cool	6.0	9.8	15.8	78	1	4	7	3652	10665	250	rc	rc	3	2.60	5.77	66.2	124.8	191.0	18.46	1.03	745.2	1034	66.5	117.97	$20,533	$18,320	0.92	7.06	1.50	0.71	1.39	0.83	1.03	0.98	1.80	1.30	64.9	90.2	25.3	*8*	*57.25*	*8*	*1.39*	*9*
12	BC/conc. slab, ceiling & wall ins, RC heat & cool	3.1	8.8	11.9	17	1	3	6	5956	10665	250	rc	rc	3	2.60	4.42	34.2	112.1	146.3	14.14	0.92	758.4	979	67.7	113.88	$22,206	$20,218	4.23	7.06	2.00	0.83	1.81	1.09	1.09	1.02	2.39	1.40	70.1	119.6	49.4	*4*	*52.00*	*6*	*1.70*	*5*
13	BV/conc slab, Ins AS2627,gas heat & evap cool	3.6	1.5	5.1	72	12	6	0.6	0	5100	240	g	ev	0.7	0.90	6.81	61.7	55.2	116.9	11.50	0.77	666.3	1007	60.0	98.32	$10,130	$8,340	1.00	0.59	1.00	8.33	1.18	1.34	1.06	1.18	1.96	0.64	32.0	98.0	66.0	*3*	*28.97*	*1*	*3.06*	*2*
14	LW const. timb fl,ceiling & walls ins,Gas heat & evap cool	8.1	1.7	9.8	106	12	6	0.6	-5530	5100	240	g	ev	0.7	0.90	13.46	138.9	62.5	201.4	19.93	1.22	592.8	1266	54.0	114.90	$5,791	$3,577	0.68	0.58	1.00	8.33	0.60	0.77	0.84	1.01	1.73	0.37	18.3	86.3	68.0	*2*	*37.20*	*3*	*4.72*	*1*
15	BC/conc.slab, ceiling but no wall ins, Gas heat & evap cool	6.0	1.4	7.4	78	7	8	0.6	3652	5100	240	g	ev	0.7	0.90	10.13	102.9	51.5	154.4	15.26	0.94	745.2	1252	66.5	113.77	$14,310	$12,332	0.92	1.07	0.75	8.33	0.79	1.01	0.85	1.02	1.84	0.90	45.2	92.1	46.9	*5*	*41.32*	*4*	*2.04*	*4*
16	BC/conc. slab, ceiling & wall ins, Gas heat & evap cool	3.1	1.1	4.2	17	8	6	0.6	5956	5100	240	g	ev	0.7	0.90	5.65	53.1	40.5	93.6	9.23	0.60	747.7	1030	66.7	96.79	$15,758	$14,084	4.23	0.88	1.00	8.33	1.42	1.67	1.04	1.20	2.47	1.00	49.8	123.5	73.7	*1*	*31.48*	*2*	*2.48*	*3*
	Reduced Solar Access																																												
17	BV/conc slab, ins AS2627, Gas heat & cool	4.6	6.9	11.5	110	7	6	5	0	10665	250	g	c	0.7	2.40	9.45	78.9	95.2	174.1	17.09	1.18	676.9	1149	61.0	120.16	$16,642	$14,514	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	50.00	50.00	0.00	*5*	*61.2*	*5*	*1.00*	*5*
20	LW const. timb fl,ceiling & walls ins, RC heat & cool	9.1	7.3	16.4	115	13	6	5	-5530	10665	250	rc	rc	3	2.60	5.84	100.4	93.0	193.4	18.69	0.77	592.8	885	54.0	92.33	$11,384	$9,160	0.96	0.54	1.00	1.00	1.62	0.91	1.30	1.30	1.08	0.68	34.20	53.95	19.74	*4*	*54.8*	*4*	*1.58*	*3*
21	LW const. timb fl,ceiling & walls ins, RC heat & cool, 15% windows	9.0	7.2	16.2	110	13	8	5	-5946	10665	250	rc	rc	3	2.60	5.77	99.3	91.7	191.0	18.46	0.76	592.8	881	54.0	91.80	$10,935	$8,723	1.00	0.54	1.00	1.00	1.64	0.93	1.30	1.31	1.09	0.66	32.86	54.50	21.65	*3*	*54.3*	*3*	*1.66*	*1*
22	BC/conc.slab, ceiling but no wall ins, RC heat & cool	7.7	9.0	16.7	100	1	8	6	3652	10665	250	rc	rc	3	2.60	6.03	85.0	114.6	199.6	19.29	0.95	745.2	1047	66.5	113.77	$20,654	$18,398	1.10	7.06	0.75	0.83	1.57	0.89	1.10	1.06	1.79	1.24	62.05	89.66	27.61	*2*	*34.9*	*2*	*1.44*	*4*
23	BC/conc.slab, ceiling & wall ins, RC heat & cool	4.6	8.8	13.4	31	1	8	6	5956	10665	250	rc	rc	3	2.60	4.92	50.8	112.1	162.8	15.74	0.92	758.4	1004	67.7	113.88	$22,440	$20,368	3.56	7.06	0.75	0.83	1.92	1.09	1.14	1.06	2.18	1.35	67.42	108.78	41.36	*1*	*34.6*	*1*	*1.61*	*2*
24	BV/conc slab, ins AS2627, gas heat&evap cool	4.6	1.5	6.1	110	76	6	0.4	0	5100	240	g	ev	0.7	0.90	8.24	78.9	55.2	134.0	13.22	0.85	676.9	1089	61.0	103.67	$10,372	$8,495	1.00	0.09	1.00	12.50	1.15	1.29	1.06	1.16	2.41	0.62	31.16	120.29	89.13	*3*	*11.6*	*1*	*3.86*	*2*
25	LW const. timb fl,ceiling & walls ins, Gas heat & evap cool	9.1	1.7	10.8	115	76	6	0.4	-5530	5100	240	g	ev	0.7	0.90	14.89	156.0	62.5	218.5	21.64	1.30	582.2	1327	53.0	118.22	$6,033	$3,732	0.96	0.09	1.00	12.50	0.63	0.79	0.87	1.02	2.23	0.36	18.13	111.59	93.47	*2*	*15.0*	*3*	*6.16*	*1*
26	BC/conc.slab, ceiling but no wall ins, Gas heat & evap cool	7.7	1.4	9.1	100	10	8	0.5	3652	5100	240	g	ev	0.7	0.90	12.56	132.0	51.5	183.5	18.18	1.09	734.6	1362	65.5	120.12	$14,721	$12,596	1.10	0.71	0.75	10.00	0.75	0.94	0.84	1.00	2.01	0.88	44.23	100.57	56.34	*4*	*14.0*	*2*	*2.27*	*4*
27	BC/conc. slab, ceiling & wall ins, Gas heat&evap cool	4.6	1.1	5.7	22	3	6	0.5	5956	5100	240	g	ev	0.7	0.90	7.79	78.9	40.5	119.3	11.80	0.73	747.7	1137	66.7	103.30	$16,120	$14,318	4.97	2.33	1.00	10.00	1.21	1.45	1.01	1.16	2.89	0.97	48.43	144.64	96.20	*1*	*39.1*	*4*	*2.99*	*3*

Table 7.5: Calculation Spreadsheet Results for Adelaide Analysis

Run Number	Description	Heating Load	Cooling Load or Power Consumption	Total Energy Load	Winter Discomfort Z1(Hrs)	Summer Discomfort Z2 (Hrs)	Peak Heat Input Load (kW)	Peak Cooling Input Load (kW)	Diff. Capital/Construction Cost	Equipment Cost, Heating/Cooling	Annual Maintenance ($)	Heating Fuel Code, G,E,W	Cooling Code, C,F,E,N	Heating Efficiency	Cooling Efficiency	*Delivered Energy Total (GJ)*	Annual Heating Cost	Annual Cooling Cost	Annual Total Cost ($)	Annual Primary Energy Total (GJ)	Annual CO2 Production (Tonnes)	Embodied Energy (GJ)	Life-cycle Energy (GJ)	Embodied CO2 (Tonnes)	Life-cycle CO2 Production	Life-cycle Cost %~1	Life-cycle Cost %~2	Winter Comfort	Summer Comfort	Winter Load	Summer Load	Annual Delivered Energy	Annual Primary Energy	LC Energy	LC CO2	Benefits Summary Valuue	LLC %~1	*Weighted Costs*	*Weighted Benefits*	*Net Benefits*	*Net Benefit Rank*	*Ideal Point Distance*	*Best Comprise rank*	*Benefit/Cost Ratio*	*Rank Benefit/Cost*
	Full Solar Access Examples																											50	50	10	10	70	50	70	70	47.6	1								
1	BV/conc slab, ins AS2627, Elec heating & cool	6.7	5.0	11.7	199	1	6	4	0	10080	200	e	c	1	2.4	8.78	234.7	73.0	307.7	29.86	3.39	666.3	1105	60.0	229.48	$17,235	$14,688	1.00	1.00	1.00	1.00	1.33	0.65	1.13	0.57	0.96	1.01	48.1	45.6	-2.6	11	52.11	10	0.95	11
2	LW const. timb fl, ceiling & walls ins., Elec heat(adj) & cool	11.7	5.5	17.2	140	1	6	4	-5530	10080	200	e	c	1	2.4	13.99	409.8	80.3	490.1	47.57	5.40	582.2	1282	53.0	323.02	$14,276	$10,814	1.42	1.00	1.00	1.00	0.83	0.41	0.97	0.40	0.83	0.84	39.9	39.5	-0.3	10	49.28	8	0.99	10
3	BC/conc. slab, ceiling but no wall ins, Elec heat & cool	11.1	6.2	17.3	200	1	8	6	5219	10080	200	e	c	1	2.4	13.68	388.8	90.5	479.3	46.52	5.28	734.6	1419	65.5	329.59	$24,873	$21,465	0.99	1.00	0.75	0.67	0.85	0.42	0.88	0.40	0.75	1.46	69.5	35.5	-34.0	16	75.58	16	0.51	16
4	BC/conc. slab, ceiling & wall ins, Elec heat & cool	7.2	5.4	12.6	121	1	6	5	7523	10080	200	e	c	1	2.4	9.45	252.2	78.8	331.0	32.13	3.65	747.7	1220	66.7	249.05	$25,087	$22,423	1.64	1.00	1.00	0.80	1.23	0.61	1.02	0.52	0.99	1.47	70.1	46.9	-23.2	14	71.10	15	0.67	14
5	BV/conc slab, ins AS2627, Gas heat & cool	6.7	5.0	11.7	199	1	6	4	0	11280	250	g	c	0.7	2.4	11.65	83.5	73.0	156.5	19.53	1.39	666.3	1249	61.0	130.47	$17,009	$14,970	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	47.5	47.5	0.0	9	50.56	9	1.00	9
6	LW const. timb fl, ceiling & walls ins., Gas heat(adj) & cool	11.7	5.5	17.2	140	1	6	4	-5530	11280	250	g	c	0.7	2.4	19.01	145.8	80.3	226.1	29.52	1.91	592.8	1543	54.0	149.38	$12,460	$10,072	1.42	1.00	1.00	1.00	0.61	0.66	0.81	0.87	0.88	0.73	34.8	41.8	7.0	7	44.04	7	1.20	7
7	BC/conc. slab, ceiling but no wall ins, Gas heat & cool	11.1	6.2	17.3	200	1	8	6	5219	11280	250	g	c	0.7	2.4	18.44	138.4	90.5	228.9	29.40	1.97	745.2	1667	66.5	164.90	$23,248	$20,846	0.99	1.00	0.75	0.67	0.63	0.66	0.75	0.79	0.79	1.37	64.9	37.4	-27.5	15	70.70	14	0.58	15
8	BC/conc. slab, ceiling & wall ins, Gas heat & cool	7.2	5.4	12.6	121	1	6	5	7523	11280	250	g	c	0.7	2.4	12.54	89.8	78.8	168.6	21.02	1.50	758.4	1385	67.7	142.58	$24,702	$22,603	1.64	1.00	1.00	0.80	0.93	0.93	0.90	0.92	1.02	1.45	69.0	48.6	-20.4	13	69.47	13	0.70	13
9	BV/conc slab, ins AS2627, RC heat & cool	6.7	5.0	11.7	199	1	3	4	0	10665	250	rc	rc	3	2.6	4.16	78.2	67.4	145.6	14.13	0.74	676.9	885	61.0	98.09	$16,240	$14,256	1.00	1.00	2.00	1.00	2.80	1.38	1.41	1.33	1.55	0.95	45.4	73.4	28.1	4	41.26	6	1.62	4
10	LW const. timb fl, ceiling & walls ins.,RC heat(adj) & cool	11.7	5.5	17.2	140	1	3	4	-5530	10665	250	rc	rc	3	2.6	6.02	136.6	74.1	210.7	20.45	0.82	592.8	894	54.0	94.83	$11,628	$9,317	1.42	1.00	2.00	1.00	1.94	0.95	1.40	1.38	1.39	0.68	32.5	66.1	33.6	3	29.32	3	2.03	3
11	BC/conc. slab, ceiling but no wall ins, RC heat & cool	11.1	6.2	17.3	200	1	4	6	5219	10665	250	rc	rc	3	2.6	6.08	129.6	83.5	213.1	20.69	0.92	745.2	1049	66.5	112.54	$22,412	$20,088	0.99	1.00	1.50	0.67	1.92	0.94	1.19	1.16	1.23	1.32	62.6	58.4	-4.2	12	60.40	11	0.93	12
12	BC/conc. slab, ceiling & wall ins, RC heat & cool	7.2	5.4	12.6	121	1	3	5	7523	10665	250	rc	rc	3	2.6	4.48	84.1	72.8	156.8	15.22	0.80	758.4	982	67.7	107.77	$23,922	$21,881	1.64	1.00	2.00	0.80	2.60	1.28	1.27	1.21	1.53	1.41	66.8	72.5	5.7	8	62.72	12	1.09	8
13	BV/conc slab, ins AS2627,gas heat(adj) & fans	7.1	0.3	7.4	147	30	6	0.5	0	3050	120	g	f	0.7	1.0	10.44	88.5	10.5	99.0	14.21	0.74	666.3	1188	60.0	96.78	$6,137	$5,038	1.35	0.02	1.00	8.00	1.12	1.37	1.05	1.35	1.25	0.36	17.1	59.1	42.0	2	19.33	1	3.45	2
14	LW const. timb fl,ceiling & walls ins,Gas heat(adj) & fans	11.7	0.4	12.1	140	36	6	0.5	-5530	3050	120	g	f	0.7	1.0	17.11	145.8	14.0	159.9	23.09	1.18	592.8	1449	54.0	112.87	$1,464	$60	1.42	0.01	1.00	8.00	0.68	0.85	0.86	1.16	1.03	0.09	4.1	49.1	45.0	1	24.31	2	12.01	1
15	BC/conc.slab, ceiling but no wall ins, Gas heat & fans	11.1	0.4	11.5	200	34	8	0.5	5219	3050	120	g	f	0.7	1.0	16.26	138.4	14.0	152.4	21.97	1.12	745.2	1558	66.5	122.76	$12,108	$10,742	0.99	0.01	0.75	8.00	0.72	0.89	0.80	1.06	0.96	0.71	33.8	45.4	11.6	6	40.86	5	1.34	6
16	BC/conc. slab, ceiling & wall ins, Gas heat & fans	7.2	0.3	7.5	121	27	6	0.5	7523	3050	120	g	f	0.7	1.0	10.59	89.8	10.5	100.3	14.39	0.75	747.7	1277	66.7	103.93	$13,678	$12,573	1.64	0.02	1.00	8.00	1.10	1.36	0.98	1.26	1.25	0.80	38.2	59.3	21.1	5	36.91	4	1.55	5
	Reduced Solar Access																																												
17	BV/conc slab, ins AS2627, Gas heat & RC cool, 17%windows	8.3	5.0	13.3	199	1	6	4	0	11280	240	g	c	0.7	2.4	13.94	103.5	73.0	176.4	22.50	1.53	676.9	1374	61.0	137.46	$17,149	$15,060	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	47.50	47.5	0.0	9	45.5	9	1.00	9
18	BV/conc slab, ins AS2627, Gas heat & fans, 17%windows	8.3	0.3	8.6	161	30	6	0.5	0	3050	120	g	f	0.7	1.0	12.16	103.5	10.5	114.0	16.43	0.84	666.3	1274	60.0	102.03	$6,348	$5,174	1.23	0.02	1.00	8.00	1.15	1.37	1.08	1.35	1.24	0.37	17.58	58.9	41.3	4	14.0	4	3.35	4
19	BV/conc slab, ins AS2627, gas heat& fans,20%windows	8.5	0.4	8.9	171	33	6	0.5	599	3050	120	g	f	0.7	1.0	12.54	106.0	14.0	120.0	17.15	0.90	676.9	1304	61.0	105.85	$7,031	$5,827	1.16	0.02	1.00	8.00	1.11	1.31	1.05	1.30	1.20	0.41	19.48	57.1	37.6	5	16.1	5	2.93	5
20	BV/conc slab, ins AS2627, gas heat& fans,15%windows	8.1	0.4	8.5	156	29	6	0.5	-399	3050	120	g	f	0.7	1.0	11.97	101.0	14.0	115.0	16.40	0.86	666.3	1265	60.0	103.09	$5,962	$4,784	1.27	0.02	1.00	8.00	1.16	1.37	1.09	1.33	1.25	0.35	16.51	59.3	42.7	3	13.0	3	3.59	3
21	LW const. timb fl,ceiling & walls ins, Gas heat(adj) &fans, 17%windows	13.2	0.4	13.6	132	35	6	0.5	-5530	3050	120	g	f	0.7	1.0	19.26	164.5	14.0	178.6	25.87	1.31	582.2	1545	53.0	118.41	$1,728	$230	1.50	0.01	1.00	8.00	0.72	0.87	0.89	1.16	1.06	0.10	4.79	50.4	45.7	2	8.9	2	10.54	2
22	LW const. timb fl,ceiling & walls ins, Gas heat(adj) & fans, 15% windows	13.1	0.4	13.5	131	34	8	0.5	-5961	3050	120	g	f	0.7	1.0	19.11	163.3	14.0	177.3	25.69	1.30	582.2	1538	53.0	117.97	$1,279	($212)	1.52	0.01	0.75	8.00	0.73	0.88	0.89	1.17	1.06	0.07	3.54	50.4	46.8	1	8.9	1	14.21	1
23	BC/conc. slab, ceiling & wall ins, Gas heat& fans, 17%windows	9.4	0.3	9.7	126	27	6	0.5	7523	3050	120	g	f	0.7	1.0	13.73	117.2	10.5	127.7	18.48	0.94	747.7	1434	66.7	113.55	$14,064	$12,821	1.58	0.02	1.00	8.00	1.02	1.22	0.96	1.21	1.19	0.82	38.95	56.7	17.7	7	35.5	7	1.46	7
24	BC/conc. slab, ceiling & wall ins, Gas heat& fans, 20%windows	9.5	0.3	9.8	133	29	6	0.5	7912	3050	120	g	f	0.7	1.0	13.87	118.4	10.5	128.9	18.66	0.95	758.4	1452	67.7	115.00	$14,470	$13,221	1.49	0.02	1.00	8.00	1.00	1.21	0.95	1.20	1.17	0.84	40.08	55.8	15.7	8	36.7	8	1.39	8
25	BC/conc. slab, ceiling & wall ins, Gas heat& fans, 15%windows	9.0	0.3	9.3	122	27	6	0.5	7264	3050	120	g	f	0.7	1.0	13.16	112.2	10.5	122.7	17.73	0.90	747.7	1406	66.7	111.80	$13,735	$12,517	1.63	0.02	1.00	8.00	1.06	1.27	0.98	1.23	1.22	0.80	38.04	58.1	20.0	6	34.5	6	1.53	6

Table 7.6: Calculation Spreadsheet Results for Melbourne Analysis

Delivered annual energy for a location but with different building/plant options shows large variations. Compare, for example, Adelaide Run9 (BV with RC heat & cool), which is estimated to require 3.8GJ, and Run6 (LW with gas heat and cool), which is estimated to require 14.6GJ. This represents a variation ratio of 1:3.8. For Melbourne the variation ratio for delivered between building/plant options is 1:4.6. These figures indicate that the building/plant options potentially have a larger influence on results than the difference between the climates.

Figures 7.4 to 7.9 show the grouped benefits and costs plotted using the performance weights for the four house "types" (defined by the performance weightings shown in Table 7.4) and the Adelaide location. Figures 7.10 to 7.15 show the same results for the Melbourne location. Figures 7.17 to 7.20 show the same form of plot for assumed rules-of-thumb benefits weightings and zero cost weight.

Table 7.7 summarises the house "type" results for Adelaide. For the weightings chosen, the results show that when full solar access in available insulated brick cavity construction with reverse cycle heating & cooling and gas heating & evaporative cooling and lightweight construction with the same plant combinations, all fall on the Pareto surface for the *Low Energy* and *Ecological/Cost Conscious* cases. Brick veneer construction with gas heating and evaporative cooling falls on the Pareto surface for the *Energy Efficient* and *Balanced House* cases. Run11, brick cavity construction without wall insulation and RC heating & cooling, also falls on the surface in two of the four cases. Options which lie on a convex hull between any two points on the Pareto set could be eliminated as suggested by Radford and Gero (1988c) by applying the exclusion rule. These solutions are indicated in the Table in italics. When solar access is restricted brick veneer, lightweight and brick cavity solutions with different plant options are found to sit along the Pareto surface. Comparing the decision models of *net benefit*, *benefit/cost ratio* and *best compromise* we see that depending on the circumstance, either fully insulated brick cavity, lightweight, and in one case a brick veneer construction solution, could be considered superior.

When fully insulated brick cavity construction is not possible at any price, because either no suitable wall insulation material is available, or because bricklayers will not cooperate to install it[19], then Run11 will sit on the Pareto surface for all except the Balanced case. In this circumstance the superior solution in terms of the decision models is shown in Table 7.7 in italics. Given this situation, brick cavity construction without wall insulation, that is Runs 11 & 22, are seen in some instances to be the preferred solution.

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[19] That is the fully insulated brick cavity (Bci) Runs 4,8,12,16, 23 & 27 would be eliminated

Table 7.7: Adelaide Analysis Summary

Solar Access Condition *House "Type"*	**Pareto Set Run Nos**	**Net Benefit Solution**	**Benefit/Cost**	**Best Compromise Solution**
Full Solar Access				
Low Energy House	**12,4**,*11,16,10*,**14**	12 *(11)*	4 *(11)*	12 *(11)*
Ecological/Cost Conscious	**12,4**,*11,16*,**10,14**	14 *(14)*	14	10 *(10)*
Energy Efficient	**12**,*4*,**16,13,14**	12 *(13)*	14	16 *(11)*
The Balanced House	**16,13,14**	16 *(14)*	14	13
Restricted Solar Access				
Energy Efficient Set1	**23**,*22,17*,**21**	23 *(22)*	21	23 *(22)*
Set2	**27**,*24*,**25**	27 *(25)*	25	27 *(24)*
The Balanced House Set1	**23,21**	23 *(22)*	21	23 *(22)*
Set2	**27**,*24*,**25**	27 *(25)*	25	25

Note: Run descriptions

4	***Bci, Elect heat & cool***
10	***LW, RC heat & cool***
11	***BCu, no wall ins, RC heat & cool***
12	***BCi, RC heat & Cool***
13	***BV, Gas heat, evap cool***
14	***LW, Gas heat, evap cool***
16	***BCi, Gas heat, evap cool.***
17	***BV, Gas heat, refrig. cool***
21	***LW, RC heat,. cool, 15% windows***
22	***BCu, no wall ins, RC heat &. cool***
23	***BCi, RC heat &. cool***
24	***BV, Gas heat & evap cool***
25	***LW Gas heat & evap cool***
27	***BCi, Gas heat & evap cool,***

Table 7.9 summaries the Melbourne results. Applying the weightings chosen for the house "types" the results show that when full solar access in available insulated brick cavity construction with RC heating & cooling, brick veneer construction with reverse cycle heat & cooling or gas heating & evaporative cooling and lightweight construction with the same plant combinations all fall on the Pareto surface. Run13 for the *Low Energy* and the *Ecological/Cost Conscious* houses may be excluded by the elimination rule as described above. It is particularly interesting to note that for the cases examined brick cavity construction appears only in the Pareto set for the *Low Energy* house option. When solar access is restricted, rather than providing maximum window area facing north as recommended by the energy efficient design rules-of-thumb, the optimum solutions on the Pareto set are those variations which have the window area reduced to 15% of floor area.

Figures 7.17 to 7.20 show the ranking of solutions against assumed prototype rules-of-thumb objective weightings as shown in Table 7.4. In these cases a zero cost weighting is applied because this objective is not considered to determine the ranking. The analysis shows that in both locations and for both solar access conditions, a fully insulated brick cavity solution appears as the top ranked solution (Runs 12 & 23 for Adelaide and Runs 12 & 25 for Melbourne). This result demonstrates that design advice following the rules-of-thumb associated with the *solar-efficient* prototype relate to only part of the net benefit function, benefits without a consideration of cost; the rules fail to take into account the range of performance objectives, for example, CO_2 emissions.

Table 7.8: Melbourne Analysis Summary

Solar Access Condition *House "Type"*	**Pareto Set Run Nos**	**Net Benefit Solution**	**Benefit/Cost**	**Best Compromise Solution**
Full Solar Access				
Low Energy House	**12, 9,10,*13*,14**	10	14	10
Ecological/Cost Conscious	**10,*13*,14**	14	14	14
Energy Efficient	**9,10,13,14**	14	14	13
The Balanced House	**16,13,14**	14	14	14
Restricted Solar Access				
Energy Efficient	**20,22**	22	22	22
The Balanced House	**20,21,22**	21	22	21

Note: Run descriptions

9	***BV, RC heat & cool***
10	***LW, RC heat & cool***
12	***BCi, RC heat & Cool***
13	***BV, Gas heat, evap cool***
14	***LW, Gas heat, evap cool***
20	***BV,Gas heat & fans, 15% windows***
22	***LW, Gas heat & fans, 15% windows***
21	LW, Gas heat &fans, 17% windows

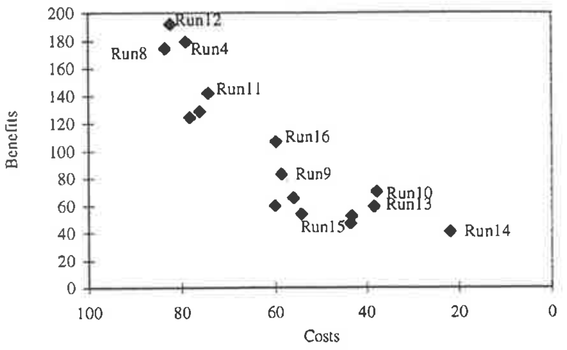

Figure 7.4: Adelaide *Low Energy House* Solution Set-Full Solar Access

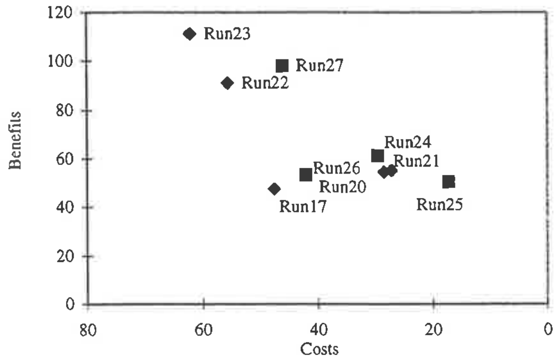

Figure 7.9: Adelaide *Energy-Efficient House* Solution Set-Restricted Solar Access

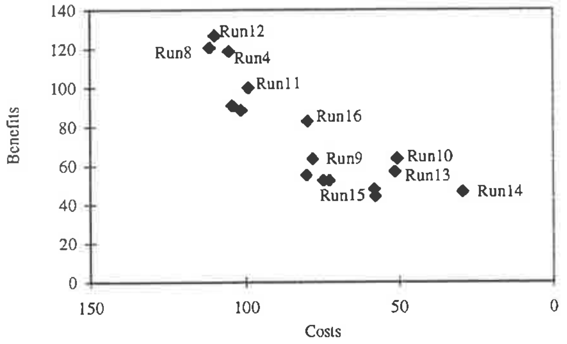

Figure 7.5: Adelaide *Ecological/Cost Conscious House* Solution Set-Full Solar Access

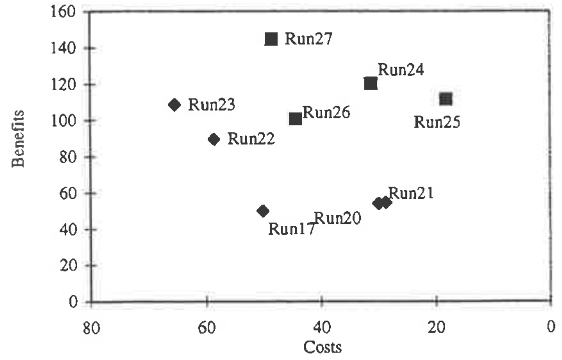

Figure 7.10: Adelaide *The Balanced House* Solution Set-Restricted Solar Access

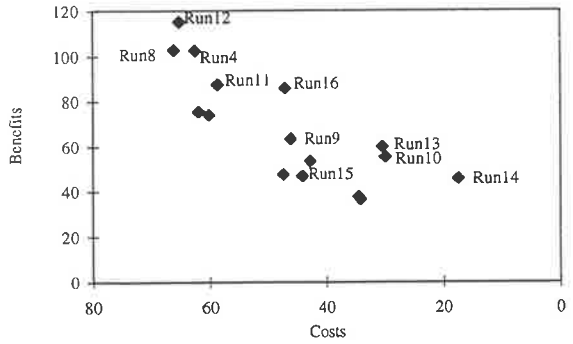

Figure 7.6: Adelaide *Energy-Efficient House* Solution Set-Full Solar Access

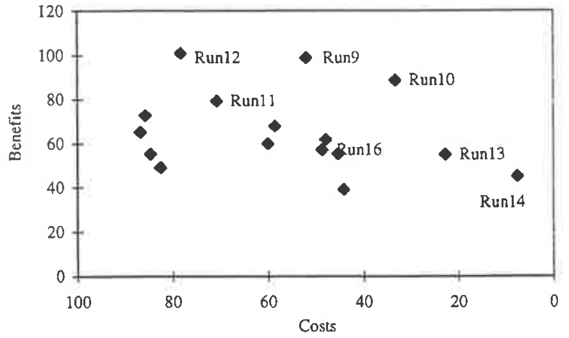

Figure 7.11: Melbourne *Low Energy House* Solution Set-Full Solar Access

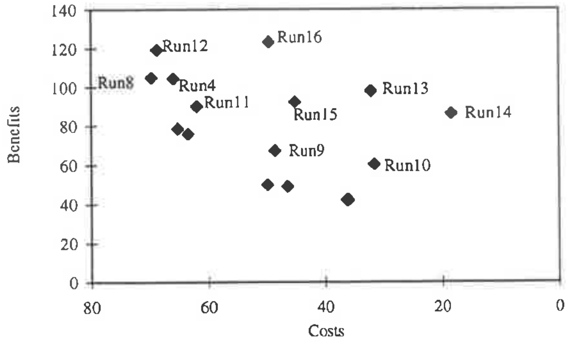

Figure 7.7: Adelaide *The Balanced House* Solution Set-Full Solar Access

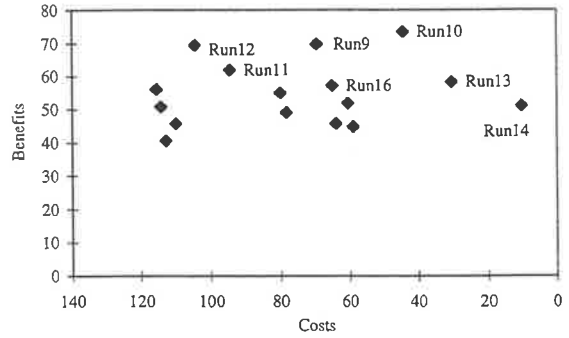

Figure 7.12: Melbourne *Ecological/Cost Conscious House* Solution Set-Full Solar Access

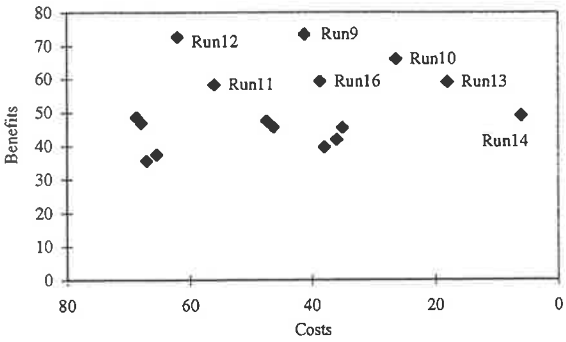

Figure 7.13: Melbourne *Energy-Efficient House* Solution Set-Full Solar Access

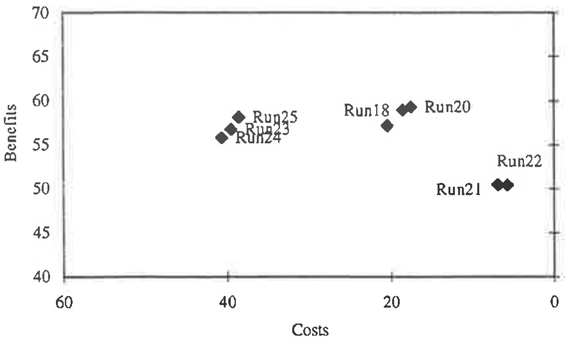

Figure 7.15: Melbourne *Energy-Efficient House* Solution Set-Restricted Solar Access

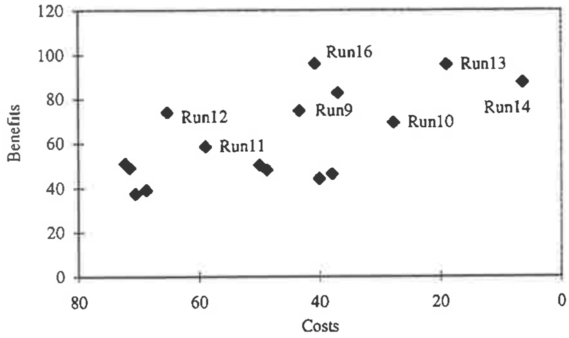

Figure 7.14: Melbourne *The Balanced House* Solution Set-Full Solar Access

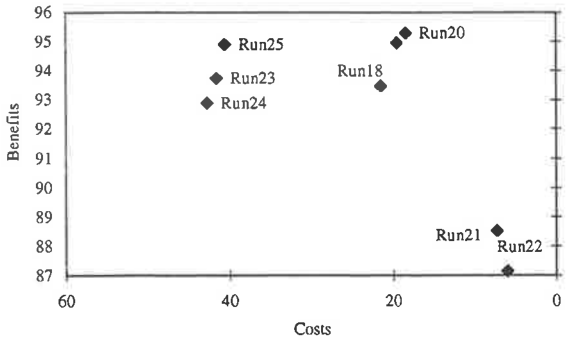

Figure 7.16: Melbourne *The Balanced House* Solution Set-Restricted Solar Access

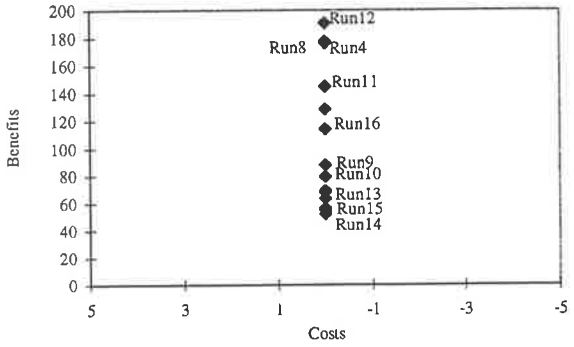

Figure 7.17: Adelaide *Rule-of-Thumb Prototype* Solution Set-Full Solar Access

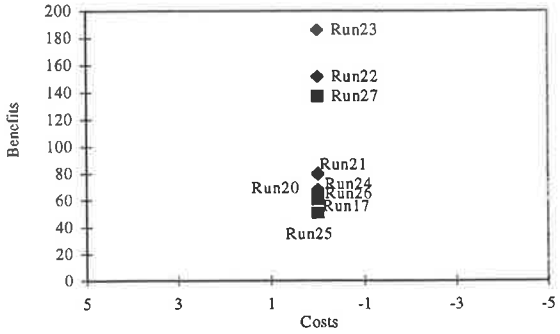

Figure 7.19: Adelaide *Rule-of-Thumb Prototype* Solution Set-Restricted Solar Access

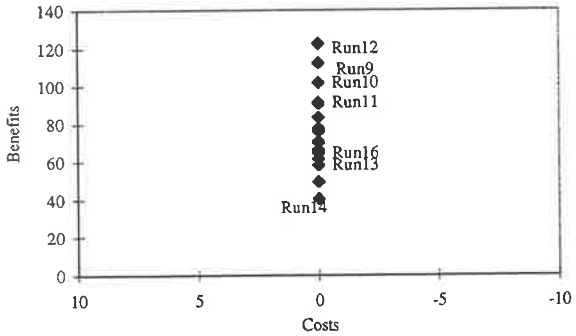

Figure 7.18: Melbourne *Rule-of-Thumb Prototype* Solution Set-Full Solar Access

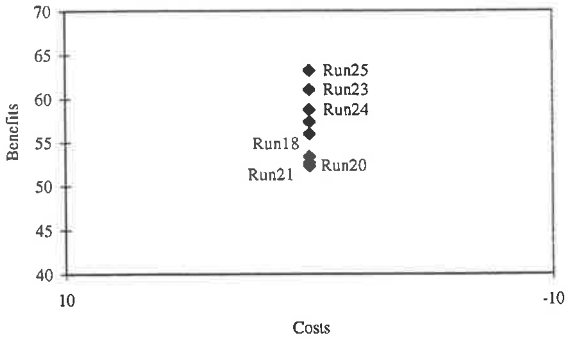

Figure 7.20: Melbourne *Rule-of-Thumb Prototype* Solution Set-Restricted Solar Access

7.3.1 Sensitivity of Results

Since the analysis above using the chosen performance objective weightings and other assumptions has brought into question the limitations of the rules-of-thumb approach in providing knowledge on energy-efficient design, within the context of the hypothesis of this thesis no further analysis is required. However, in order to test the stability of the results with respect to input data assumptions concerning cost, comfort and energy consumption estimates, a sensitivity analysis is conducted for the four house "types". Each change in input assumption set out below should move results in a direction which will favour the *solar-efficient* prototype solution. The changes to be made are,

- construction costs for brick cavity construction decreased by 2.0% (equivalent to around $14/sqm for Adelaide, $15/sqm Melbourne).
- winter and summer comfort criteria tightened, taken as equivalent to increasing the comfort weighting factors by 20%.
- delivered energy consumption is increased by 10%.

The results of this analysis are summarised in Table 7.~~10~~9 for Adelaide and Table 7.10 for Melbourne.

Table 7.9: Adelaide Sensitivity Case Summary

Solar Access Condition *House "Type"*	**Pareto Set Run Nos**	**Net Benefit Solution**	**Benefit/Cost**	**Best Compromise Solution**
Full Solar Access				
Low Energy House	**12**,**4**,*11*,*16*,*10*,**14**	12	4	12
Ecological/Cost Conscious	**12**,**4**,*11*,*16*,**10**,**14**	12	14	16
Energy Efficient	**12**,*4*,*11*,**16**,**13**,**14**	12	14	16
The Balanced House	**12**,**16**,*13*,**14**	16	14	16
Restricted Solar Access				
Energy Efficient Set1	**23**,*22*,**21**	23	23	23
Set2	**27**,*24*,**25**	27	25	27
The Balanced House Set1	**23**,*22*,**21**	23	23	23
Set2	**27,24,25**	27	25	24

Note: Run descriptions

4	***Bci, Elect heat & cool***
10	***LW, RC heat & cool***
11	***BCu, no wall ins, RC heat & cool***
12	***BCi, RC heat & Cool***
13	***BV, Gas heat, evap cool***
14	***LW, Gas heat, evap cool***
16	***BCi, Gas heat, evap cool.***
17	***BV, Gas heat, refrig. cool***
21	***LW, RC heat,. cool, 15% windows***
22	***BCu, no wall ins, RC heat &. cool***
23	***BCi, RC heat &. cool***
24	***BV, Gas heat & evap cool***
25	***LW Gas heat & evap cool***
27	***BCi, Gas heat & evap cool,***

Table 7.10: Melbourne Sensitivity Case Summary

Solar Access Condition *House "Type"*	**Pareto Set Run Nos**	**Net Benefit Solution**	**Benefit/Cost**	**Best Compromise Solution**
Full Solar Access				
Low Energy House	**12, 9,10,*13*,14**	10	14	10
Ecological/Cost Conscious	**10,*13*,14**	14	14	14
Energy Efficient	**12,9,10,13,14**	14	14	13
The Balanced House	**16,13,14**	14	14	14
Restricted Solar Access				
Energy Efficient	**20,*21*,22**	22	22	22
The Balanced House	**20,21,22**	21	22	21

Note: Run descriptions

9	***BV, RC heat & cool***
10	***LW, RC heat & cool***
12	***BCi, RC heat & cool***
13	***BV, Gas heat & fans***
14	***LW, Gas heat & fans***
20	***BV, Gas heat & fans, 15% windows***
21	***LW, Gas heat & fans, 17% windows***
22	***LW, Gas heat & fans, 15% windows***

Comparing Table 7.8 with Table 7.10 and Table 7.9 with Table 7.11 an almost identical set of Runs appear in the Pareto sets, indicating that the results overall, and the design advice that would follow, are not sensitive to the input change examined.

7.4 Summary

The multi-criteria analysis presented above shows that for the range of performance objective weightings chosen, related to four house "types", a relatively constant sub-set of the construction/plant options occur in the Pareto sets. These sub-sets are location specific and appear not sensitive to a reasonably severe change to several key input assumptions. For the Adelaide location the range of dwelling construction variations found in the sub-set includes heavyweight fully insulated brick cavity construction, brick veneer construction and lightweight construction. Reverse cycle heating/cooling and gas heating with summer evaporative cooling are the only two plant options which appear consistently in the optimal sub-set. In the Melbourne location the same three construction variations occur in the optimal sub-set with again two plant options - reverse cycle heating/cooling and gas heating with evaporative cooling to assist summer comfort.

Since there is no *a priori* justification for choosing any particular performance objective weightings and no reason to prefer any solution in the optimal sub-set over any other solution in the sub-set, all solutions should be considered possible. Design advice, which does not have a clear statement limiting consideration to specific objectives and decision criteria, should therefore relate to the range of possibilities.

The analysis demonstrates that the rules-of thumb associated with the *solar-efficient* prototype fail in several areas to provide sufficient advice. In particular the rules do not account for,

- the costs associated in achieving a design solution,
- the significance performance differences of plant options,
- the range of suitable construction variations, and
- the performance differences between full and restricted solar access situations.

These failings result in a high level of built-in ignorance. The results overall support the thesis hypothesis.

CHAPTER 8
SUMMARY AND CONCLUSIONS

8.1 Summary

This work has shown that around the mid-1970's the discourse on design advice concerning the thermal performance of housing in the temperate regions of Australia shifted. Prior to that time the main problem was seen to be concerned with the notion of providing thermal comfort, particularly "alleviating the heat of summer" (Drysdale, 1947). After the mid-1970's the scope of the problem broadened to include energy conservation, life-cycle costs, environmental concerns and householder/occupant preferences. The concept of the *solar-efficient* energy-efficient house and the associated rules-of-thumb which developed in the mid-1970's continues nowadays to be the main strategy for imparting design advice and is exemplified in documents such as AMCORD (Department of Housing and Regional Development, 1995).

Chapter 2 outlined the history of thermal performance research in Australia for the period from World War II to 1974. Research at that time was motivated by a belief in climatic determinism and that "it is common practice in Australia to build houses without regard to climate" ((Drysdale, 1947). Experimental investigations were aimed at "determining the suitability of houses for the various climatic zones" (Drysdale, 1947). The two main research centres, CEBS in Sydney, and CSIRO, DBR in Melbourne achieved some significant results and in several areas were at the forefront of international work. Design information in the period generally covered the range of construction variations most suited to a particular climate (see for example, Drysdale, 1952). From the mid-1970's new attitudes concerned with energy conservation and the quality of the environment emerged.

Chapter 3 provided the context for a paper (Williamson and Coldicutt, 1974) which enunciated a number of design strategies for a Solar House. The paper, an example of the discourse of the time, suggests that this housing prototype, suitable for the temperate climates of Australia, would achieve lower ownership costs and lower energy consumption compared with the prevailing construction and heating/cooling techniques. The *solar-efficient* house design rules-of-thumb for Australian temperate climate conditions were formulated during the mid-1970's and, rather than dealing with a range of suitable solutions, thermal performance design advice focused on just one solution type. The design objectives became ill-focused as the recognised issues increased in complexity, ranging from low (non-renewable or delivered) energy use, fossil fuel substitution and the use of solar energy, minimum life-cycle costs, improved comfort and (later) the greenhouse problem. In the mid-1970's however, the extent of knowledge concerning household energy consumption, household use patterns, appliance penetration, etc. was limited.

Chapter 4 outlined selected research projects and information sources which have added to our understanding of the issues since that time. The concept of thermal preferences is introduced as a way of providing relevant design information on occupant requirements and factors which affect overall satisfaction with the dwelling. Important knowledge relating to these preferences concerns the environmental conditions people find "acceptable" in houses. An adaptive (PMV) model is proposed which combines information from the results of both laboratory-based experiments and field studies. This model shows that people's preferred conditions can be related to the prevailing external climate, but also, that adaptation, because of contextual influences (it is suggested social, cultural, financial, etc., factors), acts to reduce discomfort. This finding explains, in part, why the observed correlation between household energy consumption for heating & cooling and climate does not follow the "theoretical" relationship. Based on the data presented in Chapter 4, recommendations are given for a suitable set of household operating assumptions to be used in computer simulation experiments.

The issues outlined in Chapters 2, 3 and 4 taken together define the core areas of concern for the designers of energy-efficient houses in the temperate regions of Australia. Other topics which may be relevant in other situations (different climates and other countries) receive relatively little attention in the literature, perhaps due to the benign climate and the local building techniques. For example, indoor air quality and health affects are taken to be within the broad range of normal design issues and are not seen as contributing extra or special dimensions to the energy-efficient design problem.

Chapter 5 dealt with the issue of computer simulation as a means of evaluating design recommendations and details certain features of the program *EnCom2* which allow it to be used in comparing performances for the normal range of housing types found in temperate locations in Australia. The Confirmation Technique was introduced as a tool for empirical validation and when applied to *EnCom2* the results suggest that the program can be used with confidence for free-running buildings.

Chapter 6 described an ignorance-based approach as a theoretical framework to consider the issues of the applicability and relevance of design advice. Ignorance-in-kind may exist where the design advice does not address the actual problem and ignorance-in-degree may exist when the design advice is based on tools which have inherent inaccuracies. Irrelevance may exist in either case if key elements of the design problem are not taken into account. Analysis of the likely uses of the rules-of-thumb by the on-the-job designer suggested that, because of a lack of clarity in the goals, there is likely to be a high level of built-in ignorance.

In Chapter 7 computer simulation employing the program *EnCom2* was used to explore the validity of rules-of-thumb based on the *solar-efficient* prototype when the multiple criteria incorporated in the goal of an "energy-efficient" house are explicitly considered. This analysis demonstrates that depending on the design problem objectives and their weightings, a range of solutions may be acceptable to achieve the energy-efficient ends. The solution variations were shown to be contextual in that they vary with location depending on, among other things, climate, occupant preferences, costs of energy, CO_2 fuel emission factors, etc. The analysis also showed that differences in heating and cooling plant options have a greater influence on the results than differences between the two climates examined and suggested that a consideration of plant may be a more appropriate starting place than climate zones. Such an approach would allow compromises between summer and winter design requirements and other more site-specific design compromises to be worked out in relation to plant (or the lack of plant). The investigation also indicated that partial application of the rules-of-thumb (for example, see Melbourne, brick cavity construction, ceiling but no wall insulation, a likely common partial application, see Table 7.7 & 7.9 -Runs 3,7,11,15) gives the least satisfactory results compared with the other construction options which are examined.

In summary, the hypothesis, that *for the temperate climate regions of Australia the presentation of advice for energy-efficient house design in the form of rules-of-thumb associated with the concept of the solar-efficient prototype is inadequate and in many circumstances can direct designers away from more applicable solutions* has been satisfactorily demonstrated.

8.2 Discussion

An enduring, faith-like, belief appears to have developed that the rules-of-thumb based on the *solar-efficient* prototype will provide satisfactory design results if correctly applied. The advocates of this practice, while admitting the complex nature of the issue, appear to presume that the rules are already informed by occupancy, economic, cultural/social and other contextual effects and deal satisfactorily with the objectives (largely unstated) of energy-efficient housing. The methodology adopted in this thesis of taking a fundamental multi-dimensional view of the problem has enabled the logic of these presumptions to be questioned.

For Australian temperate climate regions the rules-of-thumb are held to collectively describe the elements of a common *solar-efficient* energy-efficient house. The main features of this prototype house are that;

- the buildings should be sited to maximise solar access to north-facing living area windows for winter sun penetration. All windows shall have adequate shading for summer
- construction materials of high thermal mass should be used
- walls and ceilings are to be insulated.

The rules are presented as having universal application (in temperate regions) and as being a necessary condition for achieving energy-efficiency. The application of the rules can be depicted by the equation below where A, B, C, D, etc represent each rule.

$$A + B + C + D + \ldots.. \equiv Energy\_EfficientDwelling$$

In many (possibly most) instances, however, some of the rules are not possible to apply (for example, if solar access is limited), or not economically viable (for example, brick construction and a sloping site), or conflict with other goals (for example, social conventions, privacy, views, cost, comfort). In these cases the equation may be more like,

$$A + B + [notC] + [partD] + \ldots.. = ?Dwelling$$

Given the lack of guidance on prioritising the rules (for example, is thermal insulation more important than thermal mass) and the interdependence of the rules (for example, the relationship between north facing glazing, thermal mass, occupant behaviour and energy use) casual explanations informing the effects of rule variations as a function of context may be not possible. A situation of part compliance, as demonstrated in Chapter 7, can therefore lead to solutions which are less satisfactory when measured against various energy-efficiency goals than other available solutions.

If the total number of houses which have received a *Five Star Design Rating* throughout New South Wales, Victoria and South Australia since the introduction of the scheme in1985 is an indication (less than 1000[1]), then designers, builders and the public can be seen to have largely ignored or rejected the rules-of-thumb advice. Further evidence of disregarding, or perhaps a selection of the advice, may be deduced by a critical examination of the photographs of houses which are included in many of the publications giving energy-efficient design advice. In two popular and widely circulated government sponsored publications (Department of Housing and Urban Development,

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[1] Personal communication S.A., Energy Information Centre, 1995

1995; National Office of Local Government, no date) most of the houses depicted can be seen to depart in some instance from the rules-of-thumb for the *solar-efficient* prototype which the publication itself promotes, for example, in having lightweight construction, lack of shading to windows, substantial east/west windows, etc. If this is so, why has design advice persisted in this limited manner for so long? Two reasons can be proposed, both linked to the feeling that the rules-of-thumb have a certain intuitive tidiness. First, the clear cultural perception that heavyweight, "solid", buildings are better than other forms of construction, and secondly, that the climatically interactive or "passive" design approach *must* be better for the environment. Although cultural perceptions are gradually changing (consider, for example, the work of Glenn Murcutt and others who design using lightweight construction), the work to demonstrate that a range of environmentally responsible building solutions is possible is yet to be done.

Even if the majority of key stakeholders appear to reject the application of the rules-of-thumb, public information and public policy on energy-efficient housing design is heavily influenced by the approach.

The pervasiveness of the strategy is emphasised in the explanation of the approach to *Design for Climate* in the AMCORD document,

> *"The design approach adopted by AMCORD assumes the availability of solar access, even though it is recognised that this may not always be the case.....Where solar access is not available or possible......a range of design techniques will be necessary......The approach also focuses on "passive" rather than "active" design responses....and variations on recommended design approaches may be necessary if, for example, air conditioning is to be assumed..."* (Department of Housing and Regional Development, 1995 p188)

While admitting the shortcomings of the approach no design advice is offered to suggest alternative acceptable solutions for what is the norm for the majority of urban housing developments in the temperate regions of Australia; that is where solar access is limited and cannot be guaranteed and heating and cooling devices are installed in most dwellings.

The methodology adopted in the proposed Australian National Home Energy Rating Scheme (NatHERS) involving the rating of a dwelling (really the building envelope), based on the sum heating & cooling energy load (that is, excluding a consideration of plant efficiencies and fuel types), also owes much to the *solar-efficient* prototype approach. The scheme through its decision model is "designed" to demonstrate that this solution is preferred. Since issues such as total primary energy consumption (for heating and cooling), greenhouse gas emission, capital and life-cycle costs and many other relevant requirements are in fact not directly addressed in the scheme, the level of built-in ignorance-in-kind is likely to be high. The publicity about the scheme, however, presents a different picture.

> *"The Nationwide House Energy Rating Scheme (NatHERS) will give houses a rating of up to five stars, according to their design, heating and cooling energy requirements. The scheme will reduce household energy use and greenhouse gas emissions by providing information on the design and selection of cost-effective energy-efficient housing."*[2] *[my underlining]*

The success of such a scheme will depend on the extent to which all the objectives which might be perceived as being relevant, but which are not addressed by the scheme, are noticed, and taken to be important.

Figures 8.1 to 8.4 illustrate the affects of the proposed application of the scheme and also some potential problems.

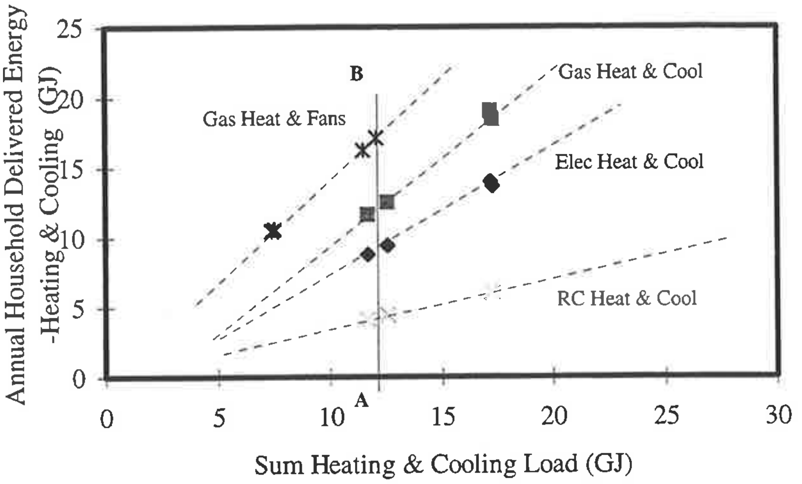

Figure 8.1: NatHERS Criteria (Sum Heating & Cooling Load) vs Annual Delivered Energy-Melbourne for a Variety of Heat/Cooling Plant Combinations

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[2] Quoted from Innovation, No.12, p.24, a newsletter of CSIRO, Division of Building, Construction and Engineering. Information attributed to the Commonwealth Department of Primary Industries and Energy, Energy Efficiency Branch, Canberra.

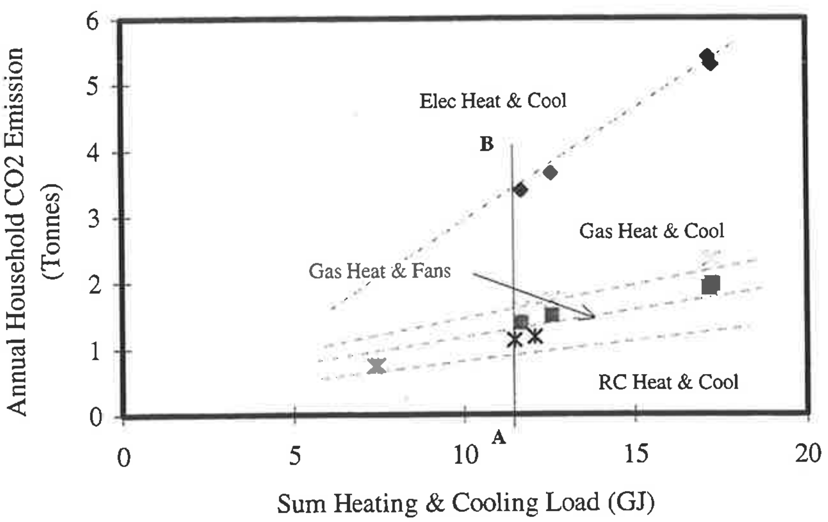


Figure 8.2: NatHERS Criteria (Sum Heating & Cooling Load) vs Net Benefits Based on CO_2 Emissions-Melbourne for a Variety of Heat/Cooling Plant Combinations

Figures 8.1 and 8.2 show "household energy use" and "CO_2 emission" plotted against the NatHERS criteria of the sum of heating and cooling load. As demonstrated by the example, line A-B, houses may achieve the same rating but in practice could have very different annual household delivered energy and CO_2 emission results depending on the plant installed. Figures 8.3 and 8.4 show that, given the large spread of results, a meaningful relationship between the total load and the net benefits using multi-criteria analysis or relative life-cycle costs cannot be determined. Since it is likely that the users will ultimately assess the scheme, at least intuitively, on these latter criteria it is prone to failure; houses receiving the same rating could have very different actual performance measured against these objectives.

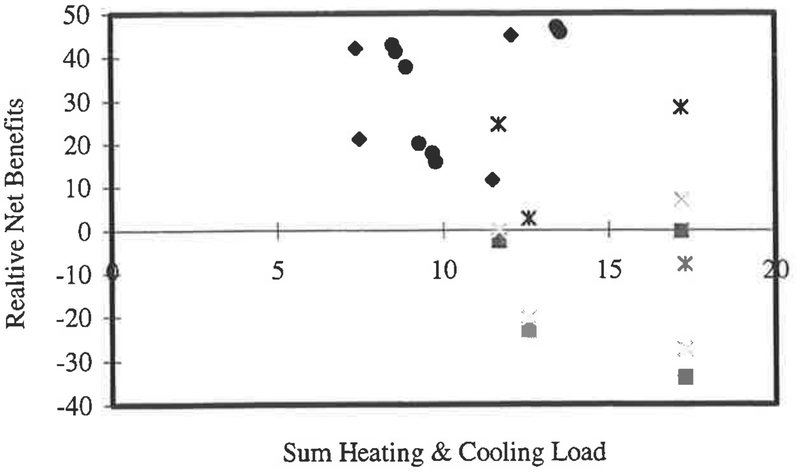


Figure 8.3: NatHERS Criteria (Sum Heating & Cooling Load) vs Net Benefits *Energy-Efficient* "Type" House-Melbourne (using objective weightings Table 7.2)

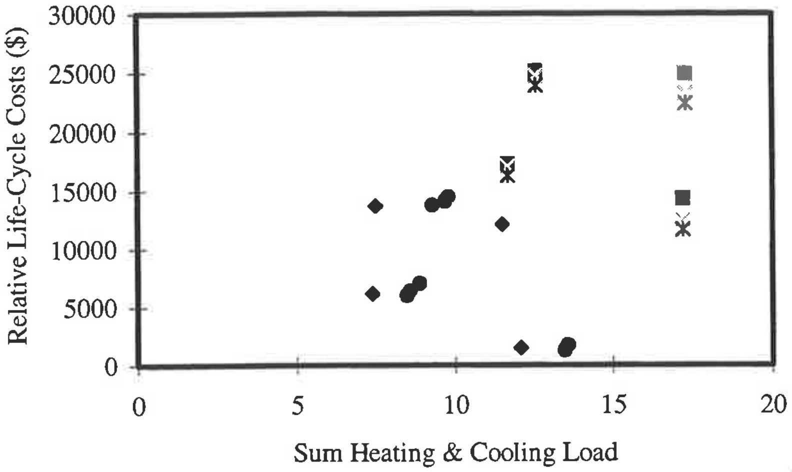


Figure 8.4: NatHERS Criteria (Sum Heating & Cooling Load) vs Life-Cycle Costs *Energy-Efficient* "Type" House-Melbourne

8.3 Indications for Future Research

Although it is not the aim of this thesis to research possible means of imparting adequate design advice, a potential way forward would include the presentation of a *variety* of prototypes designed to satisfy a range of *specific* contexts. However, because each house design problem is likely to be unique, and virtually none is only an energy-related problem, no prototype can validly indicate the solution to a particular situation, unless contained within the prototype description is sufficient information to identify that the problem resolved by the prototype is, in all relevant aspects, virtually identical to the problem at hand. In providing design advice the fundamentally multi-dimensional nature of the issue must be recognised. Future work in this area must therefore be founded on clear statements of objectives; it must include all key factors, it must account for householder preferences, and it must be presented in a way that, where objectives conflict, the trade-off decisions are transparent. The methodologies adopted in this thesis, that of identifying the perceived scope of the problem from a historical perspective, analysing the possible impact of proposed design advice from a theoretical point of view (using an ignorance analysis) and subjecting proposed solutions to computational evaluation has proved a useful procedure. Developed in this way design advice could lead to a range of energy-efficient houses for the Australian temperate regions which are appropriate to the context. All energy related design advice must serve this end.

Dean Hawkes (1996) in closing a Chapter entitled *Types, norms and habit in environmental design* seems to have reached the same conclusion from a different direction.

> *The search should be for the most appropriate solution to each particular set of problems. Within the hypothetico-analytical scheme of design, the first step would be to examine the store of stereotypes rather than simply to accept a single current notion about the nature of the solution. A process of evaluation would suggest the area in which the solution lay and the design would proceed from this. The result would be a richness of solutions inspired by the particular nature of each problem and the achievement of building science would find its true place within a proper understanding of the nature of design.* (Hawkes, 1996, p55)

Nevertheless, we must always be mindful of the words of the poet.......

In this world our colossal immodesty
has plundered and poisoned, it is possible
    You still might save us, who by now have
    learned this: that scientists, to be truthful,

must remind us to take all they say as a
tall story, that abhorred in Heav'ns are all
    self-proclaimed poets who, to wow an
    audience, utter some resonant lie.

W.H. Auden (1968). from Ode to Terminus, in City Without Walls and Other Poems
London: Faber and Faber Ltd

REFERENCES

ABARE. (1991). Projections of Energy Demand and Supply- Australia 1990-91 to 2004-05. Canberra: Australian Bureau of Agricultural and Resource Economics.

ABS. (1978,June). **Survey of Domestic Appliance and Energy Usage, Tasmania**. Hobart: Australian Bureau of Statistics.

ABS. (1979, April). **Domestic Appliance and Energy Usage: A Technical Analysis, South Australia**. Adelaide: Australian Bureau of Statistics.

ABS. (1984). **National Energy Survey Household Energy Consumption: Australia 1982-83**. Canberra: Australia Bureau of Statistics.

ABS. (1988). National Energy Survey: Annual Consumption of Reticulated Energy by Households, Australia 1985-86. Canberra: Australian Bureau of Statistics.

ABS. (1990). **Household Expenditure Survey, Australia. Summary of Results** Canberra: Australian Bureau of Statistics. (Catalogue No. 6530.0).

ABS. (1994a). **Environmental Issues: People's Views and Practices**. Canberra: Australian Bureau of Statistics. (Catalogue No.4602.0)

ACA. (1991). **The Energy Guide**. Canberra: Australian Government and Australian Consumers' Association.

Alexander, C. (1964). **Notes on the Synthesis of Form**. Cambridge, Mass.: Harvard University Press.

Alexander, L. G. (no date). Summertime Temperatures in Australian Houses. Unpublished Report (circa 1954).

Architects Advisory Service. (circa 1982). **Housing Handbook: Architects Guide for House Buyers and Builders**. Adelaide: RAIA-Architects Advisory Service.

Aronin, J. E. (1953). **Climate and Architecture**. New York: Reinhold.

ASHRAE. (1974). **ASHRAE Comfort Standard 55-74**. New York: American Society of Heating, Refrigeration and Air-Conditioning Engineers.

ASHRAE. (1989). **Handbook of Fundamentals (SI)**. New York: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. (1990). **Energy Efficient Design of New Low-Rise Residential Buildings** Atlanta: American Society of Heating Refrigeration and Air-Conditioning Engineers.

Asimow, M. (1962). **Introduction to Design**. Englewood Cliffs N.J.: Prentice-Hall.

Auliciems, A. (1983). Psycho-physiological criteria for global thermal zones of building design. **International Journal of Biometeorolgy**(2), 69-86.

Ballantyne, E. R. (1975). Energy Costs of Dwellings. In **Proc. Fifth Australian Building Research Congress** Melbourne.

Ballantyne, E. R., Barned, J. R., & Spencer, J. W. (1967). Environment Assessment of Acclimatized Caucasian Subjects at Port Moresby, Papua. In **Proc. of Third Australian Building Research Congress** (pp. 205-208).

Ballantyne, E. R., Hill, R. K., & Spencer, J. W. (1977). Probit Analysis of Thermal Sensation Assessments. **International Journal of Biometeorolgy**(1), 29-43.

Ballantyne, E. R., Hill, R. K., Spencer, J. W., & Bartlett, N. R. (1979). **A Survey of Thermal Sensation in Port Moresby, P.N.G** (DBR Tech.Pap.(Second Series) No.32). Melbourne: CSIRO.

Ballantyne, E. R., & Spencer, J. W. (1969). Solar Radiation Incident on Building Surfaces and Solar Heat Gains Through Windows. In **Symposium Environmental Physics as Applied to Buildings in the Tropics** (Vol. II, pp. c1-c29). Roorkee, India: Central Building Research Institute.

Ballantyne, E. R., & Spencer, J. W. (1972). Climate and Comfort in a Humid Tropical Area. **Build International**(July/August), 214-219.

Ballinger, J. A. (1982). **A Report to the Australian Housing Research Council on the Thermal Performance of the Solarch Experimental House Mark I, Fowlers Gap, New South Wales** (AHRC Project 22). Sydney: The University of New South Wales.

Ballinger, J. A. (1985). **Passive Solar Energy Housing for Sydney Growth Areas** (NERDDC Project 275). Sydney: The University of New South Wales.

Ballinger, J. A., Prasad, D. K., & Cassell, D. J. (1992). **Energy Efficient Housing for New South Wales**. Sydney: NSW Office of Energy.

Markham, S. F. (1944. **Climate and the Energy of Nations**. London: Oxford University Press.

Ballinger, J., Samuels, R., Coldicutt, S., Williamson, T. J., & D'Cruz, N. (1991).**A National Evaluation of Energy Efficient Houses, ERDC Project No. 1274, Final Report**. Sydney: National Solar Architecture Research Unit, University of New South Wales.

Banham, R. (1969). **The Architecture of the Well-Tempered Environment**. London: The Architectural Press.

Bareither, H. D., Fleming, A. N., & Alberty, B. E. (1948). **Temperature and Heat Loss Characteristics of Concrete Floors Laid on the Ground** (Research Report 48-1 by Small Homes Council and the Dept. of Mechanical Engineering). Illinois: University of Illinois.

Barned, J. R. (1946). **Thermal Conductivities of Building Materials** (DBR Report R2). Melbourne: CSIRO, Division of Building Research.

Barned, J. R., & O'Brien, L. F. (1970).**Thermal Conductivity of Building Materials** (DBR Report R2(Revised)). Melbourne: CSIRO, Division of Building Research.

Bautovich, B. C., & Muncey, R. W. (1961). **House and Domestic Hot Water Heating** (DBR Report of Sponsored Research for thr State Electricity Commission of Victoria). Melbourne: CSIRO, Division of Building Research.

Baverstock, G., & Paolino, S. (1986). **Low Energy Buildings in Australia: A Design Manual for Architects and Builders** (Vol. 1, Residential Buildings). Western Australia: Graphic Systems.

Beale, R. (1978,March). Government and Energy Conservation Measures in Buildings-Some Overseas Examples. In **Proc. of Conference Energy Conservation in the Built Environment** (pp. 228-238). Sydney: Department of Environment, Housing and Community Development.

Bedford, T. (1936). **Report of the Industrial Health Research Board: No 76. The Warmth Factor in Comfort at Work**. London: H.M.S.O.

Bloomfield, D. (1985). Appraisal Techniques for Methods of Calculating the Thermal Performance of Buildings. **Building Services Engineering Research & Technology**(1), 13-20.

Brookfield, S. D. (1987). **Developing Critical Thinkers**. San Francisco and London: Jossey-Bass.

Building Performance Research Unit. (1972). **Building Performance**. London: Applied Science. (University of Strathclyde, School of Architecture)

Building Research and Development Committee. (1952,Dec). **Building Research in Australia 1950-1952** (Second Report). Melbourne: Commonwealth Department of Works.

Building Research Laboratory-CSIRO. (1949,July). **Fifth Annual Report**. Melbourne: Commonwealth of Australia.

Bunning, W. (1945). **Houses in the Sun: The Past, Present and Future of Australian Houses**. Sydney: Nesbit.

Busch, J. F. (1992). A Tale of Two Populations: Thermal Comfort in Air-conditioned and Naturally Ventilated Offices in Thailand. **Energy and Buildings**, 235-249.

Cassell, D. J., & Ballinger, J. A. (1996). The Development and Capabilities of the Nationwide House Energy Rating Scheme. In **Proc. of Conference-Second National Energy Efficient Building and Planning Seminar** (pp. 1-6). Wollongong: Paraclete Building Consultants.

CEBS. (1949). **Design for Climate: Some Notes on the Design of Domestic Buildings for the Hot Arid and Hot Humid Climates of Australia** (Vol. N.S.B.1). Sydney: Commonwealth Experimental Building Station.

CEBS. (1951). **Design for Climate II: Some Notes on the Design of Dwellings for the Temperate Regions of Australia** (Vol. N.S.B.21). Sydney: Commonwealth Experimental Building Station.

Clark, J. A., & Forrest, I. (1978). **ABACUS Occasional Paper: 61. Validation of the ESP Thermal Simulation Program**. Glasgow: University of Strathclyde.

Cloher, D. V. (1981). **Domestic Insulation and Savings in Energy Consumption Domestic Space Heating and Cooling: Adelaide 1776/77 and 1979/80**. Adelaide: S.A. Dept Mines and Energy.

Cohon, J. L. (1978). **Multiobjective Programming and Planning**. New York: Academic Press.

Coldicutt, A. B. (1976). **A Direct Method of Calculating Transient Heat Flow Through Building Elements**. (Internal Report), Melbourne: Department of Architecture and Building, University of Melbourne.

Coldicutt, A. B. (1978a). **Computer Calculations of Thermal Performance of Buildings**. (Internal Report), Melbourne: Department of Architecture and Building, University of Melbourne.

Coldicutt, A. B., Coldicutt, E., & Coldicutt, S. (1978b). **An Investigation of the Thermal Performance and Life-time Costs of Public Housing in Victoria and Tasmania** (AHRC Project No.57). Melbourne: Australian Housing Research Council.

Coldicutt, A. B., Coldicutt, S., & Coldicutt, E. B. (No date). **Energy Requirements, Energy Use and User Satisfaction in Victorian Public Housing**. Canberra: Australian Housing Research Council.

Coldicutt, A. B., Coldicutt, S., & Curzon-Siggers, J. H. (1977). **Solar Control Design Aids**. Melbourne: Department of Architecture and Building, University of Melbourne.

Coldicutt, A. B., Coldicutt, S., et al. (1985). **Thermal performance of housing units in Queensland** (Australian Housing Research Council - Project 58). Melbourne: University of Melbourne.

Coldicutt, A. B., Isaacs, A., Moschini, F., & Coldicutt, E. (undated). **Energy Requirements, Energy Use and User Satisfaction in Tasmanian Public Housing** (AHRC Project No.106). Canberra: Australian Housing Research Council.

Coldicutt, A. B., & White, D. (1977). Low Energy Cost-Effective Dwellings for Melbourne. In **Proc. ANZAScA Conference** (p. 35). Melbourne: University of Melbourne.

Coldicutt, S., & Williamson, T. J. (1993). Relevance and Error. In G. Ryan (Ed.), **Research and Development in Problem-Based Learning Network** (pp. 265-277). Campbelltown: University of New South Wales.

Coldicutt, S. (1992). Ignorance and Knowledge Regarding Human's Purposeful Interventions in Environments. **Knowledge and Policy**, 3-28.

Coldicutt, S., & Williamson, T. J. (1991). An Ignorance-based Approach to Fenestration and Shading Design. In G. Woodbury (Ed.), **The Technology of Design, Proceedings of Australian and New Zealand Architectural Science Association Conference** (pp. 111-117). Adelaide: Department of Architecture, The University of Adelaide.

Cole, G., & Parnell, M. (1983). **Australian Solar Houses**, Leura: Second Back Row Press.

Commonwealth of Australia. (1974). **Australian Housing Standards Conference**. Canberra: AGPS.

Conservation of Resources Committee. (1978). **Second Progress Report Upon the Use of Insulation in Buildings and Conservation of Energy Generally** (March ed.). Melbourne: Legislative Council Victoria.

Crossley, D. J. (1980). **AES Working Paper 1/80. Social Factors Affecting Energy Use and Conservation in the Home**. Brisbane: School of Australian Environmental Studies, Griffith University.

Crossley, D. J. (1981). **Environmental Paper No.3. Non-technical Barriers to Energy Conservation by Individual Households**. Melbourne: Graduate School of Environmental Science, Monash University.

Dasgupta, A. K., & Pearce, D. W. (1972). **Cost-Benefit Analysis:Theory and Practice**. London: MacMillan Press.

D'Cruz, N. (1984).Multicriteria Performance Model for Building Design. Unpublished Ph.D. Dissertation, Department of Architectural Science, University of Sydney.

deDear, R. J., Leow, K. G., & Foo, S. C. (1991). Thermal Comfort in the Hmid Tropics: Field Experiments in Air Conditioned and Naturally Ventilated Buildings in Singapore. **International Journal of Biometeorolgy**(4), 259-265.

Delsante, A. E. (1990). A Comparison Between Measured and Calculated Heat Losses Through a Slab-on-Ground Floor. **Building and Environment**, **25**(1), 25-31.

Delsante, A. E., & Spencer, J. W. (1994). Calculation of the Proportion of Sky Seen by Windows with Finite Horizontal and Vertical Projections. **Solar Energy**(6), 547-551.

Den Ouden, H. C. (1980). **Low Energy Housing in South Australia** (Discussion Paper). Department of Mines and Energy.

Department of Construction. (1977). **Energy Use in Government Housing**. Canberra: National Capital Development Commission.

Department of Housing and Construction. (1985). **Building Information Series. Energy Efficient Australian Housing**. Canberra: AGPS.

Department of Housing and Regional Development. (1995). **AMCORD-A National Resource Document for Residential Development.** Canberra: AGPS.

Department of National Development. (1979). **Australian Energy Policy-A Review**. Canberra: AGPS.

De Zurko E.R. (1957). **Origins of Functional Theory**. New York: Columbia University Press.

d'Have, R. (1981). The Relative Importance of Performance Attributes and the Comparison of Designs. In **The Relative Significance of Different Performance Requirements** (Working Papers of CIB Working Commission W60:The Performance Concept in Building, pp. 7-11). Princes Risborough, UK: International Council for Building Research Studies and Documentation.

Division of Building Research-CSIRO. (1950,July). **Sixth Annual Report**. Melbourne: Commonwealth of Australia.

Division of Building Research-CSIRO. (1957). **Annual Report 1956-57**. Melbourne: Commonwealth of Australia.

Division of Building Research-CSIRO. (1960). **Annual Report 1958-59**. Melbourne: Commonwealth of Australia.

Division of Building Research-CSIRO. (1962). **Annual Report 1961-62**. Melbourne: Commonwealth of Australia.

Division of Mechanical Engineering-CSIRO. (1976). **Annual Report of Division:1974-75**. Melbourne: Commonwealth of Australia.

Drysdale, J. W. (1947). **Climate and House Design: Summary of Investigations 1945-1947** (Duplicated Document No.21). Sydney: Commonwealth Experimental Building Station.

Drysdale, J. W. (1950). **The Thermal Behaviour of Dwellings** (Technical Study 34). Sydney: Commonwealth Experimental Buildings Station, Dept. of Works and Housing.

Drysdale, J. W. (1951). **Climate and Design of Buildings-Physiological Study No.3** (Technical Study No.35). Sydney: Commonwealth Experimental Building Station.

Drysdale, J. W. (1952). **Designing Houses for Australian Climates** (1st ed., Bulletin No.6). Sydney: Commonwealth Experimental Building Station.

E.I.C. (1993). **Creating an Energy Efficient Home.** Adelaide: Energy Information Centre, Department of Mines and Energy.

El-Refaie, M.F. (1987). Performance Analysis of External Shading Devices, **Building and Environment**, **22**(4), 269-284.

Energy Victoria. (1994). **Energy Efficient Housing Manual - Design Guidelines and Case Studies.** Melbourne: Energy Victoria.

Eppel, H., Lomas, K. J., & Martin, C. (1993). **Empirical Validation in International Energy Agency Annex 21/TAsk 12: Final Report**. Leicester, UK: De Montfort University.

ETSA. (1992). A Survey of Household Electrical Appliances: Penetration and Usage. Unpublished Internal Report of Electricity Trust of South Australia.

Etzion, Y. (1991). An Improved Solar Shading Design Tool. **Building and Environment**, Fanger, P. O. (1972). **Thermal Comfort: analysis and applications in environmental engineering**. New York: McGraw-Hill Book Co.

Foucault, M. (1989). **The Archaeology of Knowledge**. London: Routledge.

Gadamer, H.-G. (1977). **Philosophical hermeneutics** (Translated and edited by D E Linge). Berkeley: University of California Press.

Gagge, A. P., Fobelets, A. P., & Berglund, L. G. (1986). A Standard Predictive Index for Human Response to the Thermal Environment. **ASHRAE Transactions**(2B), 709-731.

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**(5), 247-262.

Gas & Fuel Corporation and Sustainable Solutions. (1992). A Study of Factors Influencing Housing Energy Efficiency. Melbourne.

Givoni, B. (1981). **Man, Climate & Architecture** (2nd ed.). New York: Van Nostrand Reinhold Co.

GMI. (1985). **Five Star Rating-Design and Construction Manual for Energy Efficient Houses**. GMI Council of Australia.

Greenland, J., & Szokolay, S.V. (1985). **Passive Solar Design in Australia.** ACT: Royal Australian Institute of Architects.

Griffiths, A. (1990). **National Energy Management**. Canberra: AGPS.

Gupta, C. L., Spencer, J. W., & Muncey, R. W. R. (1970). A Conceptual Survey of Computer-Orientated Thermal Calculation Methods. In **Proc. of First Symposium on the Use of Computers for Environmental Engineering Related to Buildings** (Nov-Dec). Gaithersburg, Maryland

Haider, S. G., & Khachaturian, N. (1972). A Systems Approach for the Evaluation of Performance of Buildings in Design Process. In **Performance Concept in Buildings** (Vol. 1, National Bureau of Standards Special Publication 361: Proceedings of the Joint RILEM-ASTM-CIB Symposium, pp. 237-248). Philadelphia: US Department of Commerce.

Handler, A. B. (1970). **Systems Approach to Architecture**. New York: Elsevier Pub.Co.

Hawkes, D. (1996). **The Environmental Tradition**. London: E & FN Spon.

Heating and Ventilation (Reconstruction) Committee. (1945). **Heating and Ventilation of Dwellings** (Post-War Building Studies Report No.19 of the Building Research Board of the Department of Scientific and Industrial Research). London: H.M.S.O. for the Ministry of Works.

Hindmarsh, M. E., & MacPherson, R. K. (1962). Thermal Comfort in Australia. **Australian Journal of Science**(8), 335-339.

Hollo, N. (1995). **Warm House Cool House**. Sydney: Choice Books.

Houghton, F. C., & Yagloglou, C. P. (1923a). Determination of the Comfort Zone. **Transactions of the American Society of Heating and Ventilating Engineers**, 361-384.

Houghton, F. C., & Yagloglou, C. P. (1923b). Determining Lines of Equal Comfort. **Transactions of the American Society of Heating and Ventilating Engineers**, 163-176.

Howard, J. S. (1966). Ventilation Measurements in Houses and the Influence of Wall Ventilators. **Building Science**, 251-257.

Humphreys, M. A. (1975). **Field studies in thermal comfort compared and applied** (CP 76/75). Garston: UK Building Research Establishment.

Humphreys, M. A. (1978). **Outdoors Temperatures and Comfort Indoors** (CP 53/78). Garston: UK Building Research Establishment.

Humphreys, M. A. (1981). The Dependence of Comfortable Temperatures Upon Indoor and Outdoor Climates. In K. Cena & J. A. Clark (Eds.), **Studies in Environmental Science: Bioengineering, Thermal Physiology and Comfort** (pp. 229-250). Amsterdam: Elsevier Scientific Publishing Co.

Humphreys, M. A. (1995). Thermal Comfort Temperatures and the Habits of Hobbits. In F. Nicol, M. Humphreys, O. Sykes, & S. Roaf (Eds.), **Standards For Thermal Comfort: Indoor Air Temperature Standards for thr 21st Century** (pp. 3-13). London: E & FN Spon.

Huntington, E. (1915). **Civilization and Climate**. New Haven: Yale University Press.

Isaacs, A. (1996). NatHERS Heating/Cooling Data Base. Personal Communication.

ISO (International Organization for Standardization). (1984). **Moderate thermal environments - determination of the P.M.V. and P.P.D. indices and specification of thermal comfort** (1st ed.). Geneva: ISO.

Jenkins, T., & James, J. (1978). **The Wise House**. Perth: Rigby Ltd.

Judkoff, R., & Neymark, J. (1993). **Building Energy Simulation Test (BESTTEST) and Diagnostic Method: A Procedure for Testing the Ability of Whole Building Energy Simulation Programs to Thermally Model the Building Fabric** (IEA Technical Report). Golden CO.: NREL.

Judkoff, R., Wortman, D., O'Doherty, &Burch, J. (1983). **A Methodology for Validating Building Energy Analysis Simulations** (SERI/TR-254-1508 Report ed.). Golden, CO.

Kalma, J. D., & Millington, R. J. (1978). An Australian Perspective on Energy Use in the Built Environment. In **Proc. of Conference: Energy Conservation in the Built Environment** (pp. 17-21). Sydney: Department of Environment, Housing and Community Development.

Keough, J. J. (1951). **Selected Australian Climatic Data for Use in Building Design** (Technical Report No.36). Sydney: Commonwealth Experimental Building Station.

Kerby, J. (1975). Climate and Housing in Adelaide: A Survey of Attitudes, **In Proc. Fifth Australian Building Research Congress**, Melbourne.

Kerby, J. (1979a). Climatic Suitability, Indoor Climate and Household Energy Consumption: A Study of Suburban Houses in Adelaide, South Australia. Unpublished Ph.D. Thesis, Dept of Geography, The University of Adelaide.

Kerby, J. (1979b). Does Ceiling Insulation Really Save Energy? **Thermal Insulation**(4), 18-20.

Layton, R. (1992). The Influence of Air Movement on Comfort in Housing for the Humid Tropics. Unpublished B.Arch (Hons) Thesis, Department of Architecture, The University of Adelaide.

Le Corbusier. (1927). **Five Points of New Architecture**. Quoted in T. and C. Benton, D. Sharp (eds) (1975). **Form and Function: A Source Book for the History of Architecture and Design 1890-1937**. London: Crosby Lockwood Staples. (p153)

Lee, D. H. K. (1940). **University of Queensland Papers: 5. A Basis for the Study of Man's Reaction to Tropical Climates** (Vol. 1, Department of Physiology). Brisbane: University of Queensland.

Lee, D. H. K. (1944). **University of Queensland Papers: 8. Physiological Principles in Tropical Housing, with Especial Reference to Queensland** (Vol. 1, Department of Physiology). Brisbane: University of Queensland.

Lomas, K. J. (1994). Thermal Program Validation: The Current Status. In **Proceedings of Conference, Building Environmental Performance: Facing the Future** (pp. 73-82). University of York: BEPAC.

Loudon, A. G. (1968). **BRS Current Papers: CP 47/68. Summertime temperatures in buildings without air-conditioning**. UK: Building Research Station.

Luxton, R. E. (1982). The Need for Energy Management in Buildings. In P. J. Walsh (Ed.), **Proc. of Conference-Energy Management in Buildings: Progress and Prospects**. Adelaide: S.A. Energy in Buildings Consultative Committee and Building Science Forum.

MacFarlane, W. V. (1958). Thermal Comfort Zones. **Architectural Science Review**(Nov), 1-14.

Markham, S. F. (1944). **Climate and the Energy of Nations**. London: Oxford University Press.

Markus, T. A., & Morris, E. N. (1980). **Buildings, climate and energy**. London: Pitman.

Marshall, A. (1958). Observations of Indoor Discomfort Under Conditions of Dry Heat, **Proc. of the Royal Geographical Society Aust./Asia (S.A. Branch)** (58), 23-34.

Marshall, A. (1973). Energy and How We Live, **Proc. of Australian-UNESCO Seminar**, (pp. 237-257), Flinders University of South Australia: Committee for Man and the Biosphere.

McCluney, R. (1990). Awning Shading Algorithm Update. **ASHRAE Transactions**(1), 34-38.

McCluney, R. (1995). Software for Window Solar Gain Analysis. In J. W. Mitchell & W. A. Beckman (Eds.), **Proceedings of Conference Building Simulation '95** (pp. 653-660). Madison,Wisconsin: International Building Performance Simulation Association.

McQuiston, F. C., & Spitler, J. D. (1992). **Cooling and Heating Load Calculations** (2nd ed.). New York: American Society of Heating, Refrigeration and Air-Conditioning Engineers.

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens III, W. W. (1972a). **The Limits to Growth**. Washington, D.C.: Potomac Associates.

McCullough, E. A., Zbikowski, P. J., & Jones, B. W. (1987). Measurement and Prediction of the Insulation Provided by Bedding Systems. **ASHRAE Transactions**, 1055-1065.

Milbank, N. O., & Harrington-Lynn, J. (1974, May). Thermal Response and the Admittance Procedure. **Building Services Engineering Research & Technology**, 38-51.

Mills, C. A. (1944). **Climate Makes the Man**. London: Gollanz.

Morse, R. N. & Kowalczewski, J. J. (1967). A Rational Basis for Human Thermal Comfort. **ASHRAE Journal**, 9(9), 72-77.

Muncey, R. W. (1953). The Calculation of Temperatures Inside Buildings Having Variable External Conditions, **Australian Journal of Applied Science**(2), 189-196.

Muncey, R. W. (1954). The temperature of the Foot and its Thermal comfort. **Australian Journal of Applied Science**, 36-40. (CSIRO,DBR Reprint No.40)

Muncey, R. W. (1955). Optimum Thickness of Insulation for Australian Houses. **Australian Journal of Applied Science**(4), 486-495.

Muncey, R. W. (1963). Thermal Response of a Building to Sudden Changes of Temperature or Heat Flow. **Australian Journal of Applied Science**(2), 123-128.

Muncey, R. W., & Holden, T. S. (1959). **The Influences of Air Temperatures Near the Floor on the Temperatures and Comfort of the Human Foot** (DBR Technical Paper No.5). Melbourne: CSIRO, Division of Building Research.

Muncey, R. W., & Holden, T. S. (1967). Calculation of Internal Temperature-A Demonstration Project. **Building Science**, 191-196. (CSIRO, DBR Reprint No.412)

Muncey, R. W. R., Spencer, J. W., & Gupta, C. L. (1970). Methods for Thermal Calculations Using Total Building Response Factors. In **Proc. of First Symposium on the Use of Computers for Environmental Engineering Related to Buildings** (Nov-Dec). Gaithersburg, Maryland USA: NBS, ASHRAE & APEC.

National Office of Local Government, (nodate). **Australia's Guide to Good Residential Design**, Canberra: Department of the Environment, Sport and Territories. (probably 1996)

Naylor, T. H., & Finger, J. M. (1967, Oct.). Verification of Computer Simulation Models. **Management Science**(2), b92-b101.

NCDC. (1977). **Low Energy House Design for Temperate Climates**. Canberra: National Capital Development Commission.

NCDC. (1977,September). Energy Conservation in Housing. National Capital Development Commission. (An information pamphlet for home buyers and home builders)

N.G.S.C. (Dec,1992). **National Greenhouse Response Strategy**. Canberra: National Greenhouse Response Committee, AGPS.

Nicol, F., Jamy, G. N., Sykes, O., Humphreys, M., Roaf, S., & Hancock, M. (1994). **A Survey of Thermal Comfort in Pakistan: Towards New Indoor Comfort Standards** (Final Report). Oxford: Oxford Brookes University, School of Architecture.

N.S.W. Department of Energy. (1988). **Five Star Home Design**. Sydney: Department of Energy.

Olgyay, V., & Olgyay, A. (1954). Appendix Report No 1-Man as a Physiological Measure in Architecture. In A. M. Cole & J. H. Orendroff (Eds.), **Application of Climatic Data to House Design** (pp. 1-20). Washington: US Government Printing Office.

Olgyay, V., & Olgyay, A. (1963). **Design With Climate**. Princeton: Princeton University Press.

Olweny, M. R. O. (1996). Designing a Satisfactory Indoor Thermal Environment with Particular Reference to Kampala, Uganda. Unpublished Master of Architectural Studies Thesis, Faculty of Architecture and Urban Design, The University of Adelaide.

Oseland, N. A. (1994). A Comparison of the Predicted and Reported Thermal Sensation Vote in Homes During Winter and Summer. **Energy and Buildings**, 45-54.

O'Sullivan, P. (1994). Energy and Architectural Form. In R.Samuels & D. K. Prasad (Eds.), **Global Warming and the Built Environment** (pp. 113-123). London: E & FN Spon.

Perez, R., Seals, R., Ineichen, P., Stewart, R., & Menicucci, D. (1987). A New Simplified Version of the Perez Diffuse Irradiance Model for Tilted Surfaces. **Solar Energy**(3), 221-231.

Phillips, R. O. (1948). **Sunshine and Shade in Australasia** (1st ed., Duplicated Document No 23). Sydney: Commonwealth Experimental Building Station.

Pilkington Environment Advisory Service. (1969). **Windows and Environment**. London: Pilkington Bros. Ltd.

Pletzer, R. K., Jones, J. W., & Hunn, B. D. (1988). **Effect of Shading Devices on Residential Energy Use in Austin, Texas**. Austin: Centre for Energy Studies, The University of Texas at Austin.

Pradhan, A. (1993). Energy Efficiency in Adelaide's Project Homes Unpublished Architectural Studies (honours) Thesis, Department of Architecture, University of Adelaide.

Pullen, S. (1995). Embodied Energy of Building Materials. Unpublished Master of Building Science Thesis, University of Adelaide, Adelaide.

Radford, A. D., & Gero, J. S. (1988). **Design by Optimization in Architecture, Building and Construction**. New York: Van Nostrand Reinhold Co.

Rao, K. R., & Ballantyne, E. R. (1970). **Some Investigations on the Sol-Air Temperature Concept** (DBR Technical Paper No.27). Melbourne: CSIRO, Division of Building Research.

Rapoport, A. (1969). **House Form and Culture**. Englewood Cliffs,N.J.: Prentice-Hall Inc.

Rawlings, B. C. (1977). Thermal Economy in Buildings. In **Conference On Energy 1977: Towards an Energy Policy for Australia, Submission of Working Parties** (20-22 July ed., pp. 216-232). Canberra: The Institution of Engineers Australia.

Rawlinsons. (1996). **Australian Construction Handbook** (14th ed.). Perth: The Rawlinsons Group.

Riordan, P. (1992). Context Relevance in Thermal Comfort Studies. Unpublished B.Arch.St.(Hons) Thesis, Department of Architecture, University of Adelaide.

Robeson, K. A., & Burton, D. R. (1975). The Effect of Air Movement on Thermal Comfort. In **Proc. of 1975 Federal AIRAH Conference**. Hobart: Australian Institute of Refrigeration, Air Conditioning and Heating. (Paper No.14)

Roennfeldt, R. J., Ballantyne, E. R., Brown, A. M., Cummine, A. J., & Van Ocken, A. (1983,May). Energy Use and Conservation in Buildings. In **Proc of Institute of Engineers, Australia National Conference:Energy 83** (pp. 316-329). Canberra: The Institute of Engineers Australia.

Rohles, F. H., & Nevins, R. G. (1971). The Nature of Thermal Comfort for Sedentary Man. **ASHRAE Transactions**, 239-246.

SADME. (1983). **Implementation Strategy for Low Energy Housing in South Australia** (A Report by Hassell Planning Consultants Pty Ltd). Adelaide: Department of Mines and Energy.

Saini, B. S. (1980). **Building in Hot Dry Climates**. Chichester, UK: Wiley.

SA Office of Energy. (1993). **South Australian Energy Flows 1991/92**. Adelaide: Department of Mines and Energy.

Schon, D. A. (1983). **The Reflective Practitioner**. New York: Basic Books.

Schumacher, E. F. (1973). **Small is Beautiful**. London: Abacus.

Smithson, M. (1988). Ignorance and Uncertainty: Emerging Paradigms. New York: Springer Verlag.

Sommer, R. (1969). **Personal Space**. Englewood Cliffs, N.J.: Prentice-Hall.

Spencer, J. W. (1960). **Solar Position and Radiation Tables: Melbourne and Other Places Near Latitude 35degS**. Melbourne: CSIRO, Division of Building Research.

Spencer, J. W. (1974). **DBR Technical Papers. Solar Tables: Solar Position and Radiation (Various Locations)**. Melbourne: CSIRO.

Standards Association of Australia. (1983). **Thermal Insulation of Dwellings-Design Guide: Part 1-Thermal Insulation of Roof/Ceiling in Dwellings Which Require Heating** (AS2627). Sydney: SAA.

Stevens, J. C., Marks, L. E., & Gagge, A. P. (1969). The Quantitative Assessment of Thermal Discomfort. **Environmental Research**, 149-165.

Stone, P. A. (1960). The Economics of Building Design. **The Journal of the Royal Statistical Society: Series A (General)**, 237-273.

Stone, P. A. (1967). **Building Design Evaluation: Costs-in-Use**. London: E & FN Spon Ltd.

Szokolay, S.V., & Sale, R.W. (1979). **The Australia and New Zealand Solar Home Book**, Sydney: Australia and New Zealand Book Co.

Treloar, G. J. (1996). **An Input-Output Model of the Embodied Energy Pathways of Australian Residential Buildings**. Paper presented at Embodied Energy Seminar. Geelong: Deakin University.

Van Straaten, J.F. (1967). **Thermal Performance of Buildings**. Amsterdam: Elsevier Pub. Co.

Vidal de la Blache, P. (1926). **Principles of Human Geography** (Translated by MT, Bingham). London: Constable Publishers.

Viollet-le-Duc E.M. (1959). **Discourses on Architecture** (Vol. 1&2, Trans. B. Bucknall). London: George Allen and Unwin. (Written Paris 1860)

Vitruvius. (1960). **Vitruvius: The Ten Books on Architecture** (Trans. MH Morgan). New York: Dover Publications Inc.

VSEC. (1990). **Solar Efficient Design for Housing: A Manual for Architects and Designers**. Melbourne: Victorian Solar Energy Council.

Walsh, P. J. (1975). Energy Requirements of Australian Dwellings for Heating and Cooling. In **Proc. of Federal AIRAH Conf.** Melbourne: Australian Institute of Refrigeration and Heating.

Walsh, P. J. (1979). Aspects of the Passive Performance of the CSIRO Low Energy Consumption House. In **Proc. of Seminar on Developing and Marketing Solar Housing in Temperate Australia**. Duntroon, ACT: The University of New South Wales.

Walsh, P. J., Gurr, T. A., & Ballantyne, E. R. (1982). **A Comparison of the Thermal Performance of Heavyweight and Lightweight Construction in Australian Dwellings**. Melbourne: CSIRO.

Walsh, P. J., & Kerby, J. S. (1990). Energy Management Programs in Australia-Past Experience and Future Prospects. In D. J. Swaine (Ed.), **Greenhouse and Energy** (pp. 398-402). Canberra: CSIRO.

Welch, L. W. (1980). Instrumentation of the CSIRO Low Energy Consumption House. In **Proc. ANZSES Symposium on Performance Monitoring of Buildings**. Sydney: The University of New South Wales.

Welch, L. W. (1983). Active Space Heating-Passive Space Heating: An Energy Comparison for the CSIRO Low Energy Consumption House. In **Proc. Solar World Congress** (pp. 89-93). Perth: ANZSES.

White, D., Sutton, P., Pears, A., Mardon, C., Dick, J., & Crow, M. (1978). **Seeds for Change: Creatively Confronting the Energy Crisis**. Melbourne: Patchwork Press.

Williamson, T. J. (1995). A Confirmation Technique for Thermal Performance Simulation Models. In J. W. Mithcell & W. A. Beckman (Eds.), **Proc. of IBPSA Conference BS'95** (pp. 268-275). Madison, WI: International Building Performance Simulation Association.

Williamson, T. J., & Coldicutt, A. B. (1974). Comparison of Performances of Conventional and Solar Houses: A Computer Simulation. In **Proc. Symposium- Utilization of Solar Energy in Dwellings**. Melbourne: Institute of Mechanical Engineers.

Williamson, T. J., & Coldicutt, S. (1986). **Comparison of evaporative cooling and refrigerative air-conditioning for dwellings in South Australia** (SENRAC Project Report). Adelaide: Department of Architecture, The University of Adelaide.

Williamson, T. J., Coldicutt, S., Ballinger, J., Samuels, R., & D'Cruz, N. (1993, March). Performance Analysis of Energy Efficient Houses in Australia. In **Proc. of CIB Working Commission W67 International Conference: Energy Efficient Building** (pp. 247-252). Stuttgart.

Williamson, T. J., Coldicutt, S., & Penny, R. E. C. (1989). **Thermal Comfort and Preferences in Housing: South and Central Australia**. Adelaide: Dept of Architecture, University of Adelaide.

Williamson, T. J., Coldicutt, S., & Penny, R. E. C. (1991). **Thermal Preferences in Housing in the Humid Tropics** (ERDC Report No.1). Canberra: Energy Research and Development Corporation.

Williamson, T. J., Coldicutt, S., & Riordan, P. (1995). Comfort, Preferences or Design Data? In F. Nicol, M. Humphreys, O. Sykes, & S. Roaf (Eds.), **Standards For Thermal Comfort: Indoor Air Temperature Standards for thr 21st Century** (pp. 50-58). London: E & FN Spon.

Williamson, T. J., & Robinson, J. (1977). Cost/Value Appraisal of Low Energy Housing. In **Proc. ANZAScA Conference** (p. 28). Melbourne: University of Melbourne.

Wilson, B., Trieu, L. H., & Bowen, B. (1993). **Energy Efficiency Trends in Australia** (ABARE Research Report 93.11). Canberra: Australian Bureau of Agricultural and Resource Economics.

Winslow, C.-E. A., Herrington, L. P., & Gagge, A. P. (1937). Physiological Reactions of the Human Body to Varying Environmental Temperatures. **American Journal of Physiology**, 1-22.

Winslow, C.-E. A., Herrington, L. P., & Gagge, A. P. (1938). Physiological Reactions and Sensations of Pleasantness Under Varying Atmospheric Conditions. **Transactions of the American Society of Heating and Ventilating Engineers**, 179-196.

Wooldridge, M. J., & Welch, L. W. (1980). A Summary of the Major Results from the First Winter of Operation of the CSIRO Low Energy House at Highett. **Australian Institute of Refrigeration AirConditioning and Heating J.**(12), 23-34.

Wright, J. R. (1968). Measurement-Key to Performance. In **Proc. of 1st Conference: Man and His Shelter** (Issued as Building Science Series 1, 1970, pp. 11-24). Washington: US Bureau of Commerce.

Wyatt, T. J. (1973). Building Economics and Energy Conservation. **International Lighting Review**, 85-92.

Xenophon. (1923). **Memorabilia and Oeconomicus** (With English translation by E.C.Marchant). London: William Heinemann.

Williamson, T., and Coldicutt, A.B., (1974) Comparison of performances of conventional and solar houses: a computer simulation.
Proceedings of the Institution of Mechanical Engineering Symposium on Solar Energy Utilization in Dwellings, Melbourne.

APPENDIX B

ASPECTS of the MATHEMATICAL BASIS of *EnCom2*

B.1 Advancing Mean Technique

The advancing mean technique, formulated by Alan (and Beth) Coldicutt (Coldicutt, 1976) is essentially a harmonic analysis method where both the 24 hour and the annual cycle frequencies are taken into account. This technique forms the basis for heat flow through opaque elements in the TEMPAL program (Coldicutt, 1978) and the *EnCom2* program.

The heat flow q_{i_t} at hour t for a building element may be written as

$$q_{i_t} = \Gamma'\left(T'_{e_{t-\delta'}} - \overline{T}_{e_t}\right) + \Gamma''\left(T_{e_{t-\delta''}} - T'_{e_t}\right) + U\left(\overline{T}_{e_t} - \overline{T}_{i_t}\right) + Y'\left(\overline{T}_{i_t} - T'_{i_{t+\Phi'}}\right) + Y''\left(T'_{i_t} - T_{i_{t+\Phi''}}\right)$$

Equation B1.1

$\overline{T}_{e_t}$ steady state mean temperature

T'_{e_t} annual harmonic temperature $\Gamma', \delta', Y', \Phi'$ relate to the annual harmonic transfer functions, transfer modulus and admittance.

T_{e_t} 24 hour temperature cycle $\Gamma'', \delta'', Y'', \Phi''$ the 24-hour transfer functions.

With sufficient accuracy $\Gamma' = Y' = U$ for most practical building elements.

Therefore

$$q_{i_t} = \Gamma''\left(T_{e_{t-\delta''}} - T'_{e_t}\right) + U\left(T'_{e_{t-\delta}} - T'_{i_{t+\Phi'}}\right) + Y''\left(T'_{i_t} - T_{i_{t+\Phi''}}\right) \qquad \text{Equation B1.2}$$

The temperature at time t T_{i_t} may therefore be estimated from

$$q_{i_{t-\Phi''}} = \Gamma''\left(T_{e_{t-(\delta''+\Phi'')}} - T'_{e_{t-\Phi''}}\right) + U\left(T'_{e_{t-\Phi''}} - T'_{i_{t+\Phi'-\Phi''}}\right) + Y''\left(T'_{i_{t-\Phi''}} - T_{i_t}\right) \qquad \text{Equation B1.3}$$

Coldicutt suggests that values may be found such that,

$$q_{i_{t-\Phi''}} = \Gamma''\left(T_{e_{t-(\delta''+\Phi'')}} - \widetilde{T}_{e_t}\right) + U\left(\widetilde{T}_{e_t} - \widetilde{T}_{i_t}\right) + Y''\left(\widetilde{T}_{i_t} - T_{i_t}\right) \qquad \text{Equation B1.4}$$

Coldicutt has shown (Coldicutt, 1976) that an advancing mean temperature $\widetilde{T}_{e_t}$ which approximates the annual harmonic temperature for a building component/element may be calculated such that,

$$\widetilde{T}_{e_t} \approx T'_{e_{t-\Phi''}} \approx T'_{e_{t-(\delta''+\Phi'')}}$$

$$\widetilde{T}_{e_t} = \widetilde{T}_{e_{t-(1+\Phi'')}} + \left(T_{e_{t-\Phi''}} - T_{e_{t-(P+\Phi'')}}\right) \Big/ P$$

Equation B1.5

and

$$\widetilde{T}_{i_t} \approx T'_{i_{t+\Phi'-\Phi''}} \approx T'_{i_{t-\Phi''}}$$

$$\widetilde{T}_{i_t} = T'_{i_{t-(1+\Phi'')}} + \left(T_{i_{t-\Phi''}} - T_{i_{t-(P+\Phi'')}}\right) \Big/ P$$

Equation B1.6

where P is assumed equal to $5\delta''$

B.2 Shading and Solar Radiation

Shading

The program SHADING uses a ray-tracing technique employing advanced vector geometry.

A plane in cartesian space may be defined by the equation,

$$Ax + By + Cz + D = 0 \quad \text{.........} \quad \text{Equation B2.1}$$

and a line may be described in vector form by,

$$r = r_o + t \bullet l \quad \text{............} \quad \text{Equation B2.2}$$

or by,

$$\begin{aligned} x &= a + l \bullet t \\ y &= b + m \bullet t \quad \text{..........} \quad \text{Equation B2.3} \\ z &= c + n \bullet t \end{aligned}$$

where l, m, n are known as the direction numbers.

The corners of an obstruction within a plane may be defined by its cartesian co-ordinates x_i, y_i, z_i

The intersection point of a line with the plane is found by substituting for x, y and z from equations B2.3 into equation B2.1 and solving for t such that

$$t = \frac{-[D + (A \bullet a + B \bullet b + C \bullet c)]}{(A \bullet l + B \bullet m + C \bullet n)} \quad \text{.......} \quad \text{Equation B2.4}$$

Consider now a point ***P*** with co-ordinates x, y, z as the origin of a ray projected as a line. This line intersecting the plane of the obstruction at some point $\boldsymbol{IP_i}$ may, or may not, pass through the obstruction itself. (See Figure B2.1) The condition when the point $\boldsymbol{IP_i}$ is within the obstruction is that,

$$\sum_{j=1}^{n} \alpha_j = 2 \bullet \pi \quad \text{..........} \quad \text{Equation B2.5}$$

Radiation on a surface

Total Radiation Received on a Surface = Direct Beam Radiation (I_{dir}) + Sky (or Diffuse) Radiation (I_{diff})+ Reflected Radiation (I_r)

$$I_{tot} = I_{dir} + I_{diff} + I_r \quad \text{...........} \quad \text{Equation B2.6}$$

Reflected radiation may originate from the ground or obstructions. Therefore,

$$I_t = I_D + I_d + I_r \quad \text{..........} \quad \text{Equation B2.7}$$

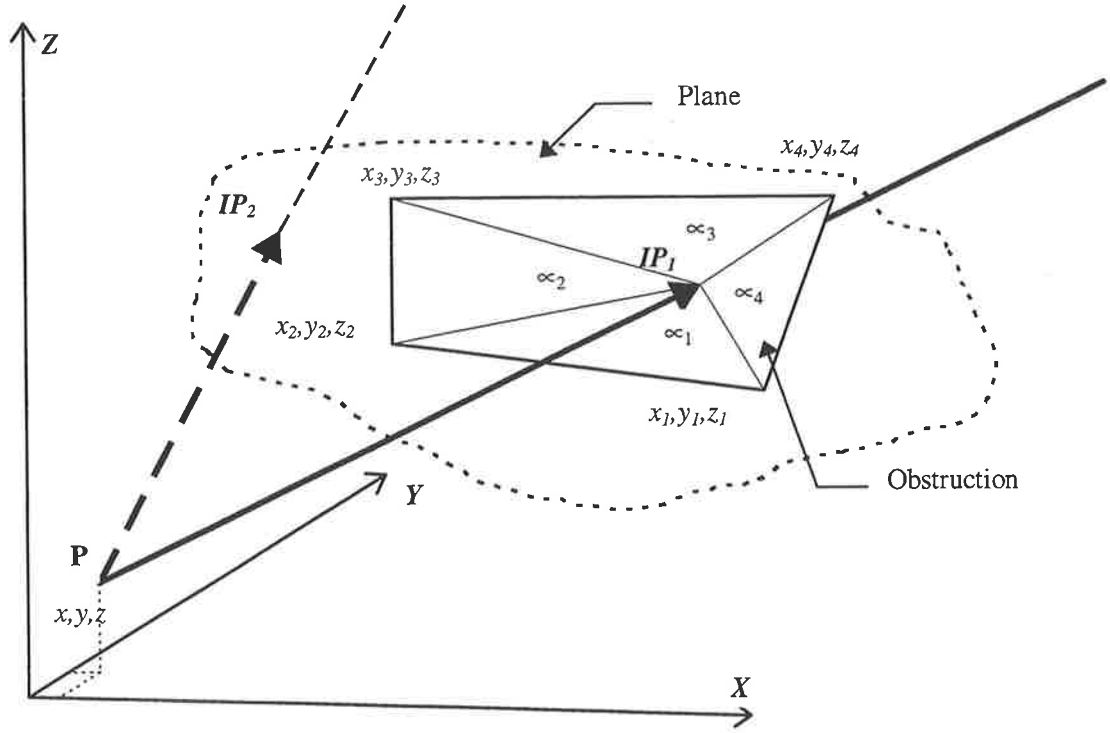


Figure B2.1: Intersection of Ray and Obstruction

Direct Radiation

If *alt* is the solar altitude and *az* the solar azimuth then the direction numbers for a line through a point P are,

$$l = \sin(az) \bullet \cos(alt)$$
$$m = \cos(az) \bullet \cos(alt) \quad \ldots\ldots\ldots \quad \text{Equations B2.7}$$
$$n = \sin(alt)$$

The intensity of direct solar radiation on a plane at point P may be written as,

$$I_D = F_n \bullet D \cos(\theta)$$

where, D is the solar radiation intensity normal to the solar beam (W/m^2)

F_n is a number 1 if no direct shading; 0 if direct shading

θ the angle of incidence between the solar beam and the normal to the plane at point ***P***

Sky Diffuse and Reflected Radiation

View factors for sky, obstructions and ground may be calculated for a point on a building element by radiating from that point a sufficient number of "rays". The view factors are defined as,

$$V_o = \frac{\sum_o R_o \cos(\theta_i)}{\sum_t R_t \cos(\theta_i)} \quad \text{..........} \quad \text{Equation B2.8}$$

where, V_o is the view factor for obstructions, the ground etc.

R_o the rays which intercept the obstruction

R_t the total number of rays emitted from the point

θ_i the angle of incidence between the *i*th ray and the normal to the plane

The total sky view factor is found by subtraction such that,

$$V_s = 1 - \frac{(\sum R_o \cos(\theta) + \sum R_g \cos(\theta)}{\sum R_o \cos(\theta)} \quad \text{..........} \quad \text{Equation B2.9}$$

The Perez (1987) simplified model for diffuse or sky radiation is incorporated into the calculations and the sky view factor is actually divided into two parts, one for elevations $0^\circ < \alpha < 6^\circ$ and another for $6^\circ < \alpha < 90^\circ$.

$$I_{diff} = I_{diff\_hor}\left[0.5(1+\cos s)(1-F'_1) + F'_1(\cos\theta/\cos Z) + F'_2 \sin s\right] \quad \text{..........} \quad \text{Equation B2.10}$$

where

I_{diff_hor} Diffuse radiation measured on horizontal plane

θ Solar angle of incidence

s slope of titled plane

Z solar zenith angle

$\mathcal{F}'_1$, $\mathcal{F}'_2$ brightness coefficients for the circumsolar region and horizon band respectively derived from lookup tables (Perez, 1987)

Ground Reflected Radiation

The calculation of ground reflected irradiance I_g assumes an albedo of λ, and when the ground is fully sunlit is given by

$$I_g = I_h * \lambda * \frac{(1-\cos s)}{2} \quad \text{..........} \quad \text{Equation B2.11}$$

where I_h global radiation on a horizontal surface

Where the ground is partly shaded by the titled surface ie. when $\cos\theta < 0$

$$I_g = I_{diff\_hor} * \lambda * \frac{(1-\cos(s-\phi))}{2} + I_h * 0.2 * \frac{(\cos(s-\phi)-\cos(s))}{2}$$ .... Equation B2.12

where ϕ apparent altitude of sun relative to surface

Solar Heat Gain Through Windows

Solar heat gain through windows is calculated using the ASHRAE technique (ASHRAE, 1989, p27.25) assuming 3mm clear glass and then adjusted for the particular case. The solar heat gain factor is defined as,

SHGF = Energy transmitted + Energy absorbed * inward flow component (N_i)

The transmitted component is given by,

$$I_D \sum_{j=0}^{5} t_j \cos^j \theta + I_d^2 \sum_{j=0}^{5} t_j/(j+2)$$ .... Equation B2.13

The absorbed energy component is given by,

$$I_D \sum_{j=0}^{5} a_j \cos^j \theta + I_d^2 \sum_{j=0}^{5} a_j/(j+2)$$ .... Equation B2.14

The ASHRAE *Handbook of Fundamentals* gives a table of values for t_j and a_j.

The inward flow component N_i is derived from,

$$N_i = h_i/(h_i+h_o)$$ .... Equation B2.15

where h_i, h_o coefficient of heat transfer for inside and outside surfaces respectively

h_i and h_o are calculated at each hour step.

Williamson, T., (1995) A confirmation technique for thermal performance simulation models.
Proceedings of International Building Performance Simulation Association (IBPSA) Conference, Madison, WI, pp. 268-275.

NOTE:
This publication is included on pages 199-206 in the print copy
of the thesis held in the University of Adelaide Library.

APPENDIX C

EnCom2 Data, Version 4.4, 1996

Climate Data

Typical year,

Adelaide - 1987

Melbourne - 1971

Description of Test House

FLOOR

100mm slab on ground construction
(See House Plan and Elevations).

Space	Area (sq.m.)	Floor Covering
Living/Family	67.2	Carpet
Kitchen	12.0	8mm Ceramic tiles
Bedrooms	57.5	Carpet
Service areas	14.7	8mm Ceramic tiles
Hallway	6.1	Carpet

total : 157.5 m²

Total floor	130.8 26.7	Carpeted slab Ceramic tiled slab

total : 157.5 m²

EXTERNAL WALLS

Brick veneer construction
110mm brickwork, insulation 10 mm plasterboard.
90 x 35 mm studs (pinus radiata) at 450 mm centres (not included in calculation)
(See House Plan and Elevations).

Space	Orientation	**Area (m²)** *for 17% window area to floor area*		Length
		Wall	**Window Opening**	
Living/Family	North	14.7	6.7	8.9 m
	South	9.6	2.2	4.9 m
	West	19.2	2.2	8.9 m
Kitchen	South	8.3	1.3	4.0 m
Bedrooms	North	15.7	5.7	8.9 m
	East	16.6	4.5	8.9 m
	South	7.4	2.2	4.0 m
Service areas	South	9.7	2.1	4.9 m
		total : 101.2 m²	***total : 26.9 m²***	***total 52.5m***

INTERNAL WALLS

Plasterboard on stud construction
10 mm plasterboard, 90 mm unventilated air gap, 10 mm plasterboard.
90 x 35 mm studs (pinus radiata) at 450 mm centres (not included in calculation)

CEILING

Plasterboard
Attic space, mineral fibre insulation, 13 mm plasterboard
120 x 35 mm rafters (pinus radiata) at 600 mm centres (not included in calculation)

ROOF

Medium coloured 20mm concrete tiles at 20 degree slope, no sarking material

Attic space assumed to be ventilated

THERMAL PROPERTIES of MATERIALS

Materials	**Density (kg/m^3)**	**Conductivity (W/m.K)**	**Capacity (J/kg.K)**	**Absorptivity**	**Emissivity**
soil	1280	1.5	2547	0.85	0.90
100 mm concrete	2400	1.45	880	0.65	0.90
10 mm carpet	186	0.05	645	0.60	0.90
8 mm quarry tiles	2100	1.40	650	0.60	0.90
110 mm brick (medium colour)	1760	1.15	977	0.50	0.92
mineral fibre insulation	70	0.05	142	0.60	0.90
4 mm glass	2510	1.18	840		
10 mm plasterboard	880	0.17	1050	0.70	0.91
20 mm concrete tiles (medium colour)	2040	0.85	867	0.50	0.93

Thermal properties for *EnCom2* input are calculated using program HEATRANT, V4.2.

ELEMENT DETAILS

Windows

Windows are aluminium frames and 4mm single glazing
Frame factor (ie. Frame area/Total opening area) to be 10%
The head of all windows to be 2100mm above floor level
Internal blinds or curtains

Infiltration/Ventilation

ACH = 0.5 + 0.3*Wind Speed (m/sec) infiltration

ACH = 3.0 + 10*√Wind Speed (m/sec) ventilation

Shading

450mm eaves to all walls.

Casual Loads

See table.

HOUR	ZONE 1 SENS	LAT	ZONE 2 SENS	LAT
1	100	0	200	100
2	100	0	200	100
3	100	0	200	100
4	100	0	200	100
5	100	0	200	100
6	100	0	200	100
7	860	400	0	0
8	860	400	0	0
9	560	200	0	0
10	240	100	0	0
11	240	100	0	0
12	240	100	0	0
13	240	100	0	0
14	240	100	0	0
15	240	100	0	0
16	240	100	0	0
17	240	100	0	0
18	1610	750	0	0
19	1760	750	100	0
20	760	150	100	0
21	760	150	100	0
22	760	150	300	100
23	100	0	300	100
24	100	0	200	100

PMV Data

Air speed related to ACH at each hour by the relationship,

Vel = $\alpha + \beta^*$ ACH where $\alpha = 0.02$ and $\beta = 0.04$ (normal conditions), $\alpha = 0.1$ and $\beta = 0.04$ (fan operating, average room conditions)

(see Layton (1992) who showed that these values matched, with acceptable accuracy, actual conditions)

Activity Rates

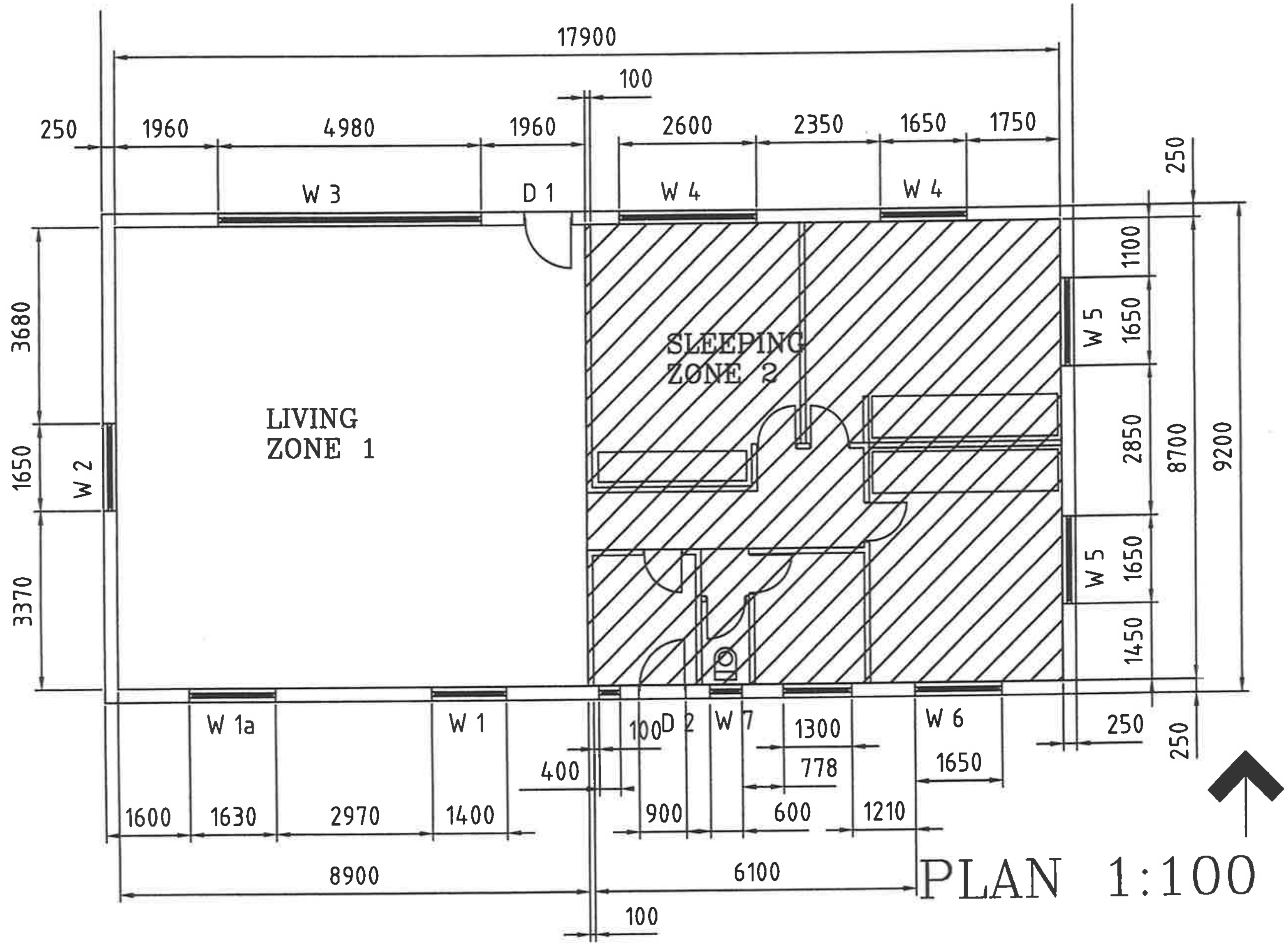
Winter day time 80 W/m^2

Summer night time 45 W/m^2

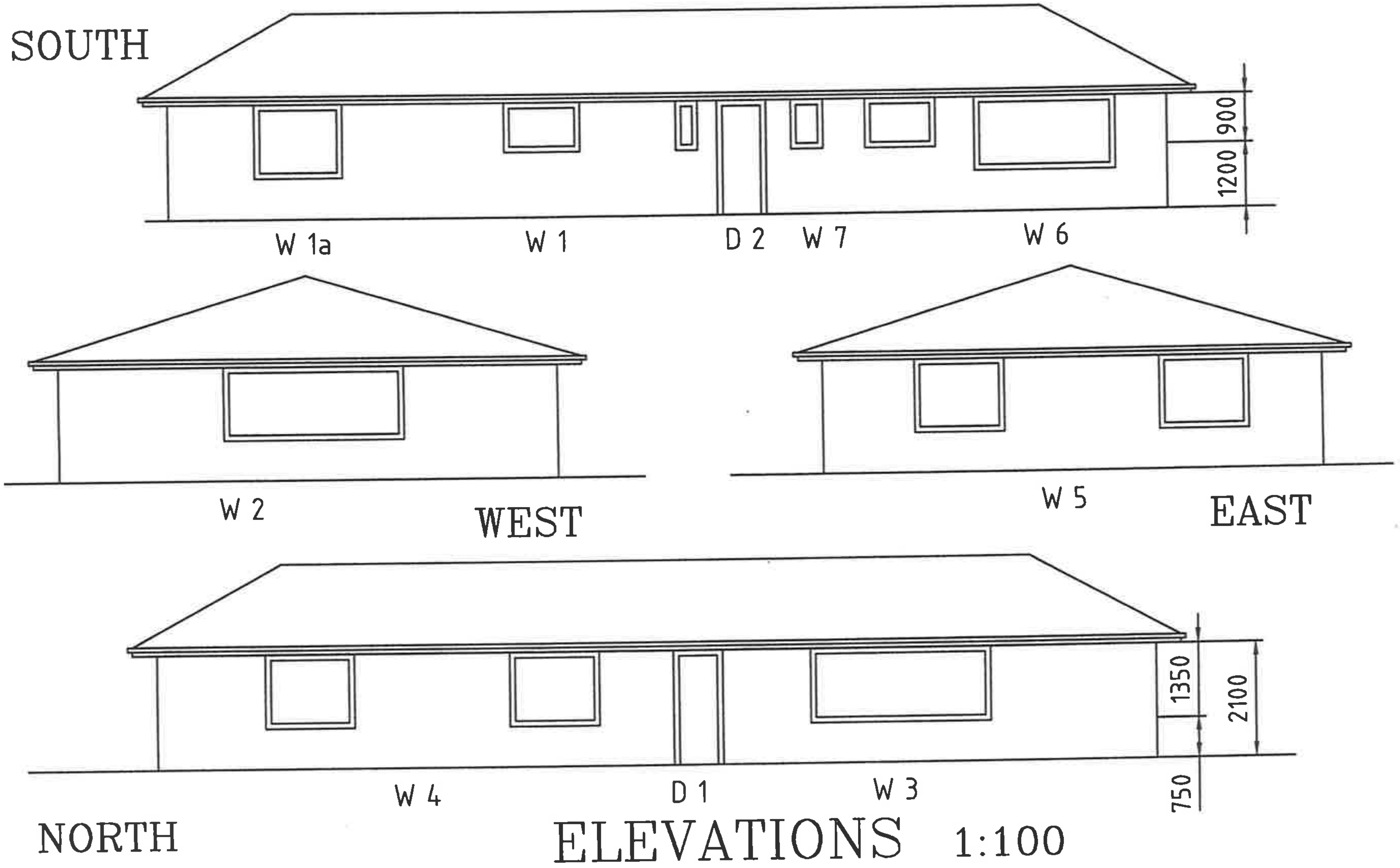
Clothing

Day time winter 0.8 clo

Night time summer in bed 1.8 clo (see McCullough, et al., 1987)


17900
100
250
1960
4980
1960
2600
2350
1650
1750
250
W 3
D 1
W 4
W 4
1100
W 5
1650
2850
8700
9200
W 5
1650
1450
3680
1650
W 2
3370
LIVING
ZONE 1
SLEEPING
ZONE 2
W 1a
W 1
100
D 2
W 7
1300
778
W 6
1650
250
250
400
1600
1630
2970
1400
900
600
1210
8900
6100
100
PLAN 1:100

House Plan



House Elevations

Sample *EnCom2* Input Data

```
DATA 1:HEADING TO PRINTOUT Thesis House a_a1_1nh.lis
**************************
LOCATION            Adelaide                                    Version 4.4
SEASON:  (Winter)  normal shading 450 eaves
CONSTRUCTION:  ins. brick veneer & SLAB FLOOR  17% windows
HEATING:  Electric Z1& Z2
DATA 2:MAJOR CONTROL DATA
*************************
DATA NO,NO.OF PERIODS,DAYS IN PERIOD,MIDDLE DAY OF 1ST.PERIOD
(MONTH AND DAY),SEASON CODE,PLOT ID.,DIAGNOSTICS(1,2,3,OR 4)
2,12,15,4,7,2,1,1
DATA 3:CLIMATIC DATA CONTROLS
*****************************
DATA NO,ACCESS DAY,WIND FACTOR 1 & 2,LATITUDE,elevation
3,1,1.0,0.5,-34.8,11
DATA 4:GROUND TEMPERATURES
**************************
MEAN MONTHLY AIR TEMPERATURES FOR YEAR, BEGIN JAN.
4,19.7,21.9,18.6,17.5,14.2,12.2,10.3,11.5,14.2,15.6,19.1,21.0
DATA 5:ELEMENTS IN EACH OF SETS 1 TO 3
**************************************
DATA NO,NO.OF ELEMENTS IN SET 1(HORIZONTAL),NO.IN SET 2
(VERTICAL-EXCEPT ATTIC),NO. IN SET 3(ATTIC-VERT.& HORIZ.) AND NON-ATTIC
INCLINED,NO.OF ELEMENTS IN EACH ZONE OF SET 1,SET 2,AND SET 3
5,0,6,4,0,0,3,3,0,0
DATA 6:SET 1 GLASS CODE AND ABSORPTANCES
****************************************
DATA NO,GLASS CODE,ABSORPTANCES OF EACH SURFACE
DATA 7:SET 1 AREAS AND EXPOSURE TO DIFFUSE RADIATION
****************************************************
DATA NO,FOR EACH ELEMENT OF SET IN TURN:
OPAQUE AREA,SKY DIFFUSE FACTOR,REFLECTED DIFFUSE FACTOR,GLASS AREA,SKY
DIFFUSE FACTOR,REFLECTED DIFFUSE FACTOR
DATA 8:SET 2 GLASS CODE AND AZIMUTHS
************************************
DATA NO,GLASS CODE,NO.OF DIFFERENT AZIMUTHS
LIST OF DIFFERENT AZIMUTHS IN ANY ORDER
8,1,4,180,270,0,90
DATA 9:SET 2 AZIMUTH ORDER
**************************
DATA NO,THE LIST OF THE ORDER OF THE AZIMUTHS
9,1,2,3,3,4,1
DATA 10:SET 2 REFLECTANCES
**************************
DATA NO,MEAN REFLECTANCES OF SURROUNDING SURFACES
FOR EACH WALL IN TURN
10,0.3,0.3,0.3,0.3,0.3,0.3
DATA 11:SET 2 ABSORPTANCES
**************************
DATA NO,ABSORPTANCES FOR EACH EXTERNAL VERTICAL SURFACE
11,.7,.7,.7,.7,.7,.7
```

```
DATA 12:SET 2 AREAS AND EXPOSURE TO DIFFUSE RADIATION
****************************************************
DATA NO,FOR EACH ELEMENT OF SET IN TURN:
OPAQUE AREA,SKY DIFFUSE FACTOR,REFLECTED DIFFUSE FACTOR,GLASS AREA,
SKY DIFFUSE FACTOR,REFLECTED DIFFUSE FACTOR
 12,
  15.2,1.00,0.41,0.03,0.51,  3.5,1.00,0.37,0.08,0.51,
  16.5,1.00,0.41,0.04,0.50,  2.2,1.00,0.39,0.07,0.50,
  12.0,1.00,0.42,0.03,0.51,  6.7,1.00,0.38,0.07,0.51,
  13.0,1.00,0.41,0.03,0.51,  5.7,1.00,0.38,0.07,0.51,
  14.2,1.00,0.41,0.04,0.51,  4.5,1.00,0.38,0.07,0.51,
  14.4,1.00,0.41,0.03,0.51,  4.3,1.00,0.36,0.08,0.51,
DATA 13:SET 3 GLASS CODE,AZIMUTH AND INCLINATION PAIRS
******************************************************
DATA NO,GLASS CODE,NO.OF DIFFERENT AZIMUTH/INCLINATION PAIRS
LIST OF PAIRS
13,9,4,180,70,270,70,0,70,90,70
DATA 14:SET 3 AZIMUTH INCLINATION ORDER,ABSORPTANCES
****************************************************
DATA NO,ORDER OF AZIMUTH/INCLINATION PAIRS,ABSORPTANCES
14,1,2,3,4,0.8,0.8,0.8,0.8
DATA 15:SET 3 AREAS AND EXPOSURE TO DIFFUSE RADIATION
*****************************************************
DATA NO,FOR EACH ELEMENT OF SET IN TURN:
OPAQUE AREA,SKY DIFFUSE FACTOR,REFLECTED DIFFUSE FACTOR,GLASS AREA,SKY
DIFFUSE FACTOR,REFLECTED DIFFUSE FACTOR
 15,
  38.6,1.00,0.91,0.00,0.00,  0.0,0.00,0.00,0.00,0.00,
  19.3,1.00,0.91,0.00,0.00,  0.0,0.00,0.00,0.00,0.00,
  38.6,1.00,0.91,0.00,0.00,  0.0,0.00,0.00,0.00,0.00,
  19.3,1.00,0.91,0.00,0.00,  0.0,0.00,0.00,0.00,0.00,
DATA 16:RADIATION PLOT CONTROLS
********************************
DATA NO,PLOT CONTROL CODE,SELECTED SURFACE(DEFINED BY ORDER OF AZIMUTH)
16,0,0
DATA 17:SHADING OF EXTERNAL ELEMENTS
*************************************
DATA NO,THE FOLLOWING ENTRIES ARE REQUIRED
FOR EACH SURFACE IN TURN OF SETS 1,2,3(OMIT IF NO ELEMENTS IN SET)
AND REPEATED FOR EACH NEW MONTH OF SHADING SEASON
CODE X9(1 OR 0),NO. OF HOURS OF MIXED SUNLIGHT X8(IF 0 OMIT THE
FOLLOWING),HOUR WHEN MIX COMMENCES,HOUR ENDS,OPAQUE AREA IN SHADE FOR
EACH HOUR,GLASS AREA IN SHADE FOR EACH HOUR(OMIT THE GLASS AREA IF THERE
IS NO GLASS IN THE SURFACE)
 17,       a_n.IN ADELAIDE, 450mm eaves 17% windows, shading normal
 1, 0
 1, 5,
    13,17,12.0, 6.1, 3.0, 0.0, 0.0,
         2.2, 1.4, 0.7, 0.0, 0.0,
 1,11,
    7,17, 0.0, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6,
         0.0, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1,
 1,11,
    7,17, 0.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0,
         0.0, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8,
 1, 6,
    7,12, 0.0, 0.0, 2.4, 2.4, 4.7,12.8,
         0.0, 0.0, 1.4, 1.4, 2.8, 4.4,
 1, 0
 1,10,
    8,17, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
 1, 9,
```

```
    9,17, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1,11,
    7,17, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1,10,
    7,16, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1, 0
1, 5,
   13,17, 8.4, 3.0, 3.0, 0.0, 0.0,
          2.1, 0.7, 0.7, 0.0, 0.0,
1,10,
    8,17, 0.0, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 0.0, 0.0,
          0.0, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 0.0, 0.0,
1,10,
    8,17, 0.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 0.0, 0.0,
          0.0, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 0.0, 0.0,
1, 5,
    8,12, 0.0, 2.4, 2.4, 4.7,12.1,
          0.0, 1.4, 1.4, 2.8, 4.4,
1, 0
1, 8,
    9,16, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1, 9,
    9,17, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1,10,
    8,17, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1, 8,
    8,15, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1, 0
1, 5,
   13,17, 8.4, 3.0, 3.0, 0.0, 0.0,
          2.1, 0.7, 0.7, 0.0, 0.0,
1,10,
    8,17, 0.0, 0.0, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 0.0, 0.0,
          0.0, 0.0, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 0.0, 0.0,
1,10,
    8,17, 0.0, 0.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 0.0, 0.0,
          0.0, 0.0, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 0.0, 0.0,
1, 5,
    8,12, 0.0, 0.0, 2.4, 4.7,12.1,
          0.0, 0.0, 1.4, 2.8, 4.4,
1, 0
1, 7,
    9,15, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1, 9,
    9,17, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1,10,
    8,17, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1, 8,
    8,15, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1, 0
1, 5,
   13,17,11.2, 3.0, 3.0, 0.0, 0.0,
          2.2, 0.7, 0.7, 0.0, 0.0,
1,10,
    8,17, 0.0, 0.0, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 0.0, 0.0,
          0.0, 0.0, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 0.0, 0.0,
1,10,
    8,17, 0.0, 0.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 0.0, 0.0,
          0.0, 0.0, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 0.0, 0.0,
1, 5,
    8,12, 0.0, 0.0, 2.4, 4.7,12.1,
          0.0, 0.0, 1.4, 2.8, 4.4,
```

```
1, 0
1, 8,
   9,16, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1, 9,
   9,17, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1,10,
   8,17, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1, 8,
   8,15, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1, 0
1, 5,
   13,17,12.0, 3.0, 3.0, 0.0, 0.0,
        2.2, 0.7, 0.7, 0.0, 0.0,
1,11,
   7,17, 0.0, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 0.0,
        0.0, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 0.0,
1,11,
   7,17, 0.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 0.0,
        0.0, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 0.0,
1, 6,
   7,12, 0.0, 0.0, 2.4, 2.4, 4.7,12.8,
        0.0, 0.0, 1.4, 1.4, 2.8, 4.4,
1, 0
1, 9,
   8,16, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1, 9,
   9,17, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1,11,
   7,17, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1,10,
   7,16, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1, 0
1, 6,
   13,18,12.7, 6.1, 3.0, 3.0, 0.0, 0.0,
        2.2, 1.4, 0.7, 0.7, 0.0, 0.0,
1,12,
   7,18, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 1.6, 0.0,
        2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 0.0,
1,12,
   7,18, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 0.0,
        1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 1.8, 0.0,
1, 6,
   7,12, 0.0, 0.0, 2.4, 2.4, 7.1,13.5,
        0.0, 0.0, 1.4, 1.4, 4.2, 4.5,
1, 0
1,11,
   7,17, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1,11,
   8,18, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1,12,
   7,18, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
1,10,
   7,16, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
DATA 18:ELEMENTS IN SETS 4 TO 12
*********************************
DATA NO,NO.OF ELEMENTS IN SET 4,NO.OF ELEMENTS IN EACH
OF SETS 5 TO 12,NO.OF ELEMENTS IN ZONE 1 THEN ZONE 2 FOR SETS
5 TO 12(OMIT SET 4)
18,0,2,0,4,4,2,0,2,2,1,1,0,0,2,2,2,2,1,1,0,0,0,2,1,1
```

```
DATA 19:AREAS OF ELEMENTS IN SETS 4 TO 12
******************************************
DATA NO,LIST OF AREAS OF ALL ELEMENTS IN SETS 4 TO 12 IN THE ORDER
IN WHICH THEY ARE NUMBERED(OMIT IF NO ELEMENT IN SET)
19,
79.2,79.2,
20.2,4.0,21.8,4.9,
47.0,8.0,41.8,9.8,
21.36,21.36,
8.0,48.16,
18.5,19.2
DATA 20:SUBFLOOR SPACE DATA
****************************
DATA NO,VOLUME OF SUBFLOOR SPACE,INFILTRATION RATE FACTOR
INFILTRATION RATE FACTOR B
DATA 21:THERMAL PROPERTIES OF SET 1
************************************
(EXTERNAL HORIZONTAL ENCLOSING HABITABLE SPACES)
DATA NO,CODE,U,T,LAG,Y,LEAD(FLOW IN),U,T,Y(FLOW OUT)
DATA 22:THERMAL PROPERTIES OF SET 2
************************************
(VERTICAL ENCLOSING HABITABLE SPACES)
DATA NO,CODE,U,T,LAG,Y,LEAD   (R1.5, p29)
22,1,
0.50,0.32,4.7,0.87,3.2
DATA 23:THERMAL PROPERTIES OF SET 3(ALL EXTERNAL ELEMENTS ENCLOSING
********************************************************************
ATTIC SPACES AND EXTERNAL INCLINED ELEMENTS ENCLOSING HABITABLE SPACES
DATA NO,CODE,U,T,LAG,Y,LEAD(FLOW IN),U,T,Y(FLOW OUT)
23,1,
1.22,1.21,0.5,1.22,0.1,2.16,2.14,2.16
DATA 24:THERMAL PROPERTIES OF SET 4
************************************
(PERIMETER SUBFLOOR WALLS)
DATA NO,CODE,U,T,LAG,Y,LEAD
DATA 25:THERMAL PROPERTIES OF SET 5
************************************
(CEILINGS BELOW THE ATTIC SPACES)
DATA NO,CODE,U,T,LAG,Y,LEAD(FLOW IN),U,T,Y,(FLOW OUT), (R2.5, p21)
25,1,
0.35,0.35,1.1,0.95,3.95,0.36,0.35,0.97
DATA 26:THERMAL PROPERTIES OF SET 6
************************************
(SUSPENDED FLOORS ABOVE GROUND)
DATA NO,CODE,U,T,LAG,Y,LEAD(FLOW IN),U,T,Y(FLOW OUT)
DATA 27:THERMAL PROPERTIES OF SET 7
************************************
(CONC.SLAB ON GROUND-PERIMETER STRIP)
DATA NO,CODE,U,T,LAG,Y,LEAD
27,2,
1.10,0.13,21.0,2.53,0.6,
1.3,0.14,20.4,4.67,0.9,
1.10,0.13,21.0,2.53,0.6,
1.3,0.14,20.4,4.67,0.9
```

```
DATA 28:THERMAL PROPERTIES OF SET 8
***********************************
(CONC.SLAB ON GROUND-CORE OF SLAB)
DATA NO,CODE,U,T,LAG,Y,LEAD
28,2,
0.8,0,28.1,1.99,0.5,
1.04,0,27.7,4.59,0.9,
0.8,0,28.1,1.99,0.5,
1.04,0,27.7,4.59,0.9
DATA 29:THERMAL PROPERTIES OF SET 9
***********************************
(FACES OF VERTICAL PARTITIONS BETWEEN ZONES)
DATA NO,CODE,U,T,LAG,Y,LEAD
29,1,
1.94,1.93,0.5,2.01,0.8
DATA 30:THERMAL PROPERTIES OF SET 10
************************************
(FACES OF NON-VERTICAL PARTITIONS BETWEEN ZONES)
DATA NO,CODE,U,T,LAG,Y,LEAD(FLOW IN),U,T,Y(FLOW OUT)
DATA 31:THERMAL PROPERTIES OF SET 11
************************************
(PARTITIONS INTERNAL TO A ZONE)
DATA NO,CODE,U,T,LAG,Y,LEAD(FLOW IN),U,T,Y(FLOW OUT)
31,2,
1.92,1.90,0.8,2.14,1.34,1.92,1.90,2.01,
1.94,1.93,0.5,2.01,0.8,1.94,1.93,2.01
DATA 32:THERMAL PROPERTIES OF SET 12
************************************
(CONTENTS)
DATA NO,U,T,LAG,Y,LEAD
32,1
1.94,1.93,0.5,2.01,0.8
DATA 33:THERMAL PROPERTIES OF THE GROUND
****************************************
DATA NO,U-VALUE OF GROUND,INTERNAL ADMITTANCE,LEAD
33,1.14,4.5,0.9
DATA 331:ANNUAL TRANSFER VALUES FOR GROUND AND SLAB
**************************************************
DATA NO,FOR GROUND THEN EDGE; ANNUAL HARMONIC, TRANSFER MODULUS & ADMITTANCE,
IF SLAB, CORE U VALUE TRANSFER MODULUS & ADMITTANCE
331,1.14,1.14,1.15,
0.48,0.47,0.61,
1.04,1.04,1.05
DATA 34:OPENINGS BETWEEN ZONES
******************************
DATA NO,TOTAL OPENING B/W ZONES,IF 2 STOREY-WHICH ZONE UPPERMOST
(OMIT IF SINGLE STOREY),MODE OF OPERATION, FOR EACH ZONE TYPE OF PLANT
34,2,2,000.20,000.20
DATA 35:ATTIC SPACES-RELATIONSHIP TO ZONES
******************************************
DATA NO,NO.OF EXTERNAL SURFACES ENCLOSING ATTIC SPACES,FOR ZONE 1
AND 2:NO.OF EXTERNAL SURFACES FOR ANY ENCLOSED ATTIC SPACE WHICH RELATES
TO THAT ZONE,NO.OF EXTERNAL SURFACES RELATING TO BOTH ZONES
35,4,0,0,4
DATA 36:ATTIC SPACES
********************
DATA NO,FOR ATTIC SPACES RELATED TO ZONE 1(REPEAT FOR ZONE 2-OMIT IF NONE)
:VOLUME,INITIAL TEMP.AT START OF RUN(2 ENTRIES IF MODE 3),
INFILTRATION FACTORS A & B,FOR ATTIC SPACES RELATED TO BOTH ZONES
: VOLUME,INITIAL TEMP.,FACTORS A & B
36,165,19,6,1.5
```

```
DATA 37:ZONE DATA
*****************
DATA NO,FOR EACH ZONE:VOLUME,FACTORS A & B FOR EACH OF THE FOLLOWING:
NATURAL INFILTRATION,NO COOLING PLANT-WINDOWS OPEN OR FAN,COOLING PLANT
CV FACTORS FOR EACH TYPE OF VENTILATION
37,
190,0.5,0.4,3,10,0.5,0.4,
138,0.5,0.4,3,10,0.5,0.4,
1,1,3
DATA 38:ZONE DATA
*****************
DATA NO,FOR EACH ZONE:INITIAL DRY & WET BULB TEMPS.,2 PAIRS PER ZONE MODE 3
UPPER COMFORT LIMIT,LOWER COMFORT LIMIT,START AND FINISH OF OCCUPANCY
38,21,15,27,18,7,22,
  21,15,24,15,23,6
DATA 39:ZONE DATA
*****************
DATA NO,FOR EACH ZONE:DESIRED TEMP.IN ZONE,THERMOSTAT SWING(ABOVE &
BELOW), NUM. OPERATION PERIODS, FOR EACH TIME ON & OFF
39,18,2,2,2,7,9,17,23
  18,2,2,1,20,23
DATA 40:PLANT CHARACTERISTICS
*************************************
DATA NO, FOR EACH ZONE, CONVECTIVE COOL OR HEAT: PLT. EFF, ACH,
THERM. LOC, TEMP.FLAG, PLANT CONFIG. FLAG.& CAP(KW)
40,100,5,0,1,1,20,
  100,5,0,1,1,20
DATA 401:IF STORAGE HEATER - FOSH
****************************
DATA NO,CALC. TIME INCREMENT, NUM CHARGE PERIODS,FOR EACH TIME
ON & OFF, FOR EACH ZONE:MAX. HEATER POWER,INT. CORE TEMP,
SIM STAT (TEMP1,POW1),(TEMP2,POW2),ONSWING
DATA 402:IF STORAGE HEATER - COSH
****************************
DATA NO,CALC. TIME INCREMENT, NUM CHARGE PERIODS,FOR EACH TIME ON & OFF,
FOR EACH ZONE:MAX. HEATER POWER,INT. CORE TEMP, SIM STAT (TEMP1,POW1),
(TEMP2,POW2),ONSWING, FAN PERIODS,FOR EACH TIME ON & OFF, THERMOSTAT SET.
DATA 41:ZONE DATA
*****************
DATA NO,FOR EACH ZONE:MEAN ABSORPTANCE OF FLOOR SURFACES,MEAN
ABSORPTANCE OF OTHER SURFACES
41,0.3,0.3,0.3,0.3
DATA 42:ZONE DATA
*****************
DATA NO,FOR EACH ZONE,HOURLY SENSIBLE & LATENT HEAT LOADS  (WATTS)
LOAD PAIRS FOR HOURS 1 TO 24 INCL.
42,
100,0,100,0,100,0,100,0,100,0,100,0,860,400,860,400,560,200,240,100,
240,100,240,100,240,100,240,100,240,100,240,100,240,100,1610,750,1760,750,
760,150,760,150,760,150,100,0,100,0,
200,100,200,100,200,100,200,100,200,100,200,100,0,0,
0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,100,0,100,0,100,0,300,100
300,100,200,100
DATA 43:INTERNAL CONTROLS ON GLAZING
************************************
DATA NO,RADIATION CONTROLS(NO=1,YES=2:ZONE 1 THEN 2),BLINDS DRAWN AT
NIGHT(NO=1,YES=2:ZONE 1 THEN 2),U-VALUE(BARE),U-VALUE(CURTAINS ETC.)
43,2,2,2,2,5.8,4.65
```

```
DATA 44:FACTORS FOR ACTUAL GLAZING USED
****************************************
DATA NO,THREE ADJUSTMENT FACTORS TO CORRECT FOR DIFFERENCE IN GLASS
TYPE AND TO ALLOW FOR ANY FIXED INTERNAL CONTROLS
44,0.94,0,2.2
DATA 45:INTERNAL RADIATION CONTROLS
************************************
DATA NO,FOR EACH ZONE(OMIT IF NONE IN ZONE):THREE FACTORS TO ALLOW FOR
THE REDUCTION IN SOLAR RADIATION EFFECTS WHEN INTERNAL CONTROLS OPERATED
W/SQ.M ABOVE WHICH BLINDS DRAWN IN SUMMER OR BELOW WHICH DRAWN IN WINTER
45,0.13,0.09,1.6,50,
  0.13,0.09,1.6,50
DATA 46 OUTPUT CONTROLS
************************
DATA NO,DAY NO.ON CLIMATIC DATA FOR BEGINNING OF 7 DAY DETAILED
OUTPUT(COUNTED FROM ACCESS DAY),Number of days for plot output, DAY NO. FOR
HEAT FLOW BY PATHS(ONE OF 7 DAYS),PUT 0 IF EITHER NOT REQUIRED,
PLOT OPTION 1=YES,2=NO
46,4,180,10,1
```

APPENDIX D

SAMPLE

PULLEN Embodied Energy Spreadsheet

Estimation of the embodied energy (in delivered energy terms) and CO2 emissions (in primary energy terms) of the materials in the Thesis House for Terry Williamson

Element	Sub-Element	Detail	Area or number m2 or no	Material	Material Intensity (kg/m2) (except items)	Energy Coeff. (MJ/kg)	Embodied Energy		CO2 Coeff. (kg CO2/kg)	Amount CO2	
							(MJ)	Prop. of Total(%)		(kg)	Prop. of Total(%)
01 Footings/Floor	Concrete slab on ground (Medium reactive soil)		158	Steel	8.6	25.79	34927	4.75	2.39	3230.57	4.93
				Concrete	528.0	1.45	120735	16.44	0.13	10720.86	16.37
				Blinding	80.0	1.38	17436	2.37	0.13	1671.45	2.55
				Membrane	0.3	76.22	3432	0.47	7.41	333.62	0.51
	Suspended timber (South Australia - 1994 design)			Steel	5.2	25.79			2.39		
				Concrete	348.0	1.45			0.13		
				Brickwork	29.5	3.53			0.30		
				Timber	18.0	19.63			1.86		
	Suspended timber (AS2870.1 design - Victoria)			Steel	2.2	25.79			2.39		
				Concrete	165.8	1.45			0.13		
				Brickwork	56.0	3.53			0.30		
				Timber	26.9	19.63			1.86		
				Drains	0.3	151.19	6806	0.93	14.70	661.60	1.01
05 Roof	Framing	Timber	158	Timber	16.8	19.63	51911	7.07	1.86	4922.26	7.51
		Steel		Steel	16.3	25.79			2.39		
	Cladding	Concrete Tile	158	Concrete Tile	52.6	5.17	54352	7.40	0.47	4971	7.59
		Clay Tile		Clay Tile	48.1	14.33			1.20		
		Steel Sheet		Steel Sheet	4.3	99.60			9.15		
				Eaves soffit	1.7	30.26	8035	1.09	2.69	713	1.09
	Insulation(R2.5)		158	Insulation	1.3	111.68	22866	3.11	9.91	2029.17	3.10
	Reflec. Insul.			Aluminium Foil	0.4	179.44			44.38		
	Ceiling			Plasterboard	7.6	12.71	15214	2.07	1.13	1350.10	2.06
	Guttering			Steel	0.5	99.60	7390	1.01	9.15	678.95	1.04
06 External Walls	Double Brick		120	Brick(Standard)	352.0	3.53	149296	20.32	0.30	12546.27	19.15
				DPC	0.1	52.55	351	0.05	5.11	34.13	0.05
				Mortar	48.6	1.45	8440	1.15	0.13	749.47	1.14
				Plaster	14.0	2.54	4267	0.58	0.23	378.68	0.58
	Brick Veneer	Standard brick		Brick(Standard)	176.0	3.53			0.30		
				Mortar	23.4	1.45			0.13		
		Modular brick		Brick(Modular)	143.0	3.53			0.30		
				Mortar	16.2	1.45			0.13		
		Timber framing		Timber Framing	7.1	19.63			1.86		
		Steel framing		Steel Framing	6.2	25.79			2.39		
		Insulation(R1.5)		Insulation (R1.)	0.9	111.68			9.91		
		RFL		RFL	0.5	494.00					
				DPC	0.1	52.55			5.11		
				Plaster Board	7.6	12.71			1.13		
	AAC Block	200mm thick		AAC Block	100.0	15.88			1.45		
				4mm Render	8.0	1.45			0.13		
				Coating	0.1	145.52			13.33		
				Plaster Board	7.6	12.71			1.13		
	Timber clad	Cladding		Cladding	10.0	19.63			1.86		
		Paint		Paint	0.2	145.52			13.33		
		Timber framing		Timber framing	7.1	19.63			1.86		
		Insulation(R1.5)		Insulation(R1.5)	1.0	111.68			9.91		
				DPC	0.1	52.55			5.11		
				Plaster Board	7.6	12.71			1.13		
07 Windows	Frames	Timber		Timber	16.3	19.63			1.86		
		Aluminium	27	Aluminium	6.0	179.44	28961	3.94	16.60	2678.81	4.09
				Glass	7.5	95.05	19176	2.61	8.25	1664.03	2.54
09 Internal Walls	Brick	Brick		Brick(Standard)	176.0	3.53			0.30		
		Mortar			25.2	1.45			0.13		
		Plaster			28.0	2.54					
	Frame	Timber	89	Timber	7.1	19.63	12376	1.68	1.86	1173.52	1.79
		Steel		Steel	4.6	25.79			2.39		
		Insulation (R1.5)		Insulation (R1.5)	1.0	111.68			9.91		
				Plaster Board	15.2	12.71	17252	2.35	1.13	1530.97	2.34
	AAC Block	100mm thick		AAC Block	50.0	13.53			1.24		
				Plaster Board	15.2	12.71					
11 Doors	Doors	Solid	1	Solid	36.0	91.54	3295	0.45			
		Hollow	7	Hollow	14.0	52.25	5120	0.70			
	Frames	Timber	8	Timber	12.0	19.63	1885	0.26	1.86	178.69	0.27
		Steel		Steel	6.0	99.60			9.15		
12 Finishes	Tiles	Ceramic Tiles	27		14.3	56.27	34373	4.68	4.73	3069	4.69
	Floor cover.	Carpet	131		2.4	95.06	29343	3.99	9.27	2860.20	4.37
	Paint	(Enter 1)	1		0.2	145.52	6884	0.94	13.33	631	0.96
15 Fitments	Cabinets	Kitchen	12		89.2	58.43	21267	2.90	5.74	2087.34	3.19
	Oven/hob		1		60.0	183.04	10982	1.50	17.52	1051.06	1.60
	Air Con.		1		58.0	183.04	10616	1.45	17.52	1016.03	1.55
17 Plumbing	Piping				16.4	451.06	7416	1.01	40.47	665.42	1.02
	Steel Sinks		2		6.0	153.42	1841	0.25	14.24	170.86	0.26
	WCs		1		12.0	56.27	675	0.09	4.73	56.74	0.09
	Handbasins		1		13.0	56.27	731	0.10	4.73	61.47	0.09
	Taps/fittings				3.6	47.00	169	0.02	4.70	16.92	0.03
	Baths		1	Acrylic	6.8	57.32	387	0.05	5.40	36.45	0.06
	Water Service		1	Gas fired	70.0	183.04	12813	1.74	17.52	1226.24	1.87
26 Wiring	Wire				22.6	152.84	3458	0.47	14.40	325.82	0.50
	Fittings		24		0.1	57.32	103	0.01	5.40	9.72	0.01
34 External	Pavers				80.6	3.85			0.35		
	Driveway			Concrete	240.0	1.45			0.13		
	Fences (lin.m.)	Timber			8.4	19.63			1.86		
		Steel			3.6	99.60			9.15		
	Pergola				10.7	19.63			1.86		
	Shed										
Total				**Embodied Energy(MJ)**			**734584**		**CO2(kg)**	**65501**	

APPENDIX E

Heater and Cooler Extent and Operation

Adelaide and South Australia country

Table E.1 - Rooms heated by Main Heater (% of Households)

Number of Rooms	Adelaide Metro	SA Country
1	35	24
2	22	26
3	20	17
4	8	9
5	6	12
6	5	6
7	2	3
8	1	3
9 rooms or more	2	1

Source: ETSA, Survey, 1992 (unpublished)

Table E.2 - Rooms served by Air-conditioning (% of Households)

Number of Rooms	Adelaide Metro	SA Country
1	18	19
2	12	15
3	15	7
4	12	14
5	18	19
6	12	15
7	7	6
8	2	5
9 rooms or more	4	1

Source: ETSA, Survey, 1992 (unpublished)

Heater Operation

Table E.3: Winter Days per Month Use Main Heater (% of Households)

	Adelaide Metro	Country
0 days per month	1	0
1-4 days per month	3	1
5-8 days per month	5	3
9-12 days per month	6	6
13-20 days per month	12	13
over 20 days per month	73	77
Average Days per Month	21.2	22.25

Source: ETSA Report Unpublished

Table E.4: Hours of Heater Operation

	Adelaide Metro		Country	
	Day time	Night-time	Day time	Night-time
0 hours	43	3	31	0
1-3 hours	35	23	32	15
4-6 hours	14	58	16	53
7-9 hours	4	10	2	10
Over 9 hours	4	6	20	23
Average Hours	*2.2*	*4.9*	*4*	*6.5*

Source: ETSA Report Unpublished

Cooler Operation

Table E.5: Summer Days per Month Use of Air-conditioner (% of Households)

	Adelaide Metro	Country
0 days per month	2	2
1-4 days per month	23	11
5-8 days per month	21	17
9-12 days per month	22	20
13-20 days per month	20	23
over 20 days per month	12	27
Average days per month	*10.4*	*13.9*

Source: ETSA Report Unpublished

Table E.6 : Hours of Air-conditioner Operation

	Adelaide Metro		Country	
	Hot day	Average day	Hot day	Average day
Not at all	3	43	2	24
Less than 4 hours	19	30	7	24
4-8 hours	34	19	26	32
9-12 hours	15	4	18	13
13-16 hours	5	1	11	2
17-24 hours	13	1	16	1
On all the time	10	1	18	2
On thermostat	0	0	2	1
Other	1	1	0	0
Average Hours	*9.8*	*2.7*	*13.0*	*4.9*

Source: ETSA Report Unpublished

APPENDIX F

Calculation Spreadsheet - Instructions for Use

The PC disk enclosed with this work contains the Excel© spreadsheet file MC.xls.
The spreadsheet WorkBook contains six WorkSheets as follows,

• ***AdelData***	contains basic input data, eg fuel costs, building costs, Primary/Delivered Energy Ratios
• ***AdelSummary***	the calculation spreadsheet. Data input to this sheet is derived from ***EnCom2*** calculations, ***AdelData*** and Pullen Embodied Energy spreadsheets (the Pullen sheets are not included on the disk, therefore click NO to update links)
• ***AdelPlots***	Plots of weighted Costs vs Weighted Benefits
• ***MelbData***	contains basic input data, eg fuel costs, building costs, Primary/Delivered Energy Ratios
• ***MelbSummary***	the calculation spreadsheet. Data input to this sheet is derived from ***EnCom2*** calculations, ***MelbData*** and Pullen Embodied Energy spreadsheets (the Pullen sheets are not included on the disk, therefore click NO to update links)
• ***MelbPlots***	Plots of weighted Costs vs Weighted benefits

The user may input Benefits weighting values and the Cost weighting on ****Summary*** sheets to assess the sensitivity of these factors (see Figure F.1).

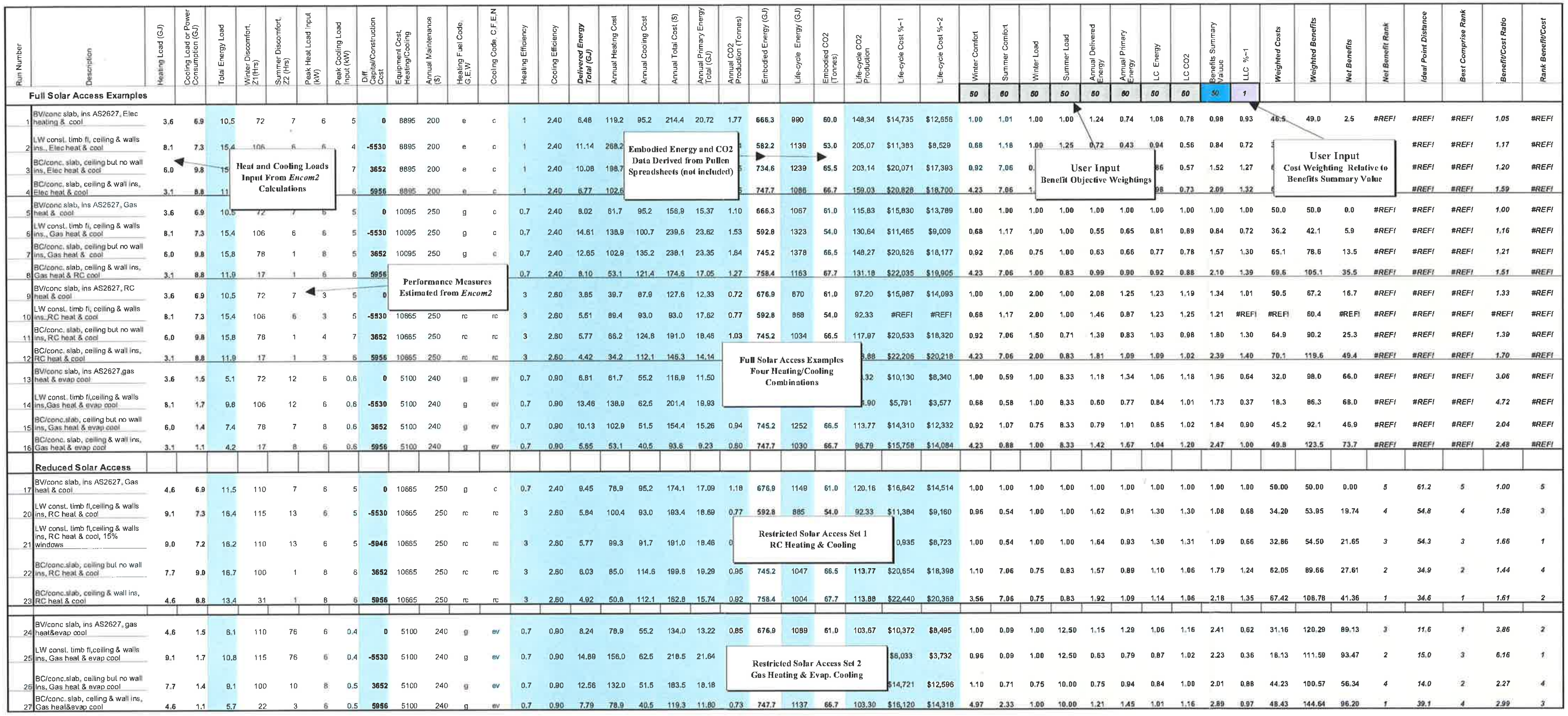
Calculations show for each building/plant variation,

- Weighted Benefits
- Weighted Life-cycle costs

and decision models,

- Net Benefits
- Best Comprise distance
- Benefit/Cost Ratio

The rank order of solutions according to the three decision models is also shown.



Run Number	Description	Heating Load (GJ)	Cooling Load or Power Consumption (GJ)	Total Energy Load	Winter Discomfort, Z1(Hrs)	Summer Discomfort, Z2 (Hrs)	Peak Heat Load Input (kW)	Peak Cooling Load Input (kW)	Diff Capital/Construction Cost	Equipment Cost, Heating/Cooling	Annual Maintenance ($)	Heating Fuel Code, G,E,W	Cooling Code, C,F,E,N	Heating Efficiency	Cooling Efficiency	Delivered Energy Total (GJ)	Annual Heating Cost	Annual Cooling Cost	Annual Total Cost ($)	Annual Primary Energy Total (GJ)	Annual CO2 Production (Tonnes)	Embodied Energy (GJ)	Life-cycle Energy (GJ)	Embodied CO2 (Tonnes)	Life-cycle CO2 Production	Life-cycle Cost %-1	Life-cycle Cost %-2
	Full Solar Access Examples																										
1	BV/conc slab, ins AS2627, Elec heating & cool	3.6	6.9	10.5	72	7	6	5	0	8895	200	e	c	1	2.40	6.48	119.2	95.2	214.4	20.72	1.77	666.3	990	60.0	148.34	$14,735	$12,656
2	LW const. timb fl, ceiling & walls ins., Elec heat & cool	8.1	7.3	15.4	106	6	6	4	-5530	8895	200	e	c	1	2.40	11.14	268.2					582.2	1139	53.0	205.07	$11,383	$8,529
3	BC/conc. slab, ceiling but no wall ins, Elec heat & cool	6.0	9.8	15				7	3652	8895	200	e	c	1	2.40	10.08	198.7					734.6	1239	65.5	203.14	$20,071	$17,393
4	BC/conc. slab, ceiling & wall ins, Elec heat & cool	3.1	8.8	11				6	5956	8895	200	e	c	1	2.40	6.77	102.6					747.7	1086	66.7	159.03	$20,828	$18,700
5	BV/conc slab, ins AS2627, Gas heat & cool	3.6	6.9	10.5	72	7	6	5	0	10095	250	g	c	0.7	2.40	8.02	61.7	95.2	156.9	15.37	1.10	666.3	1067	61.0	115.83	$15,830	$13,789
6	LW const. timb fl, ceiling & walls ins., Gas heat & cool	8.1	7.3	15.4	106	6	6	5	-5530	10095	250	g	c	0.7	2.40	14.61	138.9	100.7	239.6	23.62	1.53	592.8	1323	54.0	130.64	$11,465	$9,009
7	BC/conc. slab, ceiling but no wall ins, Gas heat & cool	6.0	9.8	15.8	78	1	8	5	3652	10095	250	g	c	0.7	2.40	12.65	102.9	135.2	238.1	23.35	1.64	745.2	1378	66.5	148.27	$20,626	$18,177
8	BC/conc. slab, ceiling & wall ins, Gas heat & RC cool	3.1	8.8	11.9	17	1	6	6	5956					0.7	2.40	8.10	53.1	121.4	174.6	17.05	1.27	758.4	1163	67.7	131.18	$22,035	$19,905
9	BV/conc slab, ins AS2627, RC heat & cool	3.6	6.9	10.5	72	7	3	5	0					3	2.60	3.85	39.7	87.9	127.6	12.33	0.72	676.9	870	61.0	97.20	$15,987	$14,093
10	LW const. timb fl, ceiling & walls ins.,RC heat & cool	8.1	7.3	15.4	106	6	3	5	-5530	10665	250	rc	rc	3	2.60	5.61	89.4	93.0	93.0	17.62	0.77	592.8	868	54.0	92.33	#REF!	#REF!
11	BC/conc. slab, ceiling but no wall ins, RC heat & cool	6.0	9.8	15.8	78	1	4	7	3652	10665	250	rc	rc	3	2.60	5.77	66.2	124.8	191.0	18.46	1.03	745.2	1034	66.5	117.87	$20,533	$18,320
12	BC/conc. slab, ceiling & wall ins, RC heat & cool	3.1	8.8	11.9	17	1	3	6	5956	10665	250	rc	rc	3	2.60	4.42	34.2	112.1	146.3	14.14					.88	$22,206	$20,218
13	BV/conc slab, ins AS2627,gas heat & evap cool	3.6	1.5	5.1	72	12	6	0.6	0	5100	240	g	ev	0.7	0.90	6.81	61.7	55.2	116.9	11.50					.32	$10,130	$8,340
14	LW const. timb fl,ceiling & walls ins,Gas heat & evap cool	8.1	1.7	9.8	106	12	6	0.6	-5530	5100	240	g	ev	0.7	0.90	13.46	138.9	62.5	201.4	19.93					.90	$5,791	$3,577
15	BC/conc.slab, ceiling but no wall ins, Gas heat & evap cool	6.0	1.4	7.4	78	7	8	0.6	3652	5100	240	g	ev	0.7	0.90	10.13	102.9	51.5	154.4	15.26	0.94	745.2	1252	66.5	113.77	$14,310	$12,332
16	BC/conc. slab, ceiling & wall ins, Gas heat & evap cool	3.1	1.1	4.2	17	8	6	0.6	5956	5100	240	g	ev	0.7	0.90	5.65	53.1	40.5	93.6	9.23	0.60	747.7	1030	66.7	96.79	$15,758	$14,084
	Reduced Solar Access																										
17	BV/conc slab, ins AS2627, Gas heat & cool	4.6	6.9	11.5	110	7	6	5	0	10665	250	g	c	0.7	2.40	9.45	78.9	95.2	174.1	17.09	1.18	676.9	1149	61.0	120.16	$16,642	$14,514
20	LW const. timb fl,ceiling & walls ins, RC heat & cool	9.1	7.3	16.4	115	13	6	5	-5530	10665	250	rc	rc	3	2.60	5.84	100.4	93.0	193.4	18.69	0.77	592.8	885	54.0	92.33	$11,384	$9,160
21	LW const. timb fl,ceiling & walls ins, RC heat & cool, 15% windows	9.0	7.2	16.2	110	13	6	5	-5946	10665	250	rc	rc	3	2.60	5.77	99.3	91.7	191.0	18.46	0					0,935	$8,723
22	BC/conc.slab, ceiling but no wall ins, RC heat & cool	7.7	9.0	16.7	100	1	8	6	3652	10665	250	rc	rc	3	2.60	6.03	85.0	114.6	199.6	19.29	0.95	745.2	1047	66.5	113.77	$20,654	$18,398
23	BC/conc.slab, ceiling & wall ins, RC heat & cool	4.6	8.8	13.4	31	1	8	6	5956	10665	250	rc	rc	3	2.60	4.92	50.8	112.1	162.8	15.74	0.92	758.4	1004	67.7	113.88	$22,440	$20,368
24	BV/conc slab, ins AS2627, gas heat&evap cool	4.6	1.5	6.1	110	76	6	0.4	0	5100	240	g	ev	0.7	0.90	8.24	78.9	55.2	134.0	13.22	0.85	676.9	1089	61.0	103.67	$10,372	$8,495
25	LW const. timb fl,ceiling & walls ins, Gas heat & evap cool	9.1	1.7	10.8	115	76	6	0.4	-5530	5100	240	g	ev	0.7	0.90	14.89	156.0	62.5	218.5	21.64						$6,033	$3,732
26	BC/conc.slab, ceiling but no wall Ins, Gas heat & evap cool	7.7	1.4	9.1	100	10	8	0.5	3652	5100	240	g	ev	0.7	0.90	12.56	132.0	51.5	183.5	18.18						$14,721	$12,596
27	BC/conc. slab, ceiling & wall ins, Gas heat&evap cool	4.6	1.1	5.7	22	3	6	0.5	5956	5100	240	g	ev	0.7	0.90	7.79	78.9	40.5	119.3	11.80	0.73	747.7	1137	66.7	103.30	$16,120	$14,318

Run Number	Winter Comfort	Summer Comfort	Winter Load	Summer Load	Annual Delivered Energy	Annual Primary Energy	LC Energy	LC CO2	Benefits Summary Value	LLC %-1	Weighted Costs	Weighted Benefits	Net Benefits	Net Benefit Rank	Ideal Point Distance	Best Comprise Rank	Benefit/Cost Ratio	Rank Benefit/Cost
	50	60	50	50	60	60	50	60	50	1								
1	1.00	1.01	1.00	1.00	1.24	0.74	1.08	0.78	0.98	0.93	46.5	49.0	2.5	#REF!	#REF!	#REF!	1.05	#REF!
2	0.68	1.18	1.00	1.25	0.72	0.43	0.94	0.56	0.84	0.72	3				#REF!	#REF!	1.17	#REF!
3	0.92	7.06	0.				86	0.57	1.52	1.27	6				#REF!	#REF!	1.20	#REF!
4	4.23	7.06	1.				98	0.73	2.09	1.32	6				#REF!	#REF!	1.59	#REF!
5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	50.0	50.0	0.0	#REF!	#REF!	#REF!	1.00	#REF!
6	0.68	1.17	1.00	1.00	0.55	0.65	0.81	0.89	0.84	0.72	36.2	42.1	5.9	#REF!	#REF!	#REF!	1.16	#REF!
7	0.92	7.06	0.75	1.00	0.63	0.66	0.77	0.78	1.57	1.30	65.1	78.6	13.5	#REF!	#REF!	#REF!	1.21	#REF!
8	4.23	7.06	1.00	0.83	0.99	0.90	0.92	0.88	2.10	1.39	69.6	105.1	35.5	#REF!	#REF!	#REF!	1.51	#REF!
9	1.00	1.00	2.00	1.00	2.08	1.25	1.23	1.19	1.34	1.01	50.5	67.2	16.7	#REF!	#REF!	#REF!	1.33	#REF!
10	0.68	1.17	2.00	1.00	1.46	0.87	1.23	1.25	1.21	#REF!	#REF!	60.4	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
11	0.92	7.06	1.50	0.71	1.39	0.83	1.03	0.98	1.80	1.30	64.9	90.2	25.3	#REF!	#REF!	#REF!	1.39	#REF!
12	4.23	7.06	2.00	0.83	1.81	1.09	1.09	1.02	2.39	1.40	70.1	119.6	49.4	#REF!	#REF!	#REF!	1.70	#REF!
13	1.00	0.59	1.00	8.33	1.18	1.34	1.06	1.18	1.96	0.64	32.0	98.0	66.0	#REF!	#REF!	#REF!	3.06	#REF!
14	0.68	0.58	1.00	8.33	0.60	0.77	0.84	1.01	1.73	0.37	18.3	86.3	68.0	#REF!	#REF!	#REF!	4.72	#REF!
15	0.92	1.07	0.75	8.33	0.79	1.01	0.85	1.02	1.84	0.90	45.2	92.1	46.9	#REF!	#REF!	#REF!	2.04	#REF!
16	4.23	0.88	1.00	8.33	1.42	1.67	1.04	1.20	2.47	1.00	49.8	123.5	73.7	#REF!	#REF!	#REF!	2.48	#REF!
17	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	50.00	50.00	0.00	5	61.2	5	1.00	5
20	0.96	0.54	1.00	1.00	1.62	0.91	1.30	1.30	1.08	0.68	34.20	53.95	19.74	4	54.8	4	1.58	3
21	1.00	0.54	1.00	1.00	1.64	0.93	1.30	1.31	1.09	0.66	32.86	54.50	21.65	3	54.3	3	1.66	1
22	1.10	7.06	0.75	0.83	1.57	0.89	1.10	1.06	1.79	1.24	62.05	89.66	27.61	2	34.9	2	1.44	4
23	3.56	7.06	0.75	0.83	1.92	1.09	1.14	1.06	2.18	1.35	67.42	108.78	41.36	1	34.6	1	1.61	2
24	1.00	0.09	1.00	12.50	1.15	1.29	1.06	1.16	2.41	0.62	31.16	120.29	89.13	3	11.6	1	3.86	2
25	0.96	0.09	1.00	12.50	0.63	0.79	0.87	1.02	2.23	0.36	18.13	111.59	93.47	2	15.0	3	6.16	1
26	1.10	0.71	0.75	10.00	0.75	0.94	0.84	1.00	2.01	0.88	44.23	100.57	56.34	4	14.0	2	2.27	4
27	4.97	2.33	1.00	10.00	1.21	1.45	1.01	1.16	2.89	0.97	48.43	144.64	96.20	1	39.1	4	2.99	3

Heat and Cooling Loads Input From *Encom2* Calculations

Embodied Energy and CO2 Data Derived from Pullen Spreadsheets (not included)

User Input
Benefit Objective Weightings

User Input
Cost Weighting Relative to Benefits Summary Value

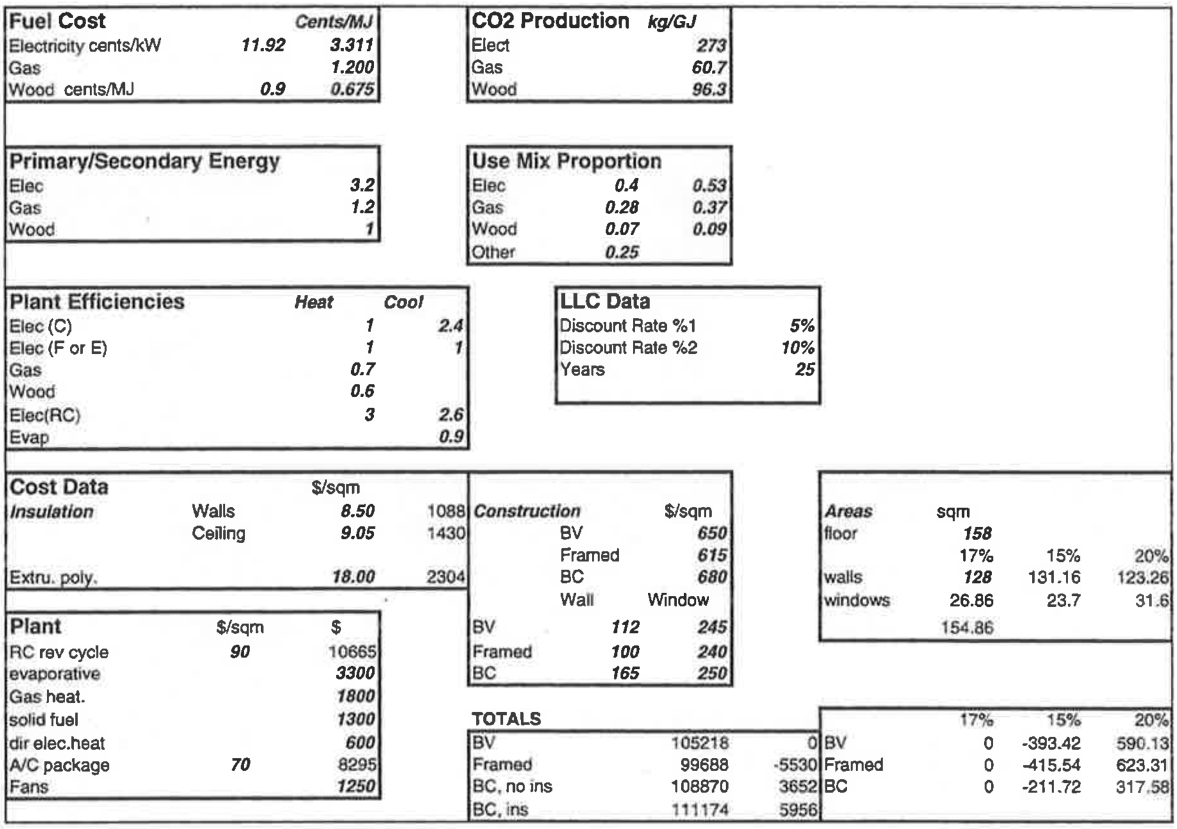
Performance Measures Estimated from *Encom2*

Full Solar Access Examples
Four Heating/Cooling Combinations

Restricted Solar Access Set 1
RC Heating & Cooling

Restricted Solar Access Set 2
Gas Heating & Evap. Cooling

Figure F.1: Calculation Spreadsheet



Fuel Cost		Cents/MJ
Electricity cents/kW	11.92	3.311
Gas		1.200
Wood cents/MJ	0.9	0.675

CO2 Production	kg/GJ
Elect	273
Gas	60.7
Wood	96.3

Primary/Secondary Energy	
Elec	3.2
Gas	1.2
Wood	1

Use Mix Proportion		
Elec	0.4	0.53
Gas	0.28	0.37
Wood	0.07	0.09
Other	0.25	

Plant Efficiencies	Heat	Cool
Elec (C)	1	2.4
Elec (F or E)	1	1
Gas	0.7	
Wood	0.6	
Elec(RC)	3	2.6
Evap		0.9

LLC Data	
Discount Rate %1	5%
Discount Rate %2	10%
Years	25

Cost Data		$/sqm	
Insulation	Walls	8.50	1088
	Ceiling	9.05	1430
Extru. poly.		18.00	2304

Construction		$/sqm
	BV	650
	Framed	615
	BC	680
	Wall	Window
BV	112	245
Framed	100	240
BC	165	250

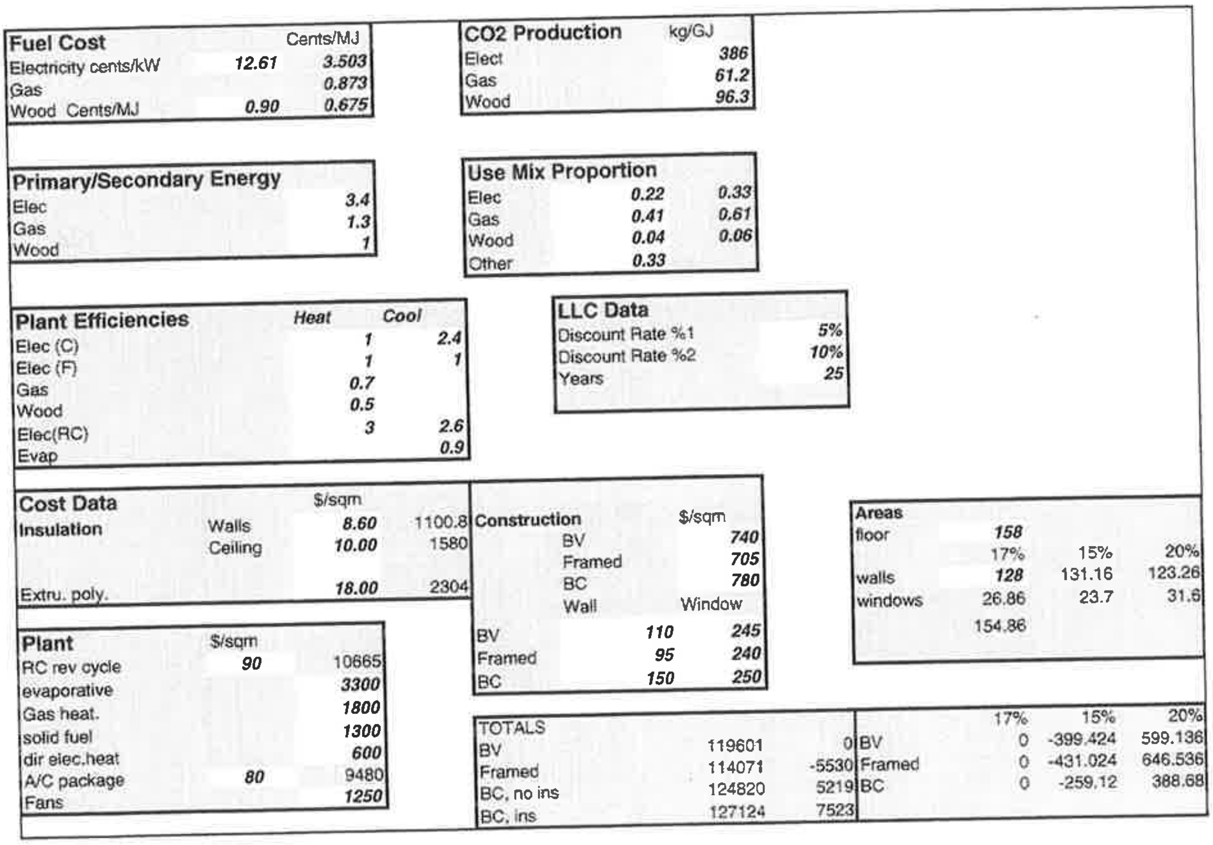
Areas	sqm		
floor	158		
	17%	15%	20%
walls	128	131.16	123.26
windows	26.86	23.7	31.6
	154.86		

Plant	$/sqm	$
RC rev cycle	90	10665
evaporative		3300
Gas heat.		1800
solid fuel		1300
dir elec.heat		600
A/C package	70	8295
Fans		1250

TOTALS		
BV	105218	0
Framed	99688	-5530
BC, no ins	108870	3652
BC, ins	111174	5956

	17%	15%	20%
BV	0	-393.42	590.13
Framed	0	-415.54	623.31
BC	0	-211.72	317.58

Figure F.2: Adelaide Input Data



Fuel Cost		Cents/MJ
Electricity cents/kW	12.61	3.503
Gas		0.873
Wood Cents/MJ	0.90	0.675

CO2 Production	kg/GJ
Elect	386
Gas	61.2
Wood	96.3

Primary/Secondary Energy	
Elec	3.4
Gas	1.3
Wood	1

Use Mix Proportion		
Elec	0.22	0.33
Gas	0.41	0.61
Wood	0.04	0.06
Other	0.33	

Plant Efficiencies	Heat	Cool
Elec (C)	1	2.4
Elec (F)	1	1
Gas	0.7	
Wood	0.5	
Elec(RC)	3	2.6
Evap		0.9

LLC Data	
Discount Rate %1	5%
Discount Rate %2	10%
Years	25

Cost Data		$/sqm	
Insulation	Walls	8.60	1100.8
	Ceiling	10.00	1580
Extru. poly.		18.00	2304

Construction		$/sqm
	BV	740
	Framed	705
	BC	780
	Wall	Window
BV	110	245
Framed	95	240
BC	150	250

Areas			
floor	158		
	17%	15%	20%
walls	128	131.16	123.26
windows	26.86	23.7	31.6
	154.86		

Plant	$/sqm	
RC rev cycle	90	10665
evaporative		3300
Gas heat.		1800
solid fuel		1300
dir elec.heat		600
A/C package	80	9480
Fans		1250

TOTALS		
BV	119601	0
Framed	114071	-5530
BC, no ins	124820	5219
BC, ins	127124	7523

	17%	15%	20%
BV	0	-399.424	599.136
Framed	0	-431.024	646.536
BC	0	-259.12	388.68

Figure F.3: Melbourne Input Data