THE COMFORT TRIANGLES: A NEW TOOL FOR BIOCLIMATIC DESIGN

John Martin Evans

Thesis submitted in partial fulfillment of the requirements of the award of Doctor of Philosophy

September 2007

The Comfort Triangles: A new tool for bioclimatic design.

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof.dr.ir. J.T. Fokkema
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op maandag 15 oktober 2007 om 10.00 uur
door **John Martin EVANS**
Architect
van de Architectural Association, London, United Kingdom,
geboren te Sutton and Cheam, Surrey, United Kingdom.

Dit proefschrift is goedgekeurd door de promotor:
Prof. Dipl.-Ing. H. J. Rosemann

Samenstelling promotiecommissie:
Rector Magnificus, voorzitter
Prof. Dipl.-ing. H. J. Rosemann, Technische Universiteit Delft, promotor
Dr. M. I. Carmona, Technische Universiteit Delft, toegevoegd promotor
Prof. ir. C. A. J. Duijvestein, Technische Universiteit Delft
Prof. ir. J. J. M. Cauberg, Technische Universiteit Delft
Prof. dr. ing. R. Lamberts, Universidad Federal de Santa Caterina, Brazil
Prof. dr. K. Steemers, The Martin Centre, University of Cambridge, United Kingdom
Prof. dr. O. Lewis, University College, Dublin, Ireland

ABSTRACT

The Comfort Triangles:
A new tool for bioclimatic design

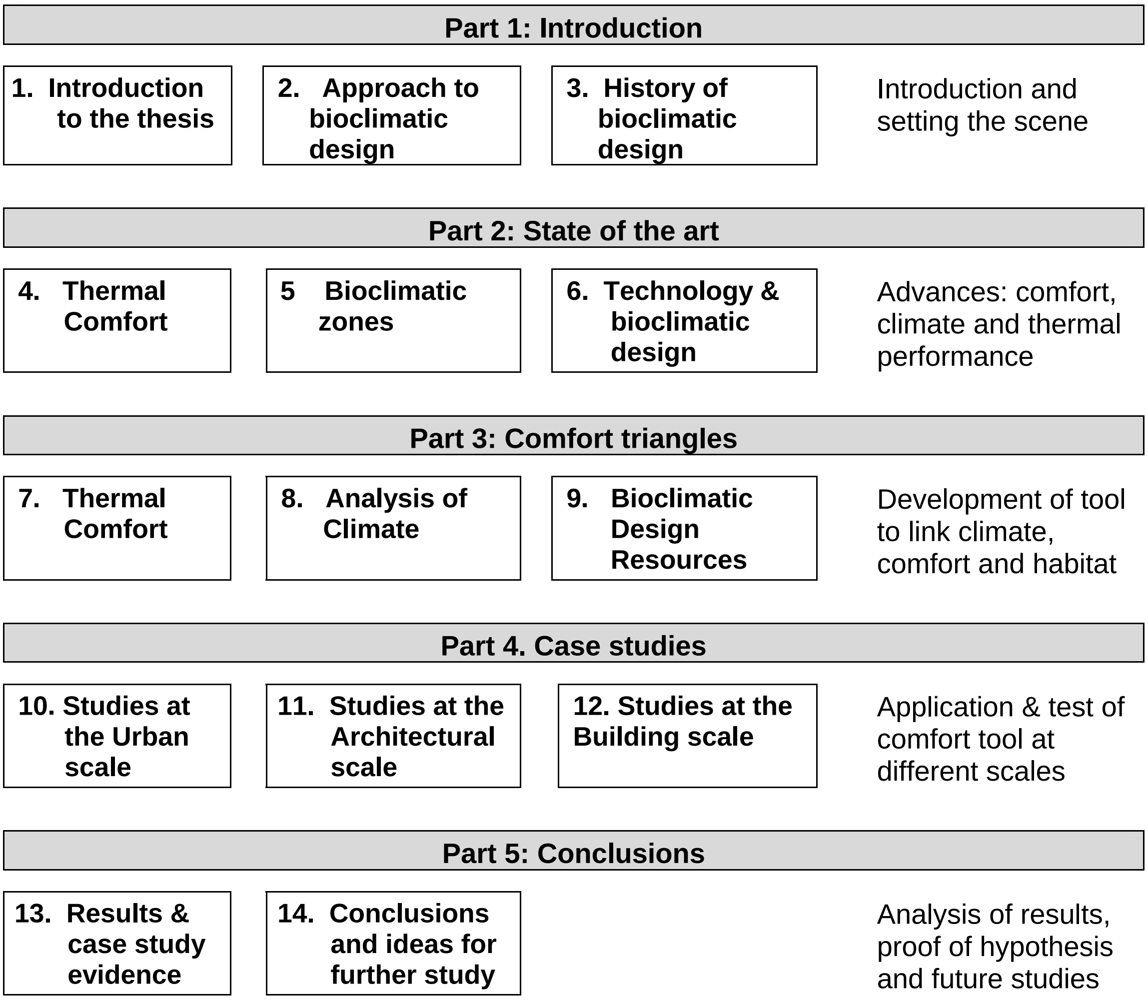
John Martin Evans

This thesis presents the development, application and testing of a new graphic analysis tool to identify, select and verify different bioclimatic strategies according to climate conditions and requirements for comfort. The Comfort Triangles tool relates outdoor daily temperature variations with the modification of thermal performance achieved indoors, using two key variables, average daily temperatures and temperature swings. The variation between indoor and outdoor average daily temperature shows the effectiveness of passive heating or cooling strategies, while the range ratio, or relation between indoor and outdoor swing shows the capacity of the building to moderate, control or maintain temperature variations in relation to comfort requirements. It is shown that many bioclimatic strategies aim to modify one or both of these variables.

Part 1 introduces concepts of bioclimatic design, objectives, methodology and thesis structure. Part 2 provides a literature review and defines the state of the art in thermal comfort, bioclimatic zoning and thermal performance of buildings with emphasis on passive strategies and natural conditioning. With this background, Part 3 describes the development of the comfort triangles concept, the use of the tool for climate analysis and evaluation of different bioclimatic design strategies, relating comfort, climate and habitat.

Part 4 of the thesis tests the tool using case studies at the urban, architectural and building construction scales. The aim is to check, demostrate and verify the use of the Comfort triangles in wide range of different climates, different situations and different building types. Studies using the comfort triangles at the urban scale show how the built environment produces modifications of the climatic conditions, modifying the temperature swing and increasing the average temperature. At the architectural scale, the studies show the impact of building form, orientation and shading on the average temperature and temperature swing. At the construction scale, studies of indoor and outdoor conditions show the results of different materials used in different climates. The Comfort Triangle clearly identifies the impact of the built environment in different climates, permitting a visualization of the change in the two key vectors, average temperature and temperature swing.

The final part of the thesis analyses the results of the case studies to show the value of this new graphic tool that allows the daily variations in indoor and outdoor temperature to be studied in a different way. It is shown that this new tool offers a valuable complement to existing bioclimatic design tools emphasizing the dynamic nature of thermal performance in bioclimatic design and natural conditioning. It is argued that factors such as global warming, urban heat islands and the excessive use of non-renewable energy resources will increase the need for the bioclimatic design approach. In this context the comfort triangles provide a new way to analyse projects in different climates and promote the selection of appropriate bioclimatic design strategies.



Part	Chapter	Chapter	Chapter	Summary
Part 1: Introduction	**1. Introduction to the thesis**	**2. Approach to bioclimatic design**	**3. History of bioclimatic design**	Introduction and setting the scene
Part 2: State of the art	**4. Thermal Comfort**	**5 Bioclimatic zones**	**6. Technology & bioclimatic design**	Advances: comfort, climate and thermal performance
Part 3: Comfort triangles	**7. Thermal Comfort**	**8. Analysis of Climate**	**9. Bioclimatic Design Resources**	Development of tool to link climate, comfort and habitat
Part 4. Case studies	**10. Studies at the Urban scale**	**11. Studies at the Architectural scale**	**12. Studies at the Building scale**	Application & test of comfort tool at different scales
Part 5: Conclusions	**13. Results & case study evidence**	**14. Conclusions and ideas for further study**		Analysis of results, proof of hypothesis and future studies

Figure 1.6 has been added here to show the thesis structure and aid navigation

Doctoral Thesis 2007

John Martin Evans

The Comfort Triangles: A new tool for bioclimatic design

CONTENTS.

LIST OF FIGURES.

LIST OF TABLES

ACKNOWLEDGEMENTS

Thanks are due to the Promotor, Prof. Jürgen Rosemann and Co-Promotor Dr Marisa Carmona, Technical University of Delft. The author thanks Dr Marisa Carmona for her kind invitation to participate in the IBIS Network of the ALFA Programme; this thesis is presented to contribute to this activity.

This thesis was prepared while the author was directing the Research Centre Habitat and Energy, Faculty of Architecture, Design and Urbanism, University of Buenos Aires, so the support provided is gratefully acknowledged. A number of the research studies cited or presented in this thesis were supported financially by the University of Buenos Aires in acredited research projects, as well as research programmes of the National Agency for Promotion of Science and Technology and Conicet. These were carried out under the supervision of the author and Dr. Silvia de Schiller, Joint Directors of the Research Centre Habitat and Energy.

The first version of the comfort triangles was published in Bio-environmental Design and Solar Achitecture '*Diseño Bioambiental y Arquitectura Solar*' (Evans and de Schiller, 1994). Special thanks to the co-author and Joint Director of the Research Centre, Dr. Silvia de Schiller, who has encouraged and supported the development of this concept over the years.

Many members of the Research Centre Habitat and Energy, CIHE-FADU-UBA, and researchers of other universities have assisted with the measurements presented in the case studies; so special thanks to all of them, particularly to:

- Prof. Climaco Bastidas, Director of ISI, and Prof. Wilson Roman, Faculty of Architecture, Central University of Ecuador. Case 4.
- Researchers Carlos Raspall and Julian Evans, CIHE-FADU-UBA. Case 5, measurements in the Curutchet House, La Plata, designed by Le Corbusier.
- Eduardo Paniagua, Director of CIVCO, and research team, Costa Rica Technological Institute, Cartago, Costa Rica. Case 8, low cost housing.
- Researcher Juan Carlos Patrone, designer of the soil-cement prototype house, constructed with the support of Tomas Vanrell, Secretary of Public Works and Services, Municipality of Florencio Varela, Buenos Aires Province. Case 10, Stabalised soil construction.
- Researcher Claudio Delbene for measurements of the Faculty of Architecture, Design and Urbanism, University of Buenos Aires.
- Technical Secretary of the CIHE Research Centre, Veronica Snoj.

The urban heat island studies were carried out with the support of the following universities and the students of postgraduate seminars, directed by the author and Dr Silvia de Schiller:

- University of Buenos Aires: Students of the postgraduate course in Bioclimatic Design, with help from Maria Leveratto in the preparation of maps. Case 1: Buenos Aires heat island.
- University of Southern Patagonia: Students of the postgraduate course in Architecture, Energy and Environment. Case 2: Rio Gallegos heat island.
- University of Tamaulipas, Tampico, Mexico: Students of the postgraduate course in Bioclimatic Design. Case 3: Tampico heat island.

The electronic spreadsheet for analysing climate data and preparing graphs of the comfort triangles ***'e-clim.xls'*** was prepared by the author with contributions from Claudio Delbene, Ana María Compagnoni and Mariano Cabezón. It was tested by students from following courses:

- Masters courses in 'Bioclimatic Design', at the University College London, 2003,
- Masters course on 'Bioclimatic Architecture, Isthmus, Panama, 2004 and 2007,
- Masters course on Bioclimatic design, University of Colima, Mexico, 2006,
- Postgraduate courses at Autonomous University of Tamaulipas, Tampico, 2004.
- Seminar on bioclimatic design Autonomous Metropolitan University, Mexico, UAM, 2004.
- Seminar on Bioclimatic design Central University of Ecuador, Quito, UCE, 2005 and 2006.
- Postgraduate seminar, Central University, Santiago, Chile, 2005.
- Seminars in the Masters course Environmental Administration, National University of Cordoba, Argentina, 2004 and 2006.
- Seminars in the Specialization postgraduate course on Bioclimatic Design, and National University of Catamarca, 2006 and 2007

The electronic spread-sheet '***e-temp.xls'*** for estimating indoor temperatures (Evans, 2006) was tested during 2006 by 60 undergraduate students, following the course 'Introduction to solar architecture' and by 30 students of the course 'Energy in Buildings' in the Faculty of Architecture, Design and Urbanism, University of Buenos Aires.

NOTE ON GRAPHS AND UNITS

Temperature.

In the Comfort Triangle Graph, the vertical axis corresponds to the daily temperature swing in degrees Kelvin, the same as a temperature difference in degrees Celsius. In the same graph, the horizontal axis is the average daily temperature in degrees Celsius. By convention and according to ISO Standards and the SI System, temperature differences are expressed as degrees Kelvin, identical to the temperature difference in degrees Celsius, while the average temperatures is indicated in degrees Celsius, as the Table below shows.

Variable	Measurement	Units
Daily temperature swing.	Difference in degrees Kelvin	8 Degrees K
Average daily temperature.	Degree Celsius	18° C

Latitude.

The examples in the case studies are all from Latin America. Costa Rica and Mexico are in the northern hemisphere, so the winter sun comes from the south in January, while in Argentina in the southern hemisphere, the winter sun comes from the north in June. Quito, Tena, and Cuenca, Ecuador, are situated very close to the equator, so seasonal variations are minimum and solar altitudes are high at midday. On the Ecuator, they range from 23.4° S of the zenith in January, 23.4° N of the zenith in June. The climates analysed in Chapter 8 include Yerivan, Armenia and Jubail, Saudia Arabia, latitudes 40° and 27° north respectively.

Thermal characteristics.

The thermal transmission of walls and roofs, the ‘U’ Value, is indicated in Watts per square metre for degree difference in temperature (W/m^2K), and the SI system is used in this thesis. In the Argentine thermal standards (IRAM, 1996), the ‘U’ Value is called the ‘K’ Value. The thermal admittance (CIBSE, 1980) has the same units as the ‘U’ value.

PART 1

CHAPTER 1. INTRODUCTION

CHAPTER 2. BACKGROUND TO BIOCLIMATIC DESIGN

CHAPTER 3. HISTORY AND EVOLUTION OF BIOCLIMATIC DESIGN

Part 1 provides the introduction to the development of the thesis with objectives, hypothesis, structure, methodology and contents of the chapters, which are presented in Chapter 1, followed a review of the background of bioclimatic design in Chapter 2, and the critical analysis of the history and evolution of the approach in Chapter 3.

Chapter 1 of the thesis aims to introduce the field of bioclimatic design in architectural practice, present the hypothesis and establish the general and specific objectives. The relevance of the thesis is discussed in the context of current developments related to energy resources and the impact of the built environment. The methodology adopted in the thesis is explained and the structure, formed by five parts and twelve chapters, is presented with the sequence of selected case studies at different scales in contrasting climates and a variety of building types, which are used to verify and prove the hypothesis.

Chapter 2 presents a brief outline of the conventional bioclimatic design approach, complemented by the identification of key topics, definition of related terms, and description of the evolution in theory and practice. This is followed by a critical analysis on the integration of bioclimatic design in project development.

Chapter 3 summarises the development of bioclimatic design resources through the history of architecture at the world scale, followed by the evolution of the field in the Latin American region, concluding with a discussion on the developing theme of sustainability in the built environment.

Part 1: Introduction

1. Introduction | **2. Background ...** | **3. History …**

Part 2: State of the art

4. Thermal Comfort | 5 Bioclimatic zones | 6. Technology …

Part 3: Comfort triangles

7. Thermal Comfort | 8. Analysis of Climate | 9. Design Resources

Part 4. Case studies

10. Urban scale | 11. Architectural scale | 12. Building scale

Part 5: Conclusions

13. Results & case study evidence | 14. Conclusions & ideas for further study

CHAPTER 1. INTRODUCTION

1.1. INTRODUCTION

The thesis presented here develops, tests and verifies the use of a new design tool to define and implement bioclimatic criteria in architectural and urban projects. It also aims to link comfort requirements, climate conditions and the thermal behaviour of the built environment, in order to contribute to the design process. The approach adopted emphasises the role of natural conditioning and bioclimatic design strategies in the production of sustainable architecture, including both indoor and outdoor spaces that provide thermal comfort by responding to the natural conditions with reduced energy demand and low environmental impacts.

Natural conditioning is a process that modifies the environmental conditions, especially the thermal variables, through the use of design alternatives and selection of materials. For this reason, the urban, architectural and detailed design decisions impact strongly in the modification of the environmental conditions, with respect to the external situation. Specifically, the architectural design decisions and construction characteristics modify the daily cycle of external temperature variations, defined by the average temperature and the temperature swing.

These two variables are used in the development of this thesis to generate a tool to analyse climate and comfort, evaluate thermal performance and select design strategies that promote effective conditions for a regional architecture based on logical principles, avoiding often subjective approaches. This instrument also contributes to the re-definition of bioclimatic zoning criteria, identifying geographic and climatic zoning where similar urban, architectural and building design resources are required for comfort and well-being of the occupants, reducing the energy requirements and the resulting environmental impacts.

The general proposal of the thesis reflects the authors deep concern for the promotion and integration of bioclimatic strategies and natural resources in the design process and implementation in practice, in the search for user comfort, energy efficiency and sustainability in architecture. This concern started during graduate studies in the Architectural Association, London, and a one-year exchange programme at the Kumasi University of Science and Technology, Ghana. In the following year, the postgraduate course in Tropical Architecture provided a theoretical and practical framework for studying and applying bioclimatic design resources, initiating a specialization in this field.

Different experiences in architectural and planning projects, combined with teaching experiences, research and technical assistance studies in Europe, North Africa, the Middle East, and Central and South America have contributed to the detection of an area of study and the importance of design guidelines applied in the initial stages of project development. The need to define and specify these guidelines with greater precision to achieve a better architectural response to the climatic impacts motivate the present thesis, in the framework of the search for a more sustainable built environment.

Architecture should offer, as a basic and fundamental concern (Szokolay, 1995), environmental conditions suitable for the activities and functions that are undertaken in both the indoor and outdoor spaces. This fundamental aptitude is linked to the health, the productivity and the response to user requirements, with the resulting economic benefits, as well as ensuring the welfare, comfort and sensation of satisfaction, with the consequent social and environmental benefits.

1.2. CONCEPTUAL FRAMEWORK

This thesis, which aims to contribute to the effective application of bioclimatic design strategies, is developed in the following framework of concerns, aims and application stages.

1.2.1. The concern of bioclimatic design.

The protection from adverse conditions of the outdoor environment, as well as the conservation of environmental variables favouring comfort, can be achieved through two alternative mechanisms: the use of bioclimatic design resources or the mechanical plant to provide artificial conditioning. However, climatic protection and taking advantage of the favourable conditions not only implies the search for comfort and well-being, but also the reduction of the demand for fossil and non-renewable energy, as well as the better use of renewable energies from natural sources such as sun and wind.

This concern, underlined by the energy crisis of the 70’s and still relevant today, is becoming more acute as a result of instability in the Middle East where more than 70 % of the world’s readily available petrol resources are found (Wikieadia, 2007), as well as the international pressures to gain control and access to energy resources.

An architectural project, through appropriate bioclimatic design, can offer thermal delight in the same way that it can provide visual and spatial delight (Heschong, 1996). The different qualities that architecture offers, originally proposed by Vitruvius (1914)[*] in one of the first architectural treatise, which specified ‘commodity, firmness and delight’, can also be related to the thermal design of the built environment.

1.2.2. The aims of bioclimatic design.

In 1953, Olgyay coined the term ‘**bioclimatic**’ (Szokolay, 1995), utilised in the sub-title of his book ‘Design with climate: Bioclimatic approach to architectural regionalism’ (Olgyay, 1970). He also developed a graphic tool, known as Olgyay’s Bioclimatic Chart (1970, pp. 22 y 23). In Chapter 2 of this thesis, the terminology of ‘bioclimatic design’ is analysed in more depth.

More recently, Szokolay (1995, p. 71) defined the objective of bioclimatic design in architecture as the need to ‘ensure the development and well-being of **biological organisms** (principally human) subject to specific **climatic conditions**’. Lloyd Jones (2002, p. 248) also proposed a wide scope and defined it as ‘an approach to design based on nature’, that applies the logic of sustainability in all aspects of a project, whose objective is to optimise the use of the natural environment.

---

[*] Date of translation used in this thesis

In this context, the resources of bioclimatic design put in place a series of mechanisms that modify, control and conserve environmental variables which affect the sensation of thermal comfort through the selection of specific strategies and design options for each and all aspects and scales of the project, at urban, architectural and construction detail.

The inter-relation of impacts and contributions involved in different design scales is a major and fundamental aspect of the bioclimatic approach proposed in this thesis. For this reason, the case studies presented encompass urban and building complexes, as well as architectural projects and construction materials used in the building envelope. In the context of this thesis, the term 'built environment' is used to cover this wide range of scales of the man-made environment which houses the activities of society.

1.2.3. The stages of bioclimatic design.

In this approach to the design process, the first stage of analysis is focussed on the study of the climatic and environmental conditions of the project's physical situation together with the variations that occur from the impact of climatic conditions in different local and regional contexts.

This analysis is based on the meteorological data, typical of the location, as well as the evaluation of the microclimatic variations produced by the characteristics of the immediate surroundings, such as topography, vegetation and nearby buildings. These environmental conditions are then compared with the variables required to achieve comfort and well-being of the occupants. For this reason, the environmental variables required for comfort are related to the climatic variables of temperature, humidity, wind and solar radiation.

The comparison between existing conditions of the environment and the desirable conditions required for comfort and well-being allow the identification of the most favourable aspects to take advantage of and the variables which could be used to improve conditions, such as solar radiation on a cold day or cooling breezes on a hot humid summer day. The unfavourable aspects that require protection can also be identified, such as cold winds in winter or strong sunshine at midday in summer.

The building design can offer these possibilities of both protection from unfavourable aspects and optimisation of favourable ones, through the use of building form, grouping of volumes, facade orientation, design of openings, colour selection, and thermal characteristics of building elements. It is argued that each and all of these aspects require design decisions that can promote the creation of favourable comfort conditions, or approach acceptable levels of habitability and energy efficiency.

However, the process of analysis and design implies the development of the capacity to manage significant variables and select appropriate design guidelines for different climate regions. It is emphasised that, for specific bioclimatic conditions, the requirements for natural conditioning vary, giving rise to a 'bioclimatic regionalism' (Olgyay, 1973 and 1998). From these basic studies, the bioclimatic zoning can be established (Koenigsberger, Mahoney and Evans, 1970) with the aim of defining regions according to thermal requirements in order to achieve appropriate natural conditioning in buildings. As an example, these criteria are set out in Argentina in the National Standard 11.603 (IRAM, 1993), applied in programmes of social housing.

In the development of this thesis, evidence is gathered to demonstrate the way in which design decisions modify, control and preserve comfort conditions. This has led to the development and application of a new design tool to define and support design decisions that improve the thermal sensation of users of the built environment, both inside buildings and in the surrounding outdoor spaces.

This design tool has also been tested and evaluated by users in the framework of an annual undergraduate course 'Energy in Buildings' given by the author in the Faculty of Architecture, Design and Urbanism, University of Buenos Aires since 1994.

In the context of the development and testing of this tool, this first chapter of the thesis aims to achieve the following objectives:

- Introduce the conceptual framework of bioclimatic design.
- Establish the context, relevance of the thesis and present the development of the approach.
- Present the hypothesis.
- Define the general and specific objectives of the thesis.
- Explain the methodology adopted and introduce the selection of case studies in different climates, scales and building types.
- Introduce the structure and sequence of the thesis, including the analysis of the background, as well as the verification and proof of the hypothesis.

1.3. CONTEXT, RELEVANCE AND DEVELOPMENT OF THE HYPOTHESIS

The central theme of the thesis responds to the concern for the rational application of resources in the production and use of the built environment and consequent environmental impacts. It covers the following three basic aspects of sustainable development:

- **Energy** in the built environment, at national and international scale, emphasising the importance of reducing present day dependence on non renewable resources.
- **Environmental impact** of the built environment, caused by energy use at local, regional and world scale.
- **Sustainability** of the built environment, including the economic, social and environmental dimensions.

These aspects are of worldwide importance though, in this thesis, the example of Argentina is taken as a clear frame of reference to illustrate the impact of energy use in the built environment in a specific context, with aditional case studies from Latin America.

1.3.1. Energy in the built environment.

During the last 30 years, the world has exploited it's abundant non-renewable energy resources according to availability and economic policies. The natural gas fields in Argentina (Guadagni, 1985) have allowed, till now, a development without political or economic dependence on imported energy supplies, though this important advantage has not been exploited sufficiently to achieve a sustained and sustainable development.

However, in moments when the economic situation of the region remains critical, aggravated by the weight of foreign debt, the gas reserves are in steady decline. According to official statistics, in the past 15 years, the reserves of gas have suffered a reduction of 13 years, at a rhythm of almost one year in each annual period (IAE, 1999).

Although the present day reserves have been estimated in approximately 8 years, the increase in demand is likely to reduce this period significantly. At the present time, there is a steady increase in energy demand in the residential sector, especially in sectors with higher incomes and higher consumption. In these sectors, there is also a strong increase of the demand for artificial conditioning, with the introduction of central heating systems and cooling installations, often with large capacities to overcome building design deficiencies.

At the same time, the industrial sector registers an economic recovery and favourable expectations, especially in sectors related to agriculture and exports, producing an increase in energy demand for productive purposes.

This regional energy context will inevitably produce an important increase in the price of energy in the short and medium term while, in the longer term, in about 7 to 9 years, the price and availability of energy resources will depend on the conditions imposed by the international markets, increasingly disadvantageous for the country. The inevitable need to use scarce foreign reserves to buy energy resources will have a negative impact on the national economy.

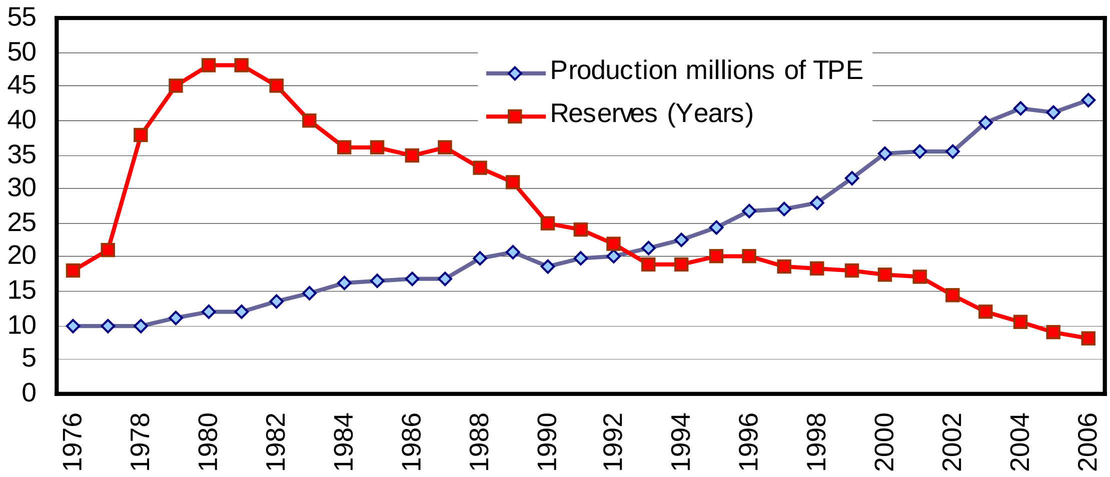


Figure 1.1. Gas production in millions of TPE, Tons of Petroleum Equivilent and years of reserves, in Argentina. Sources: Secretaría de Energía (2007) and (Rabinovich, 2006).

In this framework, the re-equipment of the industrial and transport sectors, with new plant in factories and more efficient vehicles, can be accomplished in a cycle of about 10 years, which permits a degree of adjustment to new conditions, introduce measures to reduce demand and adapt to changing fuel availability.

However, in the building stock, energy demand, especially the part that relates to buildings constructed in the period of cheap and abundant energy, will continue without possibility of adaptation, due to the long life cycle of these long-term investments and the high costs of modifying existing buildings.

In this case, it is argued that the introduction of techniques for rational energy use in building design will allow significant savings in energy demand, and greater benefits for efficient energy use. The measures to be applied in the residential sector, include: the incorporation of thermal insulation, the use of passive and active solar systems and the implementation of bioclimatic design resources for cooling and natural ventilation.

The first measure is well known and does not imply problems in the application, due to the extensive technological, industrial and marketing development, as well as legislative support, especially in the colder regions of the world where the industrialised countries of Europe, Japan and North America are located. The results obtained in these countries have proved highly successful. Significant benefits would accrue if these measures were adopted in Argentina (Tanides et al, 2006).

Following this line of development, some national standards in Argentina, especially the IRAM Standard 11.605 (1999b), have been applied for over 20 years, although this implementation is still partial and not strictly observed, being limited to national programmes for social housing (Ministerio de Infraestructura y Vivienda, 2000).

The integration of passive solar systems, direct solar gains, natural cooling and thermal inertia use concepts of periodic heat flow related to variations of temperature. All these systems require design methods and dimensional techniques of much greater complexity, whose comprehension and resolution are the concern of this thesis.

1.3.2. Environmental impact.

In this framework, it is relevant to note that the energy resources available in Argentina are of relatively low environmental impact, partly due to the low rate of emissions of greenhouse gasses from natural gas, which accounts for 50% of the primary energy used in the country (Secretaría de Energía, 2007). Coal and liquid hydrocarbons emit significantly higher quantities of greenhouse gasses. On the other hand, electrical energy produced by nuclear and hydro-power does not produce greenhouse gas emissions, according to the international methods developed to assess inventories of emissions (SRNDS, 1999a y 1999b).

These characteristics of the relatively clean energies used in Argentina implies that this country complies with the emission control requirements of the Kyoto Protocol, despite the fact that Argentina as a ‘developing country’ does not yet have binding obligations to reduce carbon emissions, like other countries in the region. However, as Figure 1.2 clearly shows, the greenhouse gas emissions produced by the built environment in Argentina are indeed significant.

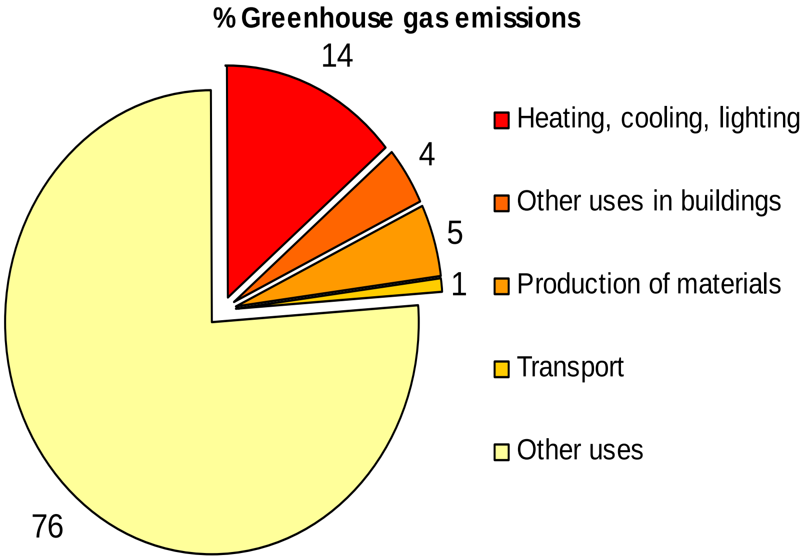


Figure 1.2. Emissions of green house gases, GHGs, in Argentina and the use of energy in buildings. Graph based on Evans (2003) with data from SRNDS (1999a y 1999b).

This estimate, prepared by the author (Evans, 2003), using the national inventories, shows that the energy used in heating and cooling is the principle source of greenhouse gas emissions of the built environment, producing 14 % of GHGs, while various other energy uses represent a further 4 %. In this scenario, the production of construction materials, especially cement, lime and steel, emit 5 %, while about 1 % corresponds to the transport emissions from the delivery of materials, recycling, maintenance and eventual removal of demolition debris.

However, with the dwindling stocks of gas, future energy supplies will swing to fuel oil, diesel and other more polluting sources, precisely in the period when the impact on global warming is receiving more attention.

For these reasons, the future energy outlook in the region not only implies higher costs but also larger environmental impacts. The use of renewable energy and natural conditioning in buildings emphasises the reassessment of the concept of thermal swing as a basic resource for implementing bioclimatic strategies, the central theme of this thesis.

Comparatively, it is interesting to note that the buildings of Europe and the United States emit between 39 to 40 % of all greenhouse gas emissions, as shown in Figure 1.3, while in Argentina, this figure is only 24 %, despite the low priority given to environmental protection and the poor thermal performance of many buildings. The rate of emissions may be exceeding the capacity of the earth to adapt (Lovelock, 2007)

The lower percentage is partly due to the important emissions of the agricultural sector. Thus part of Argentina's emissions are produced in response to the food demand in developed countries, increasing the domestic importance of building sector emissions, and also increasing emissions generated by OECD countries.

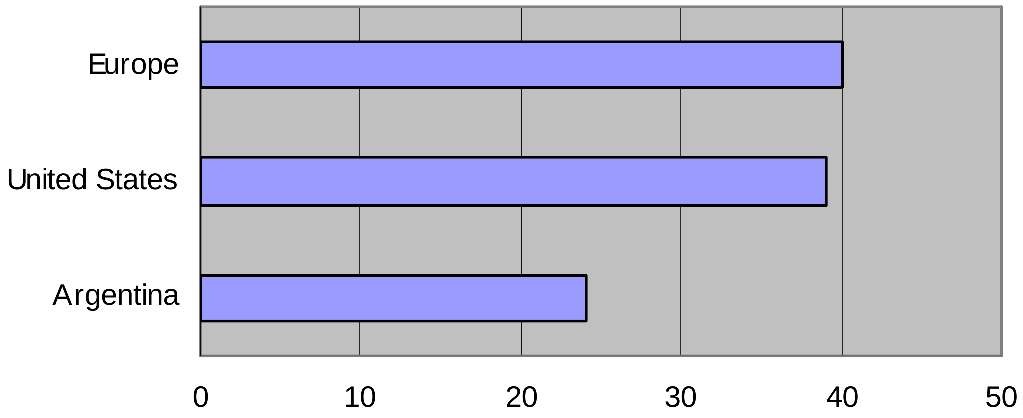


Figure 1.3. Greenhouse gases emitted by buildings as a percentage of total emissions in Europe, the United States and Argentina. Sources: Smith (2001), Rogers (2000) and Figure 1.2.

1.3.3. Modification of environmental conditions.

In the conventional methods of bioclimatic analysis, the meteorological variables are considered as fixed and related to the comparative variables required for comfort. The analysis of the conventional bioclimatic approaches undertaken in this thesis found that the external maximum and minimum temperatures are compared with the comfort requirements, typically using the meteorological means. Chapter 2 considers this comparison process in greater detail.

During the last decade there has been an increasing awareness of the impact of fossil fuels and other sources of greenhouse gas emissions that are generating climate change and global warming. The concern about the increase of carbon emissions originated with the systematic measurement of CO2, especially those in Honolulu started in 1955. They demonstrated the seasonal variation of CO2 concentrations and the steady increase, year on year (MIT, 1971), that continues till the present day (Smith, 2001). Other anthropogenic emissions of greenhouse gasses such as methane (SRNDS, 1999a) are further increasing this impact.

In the following section, the consequences of this impact are evaluated, as they potentially represent a significant change in the application of the bioclimatic design sequence, previously outlined.

The base-line used to establish the outdoor conditions was founded on past climatic records, but now may have to take into account future changes, relying on experts predictions in climate change. These changes, largely man-made, affect climate characteristics at different scales.

For this reason, in this chapter, two specific scales are emphasised: climate change at the global scale, produced by GHG emissions, and the heat island in urban areas. At the same time, predicted changes are compared with past variations to demonstrate the accelerating process of climate change and anticipate the intensity of possible impacts, especially those that affect the built environment.

The objective of this analysis is to identify the **predicted climate changes** during the useful life of buildings designed today and to **evaluate the degree of impact** compared with the changes experienced in the past.

The phenomenon of climate change at different scales is considered here in order to avoid confusion between different mechanisms of modification as well as to consider possible combined and accumulative impacts that can affect the sustainability of the built environment.

1.3.4. Climate change: past, present and future.

Different authors (MIT, 1972; Lamb, 1982, Houghton, 2004) have commented on climate variations from the pre-historic era up to the present day. The data presented by Lamb (1982) show the slow changes produced after the last ice age with a change of 3° K from 3,000 BC to the present, representing a variation of less than 1° K in a 1,000 years, although the modifications occurred in a series of steps.

On the other hand, the Report of the Inter-Governmental Panel on Climate Change (IPCC, 1999, 2001, 2006) predicts a change of between 3° and 6° K in the next 100 years, a rate of change 60 times greater than the slow changes of the past. Over the last two decades, the increase in average temperature has been close to the maximum predicted value (Lovelock, 2007), showing that past predictions have tended to be conservative.

The severity and potential impact of the predicted climate changes, largely produced as a result of man's activities, fully justifies the implementation of mitigation measures to reduce GHGs emissions (IPCC, 2001a).

In the building sector, the impact of climate change relates to two complementary aspects, mitigation and prevention, with the following considerations:

- **Mitigation:** To reduce energy demand and the resulting emissions through improvements in building design as well as the introduction of building plant with improved efficiency.
- **Prevention:** Incorporate measures in building design to respond to the predicted future changes and reduce the unfavourable consequences, an approach that Roaf (2001) has named '*future-proofing*', that calls for a new and different attitude towards project development. In contrast to the conventional approach, this implies a strong professional and ethical responsibility to the user and the environment, considering that one affects the other.

1.3.5. The Urban Heat Island.

Anthropogenic activities also generate a phenomenon known as the 'urban heat island' (Oke, 1982; Santamaouris, 2001), increasing the average and peak temperature in urban areas as a result of energy use in industry, transport and buildings, as well as the storage of heat in building materials, increasing the night-time temperature.

This effect, combined with the phenomenon of global climate change, produces a further temperature increase, adding to the energy demand for cooling, promotes a vicious circle of cause and effect, illustrated in Figure 1.4.

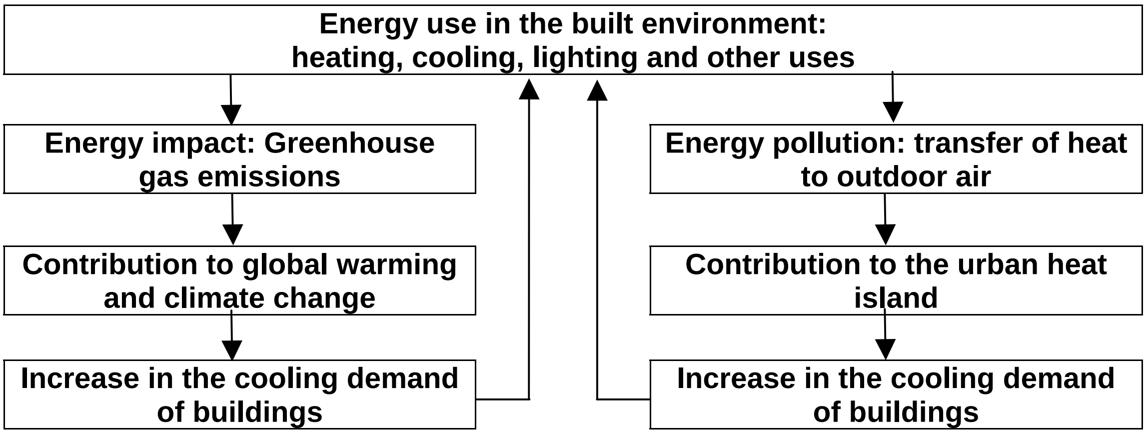


Figure 1.4. Climate change as a result of greenhouse gas emissions and increased energy use as a result of the urban heat island (based on de Schiller, 2004).

1.3.6. Impact of climate change in the building sector.

While much attention is rightly placed on the impact of climate change and global warming on the occurrence of extreme events, the slight but inexorable increase in the mean temperature will have a significant effect on energy demand for the conditioning of buildings.

At low outdoor ambient temperatures, that is with average temperatures below 14°-15°C, the heat losses will be continuous from buildings with indoor temperatures above 18°C, a normal lower limit for sedentary activities. As temperatures rise, heat losses will be intermittent. As indoor temperatures rise, the demand for refrigeration will start to increase, especially in lightweight buildings. The peak temperatures in these buildings will be significantly higher than those in heavyweight buildings.

While thermal insulation is needed to reduce buildings energy demand for heating in cold climates, thermal mass can achieve a large reduction of the energy demand for cooling, especially in climates were average temperatures are within the comfort range. The need to study the thermal swing will become more important over time as average temperatures rise slowly with global warming.

1.3.7. Energy availability in Latin America.

As the effects of climate change and urban microclimate modification are closely linked to energy use and may modify and extend the use of energy, the availability and characteristics of energy resources are evaluated.

The long time energy scenario in Latin America is rather gloomy, with the exception of Venezuela, Ecuador and Bolivia. Brazil, the largest consumer, is highly dependant on imported energy. Chile, with very limited local resources, is also dependant on gas imported from Argentina, although this source of energy was recently suspended due to domestic supply problems in the later country. Uruguay is another example without significant energy resources, except for two major hydroelectric projects, one generated by

Salto Grande, shared with Argentina, and the other by the Rio Negro dam in the centre of the country. Mexico, a former energy exporter, faces dwindling reserves and increasing dependence on the refining capacity of the United States.

On the other hand, Latin American countries, such as Venezuela and Bolivia, with the largest reserves on petrol and gas also have some of the most serious political situations, and are subject to strong pressure from the United States, the most important importer of fossil energy.

Despite the critical energy scenario in the medium and long term, there is little effort to achieve greater energy efficiency in buildings in all the vast region, an important sector of demand using over 35 % of the energy resources in buildings, principally for heating, cooling and lighting. However, national energy policies in the region do not include significant actions in this field to reduce demand for this vital resource.

For example, the requirements for thermal insulation in the Argentine national standards are not compulsory, and are not even mentioned in provincial legislation or municipal building codes. Only the standards for social housing require the application of thermal insulation standard IRAM 11.506, Level C ‘minimum’, which only aims to avoid condensation risk, with an insulation thickness less than the optimum required for lowest cost in use. Standards in other countries of the region are analysed in Part 2 of this thesis.

In this thesis, it is argued that the application of natural conditioning and the use of renewable energy in architecture will allow a more sustainable development of the built environment. This can be achieved at lower cost with greater political independence and energy autonomy.

1.3.8. Sustainability.

The issue of sustainability of the built environment, and the development of awareness of environmental consequences are of increasing concern and have motivated policies to promote low impact buildings. To introduce this theme, an analysis of the development of different approaches to sustainability are followed by an evaluation of the built environment’s contribution to sustainability.

In this context, the objective of this section is to indicate current approaches to sustainability and demonstrate their role and importance, with special reference to the built environment.

In establishing the relationship between environmental impacts and the requirement for comfort in buildings, the relevance of the theme is emphasised as well as the importance of the integration in design decisions.

A recent and relevant proposal to apply this relationship in practice is the series of 5 major criteria for sustainability proposed in the framework of the International Holcim Competition for Sustainable Building (Holcim, 2005), where these criteria were used to evaluate the submissions presented.

Table 1.1 indicates the criteria selected for Holcim Competition and their relation with the principles developed by du Plessis (1998), grouped in 5 themes, that incorporate 2 new aspects not included in previous proposals.

Table 1.1. Criteria of Sustainable Construction, developed for the Holcim International Competition (2005).

Holcim Competition Criteria	**Aspects of Sustainability**
Ethical values and social equality	Social sustainability
Ecological quality and energy saving	Environmental sustainability
Economic performance and compatibility	Economic sustainability
Quantum change and replicability	New: Scale and diffusion
Response to context and aesthetic impact	New: Visual Sustainability

The **first innovation** of the new proposal to evaluate sustainability of the projects presented is the need to consider a significant advance over the conventional practices of ‘business as usual’ and evaluate the transfer potential.

This new criteria responds to the urgency to provide answers to the environmental and social challenges, in parallel with the need to transfer and apply new solutions on a scale sufficiently wide to achieve a significant reduction in environmental impacts of the built environment in the short and medium term. This does not imply neglecting proposals that achieve small environmental, social and economic benefits with limited or partial effects, valuable at the individual scale.

However, it is considered that only the spread and application of new and effective solutions on a large scale can contribute to the creation of a sustainable built environment. This criteria is highly relevant to the building sector, where harmful impacts are the result of many small-scale decisions that, in total, produce important environmental damage.

The second innovation is the requirement to communicate visually and aesthetically the ‘sustainable qualities’ of architectural projects. In the same way that large corporations complement their policies of economic, environmental and social responsibility with the development of a corporate-image and systems of visual identity with logos, colours and typography, to create an integral visual image to identify and project the activities and products of the company, sustainable buildings also have the challenge to communicate the qualities through the design itself in a form appropriate to the context.

This criteria, which emphasises the need to demonstrate and communicate sustainable qualities in architecture, implies however certain risks and uncertainties. In order to highlight this dilemma, an analysis of ‘sustainable projects’ (Herzog, 1998; Behling and Behling, 1998; Roaf, 2001 and 2003) confirms the inexistence of a recognisable ‘sustainable style’. Additionally, the application of visible architectural features as responses of ecological symbolism, such as incorporation of photovoltaic modules in facades, the use of green roofs and selection of organic materials for finishes, do not necessarily ensure a ‘sustainable building’.

However, the expression of bioclimatic strategies, the measures of energy efficiency and the demonstration of sustainable building strategies can be shown in the architectural form, adding substantial formal significance to the project.

In Figure 1.5., the relationship between the five Holcim criteria are shown, integrating the three traditional components of sustainability with the 2 additional aspects.

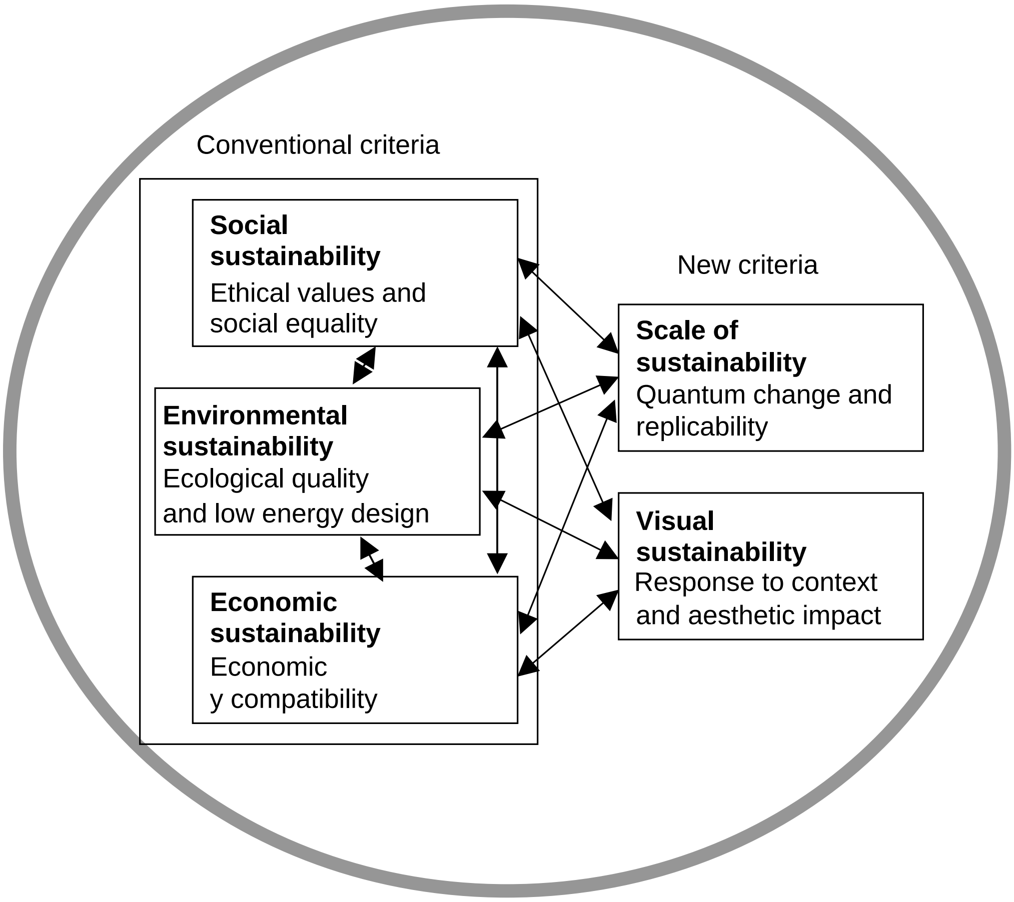


Figure 1.5. Sustainable Construction criteria, based on the Holcim Competition (2005).

1.3.9. Background to the hypothesis.

In this section, it is argued that to reduce the dependence on fossil fuels, environmental impacts and energy costs, it is imperative to reduce the energy demand for heating and cooling buildings, without affecting environmental quality for the occupants.

This can be achieved by natural conditioning, especially strategies that employ the dynamic thermal performance of buildings.

The modification or conservation of indoor conditions during the daily cycle of temperature variation can contribute to this reduction of energy demand, but requires a tool to analyse and visualise thermal performance and related the outdoor climate conditions and indoor comfort requirements.

Two key variables in this process are the average temperature and the daily temperature swing. The need for a bioclimatic design tool to analyse performance and select appropriate strategies, using these two variables, forms the basis for the postulation of the hypothesis.

1.4. HYPOTHESIS

The thesis postulates the following hypothesis:

> **A new visual design tool, which incorporates and combines two key variables, average temperature and temperature swing, allows a better understanding and integration of bioclimatic strategies in the design process, as well as an improved application of energy efficiency in buildings, through the linking of indoor and outdoor environmental conditions with the requirements for thermal comfort and well-being, at the architectural and urban scale, to achieve environmental, social and economic benefits in the framework of sustainable development.**

The terms used in the formulation of the hypothesis are discussed in the following lines:

- The relevance of **'a new visual design tool'** arises from the need to incorporate temperature variations in a graphic method to relate and visualise climatic variables, comfort conditions and modifications achieved with design decisions.
- The variables **'average temperature and temperature swing'**, especially the later, are introduced as key indicators in the bioclimatic design process.
- The **'bioclimatic strategies'** guide the implementation of design decisions.
- The phrase **'in the design process'** underlines the importance of providing guidelines for designers to understand the environmental and physical impact of design decisions and their social and economic consequences at the architectural and urban scale, with the aim of achieving a more sustainable habitat.
- The understanding of the '**requirements for thermal comfort and well-being'** allow responses to needs of building users and occupants.
- In this thesis, the expression '**built environment'** covers three different scales; urban, architectural and constructive.
- The **'better understanding and integration of bioclimatic design resources'** relate to two fundamental stages in the design sequence.
- The **'adequate application of energy efficiency in buildings'** emphasises the relationship between passive natural conditioning and the reduction in the demand for conventional energy resources while minimising environmental impacts.
- The application '**at the architectural and urban scale'** indicates the need to integrate the design process at different scales.
- The search for **'environmental, social and economic benefits'** responds to the different basic aspects that contribute to the sustainability of the built environment.

1.5. AIM AND OBJECTIVES OF THE RESEARCH

The development of the research responds to the following aim and specific objectives:

1.5.1. Aim.

The overall aim of this research presented in this thesis is to contribute to the search for bioclimatic design responses that achieve better environmental conditions in architectural and urban design. This general objective is related to the need to promote sustainable habitats, especially through the reduction of conventional energy demand and minimum use of resources, with rising economic and environmental impacts.

The aim is framed in the concern to complement and integrate bioclimatic approaches in teaching, research and technology transfer, an approach of high priority developed by the author as director of the Research Centre Habitat and Energy, CIHE-SI-FADU-UBA, during the past two decades.

1.5.2. Specific objective.

The specific objective of this thesis is to identify, develop, perfect, apply, demonstrate and evaluate a new graphic bioclimatic analysis technique, with special emphasis in the variation of temperature, the indoor and outdoor temperature swing and the modification of indoor average temperature through the use of bioclimatic design resources.

This technique allows the comparison of climatic variables of the external environment, the preferred thermal conditions for users, both indoors and outdoors and the capacity of bioclimatic design resources to achieve favourable modifications and control of thermal conditions, friendly to the environment and the user through architectural design.

1.6. APPROACH TO BIOCLIMAITC DESIGN

The research method adopted in this thesis is based on the relation between three basic components: **climate-comfort-habitat**, introduced at the beginning of the present chapter. This sequence, as well as variants proposed by different authors and analysed in the following chapter, forms the fundamental support for the development of the thesis.

The stages of the bioclimatic design process are shown in the following lines of this section, based on the sequence and terminology originally developed by Koenigsberger, Mahoney and Evans (1970). This sequence has been applied in the design subject ‘Introduction to Bioclimatic Design’, established in 1984 and given continuously at the graduate level during the last 22 years (Evans and de Schiller, 1986 and 1996), in the Faculty of Architecture, Design and Urbanism, University of Buenos Aires. The subject was developed in response to the following questions:

- **Climate:** What are the environmental conditions and context in which the design is developed? This implies a knowledge of the existing climate and environmental variables, based on local information and measurements, summarised in the meteorological data.
- **Comfort:** What environmental conditions are required in the indoor and outdoor spaces to be designed? This implies a study of the range of environmental variables that offer adequate levels of comfort, well-being and health for the users, based on studies of the subjective thermal sensation obtained in laboratory tests with climate chambers or in field studies with questionnaires of user sensation.
- **Indicators:** What are the favourable and unfavourable aspects of the climate and environment in relation to the desirable conditions to achieve comfort, according to the expected activities undertaken in and around the building or buildings?, and what are the users expectations? This can be expressed as the number of months with different critical conditions of heat, coldness, dryness or humidity.
- **Recommendations:** What are the bioclimatic design resources that can be selected to be integrated in the design with the aim of favourably modifying the unfavourable conditions and maintaining the favourable variables?

- **Integration:** In what way can these recommendations be incorporated in design? and how can the specific design guidelines be applied in the architectural project? achieving at the same time a result that is compatible with the other functional, economic, formal and symbolic requirements.
- **Testing:** How effective is the resulting environmental performance of the architectural and urban design project? This step can be undertaken with physical simulations of sun, wind and light, using models in the laboratory or with numerical simulations of the thermal, lighting, and energy performance, even before the project is finalised. The final assessment stage is the measurement of environmental conditions, the observation of building use and the survey of subjective sensations of the occupants and users, both in and around the completed project.

These questions are based on a process of project development that requires a clear dedication to apply objective criteria of assessment, testing and correction, including the reassessment and modification of initial design decisions. This attitude is of great importance in the successive stages of project development, considering that better bioclimatic techniques can support design creativity.

The relation climate-comfort-habitat, presented in this chapter, constitute a concept introduced in the large majority of texts on bioclimatic design, as shown in the following international references, together with the variations in the terminology employed:

- Olgyay (1970, p. 11) developed the sequence **‘climate–biology–technology-architecture’**, expanded in the text on the application of the method to cover climate data, biological evaluation (of comfort), technological solutions and architectural implementation.
- Koenigsberger et al (1977) present the sequence **‘climate–comfort–indicators-(design) recommendations’**, in relation to the method of the Mahoney Tables, initially presented in this publication. At the same time, two application stages are identified: ‘initial design stage’ and ‘detail design’.
- Koenigsberger et al (1980) also include the sequence developed in the Mahoney Tables.
- Givoni (1978) employs the terms **‘climate–comfort–architecture’,** used as the title of his book.
- Markus and Morris (1980) identify the elements of the environmental system for buildings without artificial conditioning as: environmental resources (microclimate); protection system (ground, vegetation, building elements); modified climatic system; human system, and the controlled environment.
- Evans (1980) proposes the sequence **‘climate–comfort–design’** in his book ‘Climate, Comfort and Housing’.

In all these references, the focus is given towards the incorporation of building design strategies which promote natural conditioning, maintaining the favourable aspects of the external environmental conditions, while offering protection from the harmful or undesirable climatic variations through a process of insulation, modification and thermal delay.

This approach has been postulated as a key tool in the production of a built environment responding to social and economic development, as opposed to a dependence on mechanical heating and cooling, especially in the developing world of emerging countries, with scarce economic resources and grave social inequality.

As an example of application, the approach was incorporated in the conceptual structure of the book of Evans and de Schiller (1986; 1996) proposing the sequence **'climate-comfort-habitat'**, while Gonzalo (2003, p. 111) adopts the relationship **'climate-habitat-man'**.

Additionally, in the introduction to the successive modifications of the Argentine IRAM Standard 11603 (1978 b, 1981, 1996^{a} y 1998), the sequence **'climate-comfort-building'** is used, while Wernly (1975) and Tedeschi (1975), the local pioneers in the introduction of the concept, adopted the approach, which is maintained in the present standards.

1.7. METHODOLOGY

This section shows how the research responds to the objectives presented previously, the methods used to obtain the evidence and the techniques employed to test the results. Therefore, following the sequence 'comfort – climate – habitat', the methodology adopted to demonstrate the hypothesis consists of the following steps:

Part 1 and 2. The key variables for bioclimatic design using periodic heat flow concepts are identified, based on the introductory analysis of the bioclimatic design process in Part 1 and the study of advances in thermal comfort in Part 2. These variables are the daily average temperature and the daily temperature swing.

Part 3. Using these two variables, a new comfort diagram is constructed based on three contributions:

- a study of two approaches to bioclimatic and solar design for hot tropical and cold climates,
- numerical simulation using existing comfort indices
- a process of logical deduction to refine the limits of the comfort zone according to different activities.

This diagram is then related to climate variables and the manner in which bioclimatic strategies present in the built environment modify thermal conditions. It should be stressed that the object of this thesis is not to develop a new comfort scale or replace existing bioclimatic diagrams, but rather to provide a new way of looking at the requirements of comfort in relation to the dynamic thermal performance of building in relation to the variations of climate.

Part 4. In order to demonstrate the application of the comfort triangles in practice, a series of case studies are undertaken to show the way in which the built environment modifies external climate conditions in order to achieve, conserve or improve comfort.

For this reason a wide range of climates, building situations and scales are studied in order to show the application of the Comfort Triangles and visualise the results in both qualitative and quantitative terms.

To provide the necessary data, measurements of indoor and conditions are made at intervals of 15 minutes to an hour over a period of days using automatic data loggers.

Again, the requirements of comfort are compared to the outdoor climate conditions to show the moderating effect of the built environment. In many cases, numerical simulations of additional alternatives complement the measured results, to show the application of the triangles to virtual as well as existing projects.

1.8. STRUCTURE OF THE THESIS

Following the methodology adopted, his thesis is developed with the following structure, explained in the corresponding sequence of five parts, each containing three chapters.

1.8.1. Part 1: Introduction.

Part 1 of the thesis is formed by three chapters. The objective is to present the structure of the thesis and a critical review of the state of the art, summarise the relevant bibliography in the context of the development of theory and practice that sustains it, as well as identifying significant advances in the field, within the context of the current environmental and socio-economic situation. In this way, the development and evolution of the concept are identified, and the present state of knowledge is defined, demonstrating the need to elaborate and perfect techniques applied during the design process, in order to cover less developed areas and provide tools to support project development and suit requirements of different environmental regions. The analysis reflects the evolution of the theory and practice on bioclimatic design and it's different ramifications in architecture.

Chapter 1 aims to introduce the theme of bioclimatic design in architectural practice, to present the hypothesis and to establish the general and specific objectives. The relevance of the thesis is discussed in the context of current developments in the field of energy resources and the impact of the built environment. The methodology adopted in the thesis is explained and the structure which forms the chapters is presented with the sequence of selected case studies at different scales in different climates and different building types used to verify and prove the hypothesis.

Chapter 2 therefore analyses the development of the theory and practice of bioclimatic design over time, considering the traditional framework of architectural history as well as the example of the application of bioclimatic design in Latin America. This thesis no only presents the development of the concept but also the application of bioclimatic design in practice, considering the relation climate-comfort-architecture. It is interesting to note that traditional bioclimatic design approaches apply the concept of climate prototypes with stereotyped responses to each condition, while the studies of thermal comfort with different stages and concepts, attempt to identify and directly respond to the users.

Chapter 3 summarises the historical development of bioclimatic design at the world scale followed by a review of developments in the Latin American region, showing how bioclimatic design strategies were developed and applied in different contexts and climates.

1.8.2. Part 2: State of the Art.

The objective of **Part 2** is to establish the state of the art in three key areas that form the core of the thesis: climate, design guidelines, comfort, thermal performance of buildings and components, relevant to the development of the concept and practice of bioclimatic architecture in the framework of sustainability of the built environment, and provide support for the development of the proposal presented in the following chapters:

Chapter 4 presents the state of the art in the analysis of thermal comfort in buildings, with emphasis on the importance of temperature swings as a factor in the evaluation of daily comfort conditions.

Chapter 5 introduces the development of bioclimatic zoning studies, with studies from different countries in Latin America, showing how comfort studies are related to evaluations of climatic variations in order to detect appropriate bioclimatic regional design responses.

Chapter 6 traces the development of the science of the thermal performance also contributes to the capacity to conceive and implement an architectural project as an environmental filter.

1.8.3. Part 3. The 'Comfort Triangles'.

The objective of **Part 3** of the thesis is to present the development of the concept and to show how the new graphic tool relates to comfort, climate and bioclimatic design resources which are exposed in the following chapters:

Chapter 7 presents in greater detail the origins and development of the new design tool, major result of this thesis. It follows the initial approach proposed by Koenigsberger, Mahoney and Evans (1971), which was then developed by Evans and de Schiller (1986 and 1996), until the final version presented in this thesis. The chapter explains the different backgrounds and origins of the concern with the use of thermal inertia and temperature swing in indoor spaces to achieve comfort, including applications in the analysis of the performance of passive solar systems and prevention of over-heating in buildings with large glazed surfaces, such as schools and offices.

Chapter 8 shows how the 'Comfort Triangles' concept can be used to analyse monthly average climate data, and daily data of average temperature and temperature swings in order to compare external conditions to the requirements for indoor comfort.

Chapter 9 demonstrates the way in which the different bioclimatic design strategies can be characterised using the 'Comfort Triangles Graph'. Each strategy and combination of strategies is used to modify the average indoor temperature and the indoor temperature swing, shown as a vector of the 'Comfort Triangles' graph. Part 3 of the thesis thus relates the three aspects of bioclimatic design, integrating comfort, climate and habitat.

1.8.4. Part 4: Case studies.

Part 4 of the thesis presents a series of case studies at the urban, architectural and building scale in order to demonstrate the utility and validity of the 'Comfort Triangles' concept, according to the following chapters:

Chapter 10 initiates a series of case studies, starting with an assessment of environmental-thermal conditions at the urban scale and the impact of the urban heat island, measured in various cities located in differing latitudes and climates, such as Buenos Aires and Río Gallegos in Argentina, and Tampico, Mexico. The comparative evaluations carried out in these cases clearly show the impact of the built environment on both the average temperature and the temperature swing when compared to the measurements outside the influence of the cities, in the rural surroundings and in the local airports.

Chapter 11 focuses on the architectural scale and presents the analysis of measurements and simulations undertaken to evaluate the thermal performance of buildings with periodic temperature variations, comparing the thermal swing and the average indoor temperature as indicators of bioclimatic efficiency in architecture. The measurements obtained in different climatic locations provide relevant evidence which prove the hypothesis and demonstrate the application and utility of the method for both analysis and design processes.

Chapter 12 analyses case studies at the building scale, presenting the thermal behaviour of buildings with heavy and lightweight construction, both traditional and non conventional, in order to complete the series of studies at complementary design scales. The chapter shows the application of the fundamental concepts of the 'Comfort Triangles' in different climates, in order to evaluate their application at the regional scale and identify appropriate design resources for each of the bioclimatic regions.

1.8.5. Part 5. Results, evidence and conclusions.

Part 5 contains the results and findings conclusions and recommendations for further development.

Chapter 13 summarises the results of the case studies presented in Part 4 in order to provide the graphic evidence of the Comfort Triangles in use to show the relation between thermal comfort, climate and bioclimatic strategies.

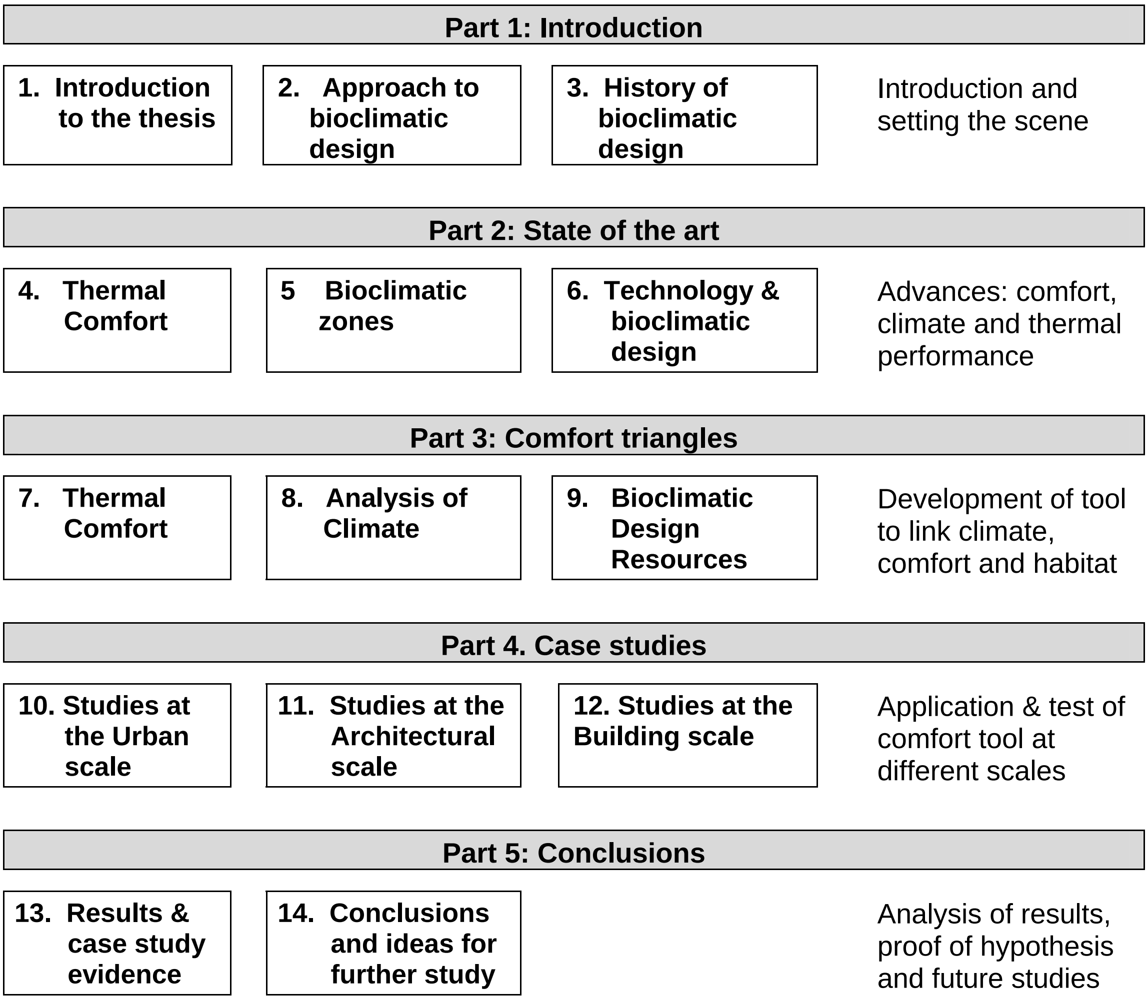
Chapter 14 demonstrates that the argument developed in this thesis and presenting the conclusions that confirm the hypothesis**.** It also indicates areas identified for further study with recommendations for the development of additional studies and complementary research. Recommendations are proposed for the application of results in teaching, research and professional practice.

1.9. CONCLUSIONS

The structure of the thesis, presented in the previous section, is organised in five sections illustrated in Figure 1.5. A sinthesis of this figure is included in the introduction of the sections of the thesis, which are organised with the following contents:

- The introduction to the thesis, presented in this chapter, followed by an introduction to bioclimatic design.
- The state of the art in bioclimatic design: approaches, comfort and technological developments.
- The development and application of the 'Comfort Triangles': definition of comfort limits, evaluation of climate and the application of different bioclimatic design strategies related to climate and design strategies.

- The testing of the 'Comfort Triangles' in a series of case studies at the urban, architectural and building scale.
- The results of the case studies, findings and conclusions on the thesis.



Part 1: Introduction			
1. Introduction to the thesis	**2. Approach to bioclimatic design**	**3. History of bioclimatic design**	Introduction and setting the scene
Part 2: State of the art			
4. Thermal Comfort	**5 Bioclimatic zones**	**6. Technology & bioclimatic design**	Advances: comfort, climate and thermal performance
Part 3: Comfort triangles			
7. Thermal Comfort	**8. Analysis of Climate**	**9. Bioclimatic Design Resources**	Development of tool to link climate, comfort and habitat
Part 4. Case studies			
10. Studies at the Urban scale	**11. Studies at the Architectural scale**	**12. Studies at the Building scale**	Application & test of comfort tool at different scales
Part 5: Conclusions			
13. Results & case study evidence	**14. Conclusions and ideas for further study**		Analysis of results, proof of hypothesis and future studies

Figure 1.6. Structure of the thesis, showing the relationship between Parts and Chapters.

CHAPTER 2. BACKGROUND TO BIOCLIMATIC DESIGN

2.1. INTRODUCTION

The development of architecture through history shows many relevant examples of responses to specific environment and climatic contexts, within the limits of the resources available, the technological advances achieved and the expectations of environmental quality.

Although the relationship between climate, comfort and architecture has been a constant concern and buildings have responded to local specific conditions to a greater or lesser degree, the **bioclimatic design approach** implies an application of a logical sequence of analysis, the detection of appropriate strategies and the conscious environmental control in response to external impacts and rational use of resources.

With this objective, the bioclimatic design strategies aim to take advantage of the favourable environmental aspects, while avoiding or moderating the unfavourable impacts through appropriate design decisions.

It is argued that this concept, together with a rational procedure to select adequate strategies, allows the designer to optimise thermal conditions for occupants and users of the built environment.

Therefore, the object of this chapter is to introduce the background of the bioclimatic design field and present the development that took place, together with a synthesis of the theory and practice, emphasising the most relevant advances and defining the present state of the art.

The critical review provided in this chapter identifies aspects of both the historical evolution and the current situation, showing the need to develop new analytical techniques as well as proposing innovative tools for designers to be applied in different climatic regions of the world.

2.2. ISSUES AND DEFINITIONS

Before evaluating the bioclimatic design process and reviewing the traditional approaches to climate classification, the key topics in bioclimatic design are evaluated and the terms and definitions are presented, in order to clarify the background to bioclimatic design.

2.2.1. Key topics in bioclimatic design.

In this context, the structure of the present chapter responds to the evolution of both theory and practice in bioclimatic design with varied and differing sources, covering the following key topics:

- **Climate:** The background of the traditional approach to bioclimatic design, with prototypical climates and the recommended responses to each situation, followed by an analysis of the identification of the basic climatic variables to define the environmental conditions required in buildings.

- **Comfort:** Studies of thermal conditions, through different stages of development and varying approaches, with the aim of identifying the environmental requirements and preferences of building users.
- **Buildings:** Development of building science in the field of thermal performance and the capacity to conceive a building as a filter or modifier of external conditions on one hand and the desirable indoor thermal requirements on the other.
- **Bioclimatic design:** Development of the concept and practice of building design considering the relationship climate-comfort-architecture.
- **Design process:** Possibilities and limitations for the integration of bioclimatic design resources and strategies during project development.

The different architectural responses to the variations within the environmental context, geographic as well as climatic, are to be found at all levels and scales of the project development taking place in the built environment.

With the aim of establishing the state of the art in this field and showing the breadth and coverage of the diversity of components and concepts involved in bioclimatic design, this chapter presents the conceptual framework of the thesis in it's multiple dimensions.

Following this introduction to bioclimatic design the next chapter presents this conceptual framework in a historical perspective, starting with examples of the typical features and characteristic variations found in architectural design in response to different climatic impacts, leading to the development of a theory of bioclimatic design and it's application in the design practice.

2.2.2. Terms and definitions in Bioclimatic Architecture.

Although a glossary of the terms used in this thesis is included in Appendix 1, a series of comments, definitions and clarifications on the key issues related to the development of this thesis is presented in this section to introduce a basic relationship between three main factors: climate, comfort and architecture.

In this context, a series of terms and denominations are used to define architectural design approaches and identify those that implement specific building characteristics and architectural features to achieve or improve user comfort in the face of external climatic impacts with low energy use and low environmental impacts.

The origins, implications and associations of these terms are therefore explained as follows in order to clarify their specific meaning in the development of this thesis.

Bioenvironmental Architecture: The term *bioenvironmental* is applied to identify an architecture that relates to its physical context, climate in particular. In Spanish, the term *bio-ambiental* is often used as a synonym of *bioclimatic*; for example, 'Zonificación Bioambiental' is the Argentine National IRAM Standard 11.603 (1998). In other Latin American countries both terms are used with the same meaning. However, it is postulated in this thesis that the term implies a wider meaning as it includes related aspects such as landscape, soil and other environmental aspects of the surroundings, in addition to the implications of the key relationship climate-comfort-architecture. It is considered that the integration of all these factors can contribute to sustainability, energy efficiency and thermal comfort, as well as a qualification for environmental quality of the built environment.

Bioclimatic Architecture: Olgyay coined the term *bioclimatic* in 1953 (Szokolay, 1995) to define the architecture that responds to its climatic environment and achieves comfort for the occupants through appropriate design decisions. Although the examples presented by Olgyay (1963) in the seminal publication 'Design with Climate' includes the cold and continental climates of the United States, the term is often used with certain emphasis on architecture for tropical climates (Szokolay, 1995). It is interesting to point out that, although Olgyay's book was first published over 40 years ago, it is still relevant today and the more recent Spanish translation is still in print (Olgyay, 1998). However, the term is sometimes associated with a passing mode or traditional approaches, a view that is rejected in this thesis.

Naturally Conditioned Architecture: The expression *natural conditioning* implies the successful modification and improvement of indoor thermal conditions through passive design decisions, such as form, orientation, materials, colour and vegetation, with little or no dependence on mechanical conditioning installations with conventional and non-renewable energy. It is sometimes currently mentioned to avoid the use of the term *bioclimatic*, considered slightly out-dated in certain circles.

Low Impact Architecture: The harmful environmental impact of architecture include the emissions of greenhouse gases that arise from energy use for heating and cooling, the impact of raw material extraction, transformation into building materials, transportation and construction impacts as well as impacts of materials on building users. Buildings also channel waste, rainwater and sewage, as well as creating impacts at the demolition stage at the end of their useful life. Therefore, this denomination applies to the architecture that consciously aims to reduce or minimise these impacts.

Ecological Architecture: The science of ecology studies the relationship between living entities and their environment. However, *ecological architecture* or *eco-architecture* often includes examples of *hi-tech architecture* (Slessor, 1997a and 1997b). For example, 'Eco-homes' is the denomination which was then applied to the environmental assessment system to evaluate sustainability issues of housing in the United Kingdom (BRE, 2002), while 'Eco-house' is the title of the book by Roaf (2001 and 2003) on ecological housing with a strong emphasis on energy efficiency and use of renewable energy in architecture.

Bio-architecture: Sometimes used as a synonym of *ecological* or *eco-architecture*, with connotations of architecture as a living organism.

Energy Efficient Architecture: It implies certain emphasis in the efficiency of installations for artificial conditioning, illumination, heating, cooling and ventilation, although in this thesis it is considered that the truly energy efficiency mainly depends on appropriate design decisions for the building and not simply the efficiency of the heating, artificial lighting and cooling installations.

Organic Architecture: This refers to architecture that reflects or copies natural forms, textures and plant materials, in some cases related to the theories of Rudolf Steiner (2003), and covering *zoomorphic architecture* (Hugh Aldersley-Williams, 2003), where buildings incorporated forms inspired by animals. In both cases, examples invoke a symbolic relationship with nature, as well as a possible functional or environmental response.

Fen Shui Architecture: Emphasises the relationship between architecture and landscape through geomancy (Papanek, 1993), developed from concepts originated in China (Pearson, 1994). Although various recommendations may coincide with those found in the bioclimatic approach, it is considered in this thesis that these are often proposed with disregard of climate and context, without local adjustments, while others have little scientific support. Additionally, the fundamental problem lies in the recipe approach oriented to particular features and solutions without developing the design method or theoretical support.

Natural Architecture: This denomination, also used by Pearson (1994), emphasises the impact of materials on the indoor environment. It also covers natural ventilation, energy efficiency and the GAIA concept to achieve planetary harmony, with a certain tendency to promote a ‘back to nature’ approach, although the Gaiana House example (Pearson, 1994, p 41) includes many bioclimatic design resources and strategies.

Passive Architecture: This expression, coined by Arthur Bowen in 1984 (Szokolay, 1995) implies the capacity of buildings to achieve comfort through design decisions rather than dependence on ‘active’ mechanical plant with high-energy demand. Appropriate design choices include building form, orientation, thermal characteristics of materials, form and location of openings, colours, landscape and design of outdoor spaces. However, *passive* buildings may require the *active* participation of users to achieve optimum comfort in rooms by opening windows, closing blinds or changing positions of specific building elements. PLEA, which stands for Passive and Low Energy Architecture, is a well established international network, which organises annual Conferences on this theme.

Solar Architecture: The energy crisis of 1970 produced a wave of new designs to optimise the use of solar energy in architecture. Active solar systems require energy to move heat from the point of collection, usually flat plate collectors, to the point of use inside the building. The expression *passive*, previously defined, is strongly associated with *passive solar*, where the systems for collection, storage and distribution of solar energy are the building fabric, without dependence of external auxiliary energy (Mazria, 1983).

Sustainable Architecture: The term *sustainable* (du Plessis, 1998; de Schiller, 2004) includes the economic and social aspects as well as the ecological related to environmental sustainability. However, it is generally applied to architecture as a design quality related to projects achieving low environmental impact. The term *architecture* emphasises the role of the design process, a wide approach that includes the initial design guidelines through all project stages, from post-occupancy assessment, durability and life cycle performance including deconstruction, recycling and recovery procedures.

Sustainable Building: Denomination that covers all aspects of sustainability, coined by a research network meeting at a series of influential world congresses (CIB, 2000; de Schiller, 2002; Du Plessis, 2002) held in Maastricht 2000, Oslo 2002, several regional meetings in 2004, and Tokyo 2005.

Green Architecture: A rather popular term (Hall, 2005) used to indicate both *natural* and *sustainable* architecture, although it is often associated with certain specific features such as organic and recycled or recyclable materials, and the use of functional vegetation for green roofs and green facades.

Vernacular Architecture: The traditional and popular architecture of specific regional features or local character which integrates near-by materials and resources with design solutions developed over time through a process of trial and error to achieve adequate levels of comfort in relation to user expectations (Oliver, 1973; 1987; 2004). Although the vernacular architecture incorporates many bioclimatic design resources, the term *vernacular* may be interpreted as traditional construction, which includes adobe and thatch. This is often associated with a romantic return to the past, rejected by those who strive for modernisation and development (Brunskill, 1970). However, the academic study of vernacular architecture, with a strong anthropological as well as ethnographical and cultural background, not only shows that the concept is applicable today and relevant to social and economic development in many parts of the world, but it is also embedded in the respect of social patterns and popular responses of the built environment, as Oliver (2004) advocates.

Although all these expressions and denominations have close links with each other, covering different aspects of the same problem with specific nuances, the terms bioclimatic and bio-environmental are used to define the field covered in this thesis, with a preference for the latter though recognising that the former is more widespread and understood in English.

2.3. TRADITIONAL BIOCLIMATIC DESIGN APPROACH

This section reviews the traditional approach to bioclimatic design, based on the identification of typical climatic regions and the development of bioclimatic design guidelines for each. While the simplicity of the approach helps to provide initial design guidelines (Koenigsberger et al, 1970), it is argued that additional guidance, based on a more developed design method may be required to optimise bioclimatic design resources in architecture.

2.3.1. Climate classification for bioclimatic design.

The classic texts of bioclimatic architecture consider a wide climatic and geographical coverage. They define representative climate types and zones with their meteorological features and present design recommendations for each case (Koenigsberger et al, 1975; Koenigberger et al, 1977; Konya, 1985; Lloyd Jones, 1998).

This traditional approach resulted in a classification of three basic tropical climates: warm-humid, hot-dry and monsoon or transitional, with three sub-climates: upland, maritime desert, and tropical island.

In each case, the corresponding brief and design recommendations are defined, emphasising the importance of controlling and modifying both the temperature range and average temperature, as shown below:

- **Warm humid climates:** These climates correspond to zones at low latitudes up to about 7° north and south of the equator, with high relative humidity, high average temperatures throughout the year, frequently cloudy skies, intense rainfall, abundant vegetation and low thermal swings, both daily and annually, with little seasonal variation. Typical design recommendations include: solar protection, lightweight construction and cross ventilation. The limited annual and daily variation of temperature does not require control of the indoor temperature swing if the impact of direct sun and strong diffuse radiation from overcast skies is avoided, while the use of breeze can achieve a useful reduction in the apparent temperature, in spite of the low average wind velocities typically found in this equatorial region.

- **Hot dry climates:** Typical of desert zones, usually found between 15° and 30° north and south of the equator, with large daily and annual temperature swings and marked seasonal variations, predominantly clear skies, intense solar radiation, scarce rainfall and very limited vegetation. Typical design recommendations include: solar protection in summer, construction with sustancial thermal inertia, controlled window sizes and protection from hot dry and dusty winds. The high external temperature variation, often exceeding 20° C, requires control measures to reduce the indoor variation. In summer, design strategies need to be implemented to reduce, or at least avoid, an increase in the average indoor temperature using selective night ventilation or evaporative cooling, while solar and internal gains should also be controlled. In winter, solar gains together with internal gains, can be used to increase the indoor average temperature.

- **Monsoon or transition climates:** These generally composite climates, found between the tropical and equatorial zones, have two clearly differentiated seasons, dry and rainy, according to the precipitation, though in India a cold season is also experienced. The design guidelines for these climates combine the opposing requirements of the dry and humid seasons with difficulty. In many examples of the traditional and vernacular architecture, separate spaces with specific responses for the different seasons are found, with lightweight construction open to the breeze for the humid season and protected heavyweight construction for the dry season.

2.3.2. Identification of sub-climates.

In the same low latitude tropical zone, further variants produced by the modifying effect of altitude and maritime influence, three sub-climates can also be identified:

- **Upland climates:** At high altitudes, the temperature is lower than at sea level, with stronger solar radiation and larger temperature swings. Classic examples include Quito, in Ecuador, at a height of 2800 metres and latitude 0°, and Nairobi, Kenya, at a height of 1600 metres, 1° south of the equator, both experiencing cool to comfortable conditions. In these cases, protection from cool or cold air at night is required, while solar radiation can be favourable during the day. Thermal mass is useful to avoid excessive indoor temperature swings and store heat absorbed during to day for the cooler nights. Average indoor temperatures need to be increased, while temperature swing reduced, compared with the outdoor conditions.

- **Maritime desert climates:** In desert zones with strong maritime influence, the climate combines the problems of desert climates with high temperatures and low rainfall, additionally to high relative humidity, a very uncomfortable combination found in areas such as the Persian Gulf and the Red Sea.

- **Tropical island climates:** Islands in regions further from the equator, corresponding to latitudes where desert climates are expected in the continental land masses, experience a warm climate with lower rainfall, constant trade winds and clearer skies than the equatorial regions (Baker, 1987). The islands of the Caribbean, Pacific and Indian Oceans are representative of these conditions. The constant breezes allow an apparent reduction in the thermal sensation and the influence of the ocean avoids excessive temperature swings.

2.3.3. Additional sub-climates.

In latitudes further from the equator, three additional climate types can be established, Mediterranean or sub-tropical, temperate and cold, classified as follows:

- **Mediterranean or sub-tropical climates:** With a rather euro-centric vision, the Mediterranean region commonly refers to the areas around the sea of the same name, although the etymological origin suggests the centre of the landmass. This climate region has two main seasons: hot dry summers and cool wet winters. Other sub-tropical climates at similar distances from the equator have variations in the annual distribution of rainfall. In these climates the cold and hot seasons have a similar impact (IRAM, 1996), while comfortable conditions are experienced for much of the year. Design recommendations combine specific seasonal strategies. In summer, solar protection is required to avoid increase in the average indoor temperature and relatively heavy construction to reduce thermal swings. In winter, sun can be welcome and thermal insulation is required to reduce heat losses and low the indoor average temperature, though temperature swings are less critical in this season.

- **Temperate climates:** At intermediate latitudes, coldness starts to be the predominant climatic concern for building design, with comfortable summers and cool or cold winters. The design recommendations suggest catching direct solar radiation and improved thermal insulation to reduce heat loss in winter, together with protection from cold winds and infiltration, while less emphasis on the control of indoor temperature swings is indicated.

- **Cold climates:** At higher latitudes, summers are comfortable or cool, while winters are progressively colder. Although winter sunshine is of low intensity due to the low altitude cloudy skies and short days, the use of solar energy for improving indoor conditions is a valid strategy for most of the year, to increase average indoor temperatures. Compact building forms and greater thickness of thermal insulation are required to reduce the heating demand.

Within the colder climates, even further from the equator, three additional sub-zones are identified: cold maritime, cold continental and mid-latitude upland (Alpine, Andean, etc.).

Like previous warmer climates in this classification, each sub-zone leads to specific bioclimatic design requirements, defined as follows:

- **Cold maritime climates:** Zone with strong maritime influence, such as the European western coast, has lower temperature swings, both daily and annually, typically with high rainfall and frequent overcast skies. For this reason, lightweight construction with low thermal mass may be more acceptable.

- **Continental climates**: In the opposite case, continental zones in the centre of large landmasses experience large temperature swings, with very cold winters and hot summers, with a large daily temperature swing. To moderate this impact, heavyweight construction combined with thick layers of thermal insulation is needed.

- **Mid-latitude upland climates (Alpine, Andean, etc.):** Upland climates, outside the tropical zone, combine comfortable summers with cold or very cold winters. The daily temperature swings also tend to increase. Wind protection together with good thermal insulation offers protection in these climates.

2.3.4. Summarising climates and sub-climates.

The characteristic climatic variables are summarised in Table 2.1., with reference to the main seasons using the climate and sub-climate classification established in subsections 3.3.1 to 3.3.3.

Table 2.1. Climate classification.

Climatic variable		Warm humid	Hot dry	Comfort	Cold	Very cold
Typical temperature °C		20 – 30	15 – 35	15 – 25	5 - 15	< 5
Relative humidity %		> 80 %	< 60 %	60 – 80	-	-
Temperature swing deg C		< 10° C	> 12° C	8 – 12	< 10° C	-
Climate classification	Latitude					
Warm humid	0 -15°	**X**				
Hot dry	20 - 35°		**X**	**X**		
Transition	10 - 30°	**X**	**X**	**X**		
Monsoon	5 - 30°	**X**	**X**	**(X)**	**X**	
Equatorial upland	0 - 20°			**X**	**(X)**	
Maritime desert	20 – 35	**X**	**X**			
Subtropical	30 – 40	**(X)**	**X**	**X**	**X**	
Temperate	40 – 50			**X**	**X**	
Alpine-Andean	30 – 50			**X**	**X**	**X**
Cool temperate	40 - 55			**X**	**X**	
Cold	> 50°			**(X)**	**X**	**X**
Very cold	> 60°				**X**	**X**

Note: (X) indicates short seasons with the defined conditions or possible climate variations.

2.3.5. Design guidelines.

Koenigsberger et al (1970), Koenigsberger et al (1977), Evans (1980), Lloyd Jones (1998) and other authors use the climate classification presented in the previous section or similar classifications to establish design guidelines for different bioclimatic regions as indicated in Table 2.2.

Table 2.2. Design guidelines for different climatic regions.

Climatic regions	**Latitude**	**Solar protection**	**Thermal inertia**	**Solar gains**	**Cross ventilation**	**Thermal insulation**	**Light colours**	**Minimum ventilation**	**Night cooling**	**Selective ventilation**
Warm humid	0 -15°	X			X		X			
Hot dry	20 - 35°	X	X				X	X	X	X
Transitional	10 - 30°	X	(X)		(X)		X	(X)		X
Monsoon	5 - 30°	X	(X)	(X)	(X)		X		X	X
Equatorial upland	0 - 20°	X	(X)			X		X		
Maritime desert	20 – 35	X	X		X	X	X		(X)	
Mediterranean	30 – 40	X	X	X		X	X		X	X
Subtropical	40 – 50	X	X	(X)		X		X		X
Temperate upland	30 – 50		X	X		X		X		
Temperate	40 - 55			X		X		X		(X)
Cold	> 50°			(X)		XX		X		
Very cold	> 60°			(X)		XX		XX		
Average temperature										
Reduction		X			X				X	
Control		X					X	X		X
Increase				X		(X)		X		(X)
Thermal swing										
Increase				X					X	X
Reduction		(X)	X			X	X	X		

2.3.6. Olgyay's representative climates.

In the same line of approach to the explanation and application of bioclimatic design principles, Olgyay (1963) presents four different climates representing extremes of the wide range of conditions found in the United States. In this case, the climates chosen are as follows:

- **Warm humid:** Miami, Florida, 24° N: high temperatures and relative humidity, with a need for solar protection during almost all daylight hours for the whole year, moderate temperature swing, though a higher annual temperature swing than that found in the warm humid equatorial zones closer to the equator.
- **Hot dry:** Phoenix, Arizona, 32° N: high temperatures all the year round, except for the morning hours in winter, with large temperature swings and intense solar radiation.
- **Temperate:** New York, 40° N: balance between heat and cold, with hot and humid summers and cold winters.
- **Cold continental:** Minneapolis, Minnesota, 44° N: a combination of very cold winters and hot summers, with high temperature swings.

For each climate, Olgyay (1978) defines and demonstrates the use of design guidelines applied at the urban, architectural and detailed design scale. The book is structured in three sections: the bioclimatic design approach, the interpretation of architectural principles and the application at different scales in each region.

The approach, originally developed by Olgyay over 50 years ago (Olgyay, 1953), is still relevant and applicable today, as the Spanish translation of the book shows, published recently in 1998 (Olgyay, 1998).

2.3.7. Limitations of the traditional bioclimatic design approach.

The recipe approach of the typical climate regions with related design guidelines, outlined in the previous subsections, although clear and easy to transmit and apply, often have two serious disadvantages:

- The solutions are often presented without the explanations, indicating ***what to do*** rather than ***why***, emphasizing results as the product, rather than the process.
- The approach does not provide useful guidance for the many intermediate climates found with conditions and characteristics ***between*** rather than ***within*** the typical regions.

Methodologies to overcome these two fundamental aspects will be presented in the following section of this chapter, while the method explained in the following chapter also responds to this situation. The survey of basic climatic types presented here shows the importance of temperature swing and average temperatures in the definition of different climate types.

2.4. BIOCLIMATIC DESIGN IN PROJECT DEVELOPMENT

In order to select and incorporate appropriate bioclimatic responses in architectural design, it is necessary to apply a design method and approach that responds to the impact of climate and the characteristics of the building type. This section therefore analyses the relative complexity and characteristics of different building types and the design method used in conventional design, contrasted with the bioclimatic design sequence.

2.4.1. Design complexity.

For the analysis of thermal performance of architectural projects and the application of bioclimatic design principles, two distinct building categories are defined (Evans, 2005):

- **Simple buildings:** with limited internal thermal gains, rooms with natural lighting and ventilation, and simple heating systems in cooler climates. In these buildings the average indoor temperature is similar to or slightly above the average outdoor temperature for most months of the year, with possibilities of using solar radiation as a supplementary heating source. This category of buildings includes most schools and housing. Traditional texts on bioclimatic design have concentrated on these situations, where bioclimatic design resources to achieve natural conditioning can often provide a large degree of comfort or reduction in the need to heat and cool by artificial means.
- **Complex buildings:** with large internal gains from occupants and equipment, as well as deep plan buildings where artificial ventilation and lighting is essential in the internal spaces. Large offices, hospitals and commercial centres are examples of this type of building. Large auditorium and complexes of cinemas also share these characteristics. In this case the indoor temperatures may rise above the average external temperatures, requiring artificial cooling in addition to artificial lighting and ventilation. In these complex buildings, bioclimatic design resources by themselves

may be insufficient to avoid the need for artificial conditioning, but are still important to reduce conventional energy demand.

The complexity of buildings is also related to the systems used for thermal conditioning:

- **Natural conditioning:** Buildings without refrigeration systems for summer, but with heating systems for those climates with cool or cold winters. This category of buildings includes low cost social housing and private sector housing, except for a small proportion with air conditioning, as well as schools, small office buildings, markets and small commercial buildings.
- **Artificial conditioning:** Buildings with mechanical control in both winter and summer: This category includes commercial centres, supermarkets, modern offices, larger hotels, cinemas and theatres. These buildings are often designed as sealed capsules without possibilities of natural ventilation.

Two additional intermediate cases can be added:

- Buildings originally design without air conditioning, in which equipment has be added later, as a result of discomfort or rising comfort expectations, including factors such as status.
- Buildings with air conditioning plant incorporated in the original project, but incorporating design features to allow natural conditioning for significant periods of the year while taking advantage of natural lighting, ventilation, favourable outdoor temperatures and possible solar gains on cooler days. Typically, natural conditioning with ventilation, illumination and solar gains or selective ventilation can be used in sectors of the building within 6 m of the facades, for considerable periods of the year in many climate zones.

In the conventional design practise, buildings with air conditioning are generally designed with little consideration for the effect of the design on plant capacity or energy demand. Additionally, the standard methods normally used to size the plant do not take into account the possible advantages of bioclimatic strategies incorporated in the design to reduce energy demand and promote comfort.

Despite the incorporation of effective solar shading or additional thermal insulation, conventional methods for plant sizing may lead to oversized and less efficient cooling systems.

2.5. INTEGRATION OF THE BIOCLIMATIC APPROACH IN DESIGN

Following the analysis of bioclimatic approaches in different climates, the discussion on the influence of building complexity and the impact of current construction tendencies, this section analyses the integration of the bioclimatic approach in the design process, comparing the conventional design sequence with the bioclimatic requirements.

2.5.1 Conventional design sequence.

During the design process of complex buildings, installations for heating and cooling are incorporated according to the project development, with vital decisions taken by both the building designer and the thermo-mechanical consultant.

The conventional design process, shown schematically in Figure 2.1., supposes an initial project development without considerations of climatic impacts on the building or the requirements of the occupants thermal comfort.

Therefore, this approach implies a total dependence on the artificial conditioning systems to achieve indoor comfort.

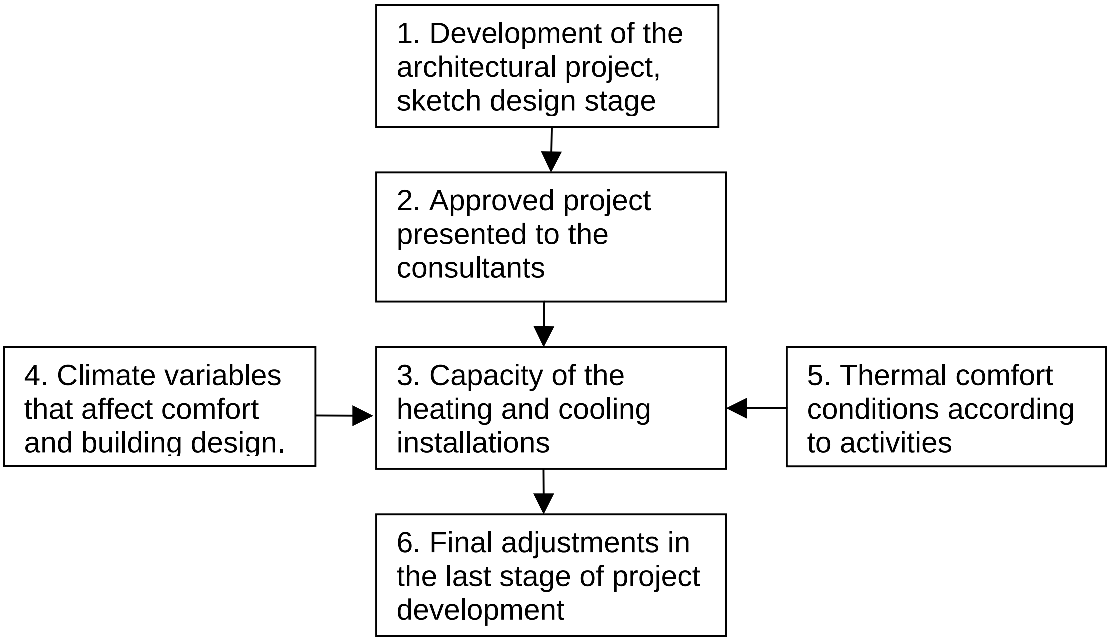


Figure 2.1. The conventional design approach.

It is stated that the stages of this conventional design process are:

1. The sketch design is developed by the architect, and presented to the client for approval. At this stage the architect may not have appointed a thermo-mechanical consultant.
2. When the sketch design is approved, the consultant is appointed and presented with the initial design.
3. The consultant evaluates the heating and cooling demand, estimates the plant capacity and indicates the sizes of plant rooms and requirements for distribution systems. The heating and cooling requirements are a result of the design of the building.
4. In the project stage the consultant adjusts the design of the installations, without possibilities of reducing the energy demand unless building design is modified.
5. Only in cases where the energy demand is clearly excessive will the consultant recommend design modifications to reduce the load and plant size. However, at this stage, the design alternatives are very limited.

2.5.2. Bioclimatic design process.

In contrast, it is argued that the bioclimatic design process, fundamentally different, follows the stages indicated below:

1. Before starting the design development, the architect analyses the environmental conditions of the site, especially the climatic data of the location.
2. The comfort conditions for the activities realised in the building are then defined.

3. A comparison between the existing conditions defined in Stage 1 and the required conditions selected in Stage 2, shows the design requirements for protection from the unfavourable impacts and the conservation of favourable aspects en each hour of the day and season of the year.
4. The needs for protection and conservation, together with the analysis of existing conditions and needs indicate the bioclimatic design resources.
5. These design resources are evaluated and integrated in project development from the initial stages.
6. Designers and consultants to determine the degree of natural conditioning then evaluate the project and comfort that is possible to achieved with natural conditioning, incorporating elements of bioclimatic design integrated in the architecture.
7. Only when the passive natural conditioning measures have been implemented, the evaluation for the need of artificial conditioning is undertaken and residual capacity of the artificial conditioning system calculated.

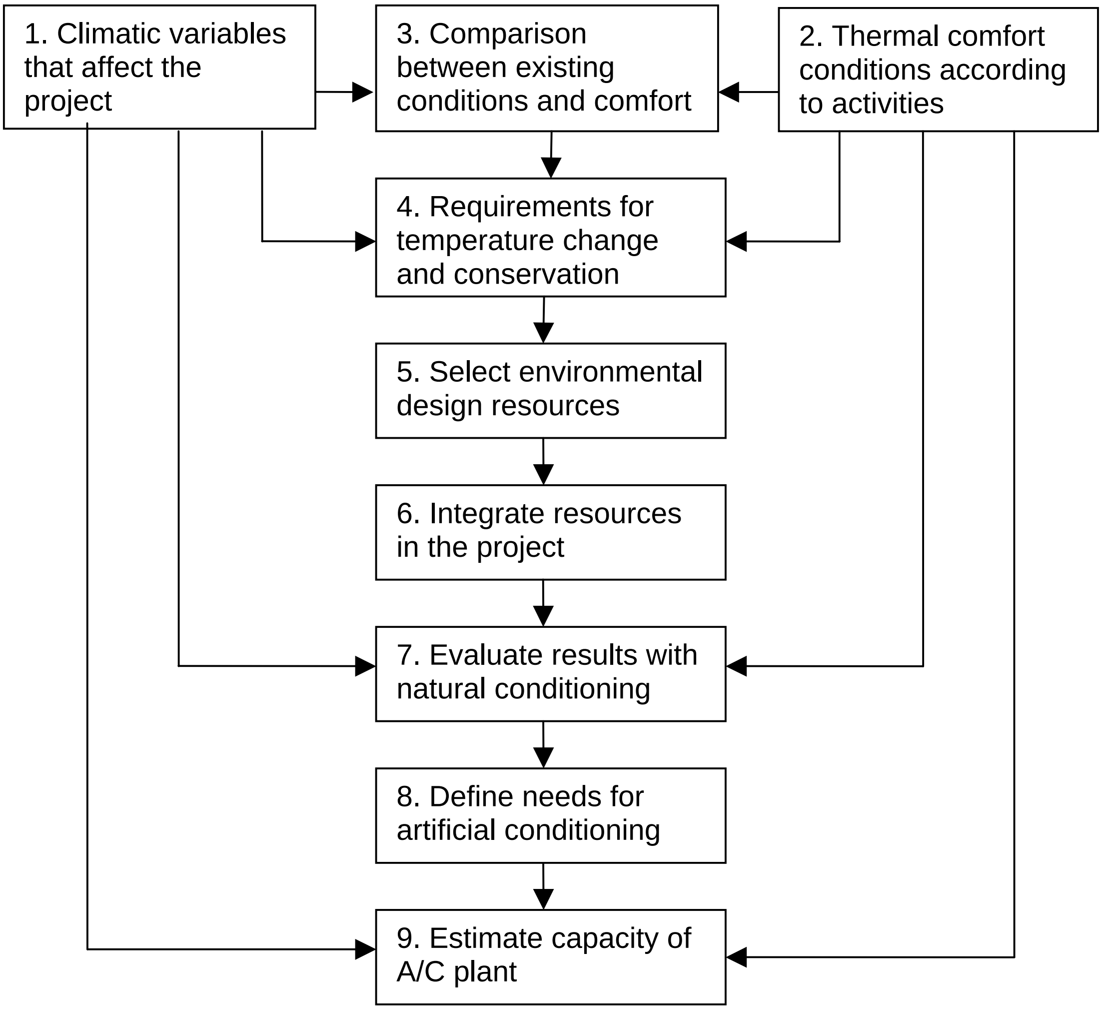


Figure 2.2. Bioclimatic design process: stages, testing, evaluation and feed-back.

It is relevant to note that the first five steps of the bioclimatic design process are undertaken before the initial design decisions are made. This procedure emphasises the concern for a correct understanding of the situation, both from the environment and user point of view, in order to ensure that the appropriate design resources are incorporated from the very start of the design process and further project development.

The application of this sequence is related to the potential of incorporating design decisions in project development. It is argued that in these initial stages of design, there is greater flexibility to incorporate design resources to achieve improved comfort and energy efficiency.

Moreover, these measures will have a greater effect over the potential to reduce environmental impacts, the improvement of living conditions as well as lowering the cost and capacity of the conditioning plant.

2.5.3. Design sequence.

The application of bioclimatic design resources can be related to the stages of design development: sketch design, project, details and specification, construction and use.

Koenigsberger, Mahoney and Evans (1970) proposed specific design guidelines according to the stage of project development, especially the recommendations for the initial sketch design stage and the detailed design stage. Szokolay (1995) emphasises the importance of predictive design tools required to detect and test bioclimatic design resources at the start of the design process.

Koenigsberger et al (1970) underline the difference between techniques to evaluate the behaviour of a design after it has been defined backward looking analysis and techniques to assist in the orientation of the design process forward looking analysis.

Table 2.3. Project design stages, with the potential to integrate bioclimatic design resources and costs at each stage.

Design stage	**Potential for applying bioclimatic and energy efficiency design resources**	**Cost of applying design resources**
Programme (building type, location, site)	Very high potential	Potential alternatives at low cost.
Preliminary sketch (initial concepts of forma and image)	High potential	Low cost (decisions on volume, orientation and form)
Sketch design (definition of architectural intentions)	Good potential	Low cost
Project (development in detail)	Limited potential to adjust bioclimatic characteristics	Increased cost
Details and specification	Very limited	Important cost of modifications
Construction	Very limited	Elevated cost of changes
Use	Extremely limited	Elevated cost of changes

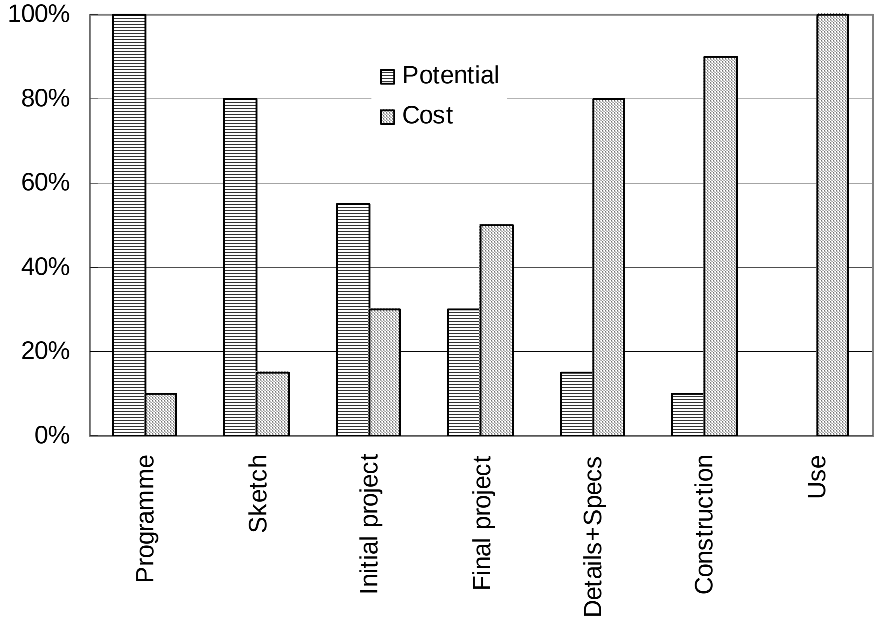


Figure 2.3. Concept of the potential to introduce and integrate bioclimatic design resources and energy efficiency, and the costs of applying these measures in different stages of design development.

Some examples help to clarify the concepts presented in Figure 2.3 and Table 2.3:

- At the programme stage, decisions about site selection and total building size have a large effect on the environmental impacts and energy demand, frequently at low cost.
- At the sketch design stage, decisions about alternative of form, height and orientation can provide improved comfort and low energy demand at low of even no cost.
- At the stage of specifications and details, the selection of alternative glazing systems and thermal insulation materials may lower energy demand, but cannot correct problems of orientation, excessive window areas or inappropriate building forms.
- At the construction stage, decisions on the purchasing of materials have a very small impact on thermal performance, environmental impact or user comfort.

2.5.4. Integration in Zoning.

The possibilities of defining design guidelines based on climate conditions and comfort requirements, independently of the initial design concepts for specific projects, allows the definition of general guidelines for each climatic region.

The study of bioclimatic requirements and standards for design presented in Chapter 4 will show how the approach outlined in this section is applied in different regions of Latin America and contributes to the definition and establishment of different bioclimatic zones.

2.6. CONCLUSIONS

The wide frame of reference and survey of antecedents presented in this chapter establishes the sequence and basis of bioclimatic design, linking climate, comfort and design resources that can contribute to improve thermal sensation in indoor and outdoor spaces. In this chapter, the following two variables are shown to be central for the study of the relation between climate, or the existing external conditions, and the desirable thermal environment, the conditions required for comfort:

- The temperature variation in a typical 24 hour cycle
- The average temperature during the same cycle

The bioclimatic design resources should, therefore, respond to the necessary modification of thermal conditions to solve the difference between the existing external temperatures and the required indoor conditions. In this framework, the two variables to consider are:

- **Mean temperature:** the average outdoor air temperature and the recommended indoor air temperature for thermal comfort.
- **Thermal amplitude:** The outdoor air temperature range or thermal swing, and the recommended indoor temperature range for comfort.

In this chapter, the approach to bioclimatic design has been presented with a summary of the basic climatic zones with their characteristics and requirements. The different denominations to describe bioclimatic architecture were considered in order to introduce the methods to identify bioclimatic design strategies in the framework of the sequence **climate – comfort – architecture**.

The integration of bioclimatic resources in the design process is analysed to show the importance of introducing this approach from the first stages of project development.

Based in this framework, the following chapter presents an historical background and the context in which bioclimatic design had evolved through history, both in Europe and Latin America.

CHAPTER 3. HISTORY AND EVOLUTION OF BIOCLIMATIC DESIGN

3.1. INTRODUCTION

The evolution of the built environment, with responses to multiple and complex requirements, started by providing the shelter needed for survival and from attack by human and animal enemies as well as protection from hostile and unfavourable aspects of the physical environment. At later stages, durability, status, fashion and improved environmental quality, were the motors of development (Rapapport, 1969). According to this sequence, the protection from climate was one of the initial factors that have remained a constant preoccupation and priority in the long process of the development of the built environment and the history of architecture (Oliver, 1987).

To back up this argument, different authors have commented on the need to develop protection from the cold, as man's settlements were established further north in the advance after the last ice age in Europe (Huntingdon, 1945; Koenigsberger, 1970). These improvements depended on different kinds of developments in clothing and shelter, fire control and the construction of housing that offered effective weather protection.

In another geographical context, and through the findings of archaeological excavations in the Middle East, the development of the courtyard-house can be traced as a typical response in the region of the Mediterranean Sea, North Africa and the Near East, where hot dry conditions prevail (Haynes, 1965).

In contrast, the long house of Northern Europe provides a compact form with central hearth, incorporating stables and storage for fodder under large double-pitched roofs. Examples of this building type have been discovered in archaeological excavations in the Low Countries, Germany, Sweden, Denmark and England (Brondsted, 1965; Wilson, 1972; Hawkes, 1973).

Other authors, such as Knowles (1981), ENEA (1983) and Behling and Behling (2000), have evaluated the background and history of the use of solar energy in the built environment of different cultures, from pre-history till present days, including the Chinese, Japanese, American, Greek and Roman civilizations.

All these analysis show that a clear response to climatic variables was evident from pre-historic constructions, offering protection from cold and strong winds and providing comfortable outdoor spaces while controlling solar impacts and moderating the large thermal swing in hot dry climates. However, by definition, the pre-historic examples can only be analysed according to the probable performance and use, without knowing if these responses were the result of chance, a process of trial and error, or conscious design decisions, as only when written records become available can these questions be answered.

However, it is possible to characterise the bioclimatic performance of primitive constructions according to the way in which they modify climatic impacts. For example, caves and thick-walled stone constructions reduce temperature swings while thatch and accumulation of organic materials reduce heat losses, allowing an increase in average temperatures.

On the other hand, open structures provide protection from sun and rain, while maintaining outdoor temperatures and permitting the use of cooling breezes. Even in pre-historic times, these examples provide evidence of an initial awareness that buildings modify climate, and that this modification can provide more comfortable living conditions.

In subsequent periods, with written records and the physical evidence of existing buildings, the application of bioclimatic design strategies can be analysed with greater certainty. The following review, supported by a wide variety of sources, introduces bioclimatic factors that are shown to have influenced the development of architecture over time, with examples from different historical stages.

3.2. BIOCLIMATIC RESPONSES IN HISTORY

This contribution expands on concepts originally developed by the author, identifying cases from Egyptian to modern architecture, through Roman, gothic, renaissance, post-renaissance, baroque, rococo, industrial and post-industrial periods, which are analysed in the following sub-sections.

3.2.1. Egyptian architecture.

The review of Egyptian architecture forms the starting point of this issue, as it is one of the earliest cultures with plentiful architectural evidence and written records. However, the Egyptian rule did not extend significantly beyond the well-defined limits of the Nile Valley and the Mediterranean coast, though their culture was influential outside these limits.

Egyptian architecture and art responded to the strong hot dry climate, with many bioclimatic features incorporated both in domestic and religious buildings. House design adopts bioclimatic strategies such as evaporative cooling with vegetation in enclosed protected gardens, small courtyards to provide shade in outdoor spaces, thick adobe walls to introduce thermal mass and inertia, and flat roofs for outdoor sleeping in summer (Fathy, 1973).

On an opposite scale, the temples at Aswan also show a clear mastery of the needs for climatic and light control in this harsh climate, with high-level clerestories providing natural ventilation and filtering daylight. The thick stonewalls incorporate much needed thermal inertia in a climate with large temperature swings. Even details show appropriate climatic responses, such as low relief's carved on the walls which are best viewed with high angle sun, providing the necessary shadow to view the carvings to best effect. The same carvings, seen in the British Museum with diffuse light, look very different.

However, it is argued that Egyptian architecture did not contribute to the theory of bioclimatic design, largely because there was little need for bioclimatic variation within the geographical limits of the Egyptian empire. Nevertheless, there is one key contribution discovered by this culture related to the apparent movement of the sun, a lesson that was unfortunately lost for many centuries. The response to solar movement, such as the precise alignment of the pyramids, was understandable in a hot dry climate with intense and nearly constant sunlight. The Egyptians developed different sundials for time keeping, from portable sundials to the high temple obelisks (Gibbs, 1976).

To support this observation, the difference of shadow lengths, between Syrene in southern Egypt and Alexandria in the north, was noted by Eratosthenes, the Greek geographer (about 276 to 194 B.C.) who, after careful measurement of the distance between these two sites, was able to determine the circumference of the earth with surprising accuracy, based on the premise of a circular globe and parallel sun's rays. This variation in solar altitude according to the latitude is a vital link in the development of bioclimatic theory noted by authors from Roman times (Vitruvius [c 50 BC], 1914*) till the present day (Olgyay, 1998).

3.2.2. The architecture of Imperial Rome.

Among the first written documents to explain the functioning of the house in relation to climate impacts are those of the Greeks and Romans. The milestone most often quoted is Vitruvius first book, c 30 BC (Vitruvius, 1914)* showing the need to modify and adjust climate protection strategies according to the regional variations. The validity and application of this written reference can be verified in changes found in Roman architecture in different regions of this extensive empire, which stretched from Spain to the Middle East and from Scotland in the north to the Sahara desert in the south (Haynes, 1965).

The Roman Empire, as its immediate predecessor, the Greek culture, developed and spread construction technology and architectural style that covered their zone of influence, reaching a continental scale as an early example of globalisation tendencies. In the case of the Greeks, the temples and theatres are the main and most characteristic monuments, but in the case of the Romans, the centralised military dominance required careful city planning at a grand scale, including urban infrastructure such as aqueducts, road networks, military defences, temples, markets, baths, amphitheatres and circuses, as well as residential sectors.

Although the central administration promoted the uniform spread of the culture and architecture as a symbol of the dominant military-political power, important regional variations can be detected in the local responses adapted to the need in order to provide comfortable buildings in very different climatic regions.

For example, the hypocaust under floor heating systems were used in the baths of the principle cities of the Empire, but this resource was incorporated in the domestic architecture of the Roman villas in the colder regions of northern Europe, such as southern England and Germany (Goodburn, 1972). This system marks the start of heating installations where the combustion chamber was totally separate from the room to be heated. The average indoor temperature and the mean radiant temperature were raised without contact with smoke, soot or ashes.

The patios of the northern villas also adopted different configurations from those found in the southern limits of the Roman Empire. In the south, the courtyard of houses in cities such as Leptus Magna, Sabratha (Libya), Dougga (Tunisia) and Volubilis (Morocco) were of limited dimensions to provide shade and protection from the hot and dusty summer winds.

---

* Date of translation

The fortified farms on the fringes of the desert had even more compact and protected courtyards (Haynes, 1965). The most typical of Roman houses were those found at Pompei, in a climate similar to Rome, with large but still compact courtyards.

However, the patios of the villa-houses in southern England adopted larger dimensions to allow the entry of lower angle winter sun, as are clearly shown in the cases excavated in Silchester. This town was developed at relatively low densities with open spaces between buildings, a tradition continued in British town planning (Bell and Bell, 1972). As Ward (1911) states, ‘any attempt to interpret the Romano-British house by reference to that of a Pompeian house is not likely to lead to satisfactory results’.

It is shown that although the Roman occupation of England lasted less than 400 years, from the initial invasion by Claudius in 43 AD to the final collapse of Roman rule and retreat soon after 400 AD, bioclimatic responses to different climates were rapidly developed. Considering that Vitruvius wrote his ten books of architecture in about 30 BC, and the Roman expansion into the colder regions of northern Europe only started in 130 BC, it can be conjectured that the regional adaptation of Roman architecture and the emergence of a theory of regional architecture was developed in about two centuries.

The prerequisites of this theory include the existence of a large empire over a wide range of climatic conditions, coupled with an effective communication network of roads for safe and rapid travel, written records and specific architectural typologies, repeated in different parts of the same political sphere of influence. It is argued here that the realisation that climate variations require different architectural responses could not have arisen in earlier times, as these pre-conditions did not exist previously in Europe or the Middle East, although they may have been present in China at an earlier date.

Although Markus and Morris (1980) throw doubt on the real application of the proto-bioclimatic treatise such as Vitruvius, Behling and Behling (2000) present a series of examples of the application of bioclimatic concepts in the architecture of Imperial Rome. In addition to the evidence of bioclimatic responses provided in this section, the Romans introduced new materials for climate adaptation such as window glass and translucent marble for lighting indoor spaces, as well as adopting galleries and porticos to provide shade in summer and protected sunny spaces in winter, supported by a growing body of knowledge on solar geometry.

The Vitruvius’s recommendations and observations represent a fundamental step in the development of the theory of bioclimatic architecture, cited in many references (Olgyay, 1963; Cofaigh et al, 1996, Evans and de Schiller, 1994). He also had a clear knowledge of the movement of the sun, demonstrated by his explanations for manufacturing sundials (Gibbs, 1976; Calvert, 1999).

The regional variation in Roman architecture recognises the need to modify building design in order to reduce or increase the average temperature according to the outdoor climatic conditions. The characteristic elements of Roman architecture, such as porticos, courtyards, and high-level windows in the basilicas, allow daylight, solar gains and microclimate protection. The form, size and orientation of outdoor and intermediate spaces also show a microclimatic response to comfort in these intensively used areas.

The limited development of glass, documented by Macfarlane and Martin (2003), restricted the use of solar gains in indoor spaces, though the thin layers of translucent marble allowed natural illumination of large Roman bath complexes without excessive heat losses, important both for occupant comfort and fuel economy, dependant on limited firewood, a resource that lead to deforestation of various Mediterranean regions (Perlin, 1991, Erhlich et al, 1980).

Many of the elements of roman architectural, both domestic and civic, can be related to the Mediterranean climate at the core of the empire, with hot dry summers and cool winters. The portico and patio with gallery provide shade and rain protection; the massive masonry walls and compact urban development incorporate thermal inertia to dampen the large summer temperature swings.

3.2.3. Gothic architecture.

Gothic and other architectural styles developed in the same period also show a response to regional variations. This is especially evident in the larger window sizes adopted in northern Europe, culminating in the late gothic decorated period, of which Kings College Chapel Cambridge is an outstanding example, where the largest windows are placed on the south facing facades to catch the sun.

This growing use of glass and the permanent increase of window size were made possible, in part, by the development of glass technology (Macfarlane and Martin, 2003). But, at the same time, increasing literacy and availability of reading material also required better daylight indoors, especially in the north of Europe where outdoor light levels are significantly lower than those found in regions closer to the equator. The ability to read in comfort, even on cold and cloudy winter days, was a major advance for the development of modern culture.

While the ever-larger sizes of glazing offered better light and the ability to catch solar gains to raise indoor temperatures in northern Europe, in the lower latitudes of southern Europe, the same dimensions and design solutions would have created uncomfortably hot indoor conditions. It is therefore logical to confirm that no church or other building in Italy, Spain or other regions of southern Europe, including France or Greece, has comparable window sizes to those found in northern Europe in this period.

The divergence between the late gothic of northern Europe and the architectural movements of southern Europe may have many explanations, but it is argued here that the climatic differences, rarely mentioned in the literature, should be added to the other technological, cultural, political and religious developments in order to understand more deeply the factors that influence architectural development.

3.2.4. Renaissance and post-Renaissance architecture.

With the rise of the Renaissance, buildings began to incorporate elements of roman architecture, although these were integrated in new morphological configurations and innovative combinations. Many of these elements have clearly defined bioclimatic characteristics, including the colonnade, the portico, the patio and the massive wall.

The bioclimatic response of these elements was well adapted to the Mediterranean climates of Florence and Rome with hot summers. High domes and vaults with lanterns and clerestories also provide natural lighting and ventilation appropriate to these hot seasons.

However, they were less appropriate in the colder climates of northern Europe, where cold winters represent the dominant climatic problem for thermal comfort. As a result of this limitation, it is argue here that the spread of renaissance architecture in the north of Europe, especially in England, Germany, and the Low Countries was slow, though it has to be added that there were also strong political and religious reasons that also delayed the adoption of this movement.

Only after the translation of the four Books of Palladio (1570), with his freer and more flexible approach to the incorporation of Roman motifs in architecture, was the movement adopted with greater acceptance in northern Europe. Inigo Jones was one of the first architects to introduce this movement to England, over 50 years after Palladios Treatise. His design for the Banqueting House of the Palace of Whitehall (1622) was one of the first renaissance buildings in England, built for the king and in a prominent position in Westminster.

The southern facade of the Queens House in Greenwich started in 1616 provides another example of this introduction. Here, it is possible to compare the rhythm of the facade with Palladio’s design for the Chiericatti Palace in Vicenza (1550) with similar proportions. However, in the case of the Queen’s House, the centre section of the first floor or *piano nobile* is intended to create a protected balcony, while the rest of the façades coincides with the outer plane, so the south facing windows catch the winter sun. The play of solids and voids in the Chiericatti Palace is exactly the opposite, with colonnades and protected facades behind the columns on most of the facade, and a projecting section in the central portion of the upper floor. This design provides better solar protection and shade in the outdoor colonnade for the hot days of summer in Northern Italy.

The Villa Rotonda provides another example of the comparison between an original Palladian design in Italy and the adaptation in England. This square building of 1567, located in the countryside outside Vicenza contains a central dome over a central space linked to the porticos on the four facades forming balconies with views over the surrounding landscape. Although the texts of Palladio emphasise the need to respond to the movement of the sun with different impacts according to orientation, the use of identical facades on the four orientations seems to ignore this intention. However, the function of this building, used for social reunions with guests invited by a retired Monsignor, should be taken into account when evaluating the bioclimatic performance. According to Ackerman (1966), in his Monograph, the building was mainly aimed for the enjoyment of the landscape, and the different orientations provide a range of alternative conditions.

In this way, different climatic conditions, such as protection from cold winds or exposure to cooling evening breezes, shade from the sun or a warm sunlit space was achieved according to the orientation and season of the year and time of day. The heart of the Villa, the two storied central space, provides a cool and stable temperature during the midday heat, while the same space, protected from direct contact with the outside air, is easy to heat in the cold winter days.

In England, a similar building was designed and built by Lord Burlington, adopting a similar plan for a similar function. This residence, the Villa of Lord Burlington at Chiswick, built in 1725, is located in the outskirts of London for social and cultural activities, and was built following his visits to Palladio's works and his acquisition of an original copy of the Four Books, now in the Library of the Royal Institute of British Architects.

However, when compared with the original model, the design incorporates two important variations. Instead of the small central skylight place over the dome in the Villa Rotonda, Chiswick Palace has a raised dome over the central space with large clerestory windows, recognising the need for more light in the more northerly climate of London, Latitude 51° N, compared with brighter skies found in the north of Italy, latitude 46° N. Additionally, instead of repeating the same facade in tour different orientations, the Villa de Lord Burlington places the symmetrical entry colonnade on the south east side, providing sun to the entrance, especially in winter. The steps down to the garden on the northwest façade are less important, recognising the more limited contact with the outdoor in the colder London climate, compared with the opportunities to sit in the shade of the porticos in Vicenza's hot summers.

Later, Thomas Jefferson, 1743-1826, 3rd president of the United States and amateur architect, reinterpreted again the language of Palladio in his design for the University of Virginia, 1817, and his own home in Montichello, Charlottesville, adjusting the orientations and window sizes to the more continental conditions of North America. In this case, the adaptation of the canons of the Renaissance and especially the writings of Paladio took about 50 years to respond to the different climatic conditions of Northern Europe.

3.2.5. Baroque and rococo.

The development and spread of baroque and rococo architecture also responds to the different climatic and daylight conditions in different regions of Europe. This can be seen in the dramatic rays of strong light penetrating the dim interiors of Italian baroque churches, compared with the luminous white and gold diffusing surfaces of German and Austrian Rococo in the colder regions at higher latitudes with lower levels of daylight.

The climate conditions in Rome, represented by the magnificent example of Boromini in San Carlo of the Four Fountains, 1638, favour the manipulation of light with limited opening sizes to achieve dramatic effects and visual emphasis. On the other hand, the Bavarian examples, represented by the Church at Weiss, 1746, with the inside surfaces covered in light entering through partially concealed openings, achieve a different but equally theatrical effect.

In the framework of this thesis, it is argued that these selected examples are representative of the conscious recognition of the need to adjust architectural solutions to the climatic needs of different regions of Europe. However, it is important to acknowledge that other factors, cultural, political and religious, also play a major part in the development, spread and acceptance of architectural innovations.

In this period, the introduction of double windows represents an interesting innovation, especially in the Central European cities of Prague, Vienna and Salzburg, where rococo was developed with greater intensity. This region experiences a continental climate with very cold winters, hot summers and important temperature swings. At this stage of architectural development, the design of fireplaces and their integration in domestic and institutional architecture is also evident.

3.2.6. Architecture of the Industrial Revolution.

The development of the capacity to mass production of industrial articles and provide cheap transport to distribute them over large distances constitutes a critical point in the history of globalisation as well as the development of bioclimatic architectural theory and practice.

The Industrial Revolution not only introduced new materials but also expanded the production of existing materials in larger quantities and better quality at lower prices, overcoming traditional barriers of distance and geography. Steel, iron, glass, cement and eventually aluminium, were introduced to provide new possibilities in architecture. The availability of plentiful and cheap energy in the form of coal allowed higher production temperatures and the development of locomotive power as well as stationary machines for milling, forging and stamping materials.

At the same time, the new technologies also required new building types, such as train stations, central post offices, large offices, workshops, factories and power stations, at a scale and size which in turn presented new challenges for the designer to provide heating, ventilation and lighting in buildings with increasing numbers of storeys and deeper plan depths.

Rapidly, new techniques were developed to introduce forced ventilation and central heating, based on coal fired boilers, as well as artificial lighting, initially using gas and later electricity. All this artificial conditioning required building plant and cheap energy to create comfortable working conditions. However, the development of artificial conditioning techniques was paralleled by new concepts for the natural conditioning of buildings, using the possibilities of new materials. Atrium, ventilation shafts, large glazed surfaces and clerestory lighting introduced both light and ventilation in deep plan buildings. Banham (1969) has documented relevant but partly forgotten examples of this development process of building plant for heating, lighting and ventilation.

The same influences that gave the initial impulse to the Industrial Revolution also promoted the process of imperial expansion and colonialism, as part of the globalisation phenomenon extending over all the continents. Once again, the centralised processes gave rise to a rapid diffusion of universal models of buildings, images and objects. However, specific responses to regional variations and local requirements can also be detected.

During this stage, the industry of exportable architecture was developed, in order to export not only building materials but also finished buildings as products. An example of this was the enterprise of Gustave Eiffel (1832-1923), who designed and built two structures that have become symbols for France, the Eiffel Tower, and the United States, the structure that supports the Statue of Liberty. As well as setting up a successful consulting firm, he also established a company to design, manufacture and export buildings, including a church in Manila, The Philippines, a market in Lisbon, an observatory in Nice, a railway station in Budapest, Hungary, and a workshop in Buenos Aires, Argentina, as well as large span bridges in Portugal and France, as well as prefabricated ones in Indochina and South

America. Provision of adequate ventilation is a key feature of many of these buildings, especially in warmer climates, an aspect related to Eiffel’s interest in wind loadings in his early bridges leading to studies of aerodynamics towards the end of his career.

But Eiffel was not the only designer and exporter of prefabricated buildings, as many companies offered off the shelf buildings from their catalogues. In India, Patagonia and the West Coast of Africa, specially designed buildings were ordered and assembled in very different climatic conditions. The timber and corrugated iron houses for the Patagonian sheep farms included glazed galleries to provide sunlit spaces protected from the wind, with local wool added in the cavities to achieve better thermal insulation. While in the West Coast of Africa, houses raised on stilts were designed to catch the breeze, with ventilated floors, mosquito screening on the openings and wide verandas to provide comfortable outdoor spaces protected from sun and rain.

The characteristics of industrially produced materials and the transport requirements encouraged the use of light weight materials, with corrugated galvanised iron, timber structures, asbestos cement sheets, etc. The rapid transformation of construction techniques towards architecture of low thermal mass and short time lags started a tendency that accelerated with the development of the Modern Architecture Movement.

The parallel development of techniques for artificial conditioning allowed the thermal deficiencies of these lightweight buildings to be overcome, at the cost of high-energy use. The rapid industrialisation process was also accompanied by the development of building science, not only for structural design but also for the study of thermal performance and environmental conditions in buildings.

2.3.7. Modern Architecture.

Although Modern Architecture, so eloquently documented by Pevsner (1968), traces it’s roots to the Industrial Revolution, it’s visual expression responds to the possibilities offered by the new materials as well as traditional ones with better quality and lower prices. It also responds to the growing social demands, a result of the excesses of capitalism in the initial stages of the Industrial Revolution, providing social housing, schools, hospitals and other facilities and community services for the growing urban populations.

The Modern Architecture Movement was often seen as a crusade to introduce a new image, eliminating historical references and the existing status quo with an important political background and strong social commitment. Many of the protagonists of this movement proposed the concept of an International Style, capable of resolving the needs of all societies.

The arguments between Frank Lloyd Wright and Mies van de Rohe were centred on the regional responses of Wright and the internationalist stance of Mies (Blake, 1963). However, both were well aware of regional climate differences. While Wright established a winter studio, Taliesin West, in the Arizona desert, as an escape from Taliesin in the cold prairie of the central plains, Mies started to design for Berlin and also continued in Chicago as well as Cuba’s warm humid climates and Mexico’s uplands.

As a result, the advance of modern architecture met with strong resistance in certain regions, where conservative forces attempted to retain traditional images. However, in Latin America, the acceptance of the movement was favoured by the emerging political tendencies and the innovative concepts of development and social advancement. This aspect will be considered in this thesis in more detail through the analysis of bioclimatic design in Latin America in the following section.

The introduction of new techniques and methods using new materials often produced serious problems of thermal conditions in new buildings. While the traditional techniques, developed by a process of trial and error ensured reasonable comfort levels, many new steel, concrete and glass buildings suffered from grave thermal defects. Severe condensation was almost inevitable in buildings without sufficient thermal insulation, as well as creating heating problems in winter. At the same time, large windows often generated overheating as a result of the lack of adequate solar protection (Banham, 1968).

The arguments developed in defence of modern architecture were often dogmatic and inflexible, promoted by the supporters of the new architecture, raising a strong barrier that prevented the correct identification of building problems and the consequent introduction of corrective measures.

It is postulated in this thesis, that even today, the process of architectural adaptation to specific climatic location has still not been adequately faced and still less completed, both in professional training and practice. On the contrary, it is generally considered that the creation of adequate environmental conditions depends, more than ever, on the mechanical installations for artificial conditioning, requiring excessive conventional energy resources.

2.3.8. Reflections on the historical background.

This brief and partial summary analyses the parallel process of the spread of architectural concepts and unified formal responses over large regions of the world, complemented by the corrective process of regional adaptation, needed to achieve appropriate solutions to local contexts.

Although this analysis inevitably follows an Euro-centric emphasis, following the conventional approach to architectural history, it shows how a continuing adaptation to regional climatic variation has developed over different periods.

In Roman times, this adaptation probably required a period of two centuries while, during the Renaissance; the modification of new architectural concepts was achieved in less than a century. Later, in the Industrial Revolution, this process was accomplished in an even briefer period, although extending over various decades, and even when Modern Architecture was developed, the adaptation period was similar.

In this section of the thesis, it is demonstrated that the continuing evolution of both society and architecture requires continuous adjustments to achieve a balance between all developing requirements. Today, the need to respond to the overall multiple imperatives of sustainability and energy efficiency while controlling environmental impacts, introduces new requirements in architectural design, posing significant challenges.

With the aim of complementing this survey focussed on the development and integration of bioclimatic concepts in architecture throughout history, the following section presents a similar evaluation of the development sequence of bioclimatic architecture in Latin America.

3.3. BIOCLIMATIC ARCHITECTURE IN LATIN AMERICA

This section provides an introduction to the evolution of bioclimatic architecture in Latin America, with representative examples of the advances achieved and the characteristics developed over seven periods defined in this study. Although the geographical climatic coverage presents a challenge, it is considered that the examples selected are representative of the development of bioclimatic architecture in this vast region, providing a synthesis of the tendencies that generated the specific regional character of bioclimatic design. The examples also identify the difficulty of promoting bioclimatic design strategies, when confronted with globalisation tendencies in architecture.

The main objective of this section is to demonstrate the development of bioclimatic architecture in a regional context. This evolution of bioclimatic architecture relates to the conceptual framework presented in the first chapter and complements the survey at the world scale developed in the previous section of this chapter.

It is appropriate to acknowledge that each country within the Latin-American region can provide relevant examples of the development of bioclimatic design, both historic and vernacular architecture as well as more recent works that apply bioclimatic strategies in conscious application design processes, complementing and expanding on the cases given in this section.

This analysis and case selection extends and amplifies the presentation originally prepared by the author for the Passive and Low Energy Architecture Conference, PLEA-2001, Brazil, the first of the series held in South America (Evans, 2001), and builds on further development published in Mexico (Evans and de Schiller, 2004).

3.3.1. Context.

The bioclimatic architecture of the Latin American region finds its roots in a blended combination of cultural heritage, climatic and geographic variations, together with the use of local materials and resources. All of these factors contribute to the development of particular bioclimatic architecture with strong regional character. For this reason, these factors are discussed before detecting, defining and exemplifying the sequential development and background to the present day situation.

The varied **cultural currents**, with diverse origins found in the region, are important actors to explain the factors that affect the development of this specific built environment.

The indigenous population has left archaeological evidence of relevant architectural and urban design achievements with clear responses to climatic conditions, as well as designs based on advanced astronomic studies (Rodriguez Viqueira, 2004). The initial settlements of the Spanish *conquistadores* repeated the patterns developed in other regions, rapidly adapted to the requirements of the different contexts found in the new world.

The successive migrations and population movements have also left their mark, with African influences in Venezuela, Guyana, Ecuador and the north of Brazil, while Japanese communities were established in Sao Pablo, Brazil, as well as smaller contingents in Misiones and Buenos Aires, Argentina, and many Chinese workers, drafted to build the railways in The Andes, settled in Peru. Later, Italians and Central Europeans in Buenos Aires, Welsh in Patagonia, Germans in Cordoba, Argentina, and Southern Brazil formed important communities. There are also many smaller ethnic groups such as Armenians, Jews, Scandinavians, Irish, Syrians, French and Dutch. This enormous melting pot has incorporated many scientific and technological influences, with specific contributions in the field of the construction industry.

3.3.2. Particular features.

Particular features characterise this vast and extended sub-continent, with an enormous diversity of geographical conditions, a great range of heights together with seismic and climatic variations contrasting with local resource availability and culture.

The wide range of **geographical conditions** has also contributed to the climatic impacts to which the built environment must respond. The range of latitudes is highly important, stretching from the equatorial region with high angle sun in all seasons of the year, to the cold southern Patagonian region, up to 55° south, with low angle winter sun. One special characteristic of the region is the wide range of latitudes found within countries. Brazil, Argentina and Chile all incorporate a wider range of latitudes than any other single country in other regions of the world.

The **range of heights** above sea level also leaves their mark on the climatic conditions and the regional architecture, from towns at sea level up to the settlements in the high Andes at 1.000 to 3.000 metres above sea level. The maritime zones, with the moderating influence of the sea, contrast with the continental areas at the centre of the landmass, with high seasonal and daily temperature swings. The Andes range, which forms the backbone of South America and it’s continuation in Central America and Mexico, creates special and contrasting climatic situations on the windward and leeward slopes.

The resulting **climatic variations** are wide and diverse, providing examples of almost all major climatic types of the world. The Amazon region, on the equator, with the largest river basin in the world, experiences a warm humid climate with very limited daily and seasonal temperature variations, associated with rain forests. At the same latitude, the high altitude central zone of Quito, in Ecuador, shows a lower average temperature, combined with higher daily swings.

Atacama, in Chile, the driest desert in the world, contrasts with the windy cold deserts of Patagonia, found at higher latitudes. The subtropical Pampas prairies in central Argentina, the wine growing region in the oases of Mendoza, the humid swamps of the Mato Grosso, the dry region with high temperatures and humidity around lake Maracaibo, the Altiplano in Bolivia and surrounding regions, the continental ice fields between southern Argentina and Chile, are all examples of the great regional climatic variation of this subcontinent.

The seismic and volcanic activity in all of the Andes region, Central America and Mexico, is another key factor that affects building form and construction techniques, limiting or accompanying the possibilities of adapting bioclimatic design strategies appropriate to the local conditions. This is especially critical in those climatic regions with large temperature swings requiring high mass building materials with large thermal capacity to moderate the variations, as they are highly dangerous when subjected to seismic movements. Building codes for earthquake resistant structures, now applied in the entire region, tend to discourage if not prohibit the use of traditional materials such as adobe, due to the danger of thick and heavy walls with little resistance to seismic movements (Rotondaro, 2004).

The strong and persistent westerly winds in Patagonia, with annual average speeds exceeding 35 km/hr (S.M.N, 1995), require resistant structures as well as designs that provide protection for occupant comfort. In the Caribbean, hurricanes and tropical rain storms, infrequent but potentially devastating, also require special precautions. The constant trade winds provide valuable cooling in the warm northeast coast of Brazil, while the low average wind speeds, typical of the Pampas, reduce the bioclimatic options available to improve comfort by natural means.

Many traditional materials found in the region, including thatch, adobe, stone, timber, lime and slate, suffered the impact of the Industrial Revolution, when the importation of manufactured materials replaced traditional ones. The use of iron, steel, Portland cement and galvanised roofing sheets, have strongly modified the aspect and form of urban and architectural development as well as the environmental quality of building interiors.

Glass, another imported material, has transformed the architecture of the Industrial Revolution and the urbanization at the end of the XIX and the start of the XXth century. Today, most materials are produced in the region in modern industrial plants, although special finishes and building installations are still imported.

The globalisation trends also imply the integration of the region in the world economy, with the export of many construction materials to world markets, including aluminium from Patagonia, hardwood from Brazil, asphalt from the Caribbean and softwood and copper from Chile.

3.3.3. The bioclimatic response.

Bioclimatic architecture (Evans and de Schiller, 1996) implies the development of a socio-environmental consciousness in the design process that, united with ethics and professional responsibility, responds to the local climate by using the favourable aspects while providing protection from the unfavourable variables in order to contribute effectively to the creation of a sustainable built environment.

This approach implies the achievement of well being (the social aspect) with the minimum environmental impact (ecological aspect) and the minimum use of resources (economic aspect), in the conviction that present day actions will contribute to the development of future generations.

In this framework, the design process analyses the meteorological variables as one of the starting points, and defines the conditions required for comfort, both indoors and outdoors, and identifies the most appropriate natural conditioning strategies to achieve this.

After comparing the existing meteorological variables with the desirable conditions for well-being, the requirements for modifying unfavourable conditions or preserving favourable ones can be detected and defined.

These requirements or indicators (Evans, 2001) allow the selection of design guidelines that promote or encourage optimum thermal conditions for occupants, according to expected activities, both indoors and outdoors, as well as intermediate and transitional spaces.

The object of this approach is to achieve a favourable modification of the environmental conditions through the choice of appropriate design elements and architectural decisions to provide adequate thermal quality avoiding artificial conditioning plant for heating and refrigeration dependant on conventional energy resources, or minimise these to achieve a less dependant architecture.

3.4. STAGES OF BIOCLIMATIC ARCHITECTURE IN LATIN AMERICA

The sequences presented below respond to the historical periods identified to differentiate the stages of architectural development, especially the capacity to modify and control environmental conditions.

Each stage covers a wide range of situations, following an approximate chronological sequence with examples over a wide geographical area, sharing common features allowing a summary of the evolution of bioclimatic responses over time in this vast region.

3.4.1. Historic periods and evolution.

This analysis allows the identification of the following series of stages and periods:

- **Pre-Colombian architecture:** This period reflects the development of varied cultures in the different climatic regions of Latin America, before the arrival of the Spanish, coming to an end in about 1500; though in many regions, the influence of these indigenous cultures lasted much later as a result of the continuing building traditions as well as the cultural heritage linked to the built environment. The principal and most imposing remains of this period are the monumental stone and masonry construction of the Incas, Aztecs, and similar cultures. Little remains of the pre-Columbian cultures of the forest regions where organic materials were used, well suited to the rainy, hot climate with low temperature swings.

- **Colonial architecture:** The expansion of the Spanish empire can be traced from 1500 till about 1850, with variations according to the different regions. The principal starting point was the introduction and adaptation of Iberian architecture, especially the typical elements from Andalusia, many of which can be traced to Arab influences. These introduced elements were modified and developed according to the requirements of the very different climates found in the region. In the same way, the Lusitanian tradition with it’s origins in the more temperate and rainy regions of the Atlantic Coast of Portugal, were introduced and modified for the different climates of Brazil.

- **Vernacular tradition:** With roots in the pre-Colombian and colonial architecture, and modifications and developments typical of popular construction, vernacular architecture provides many and varied examples of bioclimatic design resources integrated in buildings. Many of these traditions are still found in the rural and isolated regions were modern techniques and materials were introduced more slowly, and some of these modern materials have been integrated in the continuing vernacular tradition. The vernacular in Peru has clear links with the pre-Colombian culture, while the popular buildings of the humid Pampas region have closer relation to the colonial tradition. Few vernacular buildings have survived from the earliest periods, though archaeological research is providing clues, but the more recent examples provide evidence of a continuing tradition that has survived over time.

- **Architecture after the Industrial Revolution:** As pointed out in the previous section, the industrialization process not only promoted the introduction of new materials but also the production of traditional ones in larger quantities, with lower cost and better quality. It also produced new building types with new functions and forms. From 1850 to about 1930, this process was paralleled by rapid urban expansion, both in density, building height and land coverage. Despite the introduction of new building types and materials, many of the prominent examples follow the historical architectural styles, for status and image. Although this period marks the introduction of cheap and abundant energy, and an increasing dependence on artificial conditioning, many bioclimatic design resources were used to achieve thermal and visual comfort before artificial refrigeration and effective artificial lighting was widespread.

- **Modern Architecture:** The modern movement broke the trend of the historical styles and provided a new architectural image based on the expression of function, the intrinsic characteristics of new materials and introduction of the scientific method in the design process. Although this movement has its origins in Europe and the United States, it received a strong impulse and favourable reception in the more adventurous cultural climate of Latin America, from the 1930 till the 1970's.

- **Solar and Energy Efficient Architecture:** In the 1970's, the world energy crisis following the oil embargo in Europe and the United States showed that the world could not continue to depend on non-renewable fossil fuels. The environmental impacts of this dependence also began to be studied (Meadows, 1972). As a result, both in Europe and the United States, major research and development programmes were initiated in the search for greater energy efficiency and more widespread use of renewable resources. Though many countries of the region including Argentina, Chile, Uruguay and Brazil started programmes, specifically aimed at the building sector, the results have been disappointing, with little political and institutional support.

- **Sustainable Architecture:** The increasing environmental impacts, both at regional and world level have demonstrated that profound changes are now needed to achieve a more sustainable built environment. The pressures of the ecology movement in Europe have started to find an eco in the region, although once again there is little evidence of serious policies to achieve the institutional changes required. To revert current tendencies of global warming and climate change, the built environment must respond with measures to reduce impacts, control the demand for non renewable resources and provide a better quality of life for all sectors of the population, a special challenge in this region with stark social contrasts and growing inequality in the distribution of resources.

Without denying the important advances achieved during the last to stages of this review, and the underlying concern to promote renewable energy resources and reduce environmental impacts, the achievements are limited and still require further development and more widespread application throughout the region.

The strong pressures to resolve the pressing social problems and unsatisfied basic needs of large sectors of the population, especially for shelter, heath and education in both growing urban areas and rural hinterlands, often emphasise the need to respond to pressing demands in the short term, relegating and postponing comprehensive responses to critical problems in the long term.

3.4.2. Impact of the energy crisis.

The energy crisis of the decade of the 70's, which renewed interest in low energy and solar architecture in the United Stated and Europe, also had an important impact in certain groups in the region, with the promotion and development of solar architecture projects from 1975 to about 1990, when much interest faded. As a result of this movement, some experimental projects were built in Argentina, such as:

- The solar house 'Sol-1', by Arq. Elio di Bernardo, National University of Rosario.
- The solar laboratory-house *Enrique Tedeschi*, IADIZA (now CRICYT), Mendoza, shown in Figure 3.1.
- The solar house at Abra Pampa and the Rural Heath Centre at Castro Tolay, both at high altitudes in Jujuy, were designed with the support of INENCO, the National Institute for Non-Renewable Energy, National University of Salta, shown in Figure 3.2.

Figure 3.1.
Laboratory-solar house 'Enrico Tedeschi', in a cool temperate climate, with Trombe wall, direct solar gain and solar collectors for hot water.

IADIZA Experimental House, Mendoza, Argentina.

Figure 3.2.
Natural conditioning in the Altiplano, high Andes Region.

Remote health centre, Castro Tolay, Jujuy, Argentina.

Example of a well functioning solar building in an extremely cold uplands, although the architectural image is not totally resolved.

Other solar houses in the region include the Treves House, Figure 3.3, and the Fuentes-Lopez House, Figure 3.4; both in Bariloche, Río Negro, Argentina.

Figure 3.3.
The search for a new architectural image compatible with passive solar systems.

The Treves House, Bariloche, Argentina, integrates two systems, solar gains and Trombe wall, combined with thermal insulation.

Figure 3.4.
The energy crisis and the search for more sustainable solutions promoted the development of both active and passive solar systems for the thermal conditioning of buildings.

The Fuentes-López Solar House designed by the CIHE-FADU-UBA, in Bariloche, Argentina.

In all of these examples, the use of thermal storage, high heat capacity materials, walls with significant time-lag and damping of temperature swings are an important part of the bioclimatic and solar design strategies. Later in the 90's, a series of demonstration projects were developed by the Research Centre Habitat and Energy, University of Buenos Aires, such as a super-insulated solar house in the cold climate of Bariloche, Figures 3.4 and 3.5, the UNDP Biosphere Station in tropical Misiones, Figure 3.6, and the Interpretation Centre for the Ecological Reserve near the Buenos Aires city centre, shown in Figure 3.7.

Figure 3.5.
Super-insulated house with active and passive solar systems, demonstrating the economic feasibility and low impact design in cold climates.

A CIHE Demo-Project, the Fuentes-López House in Bariloche, Argentina.

Figure 3.6.
Building complex for biodiversity research, with low environmental impact and energy autonomy in a remote selvatic zone: the 'Yaboti' Biosphere Station, ‘La Esmeralda’ Provincial Reserve, Misiones, Argentina.
CIHE Demo-Project developed for the UNDP, with CFD studies and wind tunnel to design cross ventilation.

Figure 3.7.
Low impart and energy efficient building complex, with design to achieve solar gains in winter and wind protection in a sire between the River Plate and the city of Buenos Aires. Interpretation Centre in the Ecological Reserve of the Southern Coast.

CIHE Demo-Project for the Government of the City of Buenos Aires.

3.4.3. New design and simulation tools.

At the same time, new and sophisticated design tools open a wide range of possibilities to test and verify the performance of new projects and improve their thermal performance at the project stage. Numerical simulation provides the possibility to analyse thermal and energy performance to obtain indoor temperature variations, annual energy demand, daylight distribution or emissions of greenhouse gasses.

Advanced techniques of computational fluid dynamics, CFD, daylight simulation, Figure 3.8, and thermal analysis can support the development of an architecture better adapted to its context with lower environmental impacts.

Physical simulation techniques can also provide guidance for designers and building researchers, using wind tunnel, heliodon and artificial sky to test solar impact, daylight quality and wind movement in and around new projects as well as evaluating modifications of existing buildings.

Figure 3.8.
New simulation, verification and optimisation techniques for design.

Model test in the artificial sky assessing daylight performance and energy efficiency.

Interpretation Centre for the Ecological Reserve, Costanera Sur, facing the River Plate, Buenos Aires, for the Municipal Government.

Despite all these advances and design tools, recent buildings frequently have higher energy demand, larger environmental impacts and poorer indoor and outdoor environmental quality. Various reasons can be suggested to explain this situation of improved design tools and poorer environmental results. Recurrent economic crises in the region and scarcity of capital for long-term investments place an emphasis on low initial cost, at the expense of higher cost in use.

In many cases, traditional and conventional buildings in the equatorial, tropical and sub-tropical regions have low energy demand, reducing the need to improve energy performance.

Additionally, various countries in the region, such as Ecuador, Argentina and Venezuela have benefited from favourable fossil fuel resources, providing cheap energy that also reduces the incentives for energy efficiency. At the same time, the environmental quality of housing for the social sector with limited resources often suffers as a result of the emphasis on quantity rather than quality.

3.5. THE FUTURE OF BIOCLIMATIC ARCHITECTURE IN THE REGION

The report presented by the Inter-governmental Panel on Climate Change (IPCC, 2001) shows that the use of energy has a clear and growing impact at the global scale. The region therefore faces the conflicting requirements of rising expectations, dwindling energy resources and the increasingly negative environmental consequences of conventional energy use.

3.5.1. The contribution to sustainable development.

In the face of this dilemma for sustainable development, it is clear that the need for improving the quality of life for the vast majority of the regions population cannot be achieved by increasing the use of energy resources. Even in situations of plenty and favorable socio-economic conditions, where the indiscriminate use of air-conditioning is found, it cannot overcome possible average temperatures increases of up to 6°C, as predicted by the most critical IPCC scenarios (2001). The extension of conventional energy distribution networks and the incorporation of ever greater cooling and heating installations, typical of current responses, is not an option for sustainable social, economic and environmental development. The principles of bioclimatic design can provide a solution to this dilemma, improving comfort, reducing energy demand and improving the capacity to face future climate change without provoking harmful environmental impacts.

3.5.2. The challenge of change.

The development of design guidelines and new building codes to extend and up-date the legislation in this field represents a key stage. For example, in the field of energy efficient and bioclimatic design, no country in the region has general requirements for the thermal performance of buildings with the exception of Chile, which has compulsory requirements for the insulation of roofs in all heated buildings in all regions of the country, recently extended to walls. The legislation at the planning scale is also weak, with few requirements for ensuring adequate light, sun and ventilation in central areas, and poor planning control. Added to this, the tendency in the region over the past two decades is to transfer the energy industry to the private sector, which has shown little interest in controlling demand or increasing energy efficiency.

The aim of this chapter is to show that in the past many bioclimatic responses have been developed to create architectural traditions that promote comfort and well being in varied climatic contexts, reducing energy demand and adverse environmental impacts. A favourable body of knowledge has also been gathered that can contribute to the creation of appropriate living conditions at the architectural and urban scale without excessive use of non renewable energy resources, without affecting the development possibilities of future generations. The present day perspective, while representing a great challenge, is not impossible to solve. As this chapter indicates, the incorporation of bioclimatic criteria in the production and improvement of the built environment can contribute to the quality of life and the process of sustainable development in the region, continuing local traditions that have been weakened or abandoned in the recent process of accelerated globalisation.

3.6. CONCLUSIONS

In this new challenge to develop architectural responses to combined problems of dwindling resources of non renewable fossil fuels, increasing environmental impacts and the need to improve the quality of life of large sectors of the population, new responses are needed. These cannot be based on a return to the past, but rather a development of traditional responses based on new scientific knowledge, tools and materials. Studies of thermal comfort, climatic variables, thermal performance of buildings and design resources, are required to develop the sequence climate-comfort-architecture introduced in this first part of the thesis. These aspects are developed in the next part of the thesis.

PART 2

STATE OF THE ART IN THE FIELD OF BIOCLIMATIC DESIGN

CHAPTER 4. THERMAL COMFORT

CHAPTER 5. BIOCLIMATIC ZONING

CHAPTER 6. TECHNOLOGICAL ADVANCES AND NEW TOOLS

Part 2 of the thesis provides a review of the state of the art in the field of bioclimatic design, with the aim of establishing a framework for the development of a new analytical tool, presented in Part 3. Part 2 includes the following chapters:

Chapter 4 presents a review of thermal comfort studies, with emphasis on the different approaches based on climate chamber studies and subjective assessment of user comfort in buildings.

Chapter 5 shows how the bioclimatic approach, comparing climate conditions with the desirable conditions for comfort can be used to establish a regional zoning for design recommendations. The review of zoning proposals in Latin America emphasises the importance of thermal swings as a key criterion.

Finally, **Chapter 6** introduces technical and technological advances in building design, with special reference to new materials that contribute to the improvement of thermal performance of buildings and the effectiveness of bioclimatic design strategies.

Part 1: Introduction

1. Introduction
2. Background ,,,
3. History …

Part 2: State of the art

4. Thermal Comfort
5 Bioclimatic zones
6. Technology …

Part 3: Comfort triangles

7. Thermal Comfort
8. Analysis of Climate
9. Design Resources

Part 4. Case studies

10. Urban scale
11. Architectural scale
12. Building scale

Part 5: Conclusions

13. Results & case study evidence
14. Conclusions & ideas for further study

CHAPTER 4. THERMAL COMFORT

4.1. INTRODUCTION

The relationship between architecture and environment, especially the development of built environments that favour the creation of comfortable conditions in the face of external climatic impacts, was originally a slow and intuitive practice that developed by a process of trial and error, with gradual change and adaptation.

As was suggested in the last section of the previous chapter, this process has accelerated with the development of theory and the incorporation of scientific method, through observation, the search for new alternatives, research, application and testing of results. At the same time, it incorporates technological advances, with the development of new materials and innovative systems for the thermal conditioning of buildings that can offer new potential for resolving the requirements in this field, as well as new design, simulation and evaluation methods.

4.1.1. Climate, comfort and habitat.

This process of technical and scientific development related to bioclimatic architecture integrates three principal components of study:

- **Climate:** existing climatic conditions in different regions, together with evaluation of possible future changes.
- **Comfort:** thermal comfort and the environmental variables required for human activities in and around buildings.
- **Habitat:** the performance of architecture as an environmental filter modifying and controlling unfavourable impacts and preserving favourable conditions.

Centred on this relation climate-comfort-habitat, the process of bioclimatic design has experienced important advances as a result of the emphasis of energy saving and reduction of environmental impacts. Studies of thermal comfort, the use of simulation, both numerical and physical to evaluate and optimise thermal performance and the application of new and non conventional materials and components can all contribute to the process, which is analysed in this chapter.

Before summarising the advances and present state of the art in thermal comfort, a brief analysis of the terminology is developed, comparing the meaning of words such as ‘comfort’, ‘well-being’ and ‘habitability’.

4.1.2. A glossary of thermal comfort.

Comfort: The word signifies satisfaction or absence of annoyance (Geddie, 1968). The comfort zone is the range of temperatures that offer a neutral thermal sensation. In other languages comfort may have different connotations, for example in Spanish, *Confort* an Anglicism, signifies a certain level of luxury.

Habitability: This word used to indicate the acceptable levels of environmental conditions in low cost housing implies minimum but appropriate and healthy indoor conditions for the activities developed in the building, often implying the minimum acceptable conditions. Habitable implies spaces ‘that may be dwelt in’ (Geddie, 1968) but no necessarily comfortable.

Well-being: favourable conditions that promote a sensation of satisfaction and health, a state that includes wider factors than the variables of the physical environment.

The semantic nuances of comfort are significant for questionnaires of thermal sensation, since the sensation of thermal neutrality, neither hot nor cold, does not necessarily coincide with the sensation of comfort or thermal preference.

4.2. STUDIES OF THERMAL COMFORT

Scientific studies of thermal comfort were only possible after the development of the capacity to measure temperature with certain precision. This occurred in 1650 with the invention of the first liquid in glass thermometers, in Florence, in turn the result of developments in glass blowing technology (Measurements Standards Laboratory, 2005)

Fahrenheit developed the first standardised scales in 1714, followed by the scale of Celsius developed in Sweden in 1742. Originally this scale fixed 100 for freezing point and 0 for boiling, inverted by Linneaus in 1744 to form the scale still in use today. (Collinder, 1970, cited en http://www.astro.uu.se/history/Celsius_eng.html).

However, the scientific study of comfort is a result of the awareness of links between thermal conditions and productivity, evident in the expanding heavy industries of the industrial revolution. Problems were also experienced in the extreme conditions of the boiler rooms of naval vessels operating in the hot humid climates of the Indian Ocean, and in the trenches in the winters of the First World War. Both these critical situations promoted the study of acceptable thermal conditions and the measures needed to achieve them, especially ventilation and appropriate clothing.

The development of air-conditioning for offices with a capacity for precise temperature and humidity control following Carrier’s patent of 1906 also promoted the study of comfort (Banham, 1969). Originally used for environmental control for industrial production (Stamp, 1964), air conditioning for thermal comfort was introduced in commercial applications in 1924, followed by domestic appliances in 1928.

Landberg in his study of comfort in arquitecture (1954) states that comfort in buildings can be achieved with temperatures between 18 annd 32° C, while outside temperatures can range between –76° + 62° C

The studies of Webb (1960) on comfort aboard British ships contributed to the definition of the complex relationship between temperature, humidity, air movement and radiation that influence thermal comfort in the form of the Effective Temperature (ET) scale and the Corrected ET scale.

Houghton and Yaglou (1923) in the United States are other pioneers in this field whose research was adopted by Olgyay (1970) as the base for his comfort diagram. Givoni (1969) also undertook research supported by the armed forces, in order to study the effect of acclimatization. In these cases, the study of comfort and the capacity to continue operating was a matter of life or death, where the mitigation of extreme conditions improves fighting capacity. Comfort studies were also introduced in industry, especially in heavy industry, where the extreme heat of industrial processes such as steel, glass and iron production represented a danger to health and a limitation to productivity. The development of indices, such as the '4-hour sweat rate' (Edholm, 1967), are a direct result of studies in this field.

The studies on comfort and the increasingly precise limits of acceptable conditions resulted in legislation to protect workers. In cold climates, these established minimum temperatures, though sometimes allowing lower temperatures in the first hour of work, responded to the difficulty of heating conventional buildings with significant thermal inertia. Meanwhile, in Argentina, for example, the acceptable working conditions are defined in Law 19.587 and the complementary regulations in Decree 351/79 using the Belding and Hatch Index (1955), which emphasises the avoidance of thermal stress.

In the decade of the 70´s, the advances in thermal studies were lead by Fanger (1973), who aimed to define the optimum conditions for productivity and well being, with emphasis on sedentary activity in temperate climates.

This approach responds to the capacity of air conditioning installations to control the indoor thermal conditions within strict limits. Fanger's comfort index, incorporated in ISO Standard 7730 (1994), proposed a universal scale based on detailed research on the subjective responses of subjects in climate chambers and the development of a physiological model of the bodies thermal equilibrium. The results indicate the PMV, predicted mean vote and the PPD, Predicted Percentage Dissatisfied.

The first index, PMV, indicates the average comfort vote of a typical population on a scale from -3, Cold, to +3, Hot, with 0 as thermal neutrality, shown in Table 4.1. PPD shows the percentage of the population with thermal dissatisfaction, with a vote below -1 and above +1. Table 4.1. shows the relation between the two indices, according to the ISO Standard 7730.

It is relevant to note that the semantic difference between 'neutral' (without sensation of hot or cold) and 'comfortable' (an indication of thermal preference) may produce different responses in comfort votes, though differences in practice are not likely to be significant.

Table 4.1 Comfort scale ISO 7730 (1994).

Comfort scale	Sensation	Bedford's scale
+3	Hot	Hot
+2	Warm	Warm
+1	Slightly warm	Slightly warm
0	Neutral	Comfortable
-1	Slightly cool	Slightly cool
-2	Cool	Cool
-3	Cold	Cold

PMV - PPD
Relation between PMV
Predicted mean vote
and PPD, Percentage
Predicted Disatisfied

Outside limits
PMV off the scale

Fangers Model ISO7763, 1985
with the following conditions
- skin without transpiration
- sedentary activities
- temperature between 10-30ºC

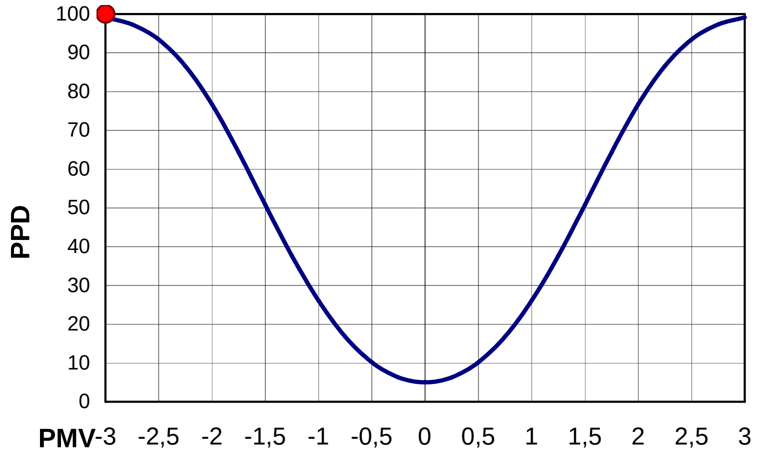


Figure 4.1. Relation between PMV and PPD, according to the ISO Standard 7738.

Table 4.2. Different comfort zones proposed by ASHRAE from 1923 to 1995.

	T Max	HR Max	T Max	HR Med	T Max	HR Min	T Min	HR Min	T Min	HR Max
ASHVE 1923 Winter	23,3	70	24,5	50	25,6	30,0	20,0	30,0	18,3	70,0
ASHVE 1923 Summer	25,6	70	27,5	50	29,4	30,0	22,2	30,0	20,0	70,0
ASHRAE-55 1966	25,3	80	25,3	50	25,3	20,0	22,8	20,0	22,8	80,0
ASHRAE-55 1974	25,3	60	26,2	40	27,0	20,0	22,2	27,0	21,9	72,0
ASHRAE-55 1981 Winter	23,0	66	23,5	45	24,0	24,0	20,3	30,0	19,5	80,0
ASHRAE-55 1981 Summer	26,2	57	26,6	38	27,0	20,0	23,0	25,0	22,4	70,0
ASHRAE-55 1992 Winter	23,0	60	23,5	41	24,0	23,0	20,5	29,0	19,8	60,0
ASHRAE-55 1992 Summer	26,0	60	26,5	40	27,0	20,0	23,0	25,0	22,5	60,0
ASHRAE-55 1995 Winter	23,2	58	23,6	40	24,0	23,0	20,4	29,0	19,0	85,0
ASHRAE-55 1995 Summer	26,5	58	26,8	39	27,0	21,0	23,4	25,0	22,3	83,0

Note: the successive pairs of temperature and relative humidity data indicate the limits of the comfort zone on the psychrometric chart.

The different comfort zones defined in five successive ASHRAE standards show the difficulty of defining a desirable comfort zone, with significant variations proposed over a period of thirty years, shown in Table 4.2.

On the other hand, researchers such as Nicol and Humphreys (2001) have questioned this approach, demonstrating that the results of Fanger are not appropriate for establishing comfort levels in buildings with natural conditioning, without artificial cooling, especially in hot climates. Studies in Pakistan (Nicol, 2003), Thailand (Busch, 1995) and Australia (de Dear, 1995) show systematic differences between the Predicted Mean Vote, PMV, and the Actual Comfort Vote, ACV, with variations of up to 1,5 in the results.

These researchers have developed the theory of 'adaptive comfort', showing that the preferred comfort conditions depend on the temperatures to which the population is accustomed to, typically the average monthly outdoor temperature.

Although the results of both theories are significantly different for hot climates and non-air-conditioned buildings, the processes of adaptation such as clothing, posture and activity levels, can explain part of the differences observed (Baker and Standeven, 1994).

These comfort scales can be applied to determine the average comfort temperature and the acceptable range of temperatures. One version of the 'adaptive comfort model' is ASHRAE Standard 55 (2004), with a variation in the temperature comfort range according to the average monthly temperature, as shown in Figure 4.2.

The adaptive model, as presented in the ASHRAE Standard (2004), acknowledges that people who know they have control accept and may even prefer a wider range of temperatures, making it easier to satisfy comfort preferences, and recognising the effect of acclimatization and adaptation to widely varying conditions.

The comfort temperature can be related to the average monthly outdoor temperature T_{med} by a formula:

$$T_{conf} = a + b \text{ x } T_{med}$$

In the ASHRAE Standard (2004), the values of a and b are 11ºC and 0.2 respectively, with a minimum and maximum limit of 21º and 27ºC for the centre of the comfort zone, and a maximum swing of 8º C.

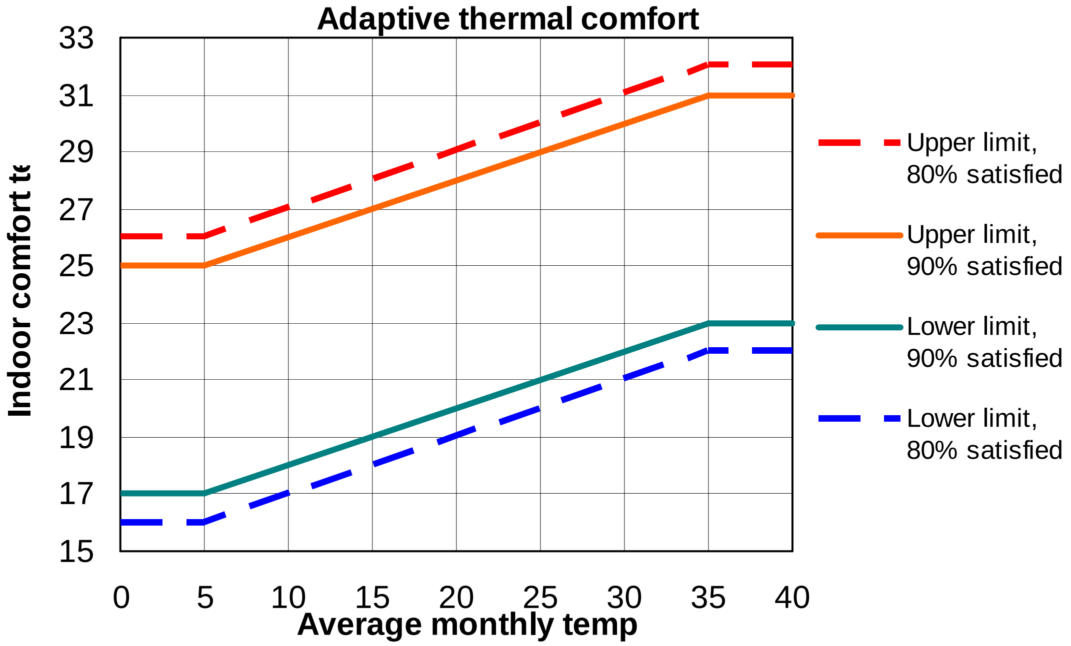


Figure 4.2. Ranges of adaptive comfort according to the average monthly outdoor temperature, ASHRAE Standard 55: 2004.

4.3. APPLICATION OF COMFORT REQUIREMENTS IN ARCHITECTURE

The average climate data for each month can be compared with the required comfort levels in order to detect the difference between the existing and desirable conditions. Initially, this may take the form of a simple comparison: temperatures above, below or within the established comfort zone.

The second step is to detect the design characteristics that promote a favourable modification of the external conditions, for example, the use of solar radiation when temperatures are below the comfort range or the use of air movement when above the zone.

Olgyay (1963) was one of the pioneers to establish this link in graphic form in his wellknown diagramme, showing three zones: the outdoor conditions of climate, the comfort zone and zones that indicate appropriate bioclimatic design strategies when 'climate' is outside the 'comfort zone'. The diagramme (Olgyay, 1960 and Olgyay, 1995), presented in Appendix 2 of this thesis uses the coordinates of dry bulb temperature on the vertical axis and the relative humidity on the horizontal axis to define the bioclimatic zones.

Only a few years later, Givoni (1970) proposed a variant of this concept using a psychrometric diagram, with dry bulb temperature on the horizontal scale and absolute humidity on the vertical scale. A number of zones can be added to these graphs to indicate conditions that require different bioclimatic design resources. Watson (1980), Szokolay (1990) and other authors have proposed modifications based on the same concepts and graphic presentation. Givoni recommends the use of the maximum values as indicators of bioclimatic design strategies.

Fanger (ISO, 1998) established the comfort conditions for different insulation values of clothing and levels of physical activity. The four environmental variables used in this scale are the dry bulb temperature, the relative humidity, the mean radiant temperature and the relative air velocity.

The result is expressed as a comfort level on a 7-point scale, from -3, cold, to +3, hot, called the Predicted Mean Vote, PMV. This is shown to be related to the proportion of the population dissatisfied with the thermal conditions, PPD Proportion of the Population Dissatisfied.

Although Nicol and Humphreys (2001) have expressed strong criticisms of the Fanger scales, this index, incorporated in the international standard ISO-EN-1994, has found wide acceptance.

4.3.1. Requirements for comfort conditions.

Izard and Guyot (1980) present seven environmental conditions required for thermal comfort, based on a proposal by Millar-Chagas and Vogt (1970), incorporating studies by Fanger and Givoni.

- Thermal equilibrium of the body, maintaining a stable and constant deep body temperature. This condition is achieved when the PMV developed by Fanger (1998) is between -1/2 and + 1/2.
- An average skin temperature of 33° C, without high or low extremes, avoiding the sensation of hot or cold in the extremities.
- Maximum transpiration rates of 100 gms / hour, to avoid excessive water loss from the body.
- Absence of sensible transpiration, to avoid a sensation of wet skin or drops of sweat that cause discomfort.
- Conditions of thermal equilibrium and skin temperature maintained with normal metabolic activity, avoiding shivering or other involuntary movements or the need to change the level of physical activity.
- Air humidity sufficiently high to avoid irritation of the eyes, throat or lungs, with a water vapour pressure of at least 10 mm hg.
- Relative humidity below 80 % in order to prevent the possibility of surface condensation and possible mould growth on surfaces with a temperature slightly below air dry bulb temperature.

In addition to the seven basic conditions proposed by Izard and Guyot (1980), three additional requirements for comfort can be added in the framework of this thesis, which stresses variations in temperature:

- Avoid excessive temperature asymmetries of surface temperatures, or large differences between the mean radiant temperature and the air temperature.
- Control the maximum air velocity according to the type of activity to avoid excessive local cooling of the skin or discomfort due to the physical action of the wind, for example moving the hair.
- Avoiding sudden changes, especially in air temperature, Fanger (personal communication) recommends a maximum change rate of 1° C in one hour to avoid a sensation of discomfort. These rates of change are known as ‘ramps’.

It is important to consider that these conditions are not rigid limits and that they may require adjustments according to the activities, expectations, climatic conditions and cultural contexts.

4.3.2. Energy and Bioclimatic Zoning.

The differences between climatic variables and the conditions required for comfort in each month of the year can indicate the bioclimatic design resources appropriate for each location. The Mahoney Tables (Koenigsberger et al, 1970) present a detailled and quantitative methodological sequence to satisfy this objective.

In a further stage of analysis, this method, or similar approaches, can be applied to identify geographic zones where the same bioclimatic design resources can be applied. Equally important is the possibility to detect change these design resources as climate conditions vary. In this way bioclimatic zones can be defined to show the geographical distribution of climate factors that affect building design, and relate these to relevant design guidelines. One example is the Argentine Standard for Bioclimatic zones IRAM 11603 (1970, 1999), which establishes 6 zones and 13 sub zones for the country. The standard ABN (2003) establishes zones for Brazil and the ChN Standards defines the zones for Chile. These bioclimatic zones are closely related to three factors that affect climate and climate variation: latitude, height above sea level and distance from the sea or continentality. This last factor indicates the impact of the moderating thermal capacity of the sea, in comparison with the large landmass in the interior of the continents.

The Mahoney Tables characterise the general climatic impact in relation to comfort using the indicators of aridity and humidity. Evans (1999) suggested adding a third indicator of coldness.

These three indicators can be related to the three extreme corners of the psychrometric chart; cold, hot-humid and hot-dry. This approach is clearly related to the relationship with the comfort zone and the search for passive strategies to modify existing conditions and approach comfort.

Another approach arises from the increasing concern about the use of fossil fuels to achieve comfort with artificial conditioning systems. This preoccupation, starting in the decade of the 70's, relates to the use of energy resources and the environmental impacts, especially those related to climate change. In this case the zoning is related to potential energy demand, indicated by the degree-days for each locality. The Argentine IRAM Standard (IRAM 11.603, 1999) incorporates the use of degree-days to define climatic zone limits. The need to search for a more sustainable habitat has its roots in the environmental, social and economic concern for achieving a built environment compatible with existing and future needs and resources.

In this context, the definition of bioclimatic zones was developed in order to identify appropriate design measures for natural conditioning that promote comfort and well being according to the climatic region. While the strong impacts of globalised influences, with architectural images and technological changes tend to encourage a built environments more dependant on energy, new approaches must be developed to contribute to a more sustainable development.

4.4. CONCLUSIONS

In this chapter, an outline of the study of thermal comfort is presented, with special reference to the application in the field of building design. Two different approaches to thermal comfort are identified; on the one hand the concepts based on detailed climate chamber studies, characterised by Fanger and the PMV method and the other based on subjective responses by building occupants, exemplified by the approach of Humphreys and Nichol. The application of thermal comfort to the study of regional architectural responses is introduced in this chapter in order to provide the background to the specific studies of bioclimatic zoning, presented in the next chapter.

CHAPTER 5. BIOCLIMATIC ZONING

5.1. INTRODUCTION

This chapter presents studies on bioclimatic zoning and examples developed in different regions of Latin America in order to detect the state of advance, the methods adopted and the levels of thermal moderation achieved. A selection of examples is included in this context, based on the following factors:

- A general lack of thermal standards and bioclimatic requirements for buildings, compared with Europe and North America, showing the need to improve this aspect of development of the man-made environment.
- The wide range of climates found in the region, extending from the equatorial region to colder high latitudes, allowing a wide range of bioclimatic requirements to be analysed. The range of altitudes and distance from the sea also widens the climatic variation, as commented in previous sections.

5.1.1. Approach to bioclimatic zoning.

Bioclimatic zoning allows geographical areas with similar climatic conditions to be identified, where architectural design with specific natural conditioning strategies can promote thermal comfort, reduce energy demand for heating and cooling, as well as reducing environmental impacts.

This panorama of the advances and implementation of bioclimatic zoning provides a critical analysis of the current state of development and application.

Changing approaches and zoning criteria are identified in different periods, according to the levels of implementation in the countries of the region. The first studies of zoning were developed to identify the design characteristics for the bioclimatic design of low cost housing, based on the techniques developed by Olgyay (1970). Studies undertaken by the Institute for Housing Research in Argentina (1965) also analysed the regional variations of vernacular housing and conventional construction methods in order to detect different responses to climate.

Various attempts to detect regional building design requirements were related with the vegetation and climatic zones such as Thornthwaite or Köppen Geiger (Kendrew, 1961) based on specific climatic variables or indicators.

However, the growth and distribution of certain types of vegetation depends to a large extent on the rainfall regime, a variation that is less important for bioclimatic building requirements, as this section will show.

Table 5.1. Criteria, indicators and meteorological data for bioclimatic zoning.

Criteria	Indicator	Meteorological data
Criteria for summer		
Comfort in summer.	Design day, typical summer day.	Temperature exceeded in 'n' days per year, with relative humidity values.
Use of thermal inertia	Average thermal swing in summer.	Maximum and minimum temperature in months with hot temperatures.
Minimize a / c	Simulation of annual energy demand for refrigeration.	Hourly temperature, relative humidity and diffuse and global solar radiation data.
Solar protection in summer	Solar altitude and azimuth when protection is required due to high air temperatures.	Average hourly temperatures.
Use of cooling breeze.	Air velocity in months with high temperatures and RH.	Direction and frequency of air movement in months with high temperatures and relative humidity.
Use of thermal insulation.	Solar heat factor: heat transfer according to external colour and insulation.	Solar radiation, wind speed and hourly temperatures on days with clear skies.
Criteria for winter		
Minimize use of conventional energy resources.	Heating degree-days.	Average monthly temperatures (approximate) or hourly temperatures for each day of a typical design year or test reference year, TRY.
Comfort and condensation control.	Indoor surface temperature and dew point.	Minimum design temperature for a cold day in winter,
Use of solar gains in winter	Solar angles that provide favourable radiation.	Latitude for solar geometry and average hourly temperatures for each month.
Use of passive solar systems.	Favourable solar radiation in cold months.	Distribution of solar radiation intensity in each month.
Minimize capacity of heating systems.	Heating demand on critical cold days.	Hourly temperatures on a design day for winter.
Other climatic criteria related to sustainability		
Control of soil erosion.	Rainfall regime.	Design values for maximum rainfall in 1 hour or 24 hours.
Use of rainwater.	Demand according to climate and offer to rainfall.	Average and minimum expected monthly rainfall and monthly temperatures.
Indoors air quality.	Potential for natural conditioning.	Temperature, relative humidity and hourly solar radiation during a typical design year.
Natural lighting.	Natural light levels.	Latitude, days with cloudy sky in winter or detailed illuminance data.
Use of vegetation.	Rainfall regime related to temperature.	Average and minimum monthly rainfall according to average monthly temperatures.

5.1.2. Zoning criteria.

The bioclimatic zoning has also been developed to establish the geographical distribution of thermal qualities of walls and roofs, necessary to achieve adequate levels of thermal comfort, efficiency in the use of energy resources and avoidance of condensation.

These requirements need specific criteria to establish maximum admissible thermal transmittance values, considering two fundamental data (IRAM, 1996):

- Number of annual degree days: indicator of the heating demand according to the duration and severity of periods below the indoor comfort level
- Minimum design temperature: used to establish thickness of insulation required to avoid internal surface condensation.

The development and distribution of the bioclimatic zones depend on the criteria adopted, related to the different climatic variables, as indicated in Table 5.1.

5.1.3. Zoning examples.

The climatic variations over the earths surface are a result of a series of factors: latitude, height above sea level, continentality or distance from the coast and barrier effects caused by mountain ranges, such as the Andes. In some countries, one factor may be dominant while in others different factors may be critical.

In the countries of Central America, for example, with limited extension in the North-South direction, the principal variations are due to height, with secondary effects due to the barrier effect on the central mountain range that produces climatic differences on the eastern and western coasts. In the Andes countries of Colombia, Ecuador and Peru, height above sea level is also the dominant factor in climatic variation. In Uruguay, the most critical climatic variations are those due to distance form the coast, with a significant increase in the daily thermal swing as distances increase. In Argentina, Brazil and Chile, with large extensions in the north-south direction, the variation due to latitude is more important, though differences of continentality, height and barrier effects are also evident. These three countries have the largest variations of latitude found in the world. The resulting bioclimatic zones are analysed in the following section.

5.2. ZONING IN LATIN AMERICA

This section presents the current situation of bioclimatic zoning in Argentina, Brazil, Chile, Uruguay, Ecuador, Mexico and other countries of the region.

5.2.1. Bioclimatic Zoning in Argentina.

The bioenvironmental zoning, centred on the design requirements for social housing was formally established the Argentine Standard IRAM 11,603 (1981). This was adjusted in 1996 and again in 2001, without significant changes in content. The principal modifications relate to the up-dating and expansion of the climate data base, the improvement of design recommendations for hours of sun, and the introduction of a method to determine the climatic zone according to height above sea level. Before this standard was approved, the Secretary of State for Housing used a zoning based on vegetation potential . Important studies of the geographical distribution of vernacular housing construction were undertaken by the Housing Research Institute, University of Buenos Aires (IIV, 1969, 1972b), as well as a study of the conventional construction in different regions, based on Census Returns (IIV, 1972a). A number of regional studies have also been carried out, although the results have not been incorporated in the national standards. The criteria adopted in the zoning defined in the IRAM Standard 11.603 (1996) use three indicators to define the limits of zones and sub-zones:

1. Heating degree days, as an indicator of winter heating demand.
2. Effective temperature on a typical summer day, as an indicator of comfort with a combination of temperature and relative humidity.
3. Average daily thermal swing, as an indicator of the need to incorporate thermal mass to moderate the external temperature range.

The use of heating degree-days in the winter season is a key indicator of the duration and severity of the heating period, which increases from north to south and towards higher locations in the Andes, as well as distance from the sea. In summer, the effective temperature indicates the degree of discomfort due to high temperatures and humidity, which also changes with location, increasing from south to north and towards the sea. As the lines of distribution of both indices coincide in the majority of Argentina, they are sued to establish 6 zones. There is a coincidence between the indices for all of the principal cities of the country and the humid pampas region, which houses the majority of the population. However, in higher zones above 800 m, the relation between the two indices does not remain constant, producing situations where the guidelines are correct for winter conditions but less adequate for summer. However, the Standard includes a graph, which allows the bioclimatic zone to be detected, according to the latitude and height above sea level, based on a study of these variables (Evans, 1981).

Zones 1, 2, 3 and 4 are divided into sub-zones, producing a total of 12 sub-zones. The limit of these sub-zones is the summer thermal swing above and below 12° C, except for zone 4 where the very large thermal swing exceeding 16° C, typical of the most continental area forms an additional zone. Finally, the colder zones 5 and 6 are divided in two, without establishing specific sub-zones: the region to the north of latitude 40° S, although cold has an important potential for using solar energy, while the southern region to the south has limited solar radiation especially in winter due to increased cloud cover and low angle winter sun. Table 5.2. summarises these zones with indicators and design recommendations.

In this way, the Bioclimatic Zoning serves a double objective, to provide general design recommendations for each zone and to indicate the geographical areas for the application of specific requirements of thermal performance of walls and roofs, according to:

- Argentine Standard IRAM 11.603 (1996a) presents design recommendations for each zone: building form, orientation, thermal characteristics of the building envelope and window sizes. The standard includes recommendation for each zone: building form, orientation, thermal characteristics of the building skin and window size. The recommended number of hours that winter sun is received through windows is also defined according to latitude and time of year. However these recommendations are only indicative, not obligatory.
- The Argentine Standard 11,604 (1996b): establishes values for the maximum allowable volumetric heat losses for each climate zones, expressed as Watts/m3. This Standard, obligatory only for social housing with government finance, ensures a level of thermal insulation related to the energy demand, although the values do not achieve an optimum thickness based on economic criteria (IRAM, 1998).
- The Argentine Standard 11.605: establishes maximum allowable thermal transmittance or U values (called K values in Argentina) for walls and roofs. The

values indicated for zones 1 to IV are based on summer requirements, especially for roofs, considering that in zones 5 and 6, summer conditions are not critical.

- The requirements for winter depend on the minimum design temperature, listed in Appendix 1 of the IRAM Standard 11,603, though this value does not relate directly to the bioclimatic zone. The standard indicates three quality levels: A ‘optimum’, B ‘regular’ and C ‘minimum’. Only level C is compulsory in social housing programmes, responding to the conditions required to avoid surface condensation in cold winter days.

Table 5.2. Bioclimatic Zoning in Argentina (IRAM, 1996a and IRAM, 1996b).

Zone	Classification	Recommendations	Roofs	Walls
1a	Very hot, ΔT>14°C, TEC in summer >26,3° C	Light colours, insulation of roofs and walls E & W, facades facing N and S, solar protection, cross ventilation.	0,72 W/m^{2}K $^{(1)}$	1,80 W/m^{2}K $^{(1)}$
1b	Very hot, Δ T < 14°C	Similar to 1a (greater amplitude y need to incorporate thermal inertia).	0,72 W/m^{2}K $^{(1)}$	1,80 W/m^{2}K $^{(1)}$
2a	Warm, ΔT>14° C, summer TEC 24,6-16,3° C.	Light colours, insulation of roofs and walls E & W, facades facing N & S, solar protection, cross ventilation.	0,72 W/m^{2}K $^{(1)}$	1,80 W/m^{2}K $^{(1)}$
2b	Warm, amplitude < 14° C	Similar to 2a, lower amplitude & need to incorporate thermal inertia.	0.72 W/m^{2}K $^{(1)}$	1,80 W/m^{2}K $^{(1)}$
3a	Temperate, ΔT>14°C, summer TEC 22,9-24,6°C	Grouped housing, thermal inertia, solar protection, light colours, less emphasis on cross ventilation.	0,76 W/m^{2}K $^{(1)}$	1,85 W/m^{2}K $^{(1)}$
3b	Temperate, amplitude < 14° C.	Similar to 3a, no need to emphasise thermal inertia.	0,76 W/m^{2}K $^{(1)}$	1,85 W/m^{2}K $^{(1)}$
4a	Cool Temperate, mountain climate	Wind protection,	0,76 W/m^{2}K $^{(1)}$	1,67 W/m^{2}K $^{(1)}$
4b	Cool temperate, maximum radiation	Wind protection, solar protection in summer.	0,76 W/m^{2}K $^{(1)}$	1,67 W/m^{2}K $^{(1)}$
4c	Cool temperate, transitional climate	Wind protection	0,76 W/m^{2}K $^{(1)}$	1,67 W/m^{2}K $^{(1)}$
4d	Cool temperate, maritime climate	Wind protection, solar protection in summer.	0,76 W/m^{2}K $^{(1)}$	1,67 W/m^{2}K $^{(1)}$
5	Cold with sun, < 40° S	Wind protection,	1 W/m^{2}K $^{(2)}$	1,67 W/m^{2}K
5	Cold without sun, > 40° S	Wind protection	1 W/m^{2}K $^{(2)}$	1,67 W/m^{2}K
6	Very cold, < 40° S	Wind protection, similar to zone 5, minimum external surface area, more thermal inertia and solar gains.	1 W/m^{2}K $^{(2)}$	1,45 W/m^{2}K
6	Very cold, >40° S	Similar to 6, with less solar energy	1 W/m^{2}K $^{(2)}$	1,45 W/m^{2}K

(1) *10 % greater transmission allowed with light colours ($\alpha < 0,6$) and 10 % less with dark colours ($\alpha > 80$ %).*

(2) *The thermal transmittance of walls in Zones 5 & 6 can vary according to the minimum design temperature.*

It is important to recognise the important contribution of the IRAM Standards to promote adequate conditions in low-cost housing, as a result of a long process of discussions in the Standards Sub-committee, measurements of conditions in existing houses and research carried out in different centres.

However, the level C of thermal insulation does not insure economy in energy use, and even then, it is only applied to a minority of residential buildings. One of the main shortcomings is the failure to contemplate the moderating effect of thermal mass in walls and roofs, especially in zones with high thermal swings. The A level of the standard takes into account the need for insulation to protect from solar radiation in summer, to such an extent that insulation thickness for roofs is greater in hot zones than in cool zones, while in walls, the requirements are reversed

5.2.2. Bioclimatic Zoning in Chile.

Chile is the second country in Latin America to develop a national standard for bioclimatic zoning, the Standard NCh 1079 (1982), which defines 7 zones applying geographic criteria with divisions according to latitude and the main regions of urban development: The coast, the central valley and the inland regions. The zoning does not contemplate variations due to height above sea level, probable due to the lack of climate data and the limited population in higher areas.

In contrast to other Latin American countries, the Chilean zoning is used to apply levels of compulsory thermal insulation in roofs, according to Ordinance 47, Ministry of Housing and Planning (MINVU, 1992) introducd in 2000 and now extended to walls (Ramirez, 2006)

Table 5.3. Thermal characteristics of roofs (MINVU, 1992, MINVU 2006).

Zone	Characteristics	Maximum thermal transmision, walls	Maximum thermal transmission, roofs.
1	North, maritime	4,00 W / m^2 K	0,84 W / m^2 K
2	North, inland	3,00	0,60
3	Centre, maritime	1,90	0,47
4	Centre, Central Valley	1,70	0,38
5	South, maritime	1,60	0,33
6	South,	1,10	0,25
7	Extreme south, very cold	0,60	0,25

In all cases, the obligatory requirements for thermal insulation are significantly better than the voluntary standard in Argentina. Once again, the standard does not take into account the thermal inertia and mass effect. However, the cold bridges produced by the earthquake resistant concrete structure is specifically excluded from the thermal requirements (MINVU, 2006)

5.2.3. Bioclimatic Zoning in Brazil.

The Brazilian bioclimatic zoning standard (ABNT, 1998) has been approved recently, based on the draft version circulated in 2003 (CBCC, 2003). The Draft standard was based on extensive studies undertaken in the University of San Pablo and the Federal University of Santa Catarina. It proposed 8 zones with the conditions indicated in Table 5.4 , organised in 4 principal group: size of openings for ventilation, need for solar protection, insulation of walls and roofs, and requirements for summer and winter.

The recommendations are based on the use of 11 possible strategies identified from a comparison between the climatic data and the comfort zones indicated in the diagramme proposed by Givoni (1992). The climatic data for a total of 330 locations were used to detect the limits of the zones shown in Table 5.4.

Table 5.4. Synthesis of Bioclimatic Zones and design recommendations for Brazil.

Zone	Openings	Sun	Walls, Table 5	Roofs, Table 5	Additional requirements for winter (W) and summer (S)
1	Average	Gains	Light	Light, insulated	W Solar gains, heavy internal walls, heating
2	Average	Gains	Light	Light, insulated	W Solar gains, thermal inertia, heating. S Ventilation
3	Average	Gains	Light, light colours	Light, insulated	W Solar gains, thermal inertia, heating. S Ventilation
4	Average	Protection	Heavy	Light, insulated	W: Solar gains. S: Evaporation and thermal mass
5	Average	Protection	Light, light colours	Light, insulated	S: Cross ventilation, heavy internal elements
6	Average	Protection	Heavy	Light, insulated	S: Evaporation and thermal mass, selective ventilation.
7	Reduced	Protection	Heavy	Heavy	S: Evaporation and thermal mass, selective ventilation.
8	Large	Protection	Light, light colours	Light, light colours	S: Ventilated double roof, cross ventilation.

The case of Brazil is similar to that described for Argentina and Chile, where the zones were developed principally for establishing the recommendations for social housing

Although the development and application of bioclimatic zoning represents a important step in the improvement of conditions of social housing in Brazil, the need to reduce energy demand of buildings has led to studies of energy efficiency in buildings with high energy demand in order to reserve vital energy resources for industrial production and economic development. For this reason, many current research projects are dedicated to reduce the energy demand of high consumption buildings, such as offices, commercial centres, etc. In the framework of this thesis, it is relevant to note that the average temperatures and the temperature swing in different seasons are the fundamental variables to determine the bioclimatic zones of Brazil.

Table 5.5. Thermal Characteristics for external elements of the building envelope in Brazil (ABNT, 2003).

External Elements	Thermal transmittance	Time lag, hours	Solar heat factor %
Light-weight walls	< 3,00 W/m^{2}K	< 4,3	< 5,0 %
Lightweight walls, light colours	< 3,60 W/m^{2}K	< 4,3	< 4,0 %
Heavy walls	< 2,20 W/m^{2}K	> 6,5	< 3,5 %
Insulated light roofs	< 2,00 W/m^{2}K	< 3,3	< 6,5 %
Insulated light roofs, light colours	< 2,30 W/m^{2}K	< 3,3	< 6,5 %
Heavy roofs	< 2,00 W/m^{2}K	> 6,5	< 6,5 %

5.2.4. Bioclimatic Zoning in Uruguay.

The Standard for bioclimatic zoning in Uruguay is relatively new and applies the concepts established in the Argentina Standard (IRAM, 1996a) achieving a continuity of the Zones 2b and 3b. However, standards for the application of thermal performance of walls and roofs have not yet been developed.

However, studies undertaken previously by the SCAA, Climate Service Applied to Architecture, (Aroztegui and Negrin, 1996) indicate two areas with separate bioclimatic conditions: one with more temperate conditions is found up to 10 km from the coast, with lower temperature swings and higher minimum temperatures, the other is found further inland with more continental conditions, higher swings and lower minimum temperatures.

Table 5.6. Recommendations for thermal transmittance in W/m^{2}K, Uruguay (Aroztegui and Negrin, 1996).

Mass, kg / m^2	0	100	200	300	400	500	600
Walls	0,75	1,2	1,5	1,6	1,65	1,70	1,75
Roofs	0,50	0,80	1,10	1,25	1,35	1,35	1,35

Table 5.6. shows the recommended thermal transmittance values, generally stricter than the equivalent recommended values applied in Argentina and Brazil for similar climate conditions, although higher transmissions are allowed with heavyweight construction.

5.2.5. Bioclimatic Zoning in Mexico.

Mexico experiences wide ranges of temperature, humidity, and thermal swings due to latitude, topography and distance from the sea. A recent study presents proposals for a bioclimatic map of Mexico (Morillón, 2003), which indicates a zone distribution and extension according to the months with heat, cold or comfort.

Another development is the Draft Standard NOM-020-ENER (CONAE, 1999) with thermal characteristics for energy efficiency in housing, while the Mexican Standard NOM-008-ENER (NOM, 2003) establishes thermal performance requirements for the building envelope of non-residential buildings.

These proposals are based on the flexible but strict approach to energy efficient building standards developed in California, to save energy and reduce environmental impacts.

Both standards allow two alternative methods favouring simple demonstration and verification of compliance using predetermined values or greater flexibility to achieve the same level of energy saving through compensation between different building elements of the envelope, considering:

- Average thermal insulation for each element, specified in tables, and limits to the area of glazing
- Thermal balance calculation to show that the building uses less energy than a reference building with fixed thermal insulation values and window sizes. For example, this option allows larger window sizes, when improved thermal insulation reduces the heat losses or gains to compensate for the higher gains or heat losses through glazing.

5.2.6. Bioclimatic Zoning in Ecuador.

The territory of Ecuador covers a limited range of latitudes, but a wide range of altitudes above sea level which can be divided into 5 regions: Coastal lowlands, Intermediate zone, Equatorial Uplands, Paramo and Amazonía.

Coastal lowlands: From the coast up to about 700 metres, there is a warm humid equatorial climate, with low average dally temperature swings and high average values, without significant variations in different seasons of the year. The rainfall is generally high with about 2000 mm annually, though some areas in this region have a rain shadow that reduces the average rainfall to 500 mm.

Intermediate zone: From 700 to 1500 metres, the climate is temperate with comfortable average temperatures and lower absolute humidity.

Equatorial Uplands: Te majority of the population live in the high valleys between 1500 and 2800 metres above sea level, with cool to temperate temperatures, comfortable relative humidity and moderate rainfall, with a drier and wetter season. Temperature swings are higher though there is very little temperate variation in different months.

Paramo: In the highest areas, above 2800 m above sea level, the temperatures are cool to cold with high daily temperature swings, high but variable rainfall and little vegetation without trees. Due to the unfavourable conditions, the population in this zone is very limited.

Amazonía: On the western side of the country in the Amazon basin, at heights below 700 metres, another warm humid equatorial zone is found with high rainfall and dense vegetation. Design requirements are very similar to those required in the western coast.

A study undertaken by the National Equatorial Standards Institute *[Instituto Nacional Ecuatoriano de Normas],* (INEN (1976), initial bioclimatic zones were defined, using the Mahoney Tables (Koenigberger et al, 1973). In a more recent unpublished study by the author, carried out in the framework of academic exchange with the Advanced Research Institute, Faculty of Architecture and Urbanism, Central University of Ecuador, design guidelines were established for each zone.

However, there is still no official delimitation of bioclimatic zones, standards for bioclimatic design or official insulation levels.

5.2.7. Bioclimatic Zoning in Central America and the Caribbean.

The countries of this region have very limited variations in latitude, without significant temperature variations at sea level, though important climatic differences are found due to the effect of altitude and topography, especially areas with rain shadow.

Although it was found that the development of national zoning standards is in the initial stages in this region, countries such as Cuba, Jamaica, Costa Rica and Nicaragua provide the following examples:

Cuba: The variation of latitude is very limited and the distance from the coast to inland areas is limited, though coastal areas have favourable sea breezes. Although the high areas of the Sierra Maestra reach 1000 m above sea level, there are no standards for bioclimatic zones or variations in the requirements for thermal performance of building elements.

Jamaica: The situation is very similar to Cuba, without bioclimatic zoning standards, though there is a standard for rational energy use in buildings, aimed at reducing imported fossil fuels.

Costa Rica: As in the case of Mexico and Ecuador, the variation in altitude, from sea level up to 3500 metres, produces larger climatic variations than the differences in latitude or continentality:

- **Hot Lands:** The low regions on the Pacific and Caribbean coast, up to 800 m are classified as hot lands, *tierra caliente,* with warm and humid conditions all the year round, and heavier rainfall between May and November. The region of Guanacaste in the northern sector of the Pacific coast has a higher daily temperature swing and lower rainfall. Lightweight construction with cross ventilation and good solar protection is essential for naturally conditioned buildings.
- **Temperate lands:** Also called the *tierra templada,* are found between 800 and 1800 metres, with reduced requirements for cross ventilation, though solar protection is desirable at midday and during the afternoons due to the intense solar radiation. At the same time, some protection for the cool or cold nights is needed.
- **Cold lands:** The *tierra fría* with lower temperatures require more effective insulation measures.

Although there are no formal standards, regional variations in construction methods show responses to the climatic differences.

Nicaragua: The conditions in this Central American country are similar to those found in Costa Rica, although the mountains are lower and the distance between both coasts is larger. The Atlantic Coast is more humid with higher rainfall, corresponding to a tropical rain forest climate, classified as **Afi**, according to the Köppen system (Kendrew, 1961), while the western Pacific Coast corresponds to the tropical Savannah **Aw** with large daily temperature swings and less exuberant vegetation. The higher zones are also different with drier conditions to the west Awh and heavier seasonal rains to the east.

5.3. CONCLUSIONS

A regional comparison of bioclimatic and thermal performance standards, design recommendations and application methods shows important differences between countries, even when climatic conditions are similar. For example, Table 5.7 shows that maximum allowed thermal transmittance of roofs at the triple frontier between Argentina, Brazil and Uruguay is very different in each country, although they share the same climate.

Table 5.7. Maximum allowable thermal transmitance of roofs, W/m^{2}K, Triple frountier between Argentina, Brazil and Uruguay

Country	Conditions	'U' Value W/m^{2}K
Argentina	Level C, IRAM 11.605	1,00
Argentina	Level B, IRAM 11.605	0,45
Argentina	Level A, IRAM 11.605	0,18
Brasil	ABNT, 2003	2,00
Uruguay	Lightwieght roofs (Aroztegui and Negrin, 1996)	0,50 (<100 kg/m^2)
Uruguay	Heavywieght roofs (Aroztegui and Negrin, 1996)	1,35 (>400 kg/m^2)

In the south of Chile, the legal requirement for the maximum thermal transmittance of roofs in all buildings is 0,25 W/m2K, while in Argentina, the voluntary standard is a maximum thermal transmittance of 1,00 W/m2K, allowing four times more heat loss in winter.

The comfort criteria are also varied in origin and application, with variants of Givoni's comfort diagram (1992) and other earlier sources, without incorporating more recent advances such as Fanger's indexes (ISO, 1995) or the adaptive comfort approach proposed by Nicol and Humphreys (2001).

The growing world and regional energy crisis requires stricter regional standards for energy efficiency and comfort, not just for housing, but also for buildings with high energy demand such as offices and commercial centres, where the potential for saving is very significant. The Mexican standards, despite difficulties in application, are a valuable and flexible response to this requirement.

Another important aspect is the need to incorporate standards for thermal performance that contemplate the benefits of thermal inertia and time lag of heavy weight construction. However, this innovation is more difficult to standardise and calculate as it involves complex calculations envolving periodic heat flow. Additionally, in many of the hot-dry regions of Latin America as in other regions of the world with these climatic characteristics, the need for thermal inertia to achieve comfort may be in conflict with other requirements such as reduced thermal mass for better earthquake resistance.

The original Argentine Standard IRAM 11.605 (1980) incorporated a variation in the maximum permitted thermal transmittance for walls and roofs, according to the weight per surface area, in order to promote better thermal inertia in climates with larger thermal swings. The IRAM Standard 11.605 (1996b), which is still in force, eliminates this requirement, though the IRAM Standard 11.603 (1996a) still maintains the bioclimatic sub-zones according to the different temperature swings, shown in Table 5.2.

This chapter on bioclimatic zoning shows the importance of temperature swing as a criteria for establishing zone limits, but in most of the ountries analysed, the temperature swing is not used to determine the thermal characteristics of walls or roofs. Therefore, in the next chapter the development and tendancies of the thermal characteristics of building amterials are analysed, as well as avances in the numerical analysis and simulation.

CHAPTER 6. TECHNOLOGICAL ADVANCES AND NEW TOOLS

6.1. INTRODUCTION

The critical analysis of bioclimatic approaches, their historical evolution, the review of thermal comfort definitions and the survey of bioclimatic zoning, presented in the previous chapters are related to methods, processes and approaches of bioclimatic design.

All of these topics are strongly linked to the context of technological advances and the development of new tools, which are reviewed in this chapter. It is also relevant to acknowledge the correlation with the stream of technological tendencies in building processes and construction materials, as well as the impact of advances in computational hardware and software.

In parallel with the approach to bioclimatic architecture, commented in Section 2, and the development of comfort studies, presented in Chapter 5, the development and promotion of new materials have introduced new challenges to the building sector. Some were specifically developed to achieve temperature control to promote thermal comfort or fuel savings, including the innovations discussed in further detail below, such as lightweight insulation, special glazing and surface treatments.

The object of this chapter is to analyse and present technological advances in building constructin, environmental measurements and building simulation that have constributed to the advance of bioclimatic design.

6.2. TECHNOLOGICAL TENDENCES

Recent developments in construction technology and their relation to the development of bioclimatic design are reviewed in this section, including the tendency to reduce the weight of building components, new advances in glazing and thermal insulation.

Alternative mechanisms in temperature control are also evaluated to show the differences between automatic controls and user friendly controls, as well as active and passive methods.

6.2.1 Reduction in weight.

There is a clear current tendency to reduce the thermal inertia of the construction as a result of the pressure to reduce costs and simplify construction methods, replacing the traditional heavyweight masonry with dry and lightweight methods that accelerate the construction process, reduce the quantity of materials and transport requirements.

For example, wall construction in housing has followed a clear sequence of weight reduction. Historically, walls were built of adobes with 30-40 cm thickness, while traditional rendered 30 cm solid brick construction common in 1900 was replaced by 26-27 cm solid bricks after 1950. In conventional construction, these have been replaced by 20 cm hollow clay blocks or even hollow concrete blocks of 20 cm in the 1970s. In Buenos Aires, 15 cm hollow clay blocks are now used in external walls.

Many new houses are now being built with lightweight construction methods, using cold-formed sheet metal profiles or timber frames with plasterboard interior finish and a water-resistant cementitious panel or timber siding on the outside. Other layers are required to avoid condensation and improve thermal properties, such as vapour barriers, breathing membranes and lightweight insulation.

Table 6.1. shows the thermal characteristics of these alternatives to demonstrate the improvement of thermal resistance, paralleled by a decrease in the thermal capacity, the admittance and the time lag.

Internal walls have also suffered a significant reduction in weight and capacity to reduce indoor temperature swings. The traditional construction of light locally fired bricks of 30 cm with a rendered finish of 2 cm, achieve an admittance of 4,5 W/m^{2}K.

Table 2.8 shows the reduction of admittance with the tendency to new light-weight construction methods currently available: 26 or 27 cm brick walls, hollow clay blocks, hollow concrete blocks and light weight framed construction with external siding and plasterboard internal finishes.

Table 6.1. Thermal characteristics of different construction alternatives

Construction	**Thermal transmittance W/m^{2}K**	**Thermal Capacity**	**Admittance W/m^{2}K**	**Time lag Hours**
Solid clay bricks 30 cm with external and internal render (3 y 2,5 cm) Total 35 cm	1,67	337	4,6	10,6
Solid clay bricks 26 cm with external and internal render (2,5 + 2 cm) Total 30,5 cm	1,86	330	2,8	3,2
Solid clay 'half-brick' wall with large bricks 17 cm with internal and external render: Total 21,5 cm	2,35	200	2,5	1,2
Hollow clay block 20 with 4 rows of cavities and internal and external render: Total 21 cm.	1,55	210	1,7	0,9
Hollow concrete block with internal and external rendering.	1,72	220	2,1	1,7
Lightweight construction with 13cm external brick finish, lightweight insulation and plasterboard panel	0,58	183	0,6	0,8

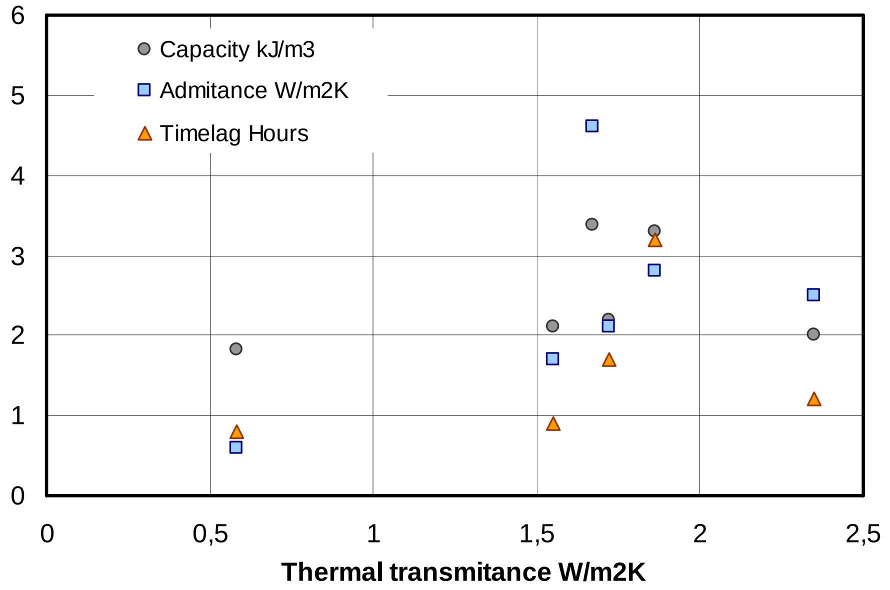


Figure 6.1. Thermal transmittance of alternative walls constructions, from Table 6.1. showing that the improvement in thermal performance with lower transmittance generally leads to a combination of lower time lag, reduced admittance and lower heat capacity.

6.2.2. Thermal insulation.

Lightweight thermal insulation materials have low densities and very low conductivity, due to the air trapped between fibres or in bubbles formed in the material. Only five decades ago, insulating materials were limited to cork, vermiculite and asbestos; today, a wide variety of cheap materials is widely distributed in a range of different formats: rigid sheets, blankets, flexible rolls and injected foam.

Materials such as fibreglass, mineral wool, expanded or extruded polystyrene, polyurethane foams and other insulation capacities with low densities, typically below 50 kg/m3, were only introduced in buildings after 1950. From the 1960’s, the relatively low costs ensured an increasing incorporation of these insulating materials, with the introduction of complementary layers such as vapour barriers and breather membranes, to control the flow of moisture vapour and avoid interstitial condensation. In the last decade, cellulose fibres and natural wood have been introduced as natural materials, as an ecological alternative to the synthetic materials.

The new insulating materials have allowed the resolution of construction elements with different layers to resolve the functional requirements: waterproofing, mechanical resistance, structural support, thermal insulation, condensation control and internal finishes.

As a result, this multi-layer approach has allowed innovations in dry mounting, lighter, lower cost and, as a whole, the development of more rapid construction methods. The thermal consequencies of these tendencies are analysed in greater detail in the following sections.

6.2.3. Glass.

Special glazing products, developed and introduced over the last decades, include security glass, both laminated and tempered, with greater resistance to breakage and reduced danger of accidents.

However, in the context of bioclimatic architecture and energy efficiency in buildings, the most important advances in the development of glass for thermal control and solar radiation filters are:

- **Sealed double-glazing,** with new sealants and adhesives, allow the reduction of heat losses to 45 % when compared to a single sheet of glass.
- **Low emission surface treatments** to reduce emission of low temperature radiation can be applied to the inner surfaces of double-glazing to reduce the heat transmission as well as the surface of insulating films facing air cavities.
- **Low conduction gasses** such as argon, an inert gas with lower thermal capacity than air.
- **Adsorbent glazing,** with colour in the glass to reduce the transmission of solar radiation up to 70 %, especially when used in combination with double glazing. When solar radiation is absorbed, the temperature of the glass is raised significantly and space of thermal expansion must be incorporated in the framing. Due to this heating effect, partial shading of the glass should be avoided, as fractures can occur due to differential stresses in the glass.
- **Reflective glazing,** produced with reflective metal particles incorporated in the surface of the glass during manufacture to reflect light and solar radiation.
- **Selective glazing,** with physical properties, especially developed to achieve low transmission of solar radiation in the infrared sector of the spectrum and increased transmission in the visible sector.

To improve existing glazing, absorbent and reflective films have been developed to modify the performance of windows without changing the glass. The polyvinyl butyral (PVB) interlayer, used in laminated glazing may also include reflective and absorbent characteristics.

More recently, further innovations in thermal control of buildings have been developed, although these have not yet achieved general commercial application, such as the following advances with the generic denomination of ‘smart glazing’:

- **Photo-chromic glazing,** with a chemical composition that achieves changing light transmission according to the incident light levels.
- **Thermo-chromic glazing,** with a chemical composition that reduces the transmission of solar radiation according to the increase in temperature.
- **Electro-chromic glazing,** where the variation in light or radiation transmission is achieved by applying a small electric current.
- **Holographic coatings,** made with special photographic film, allow the selective angular deflection of light rays.

6.2.4. Bioclimatic control mechanisms.

It is argued in the framework of this research that, while the building elements have a limited adaptability to respond to external variation and indoor temperature requirements due to their solidity and durability, the hourly, daily and seasonal variations need more flexible control and adjustment possibilities. In this context, three types of control mechanisms can be identified:

- **Instantaneous:** Controls that permit an instantaneous adjustment of the indoor conditions, such as opening a window to catch a favourable cooling breeze or close a shutter to avoid undesirable solar radiation. In artificial conditioning systems, the instantaneous controls predominate, adjusting the system constantly to keep the indoor temperature within narrow margins.
- **Cyclical:** Controls that have a delayed effect, such as night cooling of interiors, also known as selective ventilation, that achieves cooler indoor conditions for the following day. Other examples are the thermal inertia of building elements that delays heat transfer and reduces indoor temperature swings and absorption of solar radiation in passive solar systems that store and release heat to the indoors with a delay, maintaining comfort at night many hours after the sun has set.
- **Seasonal:** Controls that allow variations in thermal performance over different seasons of the year, such as fixed overhangs facing toward the equator which allow the ingress of low angle winter sun while achieving total exclusion of high angle summer sun. Another example is the use of designs that provide protection from cold winter winds from polar regions while taking advantage of warmer winds from the equator. Deciduous vegetation also provides seasonal variation in solar protection, with summer shade and winter sun, both in outdoor spaces and on windows and other elements of the building envelope.

In the framework of this thesis, the key role of architectural skill is advocated, as several of these control and adjustment mechanisms depend totally on the design while others require the intervention of the users, in contraposition to mechanical devises.

This adjustment can be achieved by change of location, as well as active and passive controls:

- **Location:** Within a space the user can move to find more comfortable conditions (Baker, 2000). In a dwelling, the occupants can move to different indoor spaces or to outdoor and intermediate spaces in galleries, balconies and colonnades, to find the most comfortable alternatives. Baker (2000) has even developed a programme to predict the optimum movement within a space as the conditions change throughout the day. In each space, locations can be chosen to take advantage of warming sun, cooling breezes or avoidance of annoying draughts. A key to the design of successful outdoor spaces is the provision of variety and alternatives (Evans and de Schiller, 1991; de Schiller, 2004). However, in buildings such as schools and offices, the possibilities of movement to optimise comfort are severely restricted.
- **Passive controls:** Passive controls are mobile or adjustable elements that can be controlled by the occupants to improve or modify comfort conditions without the use of energy for artificial conditioning. Examples include operable windows, shutters, roller blinds, curtains, awnings and adjustable sunshades. It is important to note that these passive controls will be activated by the occupants as the indoor conditions change, so a sensible variation in indoor temperature will lead to reactions such as the closing of windows or opening of blinds.
- **Active controls:** When indoor conditions exceed the comfort limits and the mechanisms of movement and passive control are not effective, active controls using artificial conditioning are employed. These can be divided into two sub-groups: simple and relatively low energy artefacts such as ventilators, roof fans and extractors under the direct control of the users, or high energy demand installation

for heating, cooling and humidity control. These can also be activated by occupants as a result of the changing comfort conditions indoors.

- **Outside user control:** However, there is an increasing tendency to avoid active or passive controls under user control with the introduction of automatic adjustments of artificial conditioning systems. Facade design often excludes elements of passive control, lacking operable windows, shutters, curtains and sunshades, movable or fixed. These buildings do not allow user intervention for microclimatic control or selection of alternative spaces, while the automatic controls frequently exclude user intervention in the control of the heating and cooling systems, that are vital in these totally dependent buildings, as comfort can only be provided by artificial means. Under these conditions the occupants may be unaware of the changing conditions as the object of the controls is to maintain stable and unchanging optimum comfort conditions. However, these controls may not create conditions that satisfy all users, and may create less comfortable conditions than user operated systems, as well as increasing energy demand.

6.2.5. Environmental sensors.

To adjust or adapt environmental conditions, two types of sensors are required to detect periods when conditions are outside the comfort zone, and initiate the actions to modify or improve conditions through control mechanisms. These are the occupants, directly involved in the perception of comfort, and thermostats, if objective measurements are required:

- **Occupants:** The occupants of buildings are the best sensors of environmental conditions, allowing a direct relationship between thermal sensation and use of passive controls. However, the occupants are not perfect sensors as they may not have high comfort expectations, or when concentrating on work, they may not be aware of changing conditions until they are well beyond the desirable comfort limits. Also, the occupant’s control of the passive mechanisms, such as opening windows, may not be optimum from the energy efficiency point of view.
- **Thermostats:** Automatic sensors that control conditions without the intervention of the users have advantages and disadvantages of mechanical devices, following the signals that control the active mechanisms, in the absence of occupants, or without taking into account the inevitable differences between the thresholds of comfort established by the control system and the requirements of the users.

6.2.6. Impact of Information Technology.

The advances in the development of new and improved construction materials in the last decades have been very significant, allowing a relevant improvement in thermal performance of buildings without excessive cost or increases of problems of integrating innovative materials in architectural projects.

While in the past, the only method of improving thermal performance and reducing heat losses was to increase the thickness of walls and roofs, today it is possible to reduce heat losses and weight of building components simultaneously.

However, the most important innovation in recent decades is the introduction of information technology in all aspects of building design and construction. The tools such as drawing (AutoCAD), cost analysis (Excel) and construction programming

(Project) together with report writing (Word), all assist the project development process. The Internet opens new possibilities of obtaining, sharing and distributing information, while e-mail allows new and more agile forms of communication.

The potentialities of numerical simulation also allow evaluation and improvement of projects in the initial design stage. In the framework of this thesis, the possibilities of simulating thermal and daylight performance in different climatic situations, for example, provide new ways of predicting environmental conditions.

This is particularly relevant to this research, especially the influence of thermal mass on heat storage, which could allow to increase or decrease the average indoor temperature and the moderation of indoor temperature swings. The advances of thermal simulation are therefore, reviewed in the next section of this chapter.

6.3. THERMAL SIMULATION OF BUILDINGS

In cold climates, where many of the principles of building physics were first developed and applied, the thermal performance of buildings were analysed for steady state conditions.

This assumption of a stable internal and external temperatures and constant heat flows is reasonable in cold climates where the indoor temperatures are maintained with heating between 16 to 20ºC, and the outdoor winter conditions can vary between –2º to +4ºC.

The temperature fluctuations of around 4 to 6 degrees during a typical day are much less than the temperature difference between indoor and outdoor temperatures that are on average 16 degrees in this example.

However, in temperate climates, the outdoor winter temperature swings are higher and the temperature difference between indoors and outdoors are lower, reducing the accuracy and applicability of the steady state concept.

As temperature swings increase and indoor-outdoor temperature differences decrease, the thermal capacity and time-lag of external walls and roofs have a growing impact on the indoor temperature variations.

The addition of variable solar heat gains and internal gains add further complications to the evaluation of indoor temperatures and thermal comfort. The complex nature of periodic heat flow requires the development of numerical thermal simulation models to establish the thermal performance of buildings.

In a recent study of simulation programs (Evans, 2006) three different categories were identified, Basic, Detailed and Complex or Integrated, Table 6.2.

In the context of this thesis, a series of electronic spread-sheets have been specifically developed to evaluate the relationship between external climate and indoor comfort and to estimate indoor temperatures in buildings with periodic heat flow.

Table 6.2. Different types of simulation programs.

Type	Objective	Method	Examples
Basic or 'tool-box (Clarke, 2001)	Evaluate design alternatives in initial stages of proyect development	Admitance method, pseudo-dynamic	Archipak (Szokolay, 1998), Arquitrop (Braszil), LT-Europe (Baker et al, 1993)
Detailled	Study thermal performance of buildings of low or medium complexity: Typical design days	Finite differences, Time constant, Fourier series	Quick (Richards, 1992) Simedif (Caermeiro and Saravia, 1984)
Complex and integrated	Evaluate the annual energy demand and plant sizing in complex buildings.	Integration of different methods	Energy 10 (Balcomb, 1998), Energy+ (Crawley et al, 2001), ESP-r (Clarke, 2001).

The spread-sheets has been used in various chapters of this thesis to analyse the data, compare alternatives and visualise results.

The spread-sheets used in the development of the thesis are the following:

- **e-clim:** a spread-sheet to evaluate the relationship between climate data and comfort conditions developed by Evans (2006).
- **e-day:** a spread-sheet to calculate the hourly outdoor temperature according to the season of the year and the maximum and minimum temperature, using the algorithm developed by Roriz (2006).
- **e-temp:** a spead-sheet to calculate the indoor temperature using the admitance method (Evans, 2006).

The use of thermal simulation of buildings allows a more controlled evaluation of the advantages of bioclimatic design resources and a better dimensioning of the building elements.

6.4. CONCLUSIONS

This chapter has presented a series of technological advances that have enabled improved building performance and better bioclimatic design. These advances include not only the materials such as glass and thermal insulation, but also the software and application of information technology to evaluate design alternatives.

The following chapter presents the development and definition of a new graphic method for analysing and visualising the relationship between climate, thermal comfort and bioclimatic design resources, the Comfort Triangles that form the core of this thesis.

PART 3
THECOMFORT TRIANGLES

CHAPTER 7.	**A NEW APPROACH TO COMFORT ANALYSIS FOR BIOCLIMATIC DESIGN: THE COMFORT TRIANGLES**
CHAPTER 8.	**CLIMATE ANALYSIS USING THE COMFORT TRIANGLES**
CHAPTER 9.	**PASSIVE STRATEGIES TO ACHIEVE COMFORT**

Part 3 of this thesis introduces the concept, development and application of the Comfort Triangles, the new graphic tool to relate comfort, climate and habitat, which constitutes the core feature and major contribution of the current research. The aim of Part 3 is to integrate the contents of Chapters 7, 8 and 9 presented as follows:

Chapter 7 presents the development and characteristics of the graphic tool, used to identify the comfort zone, expressed in terms of the two variables introduced in Part 2 of the thesis: the average daily temperature and the daily temperature swing.

Chapter 8 shows how the comfort zone can be related to the same two variables that define the existing external climate conditions during typical days describing monthly mean values or series of days during a month or year.

Chapter 9 identifies and defines the different passive bioclimatic design strategies that can be effectively used for a favourable modification of the outdoor conditions to achieve or approach the comfort zone using building design and operation rather than the use of artificial conditioning such as heating, cooling and forced ventilation.

The contents of the three chapters are strongly linked and constitute the proposal and contribution of the thesis, tested in Part 4.

Part 1: Introduction

1. Introduction
2. Background...
3. History …

Part 2: State of the art

4. Thermal Comfort
5 Bioclimatic zones
6. Technology …

Part 3: Comfort triangles

7. Thermal Comfort
8. Analysis of Climate
9. Design Resources

Part 4. Case studies

10. Urban scale
11. Architectural scale
12. Building scale

Part 5: Conclusions

13. Results & case study evidence
14. Conclusions & ideas for further study

CHAPTER 7. A NEW APPROACH TO COMFORT ANALYSIS FOR BIOCLIMATIC DESIGN: THE COMFORT TRIANGLES

7.1. INTRODUCTION

This chapter presents the origins and evolution of a new method the **Comfort Triangles** and its initial development over a 20-year period. This approach to comfort analysis incorporates the variable of the daily thermal swing in bioclimatic design, and emphasises the application of this variable in the analysis of comfort, climate and natural conditioning, a mayor innovation that forms the core of this thesis.

In contrast to other previous bioclimatic evaluation methods, this approach, analysed in Chapter 4 of Part 2, uses the variable thermal swing as a key indicator to define comfort conditions and detect appropriate bioclimatic design strategies.

The daily temperature variation was already identified in the previous chapters as an indicator of the potential need to modify thermal conditions in indoor spaces, by dampening or controlling temperature swing.

As Chapter 4 has already shown, the limit of the daily temperature swing is used in various bioclimatic zoning studies as specific criteria for defining zone or sub-zone limits.

In this context, bioclimatic strategies that make use of the daily thermal swing of outdoor and indoor temperature include the following mechanisms:

- Thermal inertia and time delay in heat transmission from outdoor to indoor air.
- Dampening or reduction of the indoor temperature swing.
- Reduction of the heat flow with periodic variations.
- Selective ventilation using different airflows according to outdoor temperature variations.
- Storage of heat or ‘coldness’ in the materials exposed to the indoor air, especially using solar heat gains.

All these related mechanisms are applied to modify and improve the indoor conditions in relation to the external air temperature variations, using the thermal mass of the building.

As a further example with a different application, passive solar heating systems, such as the Trombe wall, or the Michell-Trombe wall, the accumulator wall without ventilation (Mazria, 1978), the Barra-Constantini System and the attached sunspace also create a large temperature swing on the absorbing surface which is stored, transmitted and moderated to increase the indoor temperature.

The use of the thermal swing as a bioclimatic resource requires a design tool to comprehend the phenomenon and select appropriate strategies during project development according to the outdoor temperature variations and the acceptable range of indoor comfort conditions.

Therefore, in this chapter, the stages of the development of such a new tool is presented with the following objectives:

- Present the concept and implementation of the Comfort Triangle Method, developed by the author and published for the first time in Evans and de Schiller (1988).
- Explain the two principal origins of the comfort triangles, using concepts originally developed for evaluating passive solar systems and the Mahoney Tables (Koenigsberger, Mahoney and Evans, 1970).
- Evaluate the validity of the variable ‘temperature swing’ as an indicator of the climatic characteristics of different locations, the requirements for thermal comfort, the thermal performance of buildings and the effectiveness of different bioclimatic design strategies.
- Review the initial development of the Comfort Triangles, based on a process of deductive logic (Evans and de Schiller, 1988).
- Indicate the process of improvement of the Comfort Triangles, applying thermal comfort models (Evans, 2001).
- Clarify the widening scope of the Comfort Triangles, made possible by the use of thermal simulation programmes (Evans, 2006).
- Provide the concepts, background and theoretical foundation for the studies presented in the following chapters.

The validity and utility of this development and the results obtained in this chapter are tested and verified in the Part 4 of this thesis with a series of case studies and experiments at different design scales.

7.2. THE PRINCIPLE OF THE COMFORT TRIANGLES

The conventional bioclimatic methods, presented in Chapter 2, analyse the thermal conditions in a specific moment of time, by the use of two variables: air or dry bulb temperature and humidity, expressed as relative (Olgyay, 1963) or absolute (Givoni, 1969); these diagrams are shown in Apprendix 2.

The innovative concept, introduced in the Comfort Triangles, is also based on two variables, but these are used to define and characterise the temperature variations during a daily cycle. Thus, the Comfort Triangles emphasise the periodic thermal behaviour of a space during a 24 hours interval or the average values of a series of days, rather than the conditions of temperature and humidity at a specific moment of time.

The two chosen variables allow the analysis and visualization of the average outdoor conditions, typically obtained from the published meteorological data, according to the location and season of the year. These external variations can be compared with the range of indoor conditions required to provide thermal comfort.

According to the differences and coincidences between the existing and required conditions, the Comfort Triangles can be applied to identify the outdoor conditions favourable for comfort and well being, as well as the modifications of the outdoor conditions needed when climatic variables are found to be outside comfort limits.

7.2.1. Stages of bioclimatic design

The relationship between the given outdoor climatic variables and the required indoor conditions are the **indicators** that identify requirements to achieve comfort; these can include specific conditions such as daily temperature swings above 10° C or average monthly temperatures below the sedentary comfort limit of 18° C. Combination of conditions can also be defined as indicators, such as ‘average temperatures over 28° C with daily temperature swings below 10° C’.

The **indicators** are used to detect the appropriate **design objectives** that identify the resources to be used to reduce the difference between climate and comfort, and the selection of bioclimatic design strategies.

The objectives can also lead to **strategies** that may be used to preserve and maintain comfortable conditions when the outdoor variations are within, or close to the optimum for comfort.

The **strategies** that are identified with the indicators are, in turn, used to select the appropriate **design recommendations** or **design guidelines**, with the aim of achieving a favourable modification of the external conditions and achieve the required comfort conditions according to the activities and expectations of the thermal quality required.

The stages of this process are shown in Table 7.1. The terms ‘indicators’, ‘strategies’ and ‘design guidelines’ were developed and applied by Koenigsberger, Mahoney and Evans (1970).

Table 7.1. Stages of the bioclimatic design process.

Term	**Explanation**	**Example**
Climate data	The given outdoor conditions, according to location and season.	External air temperature between 8° and 14° C.
Comfort requirements	The required conditions to achieve thermal equilibrium according to activities, clothing and expectations.	Comfort conditions for sedentary work between 18° and 24° C.
Indicators	The differences between the existing and required conditions	Cold: temperatures below the comfort zone, (hot / comfort).
Objectives	Design objectives to reduce the differences between climate and comfort	Catch solar radiation, reduce heat losses.
Strategies	General design strategies, important to identify and incorporate in initial design decisions.	Orientation of windows towards the equator: space between buildings adequate for solar gains according to solar altitude.
Recommendations	Specific design guidance that takes into account building type, location and context.	South orientation (or N in southern hemisphere), +/- 30°, distance between buildings 3 time the height for latitude 40°N or S to catch 6 hours of solar radiation.

7.2.2. Variables.

As with the previous bioclimatic design diagrams explained in Chapter 4 and presented in Appendix 2, the two variables are indicated on the horizontal and vertical axis of a graph. However, in this case, the variables on the horizontal and vertical axis are, respectively:

- Average daily temperature, $\mathbf{T_m}$
- Average daily temperature swing, $\mathbf{A_t}$

In order to calculate the average temperature $\mathbf{T_m}$ and the temperature swing or amplitude $\mathbf{A_t}$, the following simplification is applied to obtain the average and difference using the average daily maximum and minimum temperature $\mathbf{T_{max}}$ and $\mathbf{T_{min}}$:

$$\mathbf{T_m} = (T_{max} + T_{min}) / 2 \qquad \text{or } \mathbf{T_m} = \Sigma\, T_{1\text{-}24} / 24 \text{ (average of hourly values)}$$
$$\mathbf{A_t} = T_{max} - T_{min}$$

The difference between the arithmetical mean of the hourly temperatures and the mean of the maximum and minimum daily temperatures is usually less than 5 % of the daily swing, and always less than 8 %, using the detailed analysis of daily temperature variations presented by Roriz (2006), for a wide range of localities, seasons and latitudes. The following chapter studies the average temperature and temperature swing in outdoor conditions, as well as the hourly temperatures.

This allows the validity and precision of the simplification to be tested in detail, comparing the average of hourly temperatures with the average of the maximum and minimum temperature for Buenos Aires and other Met stations. For temperature swings of up to 14 degrees, the difference is normally less than 0,7 degrees, a difference that is not significant for comfort, and always less than 1,2 degrees. The use of this simplification is therefore acceptable for the evaluation of comfort. As it is shown in Chapter 8, the error will not produce significant differences.

7.2.3. Background in the use of variables.

The average temperature and the thermal swing are both indicators of typical conditions and average temperatures which have often been used to characterise climate. Various authors have suggested the 20° - 21° isotherm as the limit of the thermal tropics, as distinct from the geographic or astronomic tropics between latitude 23.45° North and South (Stamp, 1964; Konya, 1985; Saini, 1987). Authors using the metric system normally propose 20° C, while those who use the Fahrenheit scale recommend 70° F, very close to 21° C.

Koenigsberger et al (1973, p. 3) define tropical climates as ‘those where heat is the dominant problem, where, for the greater part of the year buildings serve to keep the occupants cool rather than warm, where the annual mean temperature is not less than 20° C’. However, as explained in Chapter 2, within the thermal tropics there are very different climates, which can be identified by analysing the second variable, the thermal swing, as shown in the previous chapter. In warm and humid equatorial climates, characterised by high humidity, overcast skies and heavy rainfall, the thermal swing is low, typically less than 10° C in most months of the year.

On the other hand, the hot and dry desert climates with clear skies, low humidity and low rainfall, the thermal swing is high with values over 14° C during the hot season, though this may drop in the cooler winter months. The composite and monsoon climates, with hot dry and warm humid seasons, may have some months with high swings and others with low ones, according to the length of each season.

For example, the use of the thermal swing or amplitude in the evaluation of climate data for defining design guidelines was established to draw up bioclimatic zones for Nigeria, a large country in West Africa with a warm humid equatorial climate on the coast and a hot dry desert climate in the north, as well as a varying length of the dry season from less than one month on the coast to over 10 months in the north (Koenigsberger, 1970). This was an innovative contribution and one of the first detailled studies to emphasise the importance of thermal swing.

However, the preoccupation with thermal swing was already apparent in the 1960's in northern Europe, where school and office buildings with large glazed openings and lightweight construction began to suffer from summer overheating. This concern also included buildings of the residential sector, when passive solar systems were introduced in the 1970's, after the 1971 oil crisis, especially in the United States where most conventional house construction was and still is lightweight with little thermal mass.

7.3. THERMAL SWINGS IN DIFFERENT CONTEXTS

In the following sub-sections, these two developments are presented in greater detail, outlining the origins and objectives that have contributed to the development of the Comfort Triangle concept.

7.3.1. Thermal swings in bioclimatic zones.

In a study of bioclimatic design guidelines for schools in Nigeria (Mahoney, 1968), the thermal swing of less than 10° was considered the limit to identify the number of months with warm humid conditions, taking into account that higher swings indicate predominantly hot dry conditions. This study formed part of a project financed by the World Bank and directed by the Consultant RMJM (Robert Matthew, Johnson & Marshall) to develop standards for secondary school design. Nigeria, one of the largest countries in Africa, experiences a gradual climate transition from the warm humid conditions on the coast, only 3° north of the equator on the Golf of Guinea, to the dry desert regions in the north which form the southern limit of the Sahara Desert, latitude 26° N.

In the hot and dry desert zones with high temperatures and large thermal swings, both daily and annually, the appropriate bioclimatic strategies include controlled window sizes to reduce solar gains and glare, limited ventilation to avoid dust and high midday air temperatures, thick heavyweight walls and roofs with large thermal inertia to reduce the impact of high swings of outdoor temperature on the indoor conditions. Controlled courtyards provide protection from sun and dusty winds, allowing irrigation of limited planting to favour humidification.

In the warm humid coastal zones, the bioclimatic strategies are totally different: large windows provide welcome air movement, lightweight reflective roofs reduce solar gains and avoid storing the heat of the day which can produce discomfort at night, large overhangs and verandas provide open spaces with breeze, and protection from rain and sun. Ample open spaces promote breeze, with vegetation and shade trees to provide a refreshing outlook.

However, the difficulty to develop regional bioclimatic standards is to determine where and how to achieve a transition between one extreme and the other. The innovative solution proposed by Mahoney at that time was to develop indicators of humid and arid conditions, which allow the number of months with dry or humid conditions to be determined rapidly during the design process.

7.3.2. The Mahoney Tables.

The concept developed by Mahoney (1968) in Nigeria provided the basis of the Mahoney Tables, later developed by Koenigsberger, Mahoney and Evans (1970), published by the United Nations in English, French and Spanish, with large sections included in the widely distributed publication by Koenigsberger et al (1978).

The Mahoney Tables (Evans, 1999; Evans, 2001) proposed a climate analysis sequence that starts with the basic and widely available monthly climatic data of temperature, humidity and rainfall, such as that found in HMSO (1958) and Pearce and Smith (1990), or data published by national meteorological services, for example SMN (1995). Today, the data for most major cities can be downloaded directly from the Internet (from sites such as http://www.wunderground.com/global/AG.html, 2006).

With the data of the annual mean temperature range (AMR) and the annual mean temperature (AMT), a comfort zone can be established, using the concept of adaptive comfort, which was later developed by Nicol and Humphreys (1998). However, in the case of the Mahoney Tables, the limits of the comfort zone were established by Mahoney using answers from surveys carried out in different regions of Nigeria to indicate the months of the year that were considered to be most comfortable, both by day and night. Table 7.2. shows the resulting comfort limits.

Another relevant innovation was the introduction of two different comfort zones, one for daytime conditions and another for night time, as Table 6.2. shows. This differs from the concept adopted by Olgyay and Givoni, with differences between summer and winter. The variation between the two zones responds to the differences in the level of physical activity, the change in the insulation value of clothing as well as different expectations in different hours of the day. This consideration may have been the result of the provision of dormitories in many schools of the project.

Table 7.2. Comfort limits used in the Mahoney Tables.

Humidity Group	AMT over 20° C		AMT 15 – 20° C		AMT below 15° C	
	Day	Night	Day	Night	Day	Night
1	26-34	17-25	23-32	14-23	21-30	12-21
2	25-31	17-2	22-30	14-22	20-27	12-20
3	23-29	17-23	21-28	14-21	19-26	12-19
4	22-27	17-21	20-25	14-20	18-24	12-18

Source: Koenigsberger et al, 1974.

The comparison between the comfort zone and the daily temperatures, ranging from the average monthly maximum to the average monthly minimum, indicates the comfort conditions or thermal stress, classified simply as ‘Hot’, ‘Cold’ or ‘Comfortable’, with a separate evaluation for Day and Night. The thermal swing is determined as the difference between the average maximum and minimum daily temperature, while the humidity conditions are obtained by comparing the average monthly humidity with simplified humidity ranges for each month.

Table 7.3. Humidity groups for the Mahoney Tables.

Humidity groups	**Ranges of average values**	**Notes**
Humidity group 1	Between 0 and 30%	Very low, rarely found in practice
Humidity group 2	Between 30 and 50%	Low, desert conditions
Humidity group 3	50 and 70%	Medium, intermediate level
Humidity group 4	70 and 100%.	High, equatorial zones

Source: Koenigsberger et al (1974).

According to the conditions for comfort, the temperature swing and the humidity band, together with the monthly rainfall as a further guide to humidity, indicators of aridity and humidity are established, with the criteria shown in Table 7.4. This table shows the importance of the average temperature swing in the process to characterise the climate and define indicators. The final stage in the process is the selection of design recommendations according to the number of months with different indicators. For practical reasons relating to the decision making process in design, the recommendations were divided into two groups, the ***sketch design stage*** for initial decisions on siting, building form and outdoor spaces and the ***detailed design stage***, with indications for building components.

Table 7.4. Indicators defined in the Mahoney Tables.

Indicator	**Conditions**	**Relation with design**
A1: Arid 1	Humidity group = 1, 2, or 3 and **monthly swing > 10° C**	Thermal capacity necessary.
A2: Arid 2	Night thermal stress = hot and Humidity group = 1 or 2 or Day thermal stress = Hot and Night thermal stress = Comfort and Humidity group = 1 or 2	Outdoor sleeping desirable.
A3: Arid 3	Day thermal stress = Cold	Protection from cold.
H1: Humid 1	Day thermal stress = Hot and Humidity Group = 4 or Day thermal stress = hot and Humidity group = 2 or 3 and **Monthly swing < 10° C**	Air movement essential.
H2: Humid 2	Day thermal Stress = comfort and Humidity group = 4	Air movement desirable.
H3: Humid 3	Monthly rainfall > 200 mm.	Need for rain protection in circulation areas (a requirement for schools).

Source: Koenigsberger et al, 1974.

Note: Conditions including thermal swing are emphasised in bold, though it should be noted that humidity groups 1 and 2 also correspond to climates with high temperature swings.

The use of the monthly mean temperature range in the Mahoney Tables was an important precedent in the development of the Comfort Triangles. However, there is a considerable difference between the applications of the temperature range in the two cases. In the Mahoney Tables, a threshold of 10° C is used to differentiate between high and low temperature swings, while the Comfort Triangles, developed in Section 7.4. of this Chapter, indicate the degree of dampening of the temperature swing required to achieve comfort.

7.3.3. Thermal swings in passive solar systems.

Starting in 1945, a series of experimental buildings were tested at the MIT (AIA Research Corporation, 1976) to show the technical feasibility of solar energy in housing, using active solar systems with flat plate collectors producing hot water. However, they never achieved economic feasibility due to the widespread availability of cheap fossil fuels.

However, later, the wave of new passive solar experimental houses after the energy crisis of the 1970´s produced a series of advances in the development of these systems. In the United States, an important series of Passive Solar Energy Conferences (PSEC) were held and the Passive Solar Energy Section of the American Solar Energy Association, ASEA, was established.

In the experimental buildings constructed between 1970 and 1980 (Cook and Plowler, 1978), the implementation of passive solar systems included direct gain, Trombe walls, accumulating walls without ventilation and sunspaces or attached greenhouses. These were then promoted with government support to reduce the use of conventional fossil fuels, avoid the cost of conventional heating installations and catch solar radiation through appropriate building design. It is, however, important to note that for passive solar systems, the ‘indoor temperatures.... cannot and should not be maintained at constant temperatures’ (Strickley, 1978, p. 153).

Although many pioneer solar projects managed to raise average indoor temperatures to comfortable levels, even in the cold continental climates of the central areas of the United States, many also suffered from excessive indoor temperature swings. The solar radiation received during the day was sufficient or even more than required, but the insulation to reduce nighttime heat losses and the lack of thermal mass to store the heat and dampen the swings was insufficient to control the indoor temperature variation.

In an article presented in Passive Systems ’78 (Cook and Prowler, 1978), Strickley (1978) proposed a method to evaluate the performance of passive solar systems based on the measurement of average indoor temperatures and temperature swings, compared with the same variables outdoors. The author recommended the measurement of the indoor and outdoor maximum and minimum temperatures on a sunny day to obtain this data automatically using low cost alcohol-mercury maximum-minimum thermometers.

According to the paper (Strickley, 1978), the acceptable indoor temperatures in living spaces range between 15,5 and 23,9° C (60 to 75° F) allowing a temperature variation of up to 8,3 deg C (15 deg F). In sunspaces, attached greenhouses and glazed circulation areas, an average between 7° and 29,4° C (45 – 85° F) was proposed, resulting in a maximum acceptable swing of 22,2 deg C (49 deg F).

In both cases, a higher swing indicates the need to incorporate more thermal mass, while a temperature below the minimum show the need to increase the collecting area exposed to solar radiation or reduce the heat losses with better thermal insulation.

This paper on the evaluation of passive solar system performance represents an important step in the development of the concept of the comfort triangles, although it doesn't define the comfort limits in terms of the average temperature and temperature swing. It only considers the minimum level of thermal comfort of 15.6° C and a maximum temperature swing of 8.3° C. For living spaces, the proposed lower limit of 15.6° is considered low, even if temperatures below 18° are accepted at nighttime. Most importantly, the proposal of Strickland (1978) doesn't relate the two variables, as with a higher average temperature a higher temperature swing is acceptable and vice versa.

In the development of this concept, a minimum temperature of 21.1° (70° F) was proposed by Mazria (1978), the limit incorporated in his book of passive solar design (1983). Meanwhile, Balcomb and Macfarland (1978) developed studies with simulations of solar systems, later incorporated in the 'Passive Solar Handbook' (Balcomb and Macfarland, 1980). They adopted a minimum indoor temperature of 18,3° C (65° F), less than the 22,2° C (65° F) recommended by ASHRAE, and a maximum thermal swing of 6 deg C.

Strickley (1978) introduced a further interesting and useful concept for the evaluation of passive solar systems: the range ratio RR. This ratio is the indoor thermal swing $\mathbf{A_{t(int)}}$ divided by the outdoor thermal swing $\mathbf{A_{t(ext)}}$, an indicator of the capacity of the building to moderate, dampen or modify the external conditions.

$$\mathbf{RR} = \mathbf{A_{t(int)}} / \mathbf{A_{t(ext)}}$$

The data obtained from measurements and the use of the calculated RR leads to the following design recommendations:

- If the average temperature is below the lower limit of comfort, better thermal insulation is required to reduce heat losses, larger areas of solar absorption are required or combinations of both strategies.
- If the indoor temperature swing is higher than the limit, more thermal mass is required to reduce the variation. Ventilation by day can also help to reduce variations and excessive peak temperatures, but the increase in the average indoor temperature may be reduced as excess heat is dumped to the outside.

The functions of different bioclimatic design strategies that modify the impact of external climatic variables are discussed in greater detail in Chapter 8.

7.3.4. Maximum swings for thermal comfort.

The studies of thermal comfort, carried out by Fanger (1973) that were incorporated in the ISO and European Standard (1994), are based on a physiological thermal equilibrium model that indicates the PMV, Predicted Mean Vote, on a comfort scale from -3 to +3, with zero as optimum. The results indicate a combination of environmental conditions that achieve a PMV of 0, according to the activity level and insulation value of clothing. It is argued here that this approach promotes the use of artificial conditioning, needed to maintain these optimum conditions.

Studies were made of the variation in temperature that was acceptable with steady rises or falls of temperature over time. These variations were called ramps and a value of one degree Kelvin per hour was found to be acceptable, allowing slight adjustments of clothing and activity rates without causing annoyance or sudden discomfort.

As an example, Figure 7.1. shows a ramp superimposed on the typical outdoor temperature variation in March in Buenos Aires, based on the hourly temperature variation established by Roriz (2006). In this case, the maximum hourly outdoor temperature variation of 1,9 degrees K, with an outdoor temperature range of 10° deg K, can be considered excessive according to Fangers ramp criteria. A maximum daily temperature variation of 6 deg K will keep the hourly change below Fangers ramp criteria based on measurements in artificially conditioned spaces. With natural conditioning, it is argued that an increase in the hourly variation can be accepted, up to a maximum of 1,5°, corresponding to a maximum daily variation of 8 degrees.

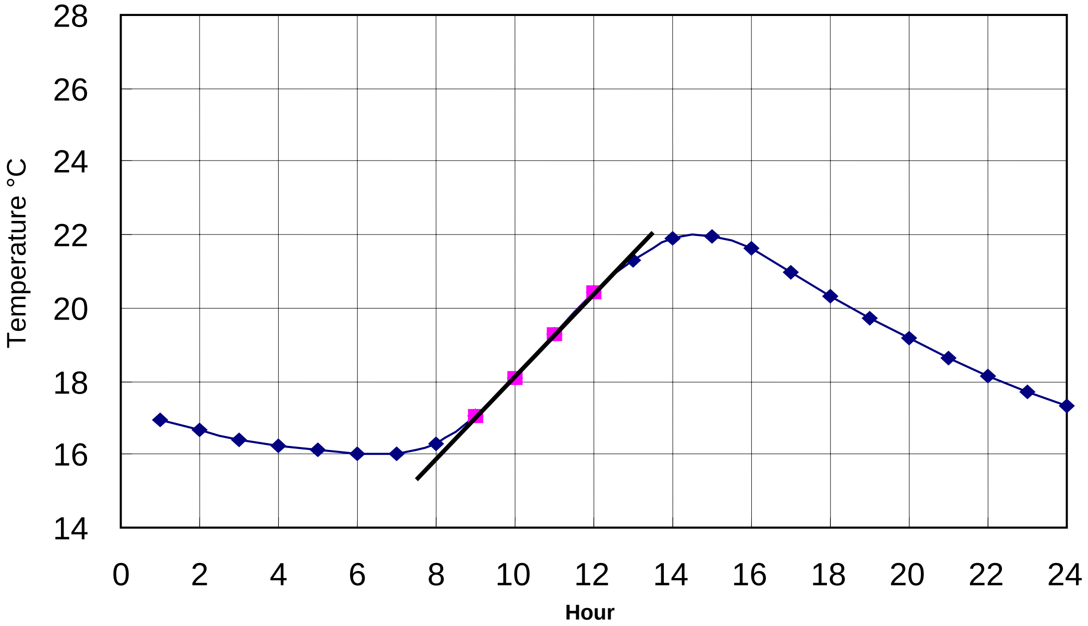


Figure 7.1. Example of a ramp of average temperature variation, for Buenos Aires in March. Data from SMN (1994) and the formula proposed by Roriz (2006).

7.3.5. Initial proposal for the Comfort Triangles.

Building on the base of the studies presented in the previous sections, the initial proposal is established for the Comfort Triangles, combining the limits for cold conditions established in Sub-section 7.3.3. and the limits for hot conditions from sub-s 7.3.2. Figure 7.2 indicates the values proposed for passive solar systems redrawn with the triangles concept while Figure 7.3 shows the initial triangles proposal proposal with the following references:

- Point 1 indicates the minimum temperature for comfort, corresponding with living rooms or spaces for sedentary activities: 18° C without temperature swings.
- The line 1 - 2 indicates the combination of average temperature and temperature swings, which is minimum when the temperature is 18° C, increasing to 10 degrees with an average temperature of 22° C.
- The line 2 - 3 is the maximum limit of the temperature swing for spaces with passive solar heating systems originally established as 10 degrees.

The innovation of the graph is the relation between the swing and the average: when the average temperature increases, the swing can also increase to ensure that the minimum temperature maintains the same value.

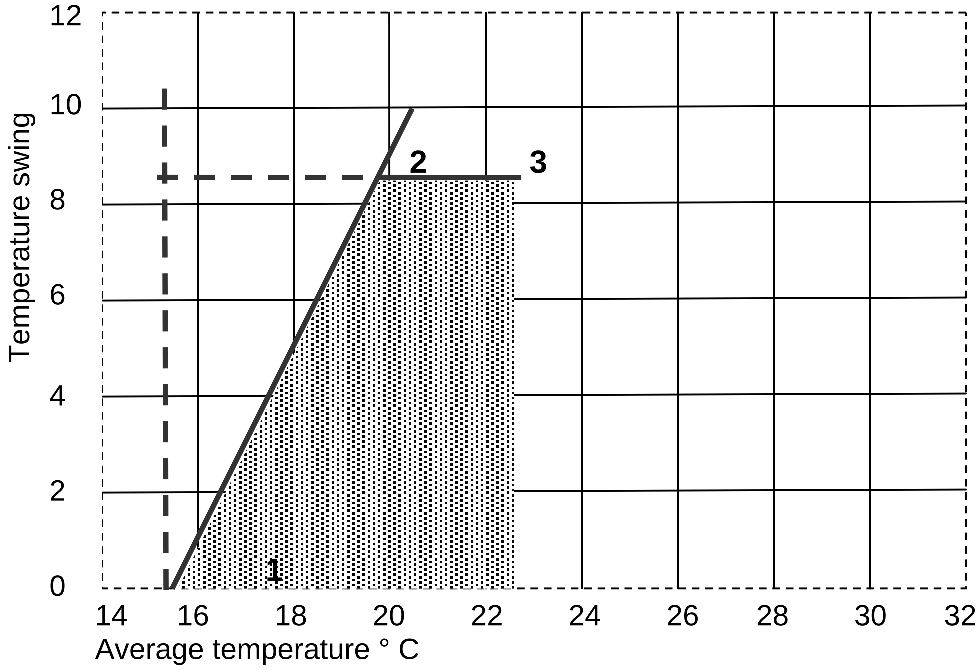


Figure 7.2. Comfort zone and thermal swing for passive solar systems. Developed by the author, based in the limits in dotted lines proposed by Strickley (1978) and plotted on a graph with average temperature and temperature swing.

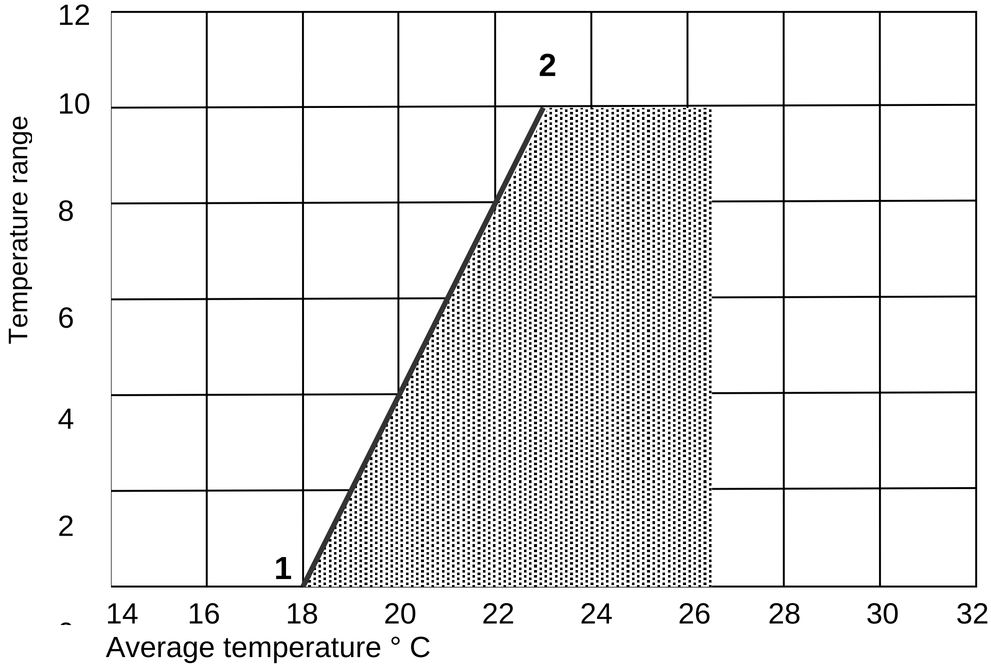


Figure 7.3. Modification of comfort limits, with a minimum temperature of 18° C.

At the other end of the scale, Figure 7.4 indicates the comfort limits proposed for warm climates with average annual temperatures above 20° C, by Mahoney (Koenigsberger, 1970 and 1974), combining day-time and night-time temperatures with the values indicated in Table 7.2.

- Point 1 indicates the minimum night comfort temperature.
- The line 1 – 2 indicates the combination of average temperature and temperature swing corresponding to a minimum limit of 17° C.
- The lines 3 – 4 indicate the maximum temperature swing during the day, according to the comfort limits proposed by Mahoney: 5, 6 o 7° C. It should be noted that Mahoney proposes a minimum comfort of 17° C in warm climates.
- The lines 4 – 5 indicate the combination of average temperature and temperature swing corresponding to a maximum temperature of 27, 29, 31 and 33° C, according to the range of humidity indicated in the text.

The grey triangle shows the combination of average temperatures and temperature swings that ensure comfort for sedentary activities by day, corresponding to humidity levels between 50 and 70%. The extension shows the link with the night comfort zone for the same humidity range.

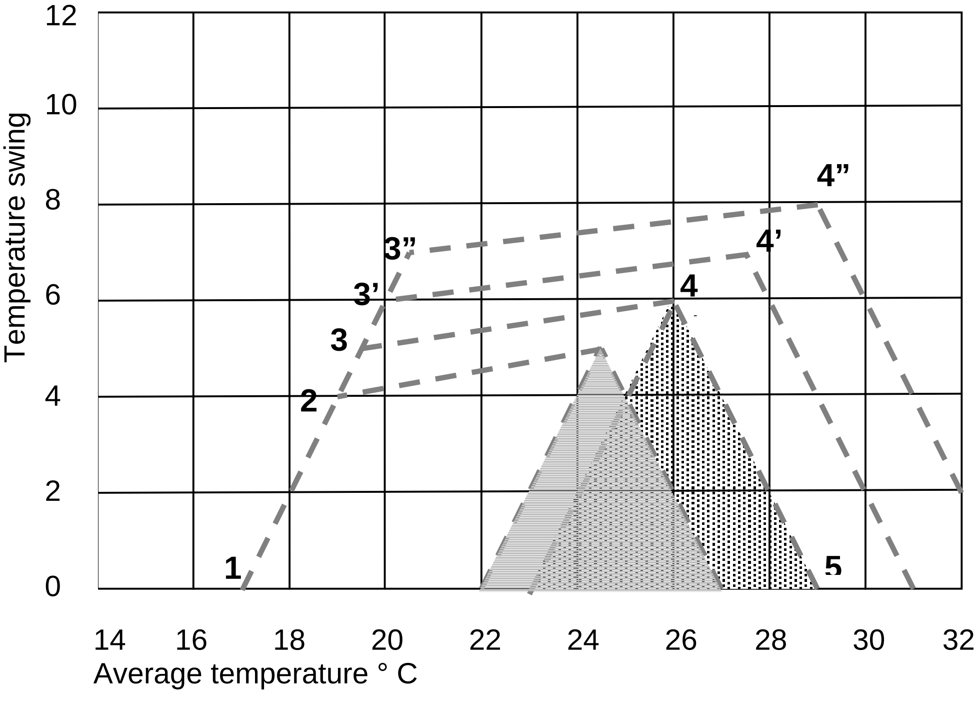


Figure 7.4. The series of comfort zones proposed by Mahoney, according to the annual mean temperature. The grey triangle shows the comfort zone for an annual mean temperature of 15-20º C and humidity group 2, 50-75%. The dotted line to the left starting from an average temperature of 17ºC shows the lower night comfort limit.

This sub-section indicates the origin of the concept of the Comfort Triangles, and presents the initial graphs, using the variables identified in the previous section. In the following sub-section, aspects of the initial generation of the first published version of the graph is analysed.

7.4. VERIFICATION BY LOGICAL DEDUCTION

In this sub-section, the conditions of thermal comfort are analysed in order to define the comfort zone for indoor spaces. This version, developed by the author, was originally included in the book by Evans and de Schiller (1988) and subsequently included in the second and third editions (1992, 1996). A modified version was published in English (Evans, 2000) with a more detailed analysis presented two years later (Evans, 2003). The temperature limits are based on values obtained from bioclimatic charts such those of Givoni (1969) and Olgyay (1970). Using these sources, the limits of comfort are established for different activity levels, expressed as the relationship between the average temperature T_m and the temperature swing or thermal amplitude, A_t. In the following analysis, these comfort zones are related to specific spaces. To be more precise, these zones are defined and developed in relation to the activities and expectations of comfort in these spaces.

Living spaces: for sedentary activities, a minimum comfort temperature of 18° C is considered, though with this value, no variation is allowed as this would lead to temperature below (and above) this lower limit. As the average temperature increases, a higher temperature swing is possible. For example, with an average temperature of 20° C, a temperature swing of 4 deg C is possible, equivalent to a variation between 18° and 22° C. In the graph, an increase of the average temperature of 1° allows an increase of the temperature swing of 2 deg C, producing a sloping line. The maximum temperature for comfort is established as 28° C, without any swing, without noticeable air movement and without significant differences between the mean radiant temperature and the air temperature. This limit is used to establish the starting point of the right-hand lower corner of the triangle. As the average temperature drops, the allowable temperature swing can increase.

Extended comfort in indoor spaces: More flexible limits are possible for transitory situations, considering that short periods with temperatures above the limit are acceptable. In the first version of the Comfort Triangles (Evans & de Schiller, 1994) an increase of 2°C is suggested, for buildings without refrigeration. With low levels of relative humidity and with sensible air movement combined with higher humidity levels, the comfort limit can be increased without producing discomfort, according to Nicol and Humphreys (2001).

Sleeping spaces: For night comfort, the comfort triangles introduce three new criteria:

- With blankets, duvets and the insulating layer provided by the mattress, it is possible to sleep comfortably even when the air temperature drops to 12° C, or even below this limit. Modern sleeping bags for camping and mountaineering can provide comfort for sleeping even with temperatures below zero.
- However, it is suggested that a temperature swing over 4 deg C during the 7- 8 hours of sleep can interrupt sleep and awaken the occupants. While awake, occupants can adjust the clothing and level of physical activity, but this is not possible when sleeping. However, it may be argued that the 4 degree temperature swing at night corresponds to an overall daily temperature swing of about 6 -7 deg C.
- As indicated by Mahoney (Koenigsberger et al, 1974), night time maximum temperatures should be lower than the daytime limits, in order to allow rest without transpiration, so an upper maximum level of 25° C is fixed.

Using these three criteria, a truncated triangle is formed to indicate the comfort limits for sleeping spaces.

Circulation: For comfort in outdoor spaces and indoor spaces used for circulation, such as passages, corridors, stairs, galleries and patios, the limits of comfort are different for those considered previously for the following reasons:

- The comfort expectations are less strict than those for indoor living and spaces.
- The time spent in the spaces is considerable less.
- Walking or climbing stair implies higher rates of metabolic activity.
- The insulation values of clothing in outdoor spaces are more flexible, and can be much higher than indoors: while indoor values have a maximum of 1 CLO, outdoors values of over 1,4 can be achieved with an overcoat, scarf and gloves. A lower limit of 0,5 CLO is acceptable in hotter conditions.

The minimum comfort level adopted was 10° C for medium activity levels and comfortable outdoor clothes (CLO max = 1), although lower values can also be acceptable in certain situations. The maximum temperature for outdoor comfort is set at 30° C. This allows a swing of up to 20° C, considering that clothing can be adapted when in outdoor spaces.

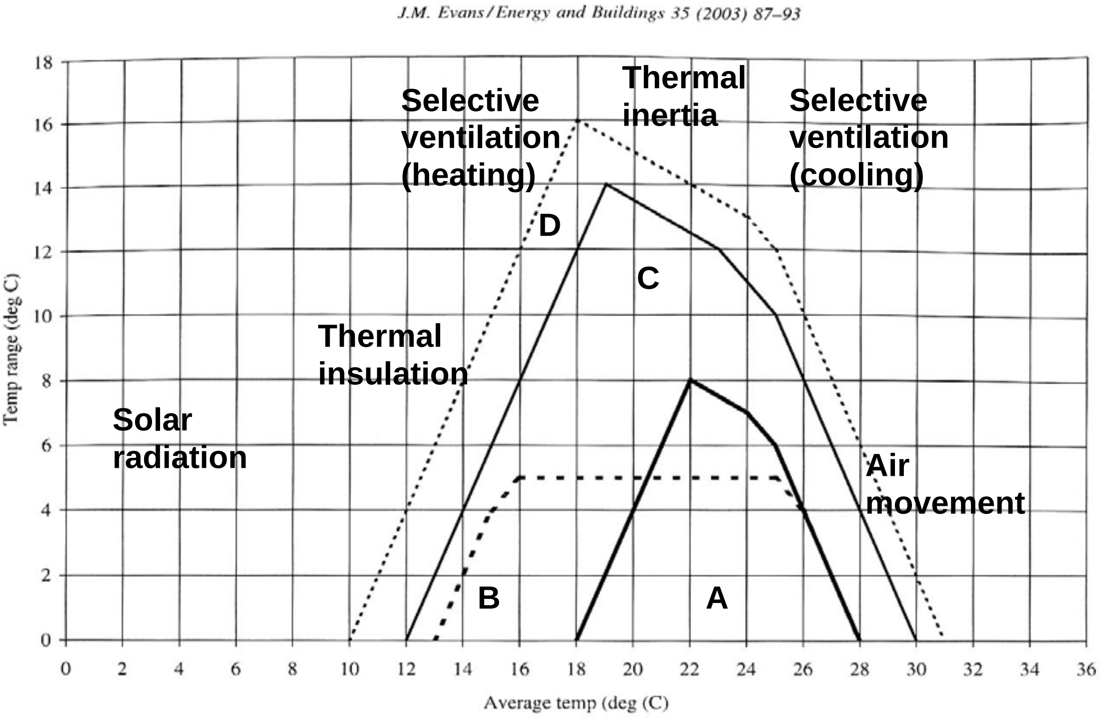


Figure 7.5. The Comfort Triangles, as published in Evans (2003) with design strategies added.

Figure 7.5. presents the Triangles developed by the author (Evans, 2003) based on the original proposal in Evans and de Schiller (1988), showing the four different zones identified, labelled A, B, C and D, for sedentary activities, sleeping, circulation and extended circulation respectively.

The diagram also includes the following bioclimatic strategies which are applied to improve comfort when the conditions are outside the respective comfort zones:

- Sensible air movement: air movement that can de sensed due to the cooling effect.

- Thermal inertia, combining time-lag and thermal damping.
- Use of solar radiation.
- Thermal insulation to conserve internal gains
- Selective ventilation: use of intermittant ventilation to cool or heat interiors.

7.5. TESTING THE COMFORT TRIANGLES METHOD

The Comfort Triangles, introduced in the previous sub-sections, was developed by a process of logical deduction, based on initial data of thermal comfort limits, using the reasoning sequence presented.

The first test of the utility and application of the Comfort Triangle Chart was it’s introduction as a bioclimatic analysis technique in the two subjects at graduate level, Introduction to Bioclimatic Design and Introduction to Solar Architecture, currently given at the Faculty of Architecture, Design and Urbanism, of the University of Buenos Aires, since 1984. It’s implementation, over a period of 22 years by approximately 10,000 graduate students who passed the subject, has shown it’s value as a bioclimatic design tool, especially in situations where the indoor or outdoor temperature swing is significant. In addition, the method was tested in postgraduate courses in universities of Argentina, Mexico, Panama, Ecuador and Chile, in Latin America as well as the United Kingdom and Spain.

This long testing process of the Comfort Triangles has provided relevant useful feed-back indicating the following aspects that need to be improved and adjusted:

- The difficulty of relating the outdoor temperature swing to the indoor temperature variation, or establishing Range Ratios RR proposed by Strickley (1978). A further response to this requirement is provided in Chapter 8 and the case studies in Part 4.
- The maximum allowable temperature swing of 10 degrees appears to be excessive and implies the need to change or adjust the clothing excessively during the day.

To solve the first difficulty, tests and measurements are required to establish RR values for buildings under real conditions. These measurements can then be used to calibrate the numerical simulation of buildings in order to verify the possible variations that can be achieved a favourable modification of the internal conditions. Thermal simulation can also be used to define the conditions that provide thermal comfort.

In this sub-section, the range of conditions that provide thermal comfort periodic heat flow are evaluated. As the previous chapter established, this evaluation can be achieved using physiological models such as that developed by Fanger (ISO, 1988) or surveys of thermal comfort based on subjective sensations in typical conditions based on the principle of adaptive comfort (Nicol and Humphreys, 2001).

The case studies with measurements in existing buildings, which are presented in Chapters 10 and 11, provide relevant data to show typical values of RR and average temperature increase of occupied buildings.

These are then used to indicate the possible modification of indoor conditions in both heavy and light buildings according to the bioclimatic design resources, relating climate, comfort and design.

7.5.1. Variation of body temperature.

The internal temperature of the human body is conventionally considered as fixed with a value of 36,4° C (Edholm, 1969). However, detailed measurements show a variation in temperature with a tendency to increase in the afternoon and decrease at night with a range that can extend between 36° and 37,5° C. Table 7.5 shows the full range of possible body temperatures.

Table 7.5. Range of human body temperatures, based on Edholm (1967).

Body temperature	**Conditions**
20 - 30° C	Hypothermia during surgery with total anaesthetic
< 36° C	Hypothermia
36 – 38° C	Temperature of the body at rest
37° C	Average temperature
38 – 39° C	Temperature with exercise
> 39,5° C	Tolerated for limited periods
38 – 41° C	Fever
40 – 42° C	Hiperthermia
> 42° C	Brain damage
> 45° C	Death

The typical daily variation of 0,55° C allows the body to respond to the expected swing of environmental conditions although, in some cases, the variation can reach 1° C without producing discomfort. As the air temperature rises in the afternoon, the body temperature also rises slightly (Edholm, 1969).

The effect of this increase can then be estimated considering a typical body weight of 100 kg, with a thermal capacity of 3000 KJ/kgK, a 0,55° C increase of temperature over a three hour period, with a surface area of the body of 1,6 m2 and a surface resistance of 0,03 W/m2K. The result shows that the body can resist an air temperature increase of 2° C over a three hour period without any additional adjustment than the normal variation of body temperature, assuming a reasonable rapid distribution of this temperature increase in the body, achieved with blood circulation.

This temperature variation also favours the work efficiency of the body (Edholm, 1967), achieving better muscular performance with slightly higher corporal temperatures. In spite of the clear evidence of body temperature variation, Fanger's model, presented in the Annex of ISO Standard (1994) takes for granted a fixed temperature of 37° C, including a variation in the comfort range as a function of the PMV, Predicted Mean Vote that is considered comfortable for a range between 0,5 and -0,5.

To achieve steady outward heat flow, the maximum skin temperature is 3° C below the body temperature, with slight variations for differences in air movement, relative humidity and mean radiant heat:

- Sensible air movement permits higher skin temperatures.
- Low relative humidity also allows higher skin temperatures.
- High relative humidity requires lower skin temperatures, often achieved through transpiration and aided by air movement.
- Mean radiant temperatures above air temperature require lower skin temperatures for the same body heat loss.

As the air temperature drops, clothing is needed to provide additional insulation to control heat losses.

Based on Edholm (1968), Figure 7.6 was constructed to indicate the range of temperature and average temperature of the body required to achieve comfort, related to the skin temperature needed to dissipate metabolic heat. This demonstrates that the Comfort Triangles can also be used to analyse body temperature variations.

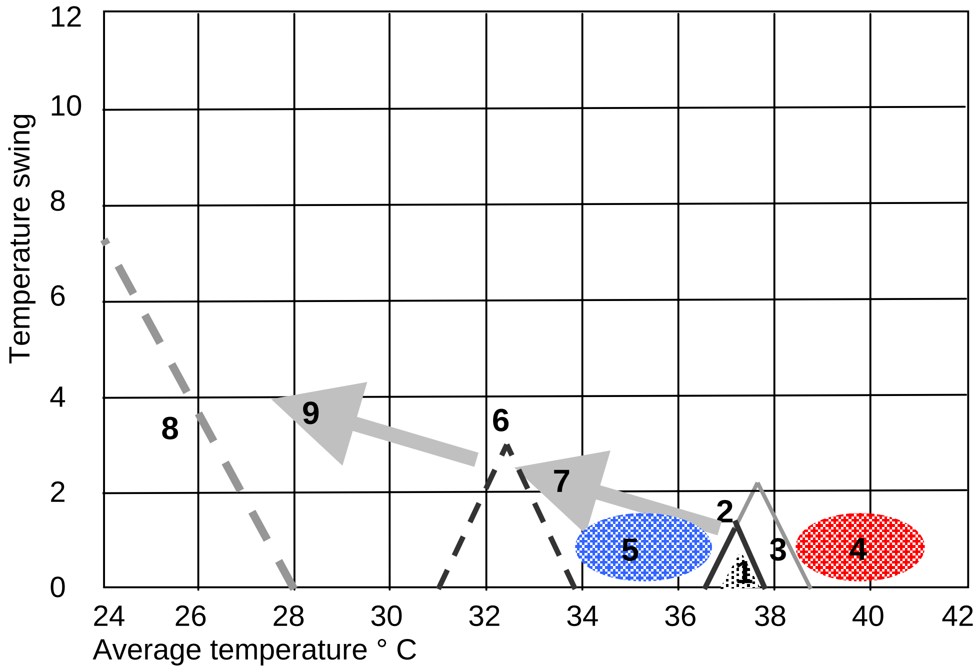


Figure 7.6. Thermal conditions of the human body:

Zone 1: Average variation at rest.
Zone 2: Maximum variation at rest.
Zone 3: Possible variation with high rates of physical activity.
Zone 4: Conditions of hyperthermia.
Zone 5: Conditions of hypothermia.
Line 6: Indicative skin temperature.
Arrow 7: Difference between body and skin temperature necessary to dissipate metabolic heat production.
Line 8: Range of comfortable air temperatures
Arrow 9: Difference between skin temperature and air temperature necessary to dissipate metabolic heat production.

Source: 1 – 6 Based on data from Edholm (1968).
7 – 9 Based on Figure 7.3

7.5.2. Skin temperature variation.

As Figure 7.6. indicates, the skin temperature should be lower than the body temperature in order to achieve a steady flow of heat to the surface, allowing the dissipation of metabolic heat.

Once again the range of skin temperatures considered comfortable can vary, though the total comfort range is 2 deg K, from 31° - 34° C. Above 34° C transpiration is likely to cause discomfort in humid climates, while temperatures below 30 are considered too cool. The possible variation according to Edholm (1968) is shown in Table 7.6.

Table 7.6. Examples of skin temperatures.

Skin temperature	Conditions
35° C	Excessive discomfort with sensation of heat
>34° C	Intense sweating with high humidity
34° C	Typical value for warm climates
33° C	Typical value for temperate climates
32° C	Typical temperature with cool climates
15° C	Absolute minimum value; start of pain.

The values are for average skin temperature, as extremities can have wider swings, and are the first to suffer from chilblains, frost-bite and other consequences of extreme values.

7.6. DEVELOPMENT AND APPLICATION OF THE METHOD

In this section of the Chapter, the original proposal for the definition of the comfort zone using the Comfort Triangles is compared with other methods to define the comfort limits. The two comfort approaches, based on climate chamber studies and questionnaires of occupants in buildings, represented by the Fanger comfort model (ISO, 1994) and the adaptive comfort model (Nicol and Humphreys, 2001), are presented in the following sub-sections.

7.6.1. Numerical simulations.

Fanger’s model (1996) establishes a thermal balance of the human body, balancing the metabolic heat production with the heat losses, according to the activity rate, the environmental conditions and the insulation value of clothing (ISO, 1994).

The program Comfort, written by the author in Quick Basic, uses the algorithms provided in the Annex of the ISO Standards (1998). It also calculates the intermediate values of the external surface area and temperature of clothing in order to calculate the heat exchange with the surrounding environment. This depends on the air temperature or dry bulb temperature, the relative humidity, the mean radiant temperature and the relative air velocity.

This has been used to calculate the range of comfort conditions, considering that the acceptable daily swing can be obtained by using a PMV, Predicted Mean Vote of comfort between -0.5 and +0,5 and an adjustment of clothing. Further possible methods of adjustment to variation in the environmental conditions include slight changes in the activity level and posture, though these were not included in the analysis of comfort ranges.

In the paper on the Comfort Triangles (Evans, 2003), the limits of the comfort zone were analysed for different levels of clothing using the Fanger´s model (1996). This exercise confirmed the need to adjust the form of the Comfort Triangles to take into account the maximum possible adjustment of clothing during a typical working day. Basically, the possibilities of comfortable clothing limit the acceptable thermal swing to 8 deg, a lower swing than originally proposed.

The revised form of the triangle was published as Figure 1 in Evans (2003), with a truncated apex to the triangle, reducing the maximum acceptable swing. The original proposal for night comfort also used this concept of the truncated triangle.

With this further test, the triangles were then adjusted and improved to respond to requirements of thermal comfort with periodic variation of temperatures. The resulting Comfort Triangles are shown in Figure 7.7. and apply to sedentary activities and rest in climates with average monthly temperatures up to about 27°C.

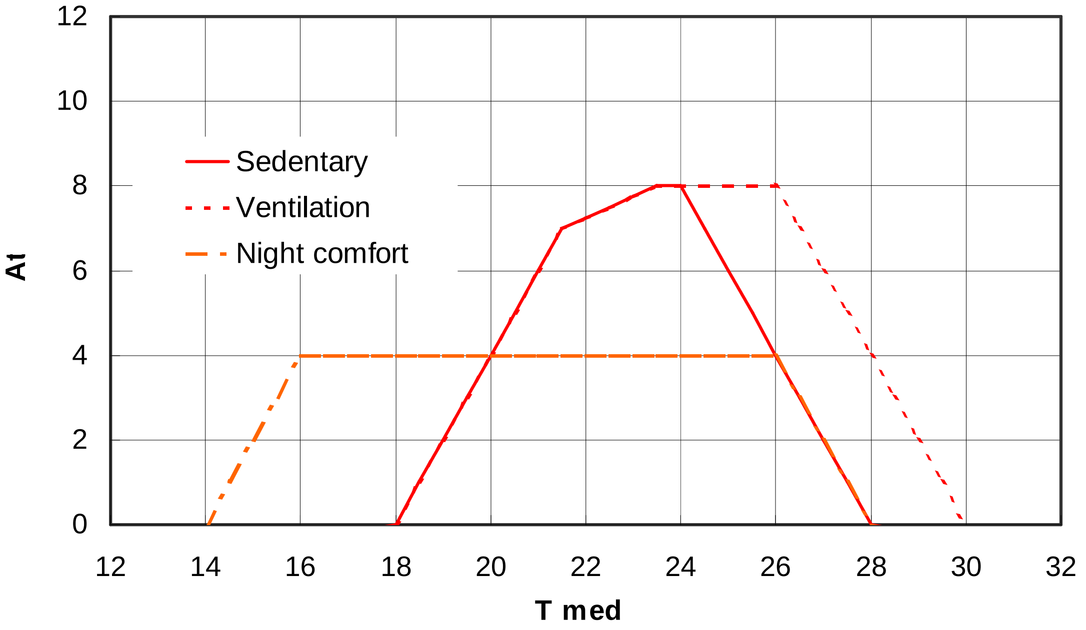


Figure 7.7. Modified form of the 'Comfort Triangles', taking into account the limitations of clothing adjustment during the day.

7.6.2. Adaptive comfort.

An alternative approach to the definition of comfort, which can give different results from those obtained by Fanger's method (Fanger,1973; ISO EN 7730, 1994) is the 'adaptive comfort' concept, arguing that the comfort zone depends in part on the temperatures that the user experiences in the same month (Nicol and Humphreys, 2001).

This approach is considered to be especially applicable for occupants of buildings without artificial cooling. In this case, the comfort zone can vary according to the monthly average outdoor temperature, or the average outdoor temperature in the previous 30 days.

An example of this approach, incorporated in ASHRAE Standard 55:2004 (Ashrae, 2004), shows the range of the comfort with an average that varies from 21°C to 27°C, with a constant range of 8 degrees to satisfy 90 % of the population, shown in Figure 7.8. A slightly wider range is achieved when this proportion drops to 80 %.

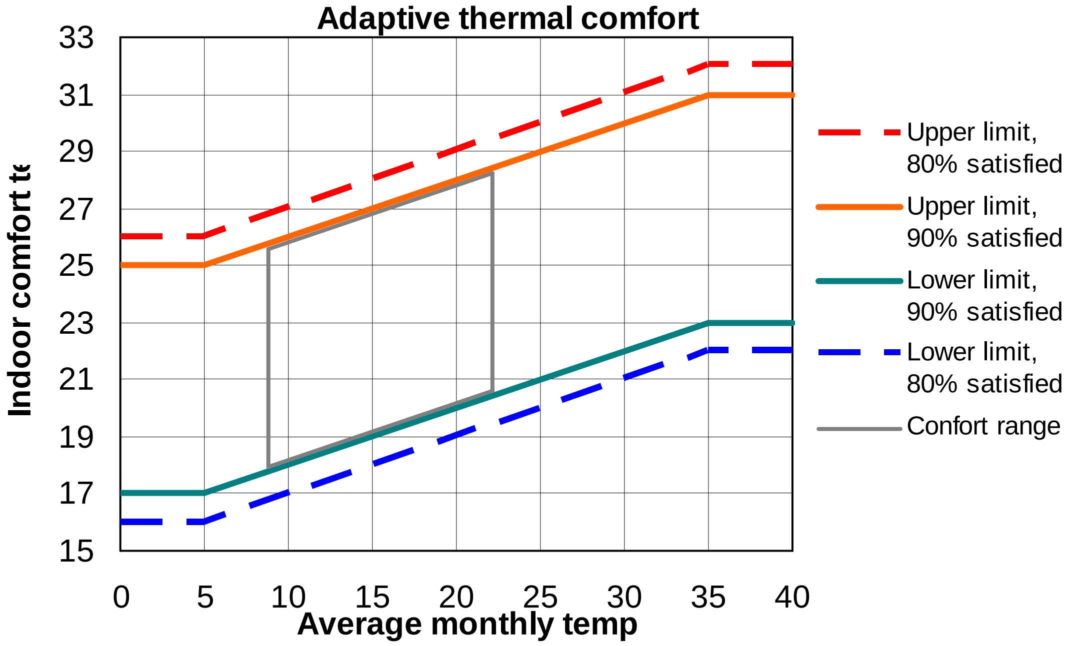


Figure 7.8. The adaptive comfort zone, related to the average monthly temperature, according the ASHRAE Standard 55:2004 (2004).

Assuming a constant indoor temperature range for 90% satisfied, as shown in Figure 7.8, the comfort zone can be redrawn using the concept of the Comfort Triangles, to obtain the graph show in Figure 7.9.

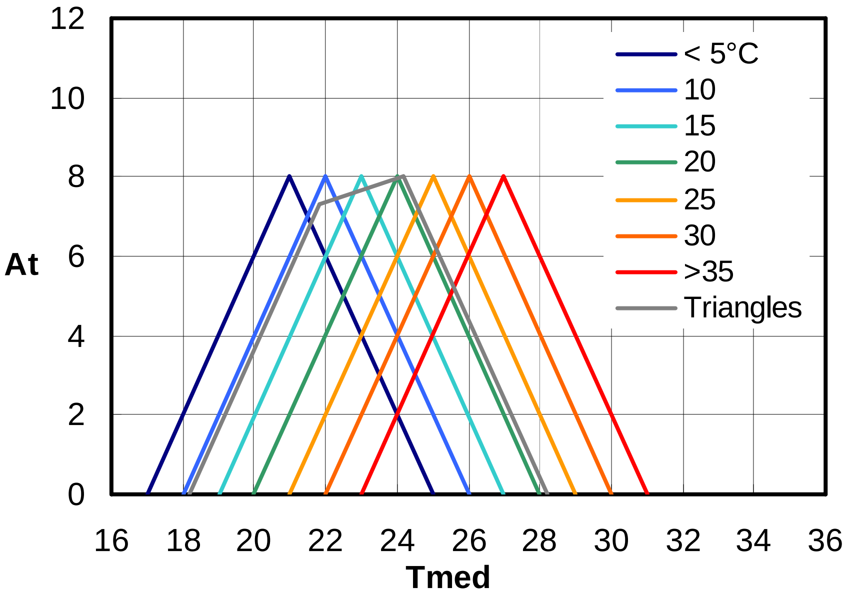


Figure 7.9. The comfort zones proposed in the ASHRAE adaptive comfort standard (2004), compared with the Comfort Triangle for sedentary activity, shown in Figure 7.4.

The result is similar to the Comfort Triangles derived in the previous sections, though the extreme limits of comfort extend slightly further, from 17° to 31° C, instead of 18° to 30° C. The maximum range of comfort is constant, while in the previous sections argued that the range decreases as the temperature drops.

Although the upper limit of the comfort range, which according to the ASHRAE Standard reaches 31°C, this only occurs when the average monthly temperature exceeds 30°C, a rare situation that seldom occurs even in very extreme climates. If average monthly temperatures above 30°C are excluded, there is a good agreement between the upper comfort limit in both approaches.

At the lower end of the comfort scale, the ASHRAE Standard implies a continuing drop in the comfort temperature when the average monthly temperature falls below 10°C.

This is not consistent with the findings of Humphreys (1981) who shows a levelling of the minimum comfort level when the average monthly temperature reaches 10° and a slight rise at very low average monthly temperatures.

Figure 7.10 shows that when the extreme climate conditions, corresponding to average monthly temperatures below 10° and above 30°C are excluded, there is a very good relationship between the comfort zone proposed in the previous section of this thesis and the comfort zone with adaptive comfort according the ASHRAE Standard (2004).

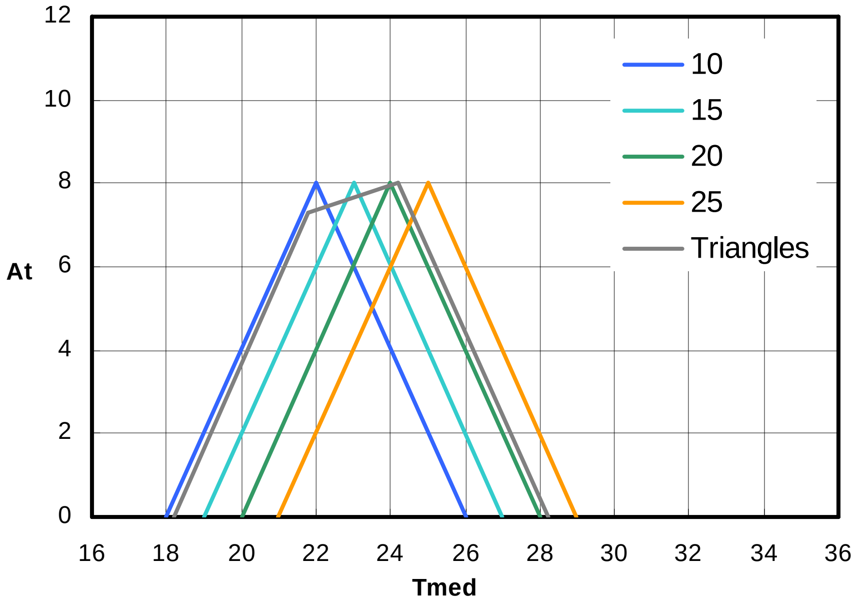


Figure 7.10. The Comfort Triangle compared with the conditions for comfort established by the ASHRAE Standard 55:2004 for average monthly temperatures between 10 and 25º C.

7.7 ADDITIONAL APPLICATIONS OF THE COMFORT TRIANGLES CONCEPT

The need to control indoor environmental conditions is not restricted to the comfort requirements for human occupation. Many other uses require a control of average temperatures and thermal swings in buildings.

In order to demonstrate the application of the Comfort Triangle concept to other situations, examples of such applications are presented in this chapter. They include:

- Museums and archives, where control of indoor conditions are needed for conservation.
- Animals, where control of conditions is required for incubation of eggs and optimum development in commercial agricultural.

The object of this section of the chapter is to present examples of the application of the Comfort Triangle concept and the development of specific comfort triangles for non-human requirements.

7.7.1. Comfort Triangles in conservation: museums and archives.

The storage of documents and works of art require very different conditions than those needed for human comfort (King, 1992). The preservation of delicate papers, valuable documents, historic paintings and other cultural artefacts require strict controls of the variation of temperature and humidity. Teygeler (2001), in an extensive annotated bibliography, emphasises the special problems of conservation, particularly in warm climates, and the disadvantages of artificial climate control, compared with natural conditioning.

Although temperature variations are less critical than the swings in humidity and the impact of light and radiation, the control of temperature variation is vital for reducing thermal movement and control of moisture content (King, 1992).

Hunter (1979) indicates the conditions of temperature and relative humidity recommended for paintings, archives, general conditions in museums and the comfort zones for visitors to museums in summer and winter, for application in the United Kingdom. As Table 8.1 shows, visitors prefer higher temperatures than the optimum for painting and other objects. These narrow limits of humidity and temperature are difficult to achieve without permanent artificial conditioning. King (1992) has questioned this approach, as intermittent air conditioning (due to power failures and economising at week-ends or at night) can be more harmful than natural conditioning in buildings designed to achieve gradual temperature changes over time.

For paintings, Fahey (2005) of the Henry Ford Museum, recommends a wider range of temperatures, between 18° and 21° C with 40 - 45% relative humidity in winter and 21° to 24° C with 45 - 55 % relative humidity in summer.

Table 7.7. Temperature and humidity ranges for museums.

Artefacts and persons	Minimum temperature	Maximum temperature	Minimum relative humidity	Maximum relative humidity
Paintings	16	18	57	63
Archives	15	24	47	63
General collections	15	24	47	68
Visitors	19-21	23-26	30	70
Visitors in summer	20-24	26-29	30	70

Source: Hunter (1979), Figure 33.39, page 291.

The Scottish Museum Council (Bouwmeester, 1995) recommends the following temperature and humidity limits in museums, with more realistic limits that, in many cases, allow natural conditioning, combined with partial heating in winter:

Temperature: Objects in museums 10 - 20°C.
Objects on display 16 - 20°C.
Objects in deposits 12 - 16°C (with climate control during transfer).
Humidity: Maximum humidity levels of 70 % (to prevent mould growth).
Minimum humidity levels of 40 % (to avoid excessive drying).

With temperatures below 10° C, humidity control becomes more difficult, especially when cool objects with low absolute humidity are transferred to or through spaces with warmer conditions. This can produce a severe condensation risk as well as the impact of sharp and damaging changes of humidity. Bouwmeester (1995) also comments on the potential risk of temperature fluctuations.

With these recommendations for the hygro-thermal design of museum spaces, specific Comfort Triangles can be developed for different gallery, museum and archive areas.

Figure 7.11. indicates the Comfort Triangles for different type of spaces and activities, demonstrating the limited combinations that can be implemented to achieve optimum conditions for visitors at museums and art galleries as well as for elements on display.

Table 7.8. Recommended conditions in museums and art galleries.

Application	**Minimum temperature**	**Maximum temperature**	**Average temperature**	**Temperature swing**
Paintings	16	18	17	2
Paintings on exhibition	18	21	19,5	3
Objects on exhibition	16	20	18	4
Objects in storage	12	16	14	4
Papers in archives	15	20	17,5	5

The application of the Comfort Triangles for objects on display is more limited in height and width of the base, than the triangles for visitors, as well as having lower averages. The area of triangles for paintings have a small surface that coincides with that for visitors, while for papers and artefacts is even more reduced, with an average temperature of 19° C and a swing of only 2 degrees.

For deposits and stores, the recommended conditions do not coincide at all with those required for human comfort, for low levels of activity.

The requirements for museums are so strict that they can only be achieved by the use of full air conditioning, with both temperature and humidity control. However, these systems can cause severe problems when there are power cuts, mechanical failures or when switched off for maintenance. Condensation risk has to be considered when warmer humid air from outdoors comes in contact with cool objects on display, as well as a danger of mould growth in ducts.

For this reason, various authorities cited by Teygeler (2001) prefer natural conditioning to achieve a more relaxed control with slow temperature variations between more flexible limits.

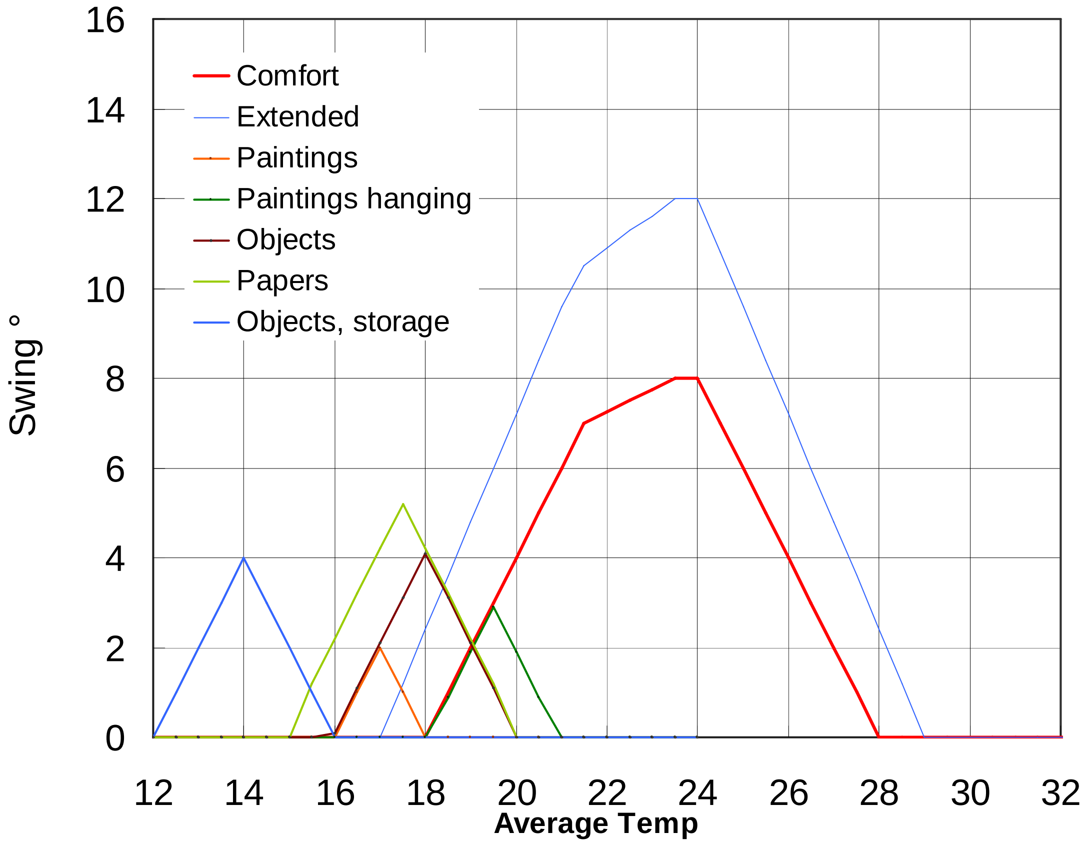


Figure 7.11. Comfort Triangles for both visitors and conservation of objects on display in museums, galleries and archives.

In this context, the approach of the Comfort Triangles allows the visualisation of thermal swing control recommended by different authors (King 1992, Hunter 1987, Bouwmeester, 1995), considering that a seasonal variation in the average temperature and the daily swing within fixed limits.

The Comfort Triangles chart, as shown in Figure 7.12., illustrates average temperatures recommended for paintings with a range form 16° to 24°, with a maximum swing of 3 degrees, while the average temperature for visitors comfort ranges from 18º to 28º C, with a maximum swing of 8 degrees, as established in the previous sections of this chapter.

The zone of conditions apt for both objects and people, shown in grey, is more limited, from 18° to 24° C, with a maximum daily swing of only 3 degrees.

This definition of comfort limits, allows the use of certain bioclimatic strategies to control temperatures naturally or to reduce the need for artificial conditioning to a minimum.

This reduces the risk of damage as the building itself acts as a temperature moderator, rather the reliance of mechanical equipment and continuous energy use.

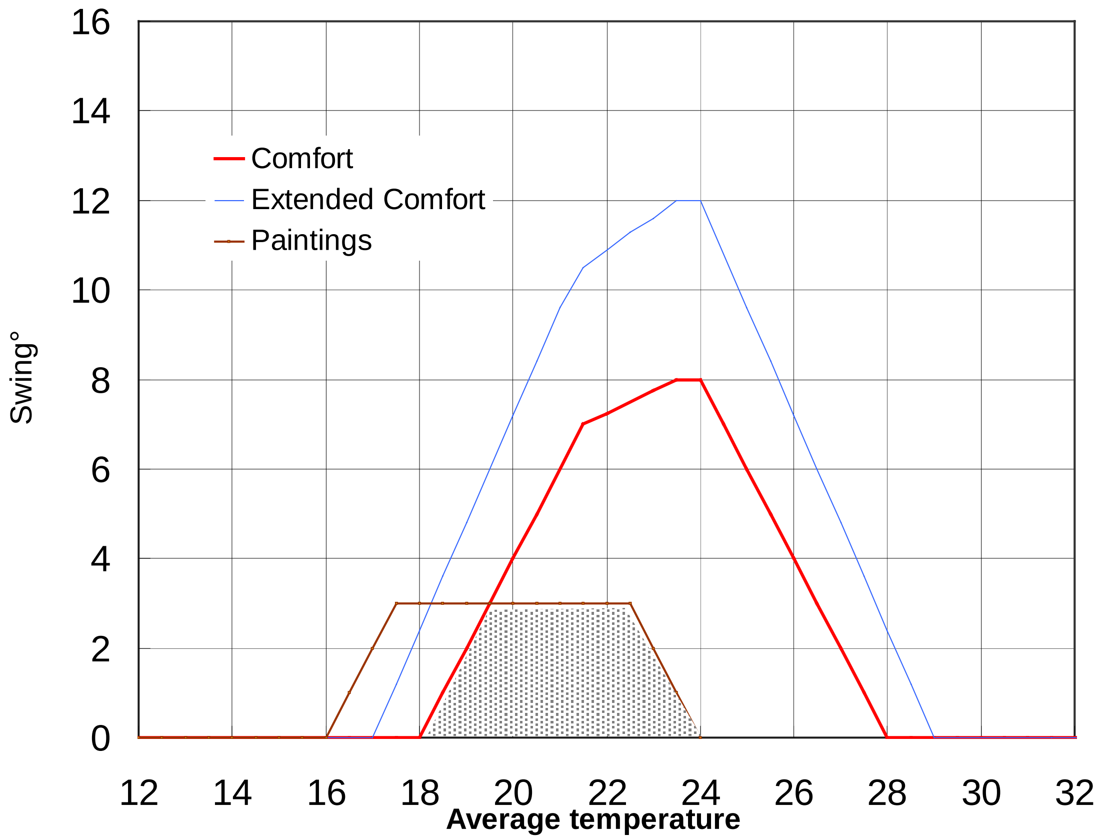


Figure 7.12. Zones for thermal comfort of visitors and conservation of paintings.

7.7.3 Application in fauna.

Animals, even cold bloodied, also require thermal conditions within certain limits that can be defined with the aid of comfort triangles. This is especially important for the incubation of eggs of birds, fish and reptiles which must be maintained within strict limits during extended periods. The conditions within sheds for the intensive rearing of birds and cattle must also be controlled to reduce mortality and improve productivity.

A specific case considered here as an application example is the design of an incubator for jacarés, a South American specie of alligator, requiring temperatures and humidity within strict limits (Evans, 1997). The design conditions required in the incubator are an average temperature of 31° C, with a maximum variation of 4 degrees to ensure the survival of the eggs. The average temperature also affects the proportion of jacarés of each sex. However, there is a reduction of the birth rate when the swing exceeds 2 degrees. The relative humidity must also be maintained between 90 and 100 %, to avoid drying of the eggs.

These conditions were achieved using 10 m^2 of flat plate solar collectors to heat water and a small photovoltaic panel to generate electricity for the pump and control system. The incubator was installed in a room of 3m x 3m x 2,6 m high, with solid brick walls of 15 cm, two of which are exposed to the outdoor air, both painted white.

The Jacaré Comfort Triangle show the need to maintain the temperature difference of 4 degrees between the required indoor average of 31° C and the average summer outdoor temperature of 27° C in the Chaco region, on the Parana River, in the North of Argentina, 50 km north-west of the city of Resistencia.

The energy demand could be reduced by incorporating thermal insulation, in this case 12 cm of polyurethane sprayed on to the inside of the walls and ceiling. The swing also had to be reduced from an average of 13 degrees outdoors to a value of 2 degrees indoors. Large quantities of water in four 600 litre barrels were used to reduce the indoor swing absorbing heat when the temperature rises and returning heat when the temperature falls.

The system, designed under the direction of the author following a cooperation agreement between the Faculty of Architecture, Design and Urbanism of the University of Buenos Aires and the Argentine Wild Life Foundation, has been in operation for 8 years with favourable results, achieving a survival rate of about 90 %, much higher than the 25 % achieved in nature.

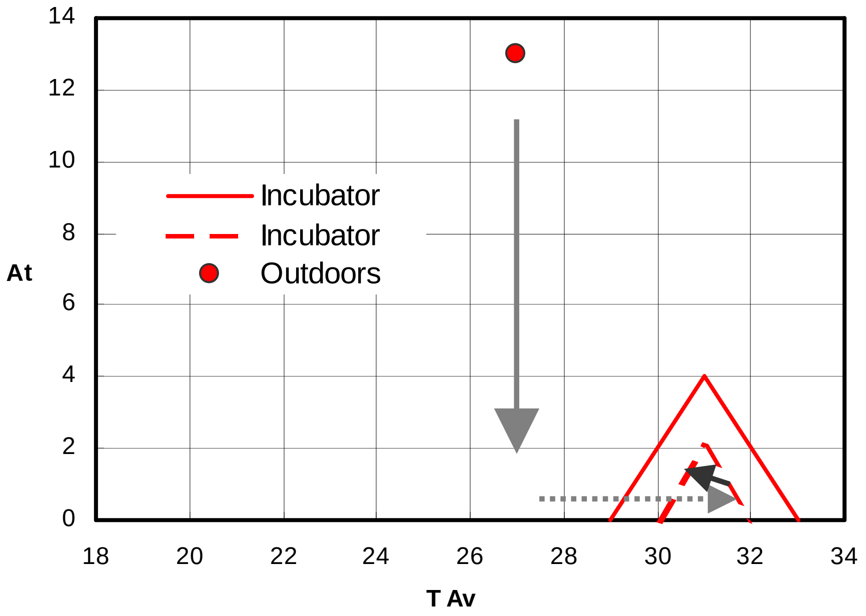


Figure 7.13. Average outdoor temperature variation in summer in Chaco (red circle), compared with the required temperature limits in the incubator, extreme (solid line) and recommended (dotted line). The vertical grey arrow shows the reduction of swing achieved with thermal inertia, the dotted horizontal line shows the heating effect using solar energy and the black arrow shows the slight reduction as a result of evaporation to obtain the necessary relative humidity in the incubator.

The Comfort Triangles may also be used in applications such as rearing of chickens, cattle and other animals. The temperature for poultry incubators should be maintained within 37,4 to 37,7, with an optimum average of 37,5 and a maximum swing of 1 degree. Swings of more that 2,5 degrees can be lethal. In this case, humidities between 55 and 60 % are required, though they should be increased to 70 % for the final 3-4 days of the incubation period (Hermes, 1995).

Unlike the jacaré eggs which should be maintained in the same position, poultry eggs should be turned back and forth three time a day. The incubation period is also shorter, between 20 and 30 days (University of Saskatchewan, 1987). During the period of egg production, hens require a temperature between 12 and 26° C, lower increase feed intake to compensate for heat losses as temperatures should never drop below freezing.

Once again the Comfort Triangles proves to be valuable graphic tool to show the design conditions and relate these to the typical outdoor variations.

7.8. CONCLUSIONS

The Comfort Triangles were developed with a series of improvements and adjustments from the initial conception in 1989 to the latest version presented in this chapter. In this chapter the antecedents of the method and identification of the concepts are presented to establish the comfort limits in the graph and to show the range of applications of the comfort conditions with periodic heat flow.

The application of the Comfort Triangles was tested by graduate and postgraduate students over a period of 20 years. The triangles were found to be a valuable tool to explain the thermal performance of passive solar systems and to select alternative building options to make use of solar energy in architecture. The most relevant aim of the Comfort Triangles is to provide support and facilitate the understanding of the complex variation of temperature in the interior areas of buildings, compared with the external variations. This understanding and visualisation provides a useful design tool to help defining strategies of natural conditioning and selecting bioclimatic recourses to achieve favourable modification of the conditions.

The Comfort Triangles are therefore proposed as a design guide to evaluate the variation of thermal conditions during a 24 hour cycle, while comparing the desirable conditions, the external conditions and the potential modification of these conditions through bioclimatic design strategies at different scales.

One possible criticism of the Comfort Triangles concept is the exclusion of relative humidity as a variable. To respond to this omission, there are various reasons that can be put forward to justify this simplification.

- Many other comfort diagrams also omit relevant variables in the need to present graphs in 2 dimensions: both Olgyay's comfort graph (1963, 1998) and Givoni's graph (1976) omit both air movement and radiation, adding these variables as alternative comfort zones.
- As Balaras (1996, p 151) states 'simple indices such as air temperature appear to be, in some cases, as good as more complex indices'.
- As is shown in this and the following chapters, the variable $\mathbf{A_t}$, temperature range is an indirect indicator of humidity, with higher outdoor temperature ranges in drier climates and lower values in humid climates.

The concept of the Comfort Triangles, developed here to define thermal comfort for indoor spaces, can also be used to evaluate and define the acceptability of temperature swings in other applications, as the next chapter demonstrates.

CHAPTER 8. CLIMATE ANALYSIS USING THE COMFORT TRIANGLES

8.1. INTRODUCTION

The use of the Comfort Triangles to define limits of indoor comfort, developed in the previous chapter, also allow the comfort zone to be related to the external climate conditions.

This chapter, therefore, shows the way in which the outdoor temperature swing and the average outdoor temperature can be related to the conditions required for comfort. As it is shown, the outdoor conditions rarely fall within the comfort zone, so measures are required to modify the outdoor temperatures, preferably through the choice of appropriate thermal characteristics of the building envelope.

Indeed it is an objective of this thesis and the development of the Comfort Triangle Tool to promote the use of passive measures incorporated in the architectural design to achieve a favourable modification of the thermal conditions.

The first step in this analysis is to determine the changes that the building skin should promote to favour more comfortable indoor conditions. This can be defined in terms of the change required in the average temperature and the desirable reduction in the temperature swing.

In this context, three basic alternative strategies can be defined:

- Increasing the average temperature in cold climates.
- Reducing the average temperature in warm climates.
- Moderating the temperature swing in climate with high diurnal range.

In practice, the outdoor climate will normally require a combination of two different strategies, for example, the increase of average temperature and the reduction of the temperature swing.

For passive design, the challenge is to detect the thermal characteristics of the building that will achieve the best modification of external conditions, considering the changing requirements in different seasons of the year.

Therefore, the object of this chapter is to demonstrate use of the Comfort Triangles in climatic analysis for bioclimatic design, with the following studies:

- Demonstrate that the mean between the maximum and minimum temperature, proposed in the previous chapter is sufficiently close to the average of the hourly temperatures for use in climate evaluation.
- Show the visual relation between the external climate and the desirable indoor conditions, defined by the Comfort Triangles.
- Compare the average monthly temperature and temperature swings in different climates to show the characteristic climatic signatures in different regions.
- Evaluate the differences between the average monthly conditions and the daily conditions of average temperature and temperature swing.

8.2. CLIMATE AND THE COMFORT TRIANGLES

In the previous chapter, the mean of the maximum and minimum daily temperature was proposed for the application of the Comfort Triangle concept. However, this may differ from the average of the hourly values. To evaluate the consequences and degree of possible error by applying this simplification, the climate data recorded in different meteorological stations have been analysed.

8.2.1. Data from Buenos Aires.

In a first study, data from the meteorological station located on the roof terrace of the Faculty of Architecture, Design and Urbanism, University of Buenos Aires, and data from the nearby station of Aeroparque, the Buenos Aires domestic airport, were used to compare the monthly average of the hourly temperatures with the average of the daily maximums and minimums for the same month.

The typical curves for the months of January, with the sinusoidal curve, as shown in Figure 8.1., are also included to compare the *ideal* with the *real* temperature variation.

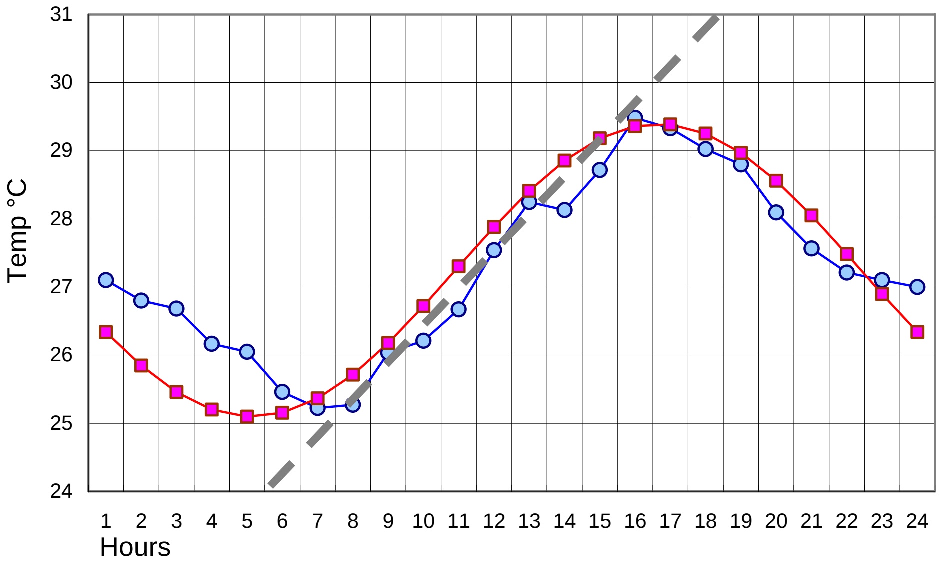


Figure 8.1 Average hourly temperatures, Aeroparque, Buenos Aires, for January 2000, with the sinusoidal variation and equivalent temperature variation ramp.

The difference between average of the maximum and minimum daily temperature and the average of the hourly temperatures for the same period is typically less than 3 % of the swing for the same period. This difference of less that 0,5° C is not significant in terms of the variation that can be detected by human thermal subjective sensation, about 0,8° C.

This difference is a consequence of the mechanism that produces the temperature swings. In the morning, there is typically a rapid heating of the earth's surface due to the incident solar radiation from sunrise to midday. The solar radiation continues to heat the earth's surface until 2 to 3 hours after midday, solar time, although the intensity of solar radiation starts to drop. From mid afternoon the temperature drop is more gradual as the air temperature is still high. The drop in temperature continues throughout the night, as the earth's surface loses heat to the cold night sky, reaching a minimum just before sunrise.

Thus the variation in daily temperature reflects the thermal inertia of the earth's surface and the difference between the sinusoidal variation in heat gain from solar radiation during the day and the steady cooling of the earth surface without significant variations during the night.

It is noted that various methods used for the analysis of periodic heat flow are based on the concept of sinusoidal variation, such as the admittance method (CIBSE, 1980) and the time constant method (Matthews and Richards, 1993).

8.3. ANALYSIS OF DAILY DATA

In this section, the average temperature and the temperture swing in three different climates are analysed:

- Buenos Aires, Argentina: hourly data in a sub-tropical temperate climate recorded during one year on the roof of the faculty.
- Jubail, Saudi Arabia: average hourly temperature for each month of the year recorded during a year on the site o a new town in a martime desert climate.
- Yerivan, Armenia: hourly data in a continental climate recorded during one year.

8.3.1. Buenos Aires

The data set for an analysis of daily data was recorded in the roof terrace of the Faculty of Architecture, Design and Urbanism, University of Buenos Aires. The data was recorded using a Li-1400 Licor portable data-logger, housed in a specially designed station for recording illuminance, irradiance, temperature and relative humidity.

The temperature data were recorded every half hour and the data shown here are for the second half of 1999. The advantage of using half a years data is that the individual data can be seen more clearly. The 193 data pairs obtained, with only 10 days missing, are the daily average and the daily swing, for a conventional day starting with 0 and finishing at midnight, 24 hours.

Figure 8.2. shows the maximum, average and minimum temperatures for the sequence of days. The general trend of increasing temperature can be seen, from the low average temperatures in June, winter in the summer hemisphere to around 24º C in the end of December at the start of summer.

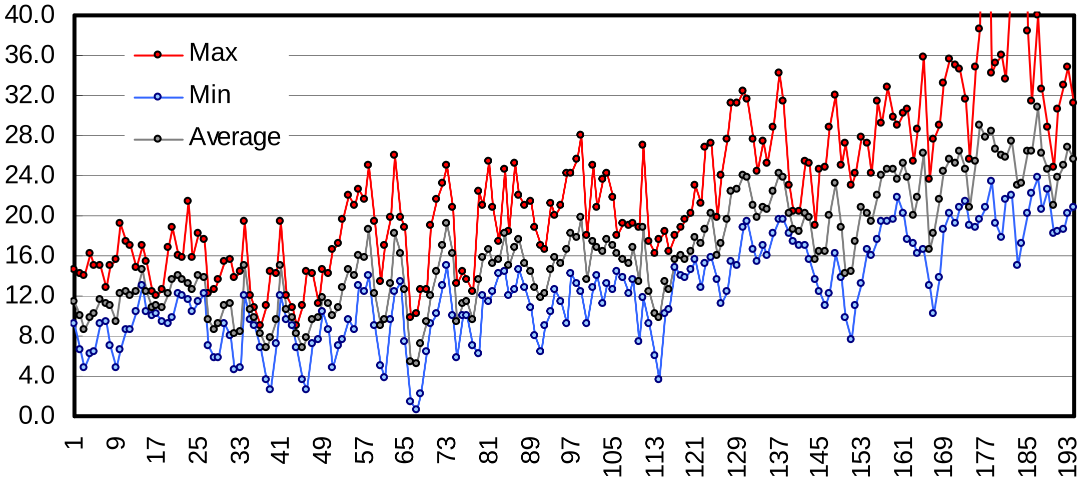


Figure 8.2. Maximum, average and minimum daily temperatures for Buenos Aires, based on measurements made in the roof of the Faculty of Architecture, FADU-UBA.

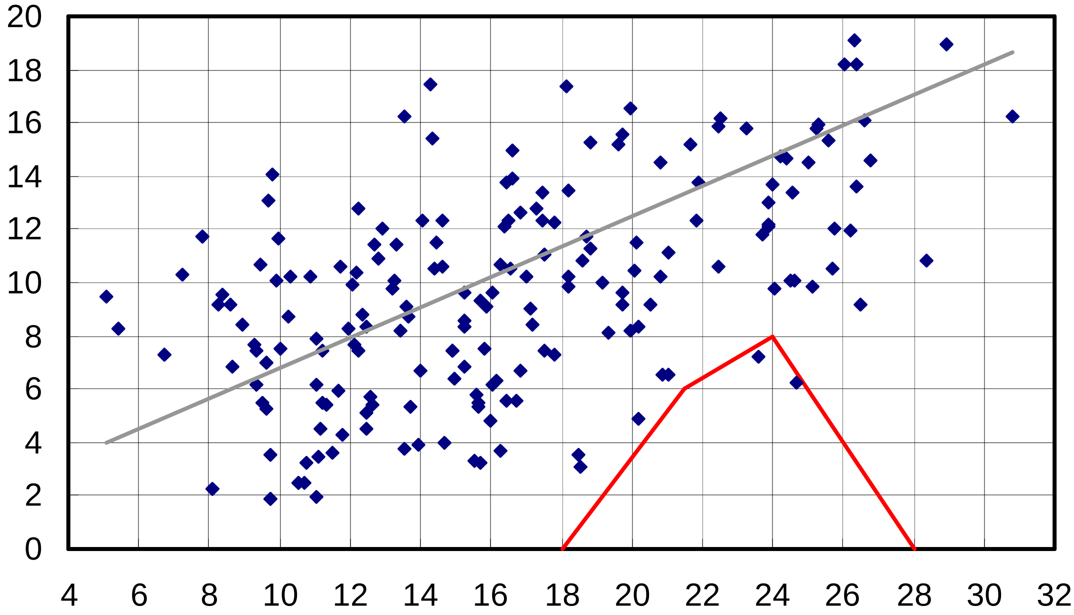


Figure 8.3. Data of average average temperature and daily temperature swing for 1999, Buenos Aires, Argentina

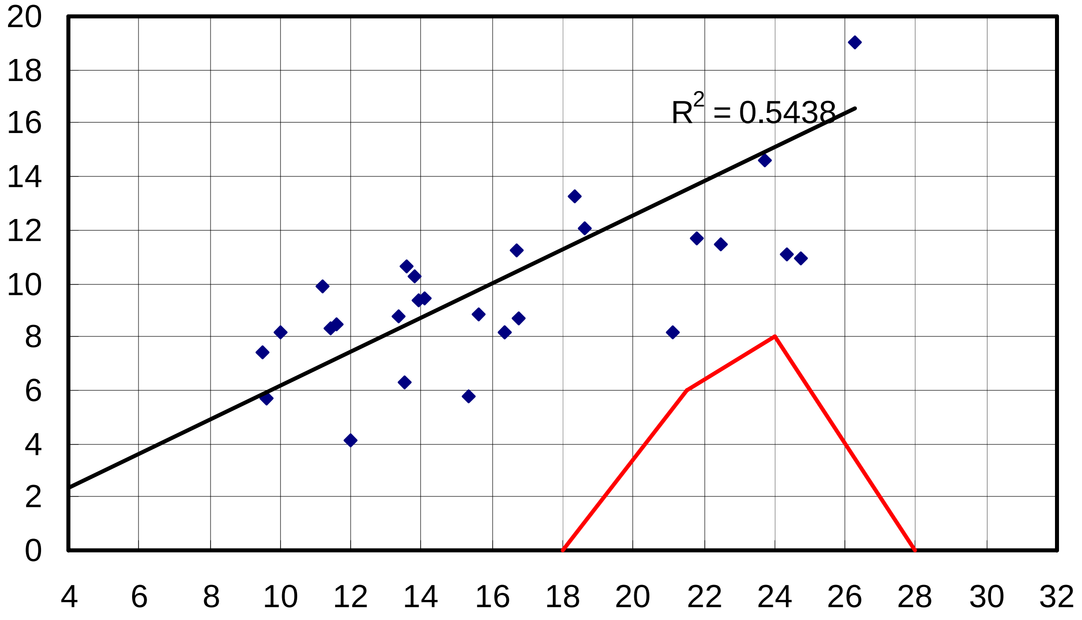


Figure 8.4. Increase in temperature swing related to increasing average temperature using average weekly values.

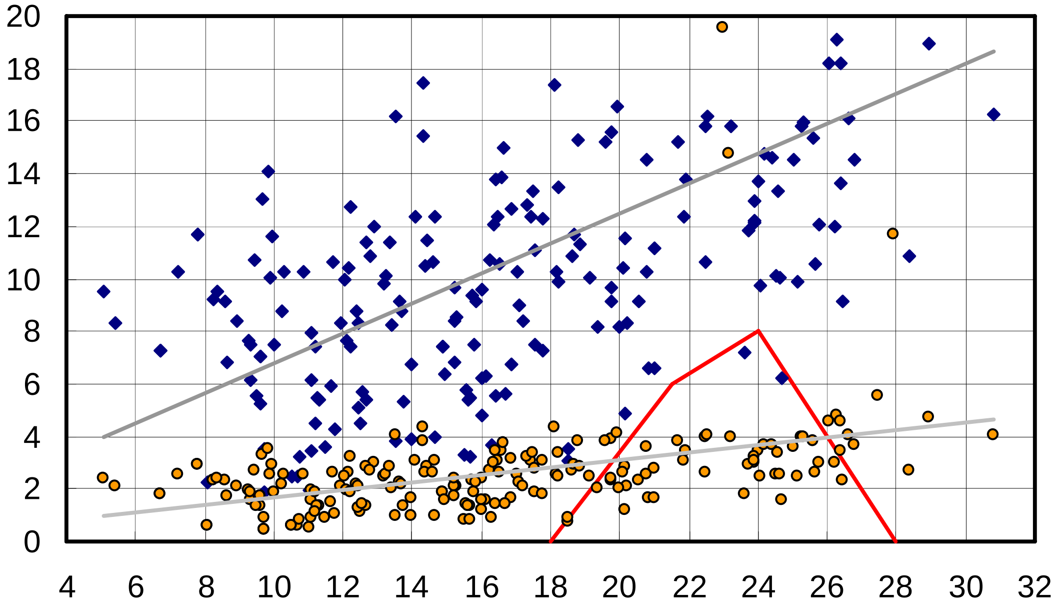


Figure 8.5. Plot of average temperature and thermal swing for Buenos Aires in blue circles, showing the effect of thermal mass to reduce the external temperature swing by 60%, in orange circles.

Figure 8.3 shows the range of conditions for days during 1999 in Buenos Aires; each point represents the range of conditions on a day. The grey trend line of the graph confirms the increase of average temperature swing as average temperatures rise. When weekly averages are used, Figure 8.4, the slope of the trend line is steeper. Finally, Figure 8,5 shows how the moderating effect of thermal mass, reducing the temperature swing by 60 %, achieves comfort in the summer months, except for the hottest days. Most of these are very close to the comfort zone, so air movement can achieve comfort.

8.3.2. Jubail, Saudi Arabia.

The month data for the City of Jubail, Saudi Arabia, is shown in Figure 8.6. In this maritime desert climate the daily swing is low, ranging from 6° C in winter to almost 12° C in summer, due to the moderating influence of the Arabian Gulf. The average monthly temperature swing increases as average temperatures rise in summer.

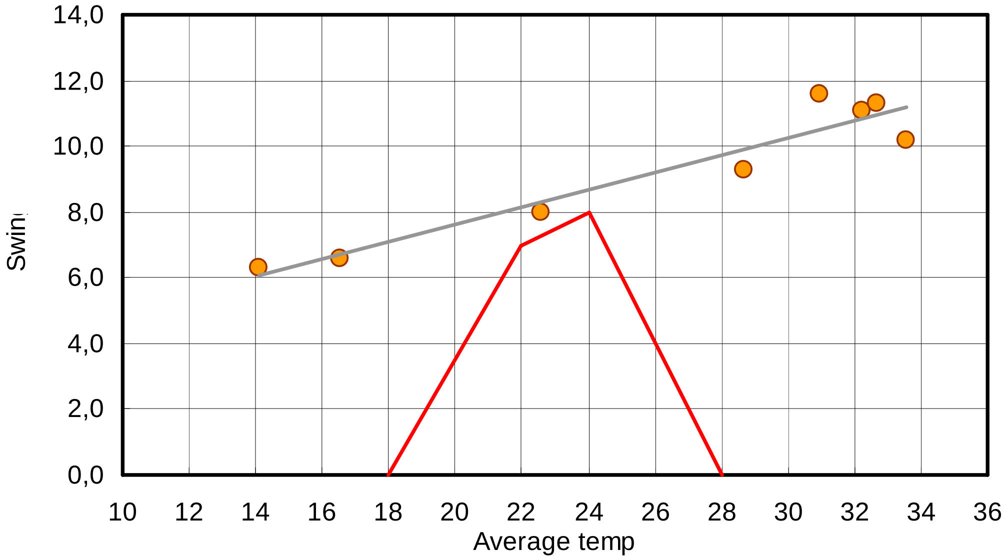


Figure 8.6. Data for Jubail, Saudi Arabia

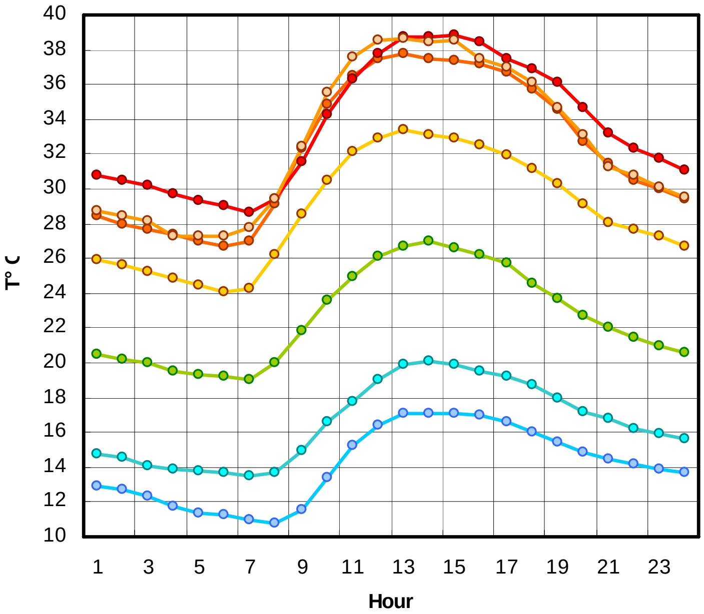


Figure 8.7. Average daily temperatures for different months, Jubail, Saudi Arabia.

8.3.3. Yerivan, Armenia

This sub-section shows the application of the Comfort Triangle concept comparing the use of monthly averages with the use of daily values in the cold continental climate of Yerivan, Armenia.

The dots in Figure 8.8. represent the relationship between the monthly average temperature and the temperature swing. It is relevant to note that there is a tendency to increase the swing as temperatures increase. This example uses daily meteorological data from a continental climate in Armenia, the month average swing increases from 7 to 14 degrees as the average monthly temperature increases from –5 to 28º C. This increase can be explained by the high solar radiation in summer months which produces a rise in the temperature swing. However, the average monthly temperatures are a simplification of the daily values. Figure 8.9. shows the daily values of average temperature and temperature swing for the same climatic data shown in Figure 8.7. Naturally the scatter is much greater although the general tendency is still clear, with an increase in the swing corresponding to higher average temperatures.

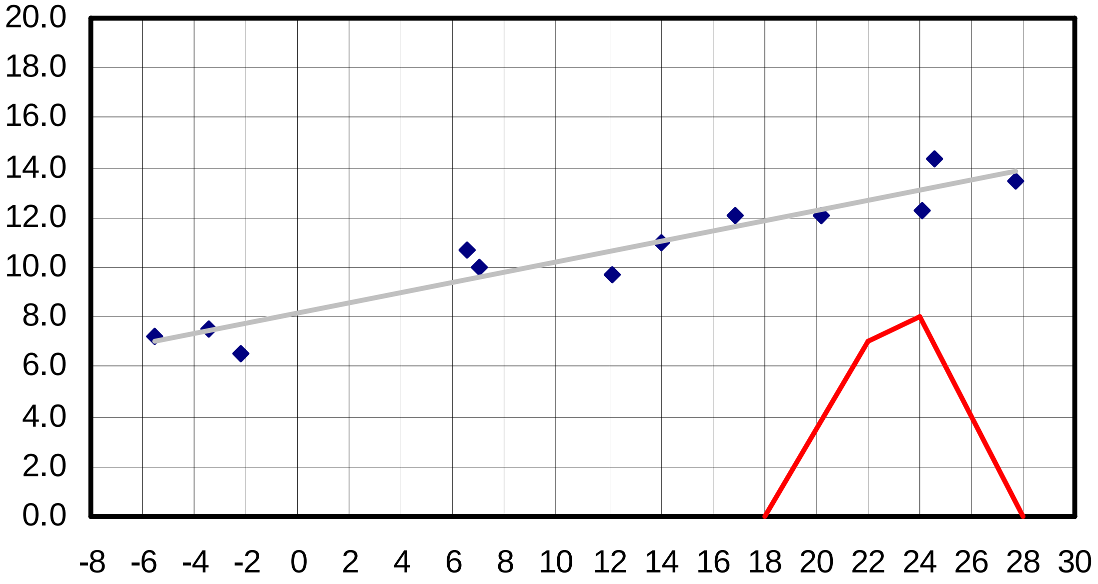


Figure 8.8. Average monthly temperatures and temperature swings: example for a continental climate, Yerevan, Armenia.

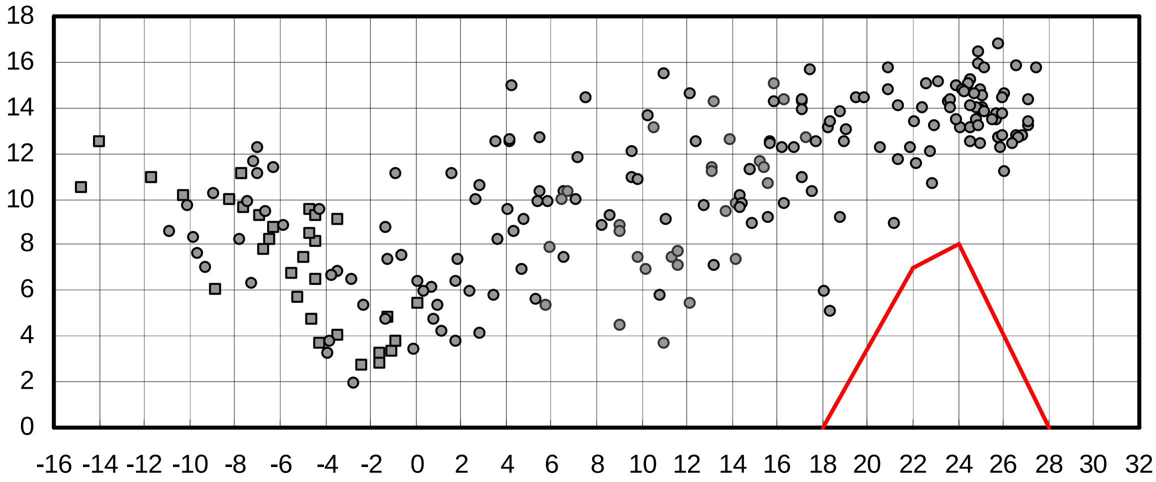


Figure 8.9. Daily temperature conditions; average temperatures and temperature swings. An example for a continental climate, Yerevan, Armenia.

When the daily values for each month are examined as individual sets, a different picture emerges as shown in Figure 8.10.

In the cold months 1 and 2, the temperature swing rises with decreasing temperatures, while in the warmer months 5, 6 and 7, the temperature swing rises with rising temperature. The blue lines to the left of Figure 8.10, representing the tendency in cold conditions show the rise in swing in very cold days.

Two possible reasons for this tendency are as follows: in cloudy days with overcast skies, the solar radiation is reduced but so is the outgoing night radiation, while on nights with clear skies, outgoing radiation produces a more severe temperature drop. Alternatively, the higher swings are the result of sudden inflows of colder air from the north. This explains drops in average temperature but not the increased swings, unless associated with clear skies and solar radiation by day.

.

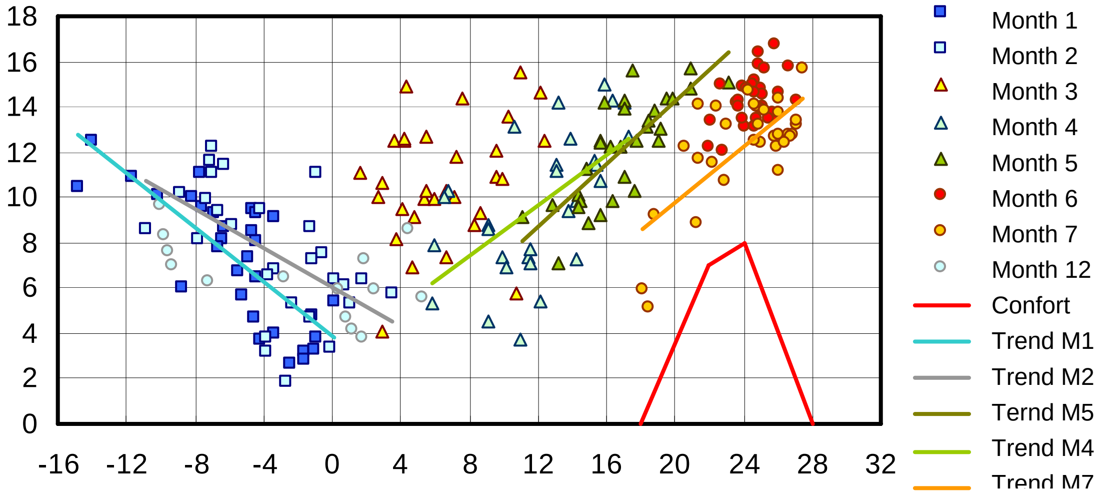


Figure 8.10. Daily data for different months in Yerevan, Armenia showing tendencies

In summer months in the same climate, the tendency is opposite: higher temperatures are associated with higher swings as the yellow and green lines in Figure 8.10. show.

The following question arises: Is the difference between the scatter of individual days and the monthly averages significant for the selection of bioclimatic design strategies? In summer months, the average temperatures are within the comfort range, so a reduction in temperature swing is required. A reduction to 30 % of the outdoor swing will bring all days within or very close to the comfort zone.

In the colder winter months, conventional heating will be required, as passive solar design will not be able to provide sufficient heat when temperatures are below freezing (Balcomb and Macfarland, 1980). With artificial or conventional heating, the high temperature swings in the coldest days can be resolved. However, the reduction of the temperature swing required in summer will also be favourable in winter, as the thermal mass involved will reduce the impact of the severe drop in winter night temperatures.

8.4. TEMPERATURE SWING AND HUMIDITY

A possible criticisms of the comfort triangles, compared with other bioclimatic comfort graphs, is the lack of relative humidity as a variable. This was mentioned in the final section of the previous chapter. In this section the relation between the relative humidity and the temperature swing are explored to determine the relation between the two. The relation between the average monthly temperature swing and average monthly relative humidity is shown in Figure 8.11., using data from 10 different meteorological stations in different representative climatic regions of Argentina. Despite the wide scatter, the lower relative humidity are related to the higher temperatures swings. Figure 8.12 shows a difference between months with average temperatures below and above 20°C, with the months of lower temperature showing very high swings. This is due to the very strong influence of the high upland climates of the Andes, with very large temperature swings, exceeding 24 degrees in the coldest months.

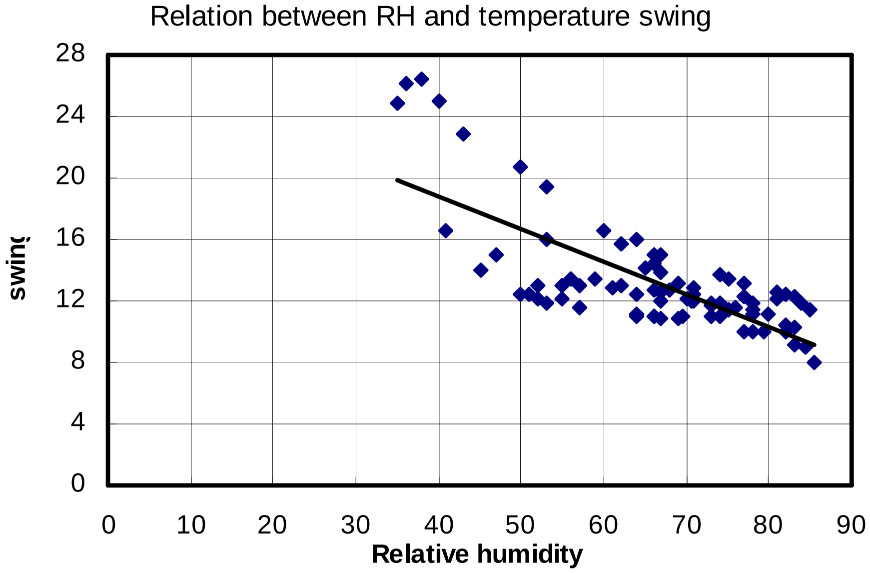


Figure 8.11. General tendency of decreasing temperature swings with increasing relative humidity.

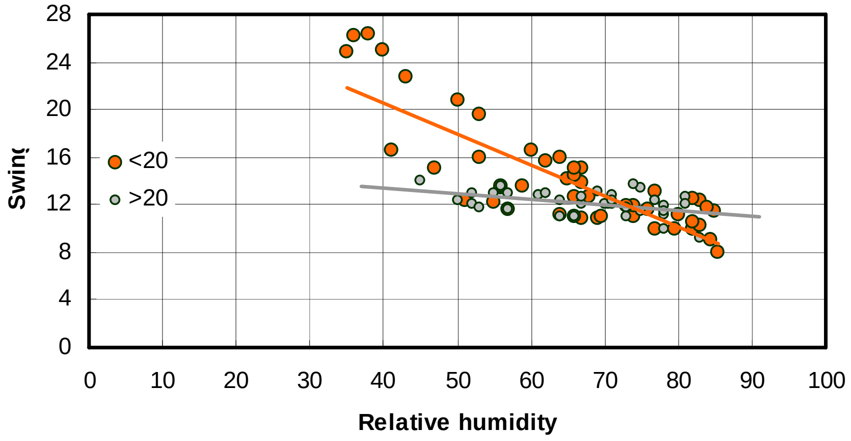


Figure 8.12. Temperature swing and relative humidity for average temperatures below and above 20° C.

If minimum relative humidity, coinciding with the maximum temperature is considered, the relation between temperature swing and humidity is much clearer with a strong relation between minimum RH and swing. It should be stressed that the humidity just after midday, with maximum temperatures, is more critical for comfort..

8.5. CLIMATE SIGNATURES

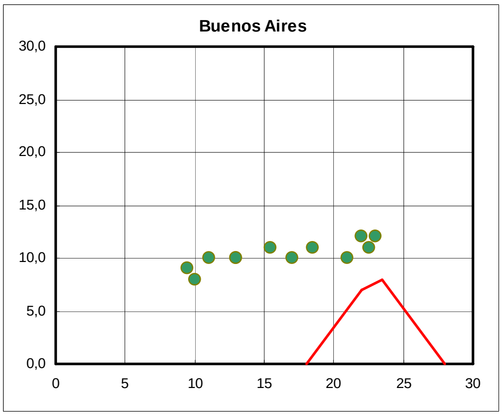


Figure 8.13. Signature, Buenos Aires, Argentina: temperate sub-tropical climate.

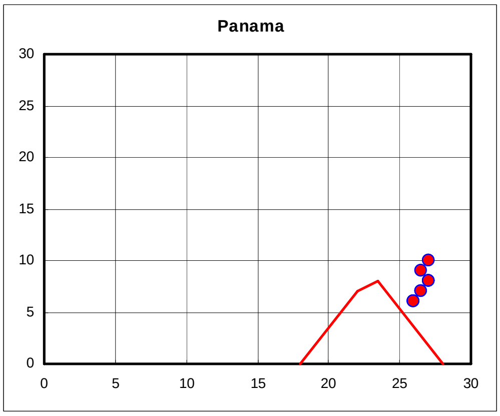


Figure 8.14. Signature, Panama City: warm humid equatorial climate.

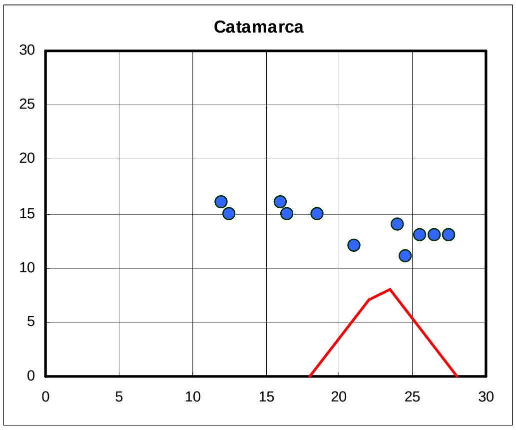


Figure 8.15. Signature, Catamarca, Argentina; hot dry sub-tropical climate.

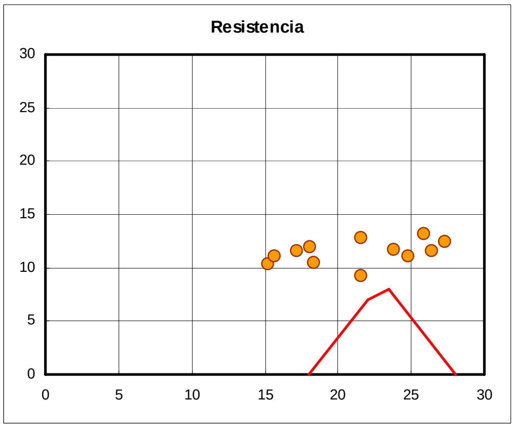


Figure 8.16. Signature, Resistencia, Chaco, Argentina: warm sub-tropical climate.

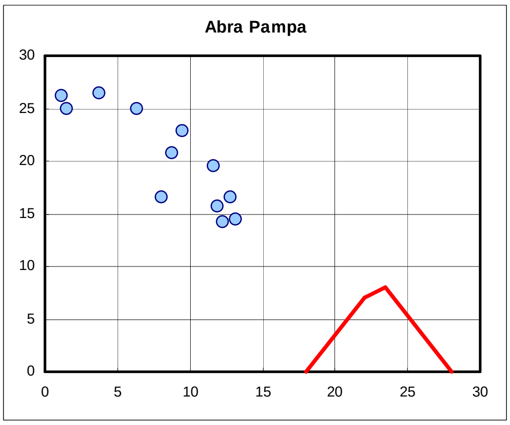


Figure 8.17. Signiture: Abra Pampa, Argentina: tropical upland at 3600 m

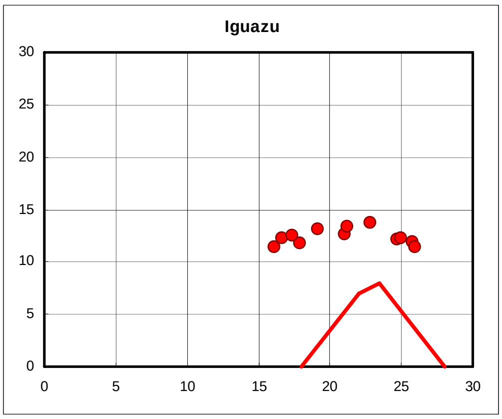


Figure 8.18. Signiture, Iguazu, Argentina: warm sub-tropical climate

Figures 8.13 to 8.18 show monthly data for different climates on the Comfort Triangles, with the extremes of the equatorial warm humid climate of Panama and the upland climate of Abra Pampa, as well as the more subtle differences between similar climates

8.6. COMFORT AND CLIMATE CHANGE

One important contribution of the Comfort Triangles is the demonstration of the impact of climate change and global warming on human comfort. As temperatures drop, the heat losses from the body can be controlled and reduced by more layers of insulating clothing or the better insulation of buildings. Strategies such as compact building form, taking advantage of solar gains and better thermal insulation can promote or improve comfort without requiring more conventional energy use.

However, as temperatures rise, the body has greater difficulty to lose metabolic heat. As was shown in Figure 7.6, Chapter 7, skin temperature must be below body temperature and air temperature must be below skin temperature in order to maintain the thermal equilibrium of the body. In dry climates, evaporation of transpiration can be used to promote heat loss, allowing higher air temperatures, but there are limits to this mechanism. Excessive sweat loss bring danger of dehydration and disturbs the balance of body heat control, while high sweat rates with wet skin are also produce discomfort.

If peak temperatures are above comfort and temperature swings are significant, thermal inertia and selective ventilation can be used to provide comfortable conditions indoors, as the next chapter shows. However as average air temperatures reach the skin temperature, it is much more difficult to maintain the thermal equilibrium of the body and achieve comfort. Thus global climate change may create regions where thermal comfort is only possible with refrigeration. A further problem related to increasing temperatures is the difficulty of removing heat from deep plan buildings with high internal heat loads. Buildings such as offices, hospitals and commercial centres have significant internal gains from occupants, lighting and equipment.

As already commented in Chapter 5, these complex deep plan buildings may allow lower costs per occupant, but increase energy demand. At low temperatures, heat can be removed by ventilation. As outdoor temperatures rise, artificial ventilation may be required to remove heat more rapidly. Finally, artificial cooling and ventilation will be needed to avoid discomfort in the deep core areas.

8.7. CONCLUSIONS

This chapter show how the climatic data can be visualised using the same variables used in the comfort triangles, average temperature and temperature swing. The average monthly data and the daily values are compared to show specific aspects of the climate. The relation between temperature swing and humidity are also analysed to show how the swing is an indicator of relative humidity levels.

In the next chapter, the mechanisms to modify indoor climate are described and analysed, using the same variables as those used in this and the previous chapter, raising or lowering average temperatures and reducing temperature swings.

CHAPTER 9. PASSIVE STRATEGIES TO ACHIEVE COMFORT

9.1. INTRODUCTION

The previous two chapters presented the definition of the comfort zone in terms of the average daily temperature and the daily temperature swing, and the relation with the climate conditions. In this chapter, the passive strategies to achieve comfort are presented, modifying the external climatic conditions to improve thermal comfort using the thermal characteristics of the building envelope and other strategies such as ventilation.

Therefore, the object of this chapter is to complete the analysis of bioclimatic design strategies, complementing the comfort analysis and the evaluation of climate with the study of alternative bioclimatic design strategies in order to show how they can modify the external climatic conditions in order to improve indoor comfort, acting as a filter, moderator or amplifier to reduce the indoor temperature swing and increase or reduce the average temperature.

In this chapter, the bioclimatic design strategies are divided into various categories according to the way in which the building and users can improve or maintain indoor thermal comfort:

- Strategies to **reduce the average temperature**, applied when the external average temperatures are above the comfort zone, including strategies that reduce the apparent air temperature.
- Strategies to **avoid an increase in the average temperature** when the external average temperatures are above or close to the upper limit of the comfort zone
- Strategies to **reduce the indoor temperature swing** when the outdoor swing is greater than the maximum indoor swing required to maintain comfort.
- Strategies to **avoid an increase in the indoor temperature swing** when the outdoor swing is greater than the maximum indoor swing required to maintain comfort.
- Strategies to **increase the average temperature**, applied when the external average temperatures are below the comfort zone.
- Strategies to **avoid a decrease in the average temperature** when the external average temperatures are above or close to the upper limit of the comfort zone

In most cases there are also combinations of strategies, for example to increase the average indoor temperature and the reduce the swing simultaneously. Most passive solar heating strategies apply this combination in order to raise temperatures while avoiding peaks of overheating. As this chapter shows, the strategies of selective ventilation can also reduce the average temperature and the temperature swing.

Although the emphasis in this chapter is indoor comfort, there are measures and strategies to modify conditions in outdoor spaces, achieving a favourable modification of external microclimate. Examples of this modification will be presented in the case studies in Part 4 of this thesis.

At the end of this chapter, examples will be given of the analysis of climate data series to show how the percentage of days during a year when different bioclimatic design strategies can achieve comfortable conditions, using the Comfort Triangles concept.

The next section of the chapter present an analysis of the strategies and illustrates the environmental modifications achieved using the Comfort Triangles diagram.

9.2. BIOCLIMATIC DESIGN STRATEGIES

This thesis argues that bioclimatic design strategies can be classified according to the way in which the average indoor temperature and temperature swing are modified.

The following sub-sections illustrate the different ways in which this modification can be achieved.

Figure 9.1. shows the objectives of the bioclimatic design strategies described in this section, in order to approach or archive comfort by decreasing the average temperature (Sub-section 9.2.1) reducing the indoor temperature swing (Sub-section 9.2.3.) or increasing the average indoor temperature (Sub-section 9.2.5).

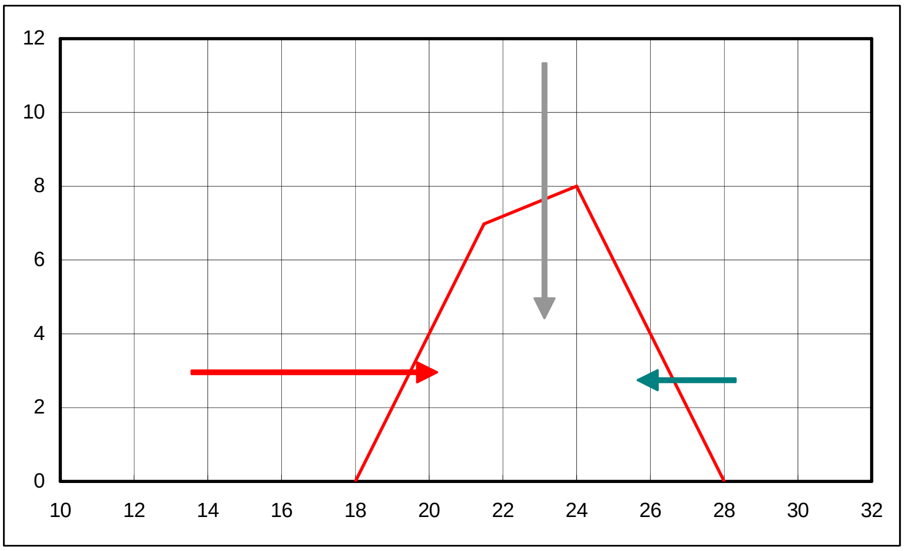


Figure 9.1. Three favourable modifications of the external conditions to achieve more favourable comfort conditions:

- Blue arrow (right): decrease of the average temperature (Sub-section 9.2.1.)
- Grey arrow (upper): reduction of the temperature swing (Sub-section 9.2.3.).
- Orange arrow (left): increase of the average temperature (Sub-section 9.2.5.).

Figure 9.2. shows the complementary strategies adopted to avoid increases on indoor comfort; avoidance of increase in average temperature (Sub-section 9.2.2.), avoidance of increase in the indoor temperature swing (Sub-section 9.2.4.) and avoidance of decrease in the average temperature (Sub-section 9.2.6.).

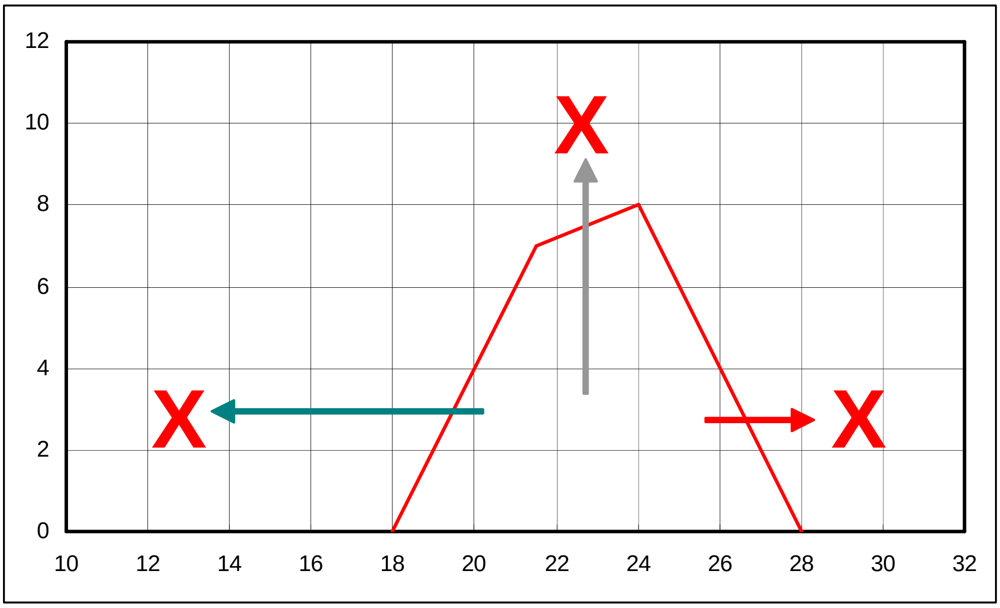


Figure 9.2. Three strategies to modify external conditions to avoid external impacts that increase discomfort :

- Orange arrow (right): avoidance of increased in average temperature (Sub-section 9.2.2.).
- Grey arrow (upper): avoidance of increase in temperature swing (Sub-section 9.2.4.).
- Green arrow (left): avoidance of decrease in average temperature (Sub-section 9.2.6.).

9.2.1. Reduction of the average indoor temperature and apparent temperature.

In hot conditions when the average outdoor temperatures are above the levels required for comfort, there are two mechanisms to achieve comfort: produce a drop in air temperature or an apparent drop in temperature. Air movement is an example of the second mechanism, where the air temperature is not reduced, but a cooling effect due to improved heat dissipation and evaporation of transpiration on the skin can produce a cooling effect.

Air movement: One of the principal strategies to reduce the apparent indoor temperature is the use of cross ventilation or sensible air movement. An indoor velocity of about 1 m/s can reduce the thermal sensation or the apparent temperature by up to 2°C (Evans and de Schiller, 1994). However, when this is achieved using cross ventilation, the high ventilation rates may reduce the possibility of reducing the temperature swing as the air movement introduces outdoor air, and produces indoor swings closer to the outdoor swing.

Night radiation: On nights with clear skies and hot temperatures, the out-going radiation to the cold sky can reduce the air temperature and the thermal sensation in outdoor spaces. Various authors have shown how this cooled air can the used in courtyard houses (Dunham, 1968; Fathy, 1972; Al Azzawi, 1990) to reduce the average indoor temperature. Average reductions of 4° can be achieved in indoor spaces under favourable conditions.

Selective ventilation: The variation of ventilation rates at different times of the day, increasing cooling when air temperatures are lower at night can achieve a significant reduction in the average

All of these strategies may be intermittent, as they are dependant on the variation of conditions at different times of the day. Air movement will typically be most needed at midday when temperatures are higher, while radiation to a cold night sky is only effective in the hours of darkness.

9.2.2. Avoidance of increase in the average indoor temperature.

In addition to the strategies to reduce air temperature, real or apparent, complementary strategies must be applied to avoid climatic impacts that can increase discomfort and raise indoor temperatures.

Solar protection: To avoid an increase of average indoor temperatures, solar protection is essential as radiation through glazed openings can increase the average indoor temperature during a daily cycle of temperature variation in up to 10° or even more in unfavourable design situations.

Selective ventilation: In addition to cooling by night ventilation, the reduction of the ingress of hot air at midday helps to avoid an increase in the maximum day temperature as well as controlling the average indoor temperature.

Control of internal heat gains: Internal heat gains due to occupants, artificial illumination and other internal sources of heat will raise the average internal temperature. A reduction of these gains, for example, by the use of more efficient lighting installations, can help to avoid the rise in internal temperature.

9.2.3. Reduction of indoor temperature swing.

Internal thermal inertia: The use of high thermal mass in the inside of the building will reduce the indoor temperature swing, acting as a ‘thermal sponge’ absorbing heat as the temperature rises, while releasing heat as the temperature falls. In a building with a well insulated external envelope, the addition of internal mass can reduce the temperature swing by up to 80% of the external swing.

External thermal inertia: The external envelope with high thermal mass will delay and reduce the conduction of heat to the interior of the building by day as well as reducing the night time losses. Typically, heavyweight walls and roofs can reduce the internal surface temperature swings by 70%. A combination of thermal mass in the building envelope and internal walls can reduce the internal temperature swing even more, as is show in the case study in the Central University of Ecuador, Quito, in the next part of the thesis.

Selective ventilation and ventilation control: A reduction of day ventilation will tend to reduce the internal swing due to the variation in outdoor air temperature. A general reduction in the ventilation rate will also contribute to a reduction in the indoor temperature swing.

9.2.4. Avoidance of indoor temperature swing increases.

Solar protection: The solar heat gains by day and the lack of night time gains will increase the temperature swing. Therefore solar protection will provide a mayor contribution to the avoidance of indoor temperature swings, as well as reducing the average indoor temperature.

Controlled ventilation: High levels of ventilation will produce internal temperatures closer to the external temperatures. Thus a reduction of the ventilation rate will help to avoid an increase in the indoor temperature swing. When thermal inertia is used to reduce indoor swings, a high ventilation rate will cause a short circuit, increasing the indoor swing again.

9.2.5. Increase of average indoor temperatures.

Solar heat gains: The use of passive solar systems can increase the average indoor temperature by up to 10°C, though this is also dependent on the simultaneous conservation of the heat gains using a well insulated building envelope and minimum ventilation.

Conservation of internal heat gains: The use of adequate thermal insulation in the building envelope will reduce heat losses, permitting the use of internal heat gains to increase the average internal temperature. It should be noted that the increase achieved depends on the magnitude of the internal gains and the levels of thermal insulation. The use of energy efficient equipment will require a corresponding improvement of thermal insulation to achieve the same temperature increase with less energy use.

9.2.6. Avoidance of temperature reductions.

Ventilation: In cold climates the ventilation rates must be reduced to the minimum levels compatible with hygienic and air quality requirements to avoid a drop in the average internal temperature.

Reduction of heat losses: The use of adequate layers of thermal insulation in walls and roof will help to avoid heat losses and a drop in the indoor air temperature.

9.3. COMBINATIONS OF STRATEGIES

As the previous sub-section has shown, many bioclimatic or passive solar design strategies achieve improved comfort through a combination of effects, modifying the indoor swing and the average indoor temperature simultaneously. In the first presentation of the Comfort Triangles (Evans and de Schiller, 1996) showed that this graphic tool can indicate the way in which passive solar systems achieve successive modifications of average temperatures and swings.

The Michell-Trombe wall, often known as the ‘Trombe wall’ or ‘ventilated accumulator wall’ (Mazria, 1978) achieves a favourable modification of the outdoor conditions in a series of steps, using different thermal properties of glass, surface absorptance and thermal mass in successive layers of the construction.

A similar system without ventilation heat transfer is equally effective, without the potential problems of heat losses through reverse flow at night.

Unventilated accumulator wall: The average outdoor winter temperature is typically much lower than the required indoor temperature and the swing is low (Figure 9.3., point 1). During the day the sun passes through the outer glazing layer and is absorbed on the dark surface facing the air cavity, increasing the average temperature by up to 10° C, but also increasing very significantly the temperature swing (Figure 9.3., point 2). The mass wall of dense material with high heat capacity creates a modification of these conditions, reducing the swing on the indoor side by over 50% (Figure 9.3., point 3). The indoor air temperature is lower than the inner surface temperature of the mass wall, allowing the wall to deliver heat to the room (Figure 9.3., point 4). This difference is similar to the inlet temperatures of air heating systems that are higher than the room temperature and in turn higher than the average surface temperatures.

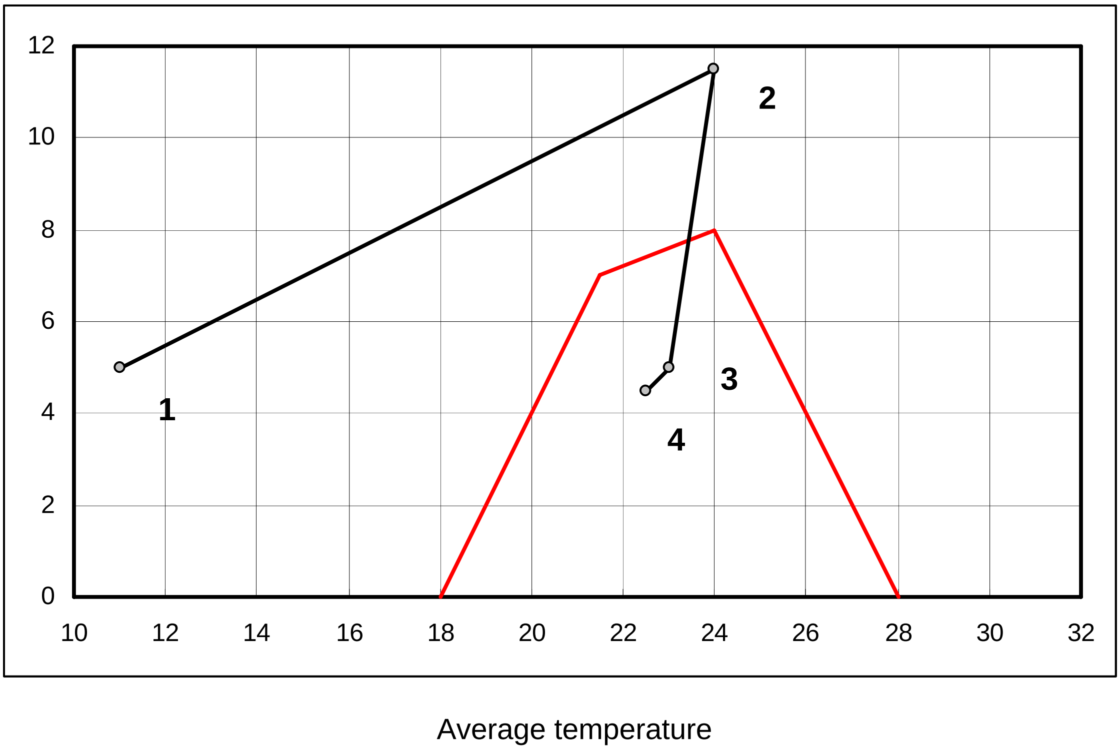


Figure 9.3. Combined strategies, functioning of a passive solar system: mass wall.

A second example is the use of night ventilation to achieve a simultaneous cooling effect on the average temperature and a reduction in the temperature swing. This is shown in figure 9.4 where the average outdoor temperature is above the average indoor temperature required for comfort and the temperature swing of 11,5°C is excessive.

Night ventilation: A lowering of the average temperature will improve comfort slightly, as shown in the horizontal vector in Figure 9.4, but the conditions are still way above the comfort zone. A very effective reduction of the temperature swing will just achieve comfort, but a reduction from 11,5°C to 1°C, as shown by the lower grey arrow, will be very difficult to achieve in practice.

However, the use of two simultaneous strategies will provide comfort conditions, by a simultaneous reduction of the average temperature and the temperature swing. The night ventilation reduces the minimum night temperature, while the reduction of day ventilation avoids an increase in the maximum indoor day temperatures. In this way the average temperature can be reduced. At the same time, a building with internal elements of high thermal mass will tend to reduce the indoor temperature swing.

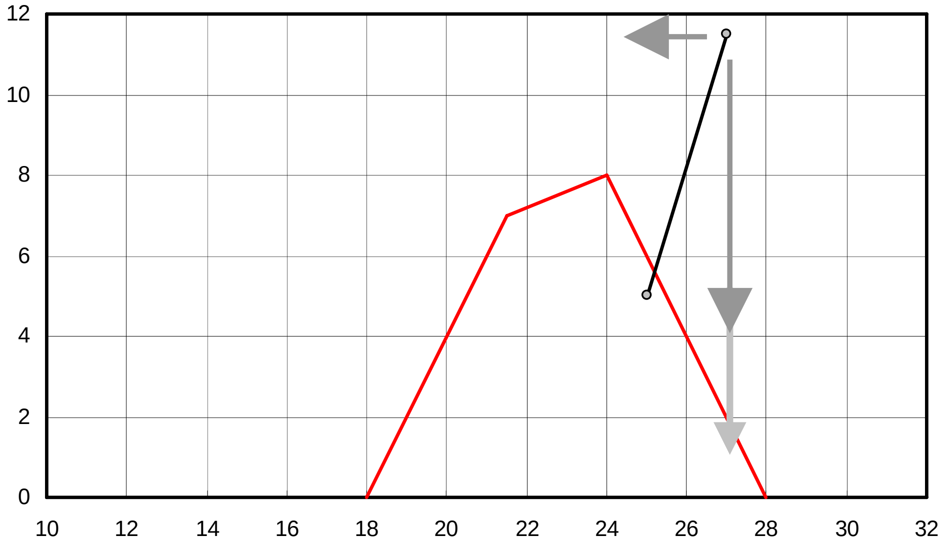


Figure 9.4. Combined strategies, functioning of night ventilation in a heavy weight building.

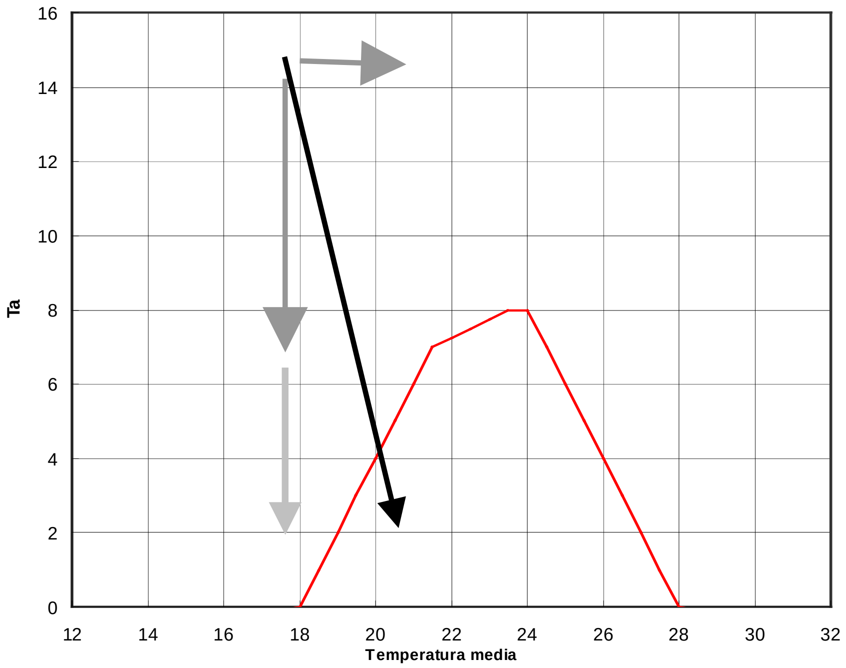


Figure 9.5. Combined strategies, functioning of day ventilation in a heavy weight building.

Day ventilation: When outdoor average temperatures are below the comfort zone and temperature swings are high, the opposite strategies can be used to achieve a simultaneous reduction in the swing with an increase in the average temperature. Windows are opened to ventilate the interior when outdoor temperatures are comfortable, and closed as the outdoor temperatures drop. The warm air heats the internal mass where it is stored, the average temperature is increased, while the large indoor thermal mass reduces the indoor swing.

9.4. CONCLUSIONS

This chapter has shown the way in which the comfort triangles concept can be used to explain the function and objectives of the different bioclimatic design strategies used to achieve a favourable modification of the external climate and approach or achieve conditions in the comfort zone without recourse to artificial conditioning or energy resources.

The comfort triangles can also be used to select appropriate bioclimatic design strategies according to the relation between the indoor comfort requirements and the outdoor climate conditions. The triangles thus link comfort, climate and habitat, completing the sequence presented in this part of the thesis.

These modifications of the external conditions through the use of the thermal characteristics of the building skin, the constant or variable ventilation and the use of internal heat gains are based on the theoretical thermal performance. It is therefore necessary to show that the theoretical modifications of outdoor comfort to achieve or approach the comfort zone can be achieved in practice.

Therefore, in the next chapters, a series of experiments are presented, based on measurements in urban spaces, architectural projects and building designs using alternative construction systems. These demonstrate the potential of the built environment to modify the external conditions, altering the average temperatures and thermal swing through strategies of natural conditioning.

These experiments are also used to compared measured conditions with simulations in order to extend the testing of the Comfort Triangles. They will demonstrate the practical value of the Comfort Triangles as a design and analysis tool for existing as well as projected buildings.

PART 4
CASE STUDIES

CHAPTER 10: URBAN SCALE

CHAPTER 11: ARCHITECTURAL SCALE

CHAPTER 12: BUILDING COMPONENT SCALE

Part 4 of the thesis presents a series of case studies carried out at different scales, supported with measurements and simulations of indoor and outdoor temperatures in a wide variety of climates, in order to demonstrate and evaluate the use of the Comfort Triangles as a tool for analysis, allowing effective assessment, evaluation, verification and selection of appropriate design resources. The objectives of Part 4 are:

- **Show the application** of the Comfort Triangles concept in urban spaces and buildings, using measurements in existing situations and simulations of thermal performance.
- **Test the validity** of the theoretical development of the Comfort Triangles presented in the previous part of the thesis.
- **Demonstrate the utility and value** of the Comfort Triangles as a design and analysis tool for selecting bioclimatic design strategies.

Chapter 10 presents the urban case studies to show how the built environment influences the temperature regime, changing both the average daily temperature and the temperature swing. The examples show the effective use of the Comfort Triangles to analyse this phenomenon and relate the outdoor conditions to the range of desirable indoor temperature variations, illustrated by examples of the heat island of three cities.

Chapter 11 presents a series of case studies at the architectural scale with measurements in different buildings in Argentina, Mexico and Ecuador.

Chapter 12 evaluates the effect of different construction methods and building materials, with studies of the influence of alternative solutions at the building scale.

Part 1: Introduction

1. Introduction
2. Background ,,,
3. History …

Part 2: State of the art

4. Thermal Comfort
5 Bioclimatic zones
6. Technology …

Part 3: Comfort triangles

7. Thermal Comfort
8. Analysis of Climate
9. Design Resources

Part 4. Case studies

10. Urban scale
11. Architectural scale
12. Building scale

Part 5: Conclusions

13. Results & case study evidence
14. Conclusions & ideas for further study

CHAPTER 10. CASE STUDIES AT THE URBAN SCALE

10.1. INTRODUCTION

This chapter presents a series of studies and measurements of the variations of climatic conditions produced in urban areas as a result of the impact of the built environment. The author made the measurements of these variations with students of postgraduate courses in different cities of Latin America in the framework of specialised seminars of diploma and master courses, providing an effective experimental arena to test results and promote useful discussions.

Therefore, the two main objectives of this chapter are:

- **Demonstrate** the application of the Comfort Triangles in specific cases at the urban scale. This will be followed by examples and case studies at the architectural scale in Chapter 10 and the building scale, Chapter 11 considers the conditions in existing and occupied spaces in different climates and geographic regions, in order to show the use of the analysis method to detect, visualise and quantify the modification of microclimate conditions in man-made spaces in comparison with the typical variation natural conditions.
- **Evaluate** the Comfort Triangles as an analytic tool and approach to the evaluation of thermal conditions using the case studies of different urban situations, compared with suburban and peripheral areas.

10.2. STUDY OF THE URBAN HEAT ISLAND

The urban heat island experiments presented in this Chapter provide evidence of the impact of the built up area on the environment, producing simultaneously an increase in the average temperature and a variation in the temperature swing, when compared with the surrounding rural area.

As these two variations correspond to the variables used in the Comfort Triangles, this graphic format can be applied to compare the environmental conditions in urban and rural areas, in the same way as the application to compare indoor and outdoor temperature variations; examples of this situation in buildings are presented in Chapter 10.

10.2.1. Review of the heat island phenomenon.

The phenomenon of the heat island has been studied in many urban regions (Chandler, 1965; Oke, 1982; Oke et al, 1991), although a lower number have been carried out in developing countries (Jáuregui, 1986 and 1999). A recent survey by Santamouris (2001b) summarises urban heat island studies in different climatic and economic contexts. A recent study by de Schiller (2004) presents measurements of the Buenos Aires heat island.

In cold climates, the increase in the average temperature of urban areas may be considered favourable, improving outdoor thermal comfort and reducing the energy demand for heating, although the increase in the average outdoor air temperature can be partly due to the heat losses from buildings, accompanied by the related environmental impacts of using fossil fuels, especially in situations where buildings have poor thermal insulation (Evans and de Schiller, 1998; Evans et al, 2001).

However, in warmer climates, the urban heat island produced by large cities can be harmful, reducing thermal comfort and significantly increasing the energy demand for cooling. Even in temperate climates, a rise in the outdoor temperature combined with important internal heat gains in commercial and administrative buildings can increase the energy demand and environmental impact of refrigeration.

The urban heat island is produced by the following combination of factors:

- Heat losses from buildings with heating systems and from other internal gains
- Heat transferred to the outdoor air by the cooling towers of refrigeration systems of buildings.
- Heat absorbed by the sun during the day and stored in building materials with high heat capacity
- Heat generated by energy use in industrial processes
- Heat generated by the internal combustion engines of vehicles

Additionally, the transformation of natural landscape to urban development also produces the following changes in the surface heat balance:

- Lack of vegetation with less shade and lower evaporation levels.
- Lower albedo or surface reflectance, especially in the street canyon

The studies presented in this chapter are the result of a series of experiments to measure the intensity of the urban heat islands of cities in both temperate and cold climates of Argentina, a hot and humid climate of Mexico and a cool climate of upland Ecuador. The chapter presents the method used to measure the spatial distribution of temperature in the urban area, with mobile stations for measurements using temperature data loggers in the evening shortly after sunset, the hour of maximum heat island intensity (Oke, 1991).

The results obtained indicate the urban sectors with higher temperatures, which coincide with different characteristics of the building fabric, analysed in this study. The temperature variations are also shown to respond to the influence of large water surfaces, such as rivers, lakes and lagoons, which produce a significant reduction in the temperature of adjacent urban areas. The measurements also indicate the favourable influence of parks and large green areas in the city, the variations caused by topography, the built urban density and the average building height.

The measurement of the urban heat island demonstrates the impact of the built environment on the temperature regime and allows the identification of design variables that contribute to the reduction or control of this impact. Various systems for the evaluation of sustainable buildings (BRE, 2000 and 2002; LEED, 1998) favour design alternatives that mitigate or reduce the heat island intensity. In recommendations for urban development in a warm humid climate, such design strategies were proposed at the urban scale as an important environmental measure (Evans and de Schiller, 1994). For this reason, the measurement of the urban heat island constitutes an important tool to verify and quantify the effectiveness of these measures and the evidence of the phenomenon as a result of the energy use in the built environment.

10.2.1. Measurement method.

The practical experiments presented in this chapter introduce measurement techniques in the context of postgraduate courses on planning and architectural design in the framework of sustainable development. In all the cases presented in this chapter, postgraduate students undertook the surveys and the initial data processing with the supervision of the author.

The object of these studies is to establish and demonstrate the variation in average temperature and thermal swing between the central areas of cities and the surrounding rural areas without the impact of anthropogenic heat related to the built environment, produced by the energy use in buildings and transport.

In the following heat island experiments, the distribution of temperature was obtained using miniature data loggers such as Tiny-Talk (Gemini Data Logger UK Ltd) and HOBO, Model H8 (Onsett). These were located on the outside of a series of 4 to 7 vehicles, according to the availability of measuring instruments and vehicles in each experiment. The temperature data were measured each 10 to 15 seconds, with a thermistor located on the outside of the data logger housing to ensure a rapid response to the air temperature variations.

Figure 10.1 shows how the sensor is placed in the outside of the box, with care to prevent damage to the copper wire connection. In the case of the TinyTalk data loggers, which have the sensor fixed to the circuit board, the housing was perforated to ensure a direct airflow over the sensor, when the vehicle was in motion.

The data loggers were fixed to the right-hand external rear-view mirror, opposite to the driver’s side, to reduce the possible influence of motor heat and exhaust heat from adjacent vehicles. Although the sensors were placed in flexible polyurethane tubes for the experiments carried out in the cities of Buenos Aires and Rio Gallegos, Argentina, Tampico, Mexico, and Quito, Ecuador, this protection from possible radiant heat sources was omitted, with equally satisfactory results.

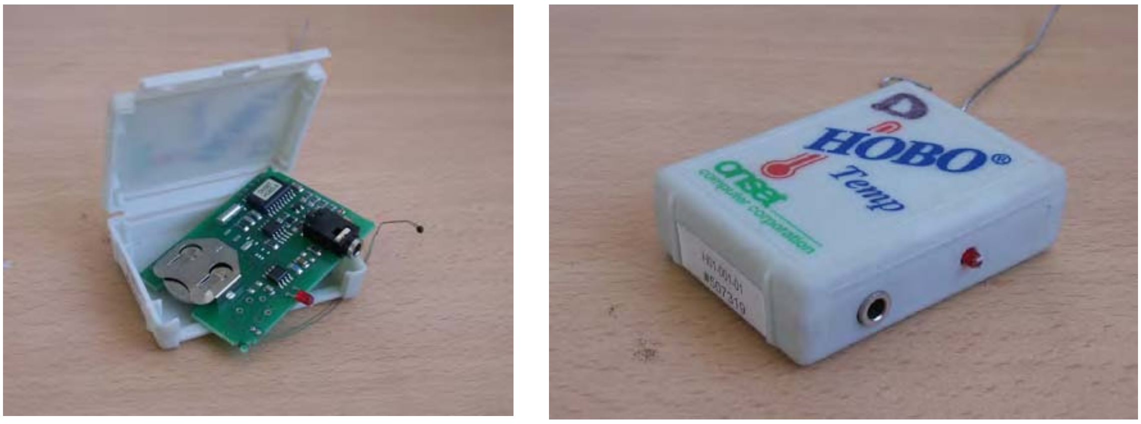


Figure 10.1. Miniature temperature data loggers, Onset HOBO, with the sensor and copper wire outside the box to obtain a rapid response to temperature variation.

After each experiment, the data was transferred to a PC with the software provided and then incorporated in an electronic spread-sheet to analyse, compare and visualise the results, comparing the measurements of different data loggers and undertaking an initial analysis of the variations with time, comparing the evolution of temperature with the location within the urban area where measurements were made.

The reading of the data loggers were compared before and after each experiment, with all of the loggers in the same container, exposed to the same conditions during 24 hours. The maximum difference registered was 0,4°C, though the most frequent difference and average difference was 0°C, indicating a very satisfactory relative precision of the instruments.

The vehicular circuits were planned to obtain a good coverage of the urban area, travelling through zones with different urban features and spatial characteristics, such as dense central areas, commercial centres, lower density suburban areas, parks, lakes, rivers, and surrounding rural areas. The circuits were designed to be covered in less than an hour, to minimise the temperature variation during the experiment. The routes were also designed to cross each other at certain points in order to check the compatibility of measurements made in all different vehicles.

10.3. HEAT ISLAND CASE STUDIES

This section presents the results of the heat island experiments undertaken in the Cities of Buenos Aires and Rio Gallegos, Argentina, Tampico, Mexico and Quito, Ecuador. The examples presented cover a range of very different climatic conditions and latitudes of Latin America, as shown in Table 10.1.

Table 10.1. Studies of urban heat island reported in Chapter 10.

Location	Latitude	Season	Climate
Buenos Aires	34° South	Summer and winter	Temperate, sub-tropical
Rio Gallegos	51° South	Winter	Cold
Tampico, Mexico	20° North	Summer	Hot-humid
Quito, Ecuador	0° North	Rainy	Equatorial, height 2800 m

10.4. BUENOS AIRES URBAN HEAT ISLAND

With the support of researchers from the Research Centre Habitat and Energy and postgraduate students of the Faculty of Architecture, Design and Urbanism, Buenos Aires University, studies were carried out (de Schiller, 2004) and the intensity and distribution of the urban heat island of Buenos Aires were registered on two occasions in different seasons of the year. The initial results were reported by de Schiller et al (2001) and in de Schiller (2004). All measurements recorded by the data loggers were prepared, transferred to computer and incorporated in an electronic spreadsheet by the author.

10.4.1. Winter. June 1999.

Figure 10.2 indicates the results of the first experiment to measure the Buenos Aires urban heat island, related to the distribution of population density (MCBA, 1999) in the base plan. The upper arrow shows the wind direction prevailing during the experiment, while the lower arrow shows the orientation.

During the study, a maximum temperature of 13,8 C was registered in a dense area of the centre, while the minimum temperature of 10,5 C was measure on the boundaries of the Federal Capital, reaching a total range of over 3° C.

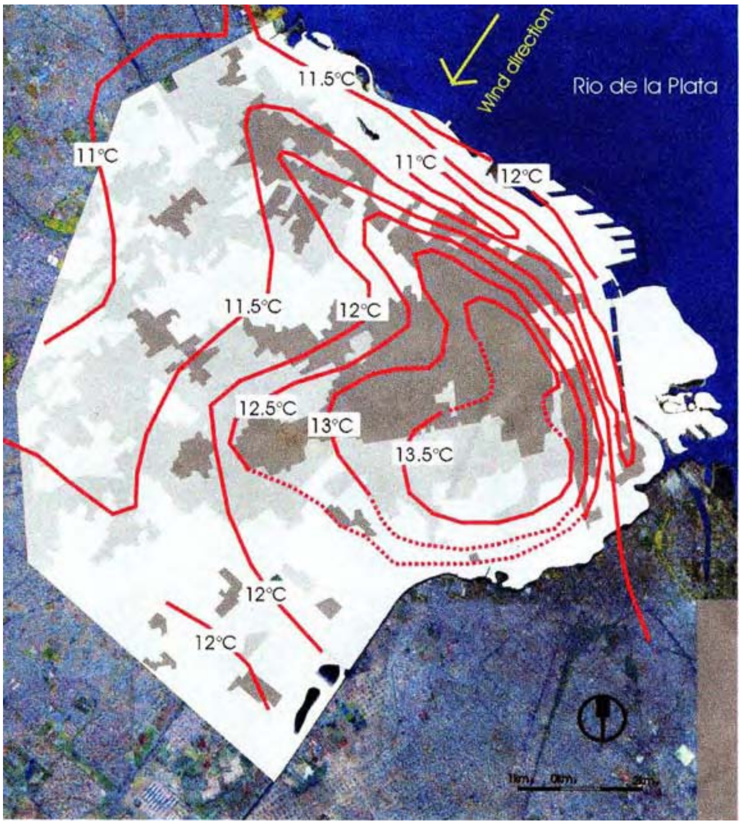


Figure 10.2. The heat island intensity of Buenos Aires, in winter at 9 pm, June 22nd, 1999. Source: de Schiller, 2004.

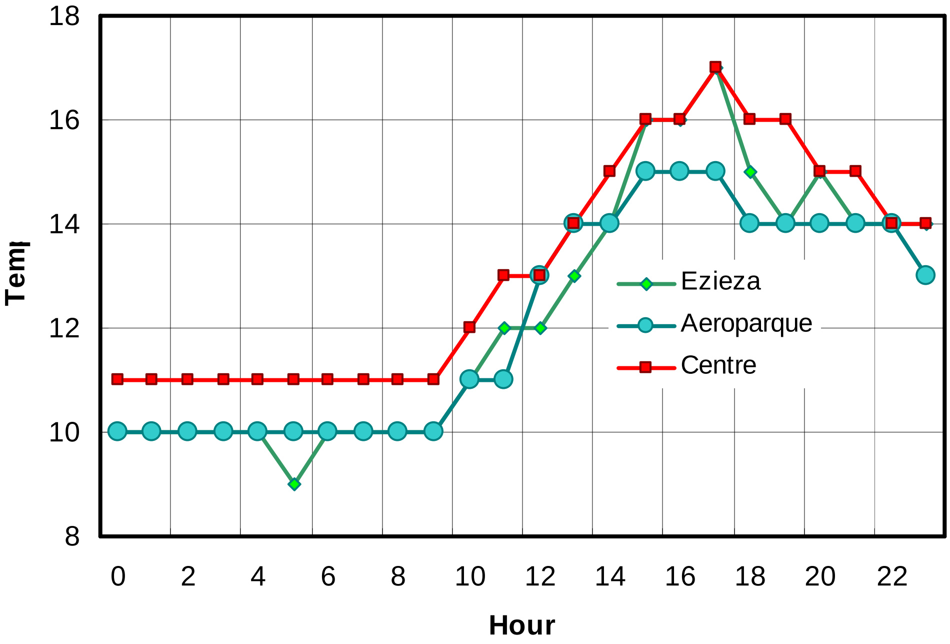


Figure 10.3. Temperatures measured at three points during the day of the heat island experiment in Buenos Aires.

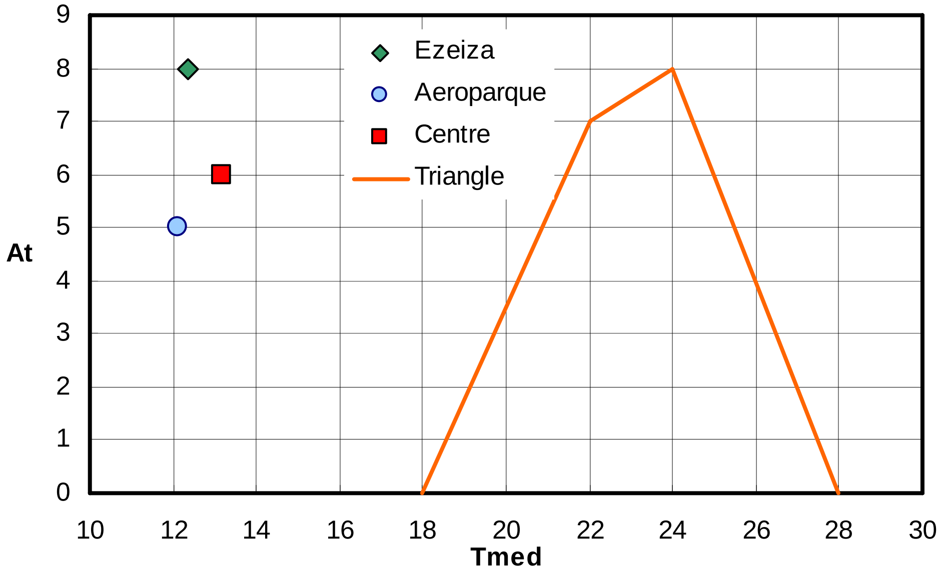


Figure 10.4. Conditions during 24 hours in 3 measuring points, compared with the Comfort Triangle.

Figure 10.3 shows the temperatures registered on the day of the experiment in three different locations:

- Domestic Airport of Aeroparque, to the North of the centre in a park area on the shores of the River Plate Estuary.
- International Airport of Ezieza on the edge of the urban area, outside the Federal Capital.
- Temperatures measured on the roof of the Faculty of Architecture, Design and Urbanism, considered to be representative of the central area, due to the location of the sensors, in the centre of a large expanse of concrete.

Figure 10.4. plots the data of average temperature and temperature range for the three locations on the Comfort Triangle. This shows that conditions throughout the day are warmer in the central area with lower temperature swing. The area close to the River Plate also shows a low temperature swing, with lower average temperatures than the centre. The international airport, further inland, has a significantly higher temperature swing than the other stations.

Figure 10.5 shows the temperatures recorded in Ezeiza Airport in the periphery of the metropolitan area, Buenos Aires Aeroparque, the local airport on the shores of the river plate estuary and the measurements made in the roof of the Faculty of Architecture, considered to be representative of the conditions in the central area.

The results presented in Figure 10.6 show that in this series of measurements, the influence of the River Plate reduces both average temperatures and the temperature swing, creating more comfortable conditions.

The central area has a higher average temperature and intermediate temperature swing, while the inland site at the Ezeiza International Airport has the highest temperature swing and intermediate average temperatures.

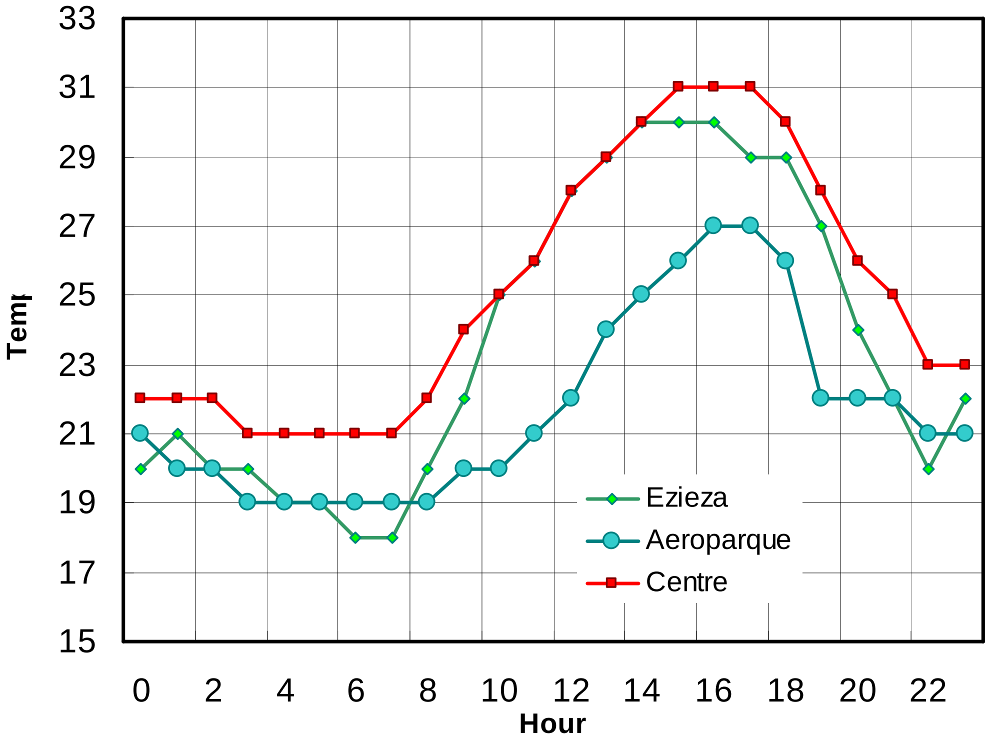


Figure 10.5. Temperatures measured at three points during the day of the autumn heat island experiment.

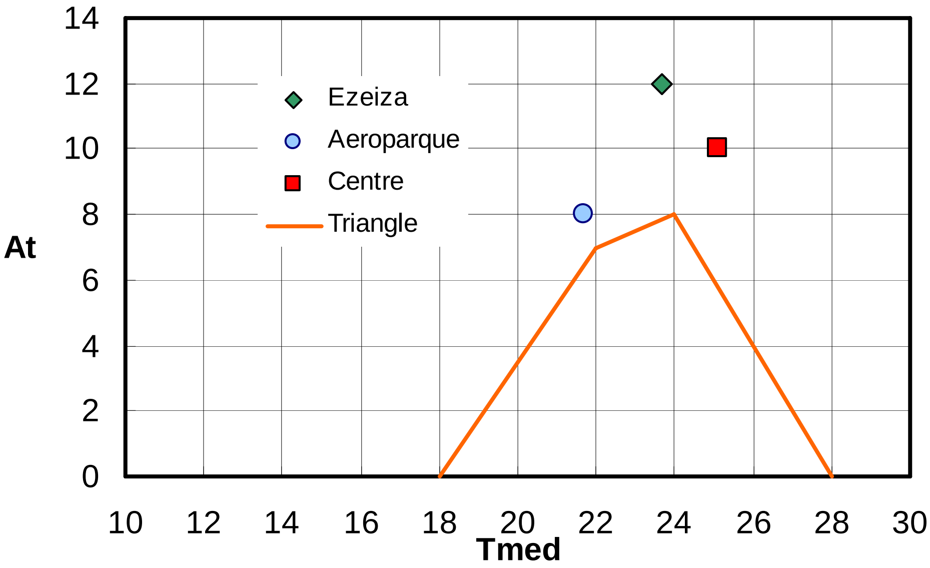


Figure 10.6. Conditions during 24 hours in three measuring points, compared with the Comfort Triangle for the autumn heat island experiment, based on the measurement shown in Figure 10.6..

10.4.2. Autumn, 1999

Figure 10.7 shows the heat island measured in October, with a similar intensity, but lower temperatures.

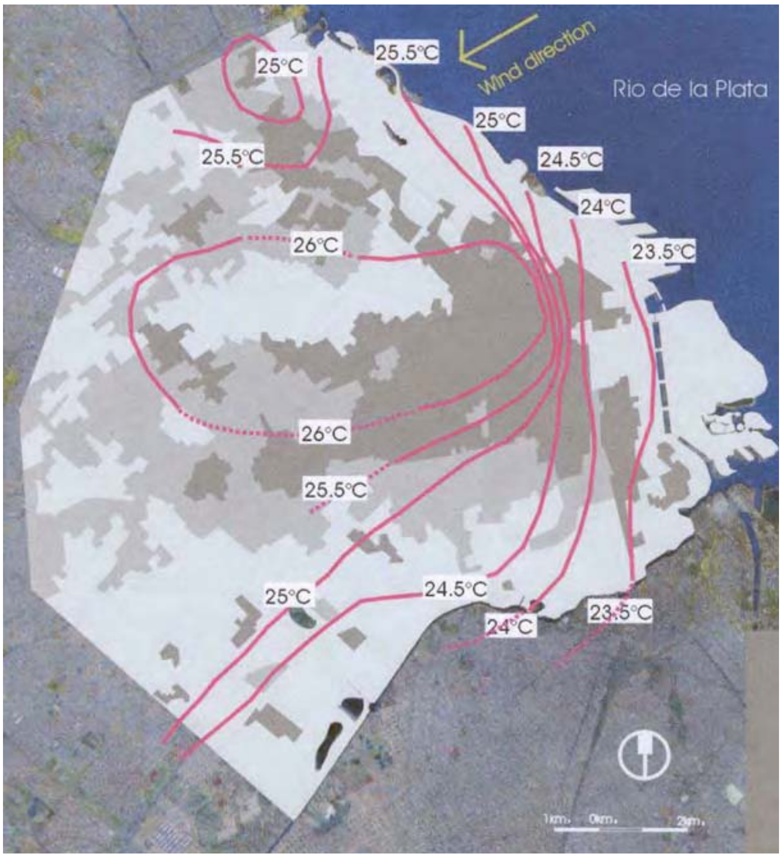


Figure 10.7. The Buenos Aires urban heat island, measured in autumn, 9 pm, October 19th, 1999. Source: de Schiller (2004).

10.4.3. Results.

The heat island measurements in Buenos Aires show the increase in temperature produced in the central area. In both experiments a difference of about 3 degrees was found. The Comfort Triangles show the relation between the daily temperature variation and the comfort zone, with significant differences between different locations.

10.5. RÍO GALLEGOS URBAN HEAT ISLAND

In 2001, a study of the urban heat island of Rio Gallegos in the south of Argentina was undertaken by students of the Postgraduate course organised by the National University of Southern Patagonia. This city, located at latitude 51° S, is the most important city of Southern Patagonia with a population of 100,000 inhabitants.

When this study was first proposed as a practical exercise to search for evidence of the impact of the built-up area to the environment, it was considered doubtful that a significant heat island would be detected, due to the following series of unfavourable conditions for the detection of this phenomenon:
- Persistent and very high wind velocities, typical of the Patagonian Region.
- Open urban tissue with wide streets.
- Predominantly low buildings, many with low thermal mass, and scarce vegetation.
- Very limited traffic at the hour of the measurements.
- Insignificant heat generation by industry.

However, when the measurements were made, the variation of temperature detected was even higher than that measured in the previous experiments in the dense, temperate and busy city of Buenos Aires, with a total population one hundred times larger than the city of Rio Gallegos.

It is indeed relevant for the purpose of the exercise to note that this was detected in spite of the unfavourable climate, the lower population, the lower building density, the lack of vegetation and the lower emissions of heat from transport and industry.

10.5.1. Location and climate.

The city of Rio Gallegos, typical of Patagonian settlements, is situated on the southern side of the estuary, with a relatively flat topography with little natural vegetation. The majority of the buildings are one or two storeys high, with a few higher buildings in the centre and in social housing projects, though these rarely exceed 4 storeys.

This city is located in the Bioclimatic Zone 6, Very Cold, according to the classification in the IRAM Standard 11.603 (1996) and the heating degree days exceed 3100 with a base temperature of 18°C, three times the value found in Buenos Aires.

In spite of this difference and the low design temperatures, the typical values of thermal transmittance of walls and roofs of heated buildings are very high, resulting in high heat losses.

10.5.2. Results.

The resulting isotherms, plotted on the aerial photo of the city, seen in Figure 10.10., show the influence of the following factors:

- The isotherms based on the temperatures measured by the mobile stations clearly show the formation of a heat island, with higher temperatures related to the central area of the city.
- The tidal estuary of the *Ría*, which forms the northern boundary of the city, shows it’s influence on the temperature distribution.
- The sectors with little urban development to the south and south-west, occupied by army bases, have lower temperatures than the adjacent urban areas.
- The prevailing winds from the west and south-west, with a velocity between 14-18 km / hour (4.5 m/sec), measured at a height of 1.50 metres in the urban area, produce a displacement of the warmed air towards the east. In the airport, an average wind speed of 44 km/hr was recorded at a height of 10 metres with a westerly orientation, and gusts of up to 66 km/hr at the time of the experiment.
- The form of the isotherms and the variation in temperatures measured exceed the values that could be generated by geographical factors, such as the river estuary to the north, the Atlantic ocean several kilometres to the west, or the limited differences of altitude.

The minimum temperature of -2,7° C was registered in open country on the road to the airport, situated some 4 kilometres to the west of the city. The temperature measurements, registered at the airport met station, indicate a temperature of 1°-2° C at the time of the survey.

The shorter distances covered during the heat island experiment, compared with those of Buenos Aires, reduce the time to complete the circuits and minimise possible errors due to temperature variations. The total daily temperature variation was only 7°C, with high winds and predominately cloudy skies.

10.5.3. Discussion.

The significant intensity of the urban heat island measured in the city of Rio Gallegos is surprising, considering the very limited vehicular circulation at that hour, the open urban tissue and wide streets, high wind velocities and overcast skies.

The majority of the buildings, especially those of traditional buildings, are of lightweight construction with timber structure, corrugated iron roofs and, in many cases, walls of metal sheets or timber siding. More recently, housing was constructed of concrete block or hollow clay blocks, with lightweight roofs. The typical construction, therefore, has little thermal capacity to store the limited heat of the day to night-time.

The maximum temperature difference between open countryside and the city centre exceeds 5° C. In this case, the contribution of transport, industrial activities and the thermal capacity of buildings to store heat from the day to the evening hours is very limited. Therefore, it is deduced that the principal cause of the heat island detected is the high heat loss from buildings.

The thermal performance of typical buildings and the contribution of the special energy tariff structure, heavily subsidised by the central government with special consideration in this remote and cold region of the country, are considered to be the main contributary factors.

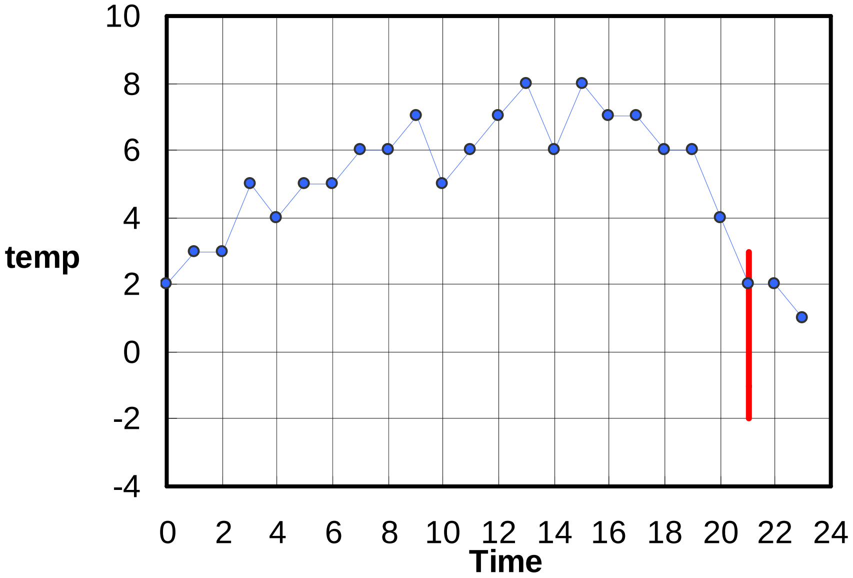


Figure 10.8. Temperature at the airport on the day of the heat island experiment: the red line shows the temperature range measured in the city during the experiment: 1st June, 2001, at 9 pm.

In most cases, the thermal performance of walls and roofs are designed to comply with the minimum levels established in the IRAM Standards (IRAM 11.605, 1998), scarcely sufficient to avoid surface condensation, though even this level of insulation is not compulsory. Housing construction using hollow concrete blocks, frequently used in the low cost private sector, does not even reach this minimum standard, while the earthquake resistant structures of concrete frames introduce important cold bridges, increasing heat losses and the incidence of internal surface condensation.

From direct experience of the indoor temperatures in housing and conversations with local residents, it was confirmed that indoor air temperatures frequently exceed 23° C and may reach 25° C, values well in excess of those required to ensure comfort. However, these temperatures may be adopted to compensate for the low surface temperatures of walls and roofs without adequate thermal insulation. This increase in the indoor temperature may produce additional heat losses in the order of 30 to 40 %.

An additional factor that contributes to high heat losses in buildings is the subsidy included in the provision of natural gas in Patagonia, intended as a social benefit for the inhabitants of urban areas in the southern region, many of whom are government employees with relatively low salaries. This allows families to heat the poorly insulated public housing during the extended cold season. However, this benefit does not extend to rural areas without access to the natural gas network which only serves urban areas. The subsidy is also intended as a compensation for the inhabitants of provinces which produce natural gas and petrol.

It should be noted that the internal domestic natural gas tariff in urban areas is well below the industrial tariff, which in turn is below the cost in most other countries. The additional subsidy of 50 % in Patagonia is now equivalent to over 80 %.

The gas in canisters used in rural areas and marginal suburban areas has no subsidy, leading to prices 5 to 6 times the urban tariff, resulting in social inequality. The result is a total lack of incentives to save energy or improve the thermal characteristics of the building envelope. Studies by ENERGAS (2006), the organization responsible for controlling the privatised gas production and distribution industry, found that gas consumption in areas with this additional subsidy was twice as those found in areas without subsidy, for the same difference between outdoor and indoor temperature (set at 20° C).

An important result of this study is the evidence of large heat losses from buildings, especially residential ones, for it is argued that these are the main cause of the Rio Gallegos heat island measured and included in this study. These heat losses are not only a result of the poor thermal transmittance of walls and roofs, but also the form and grouping of buildings. A large proportion of residential buildings in Rio Gallegos are single storey and free standing.

Therefore, a 5° C increase in the air temperature implies a significant environmental impact due to the use of fossil fuels, directly related to the architectural design and construction systems used. Although the small increase in the outdoor temperature could be considered favourable, both for users of outdoor spaces and for the reduction in the heating demand, this is achieved as a result of excessive heat losses and uncontrolled energy use in buildings.

There is an apparent difference between the temperatures measured in the airport in a Stevens Screen, obtained from Wunderground (2006) and in the mobile stations measured at the same time during the heat island experiment. Despite the strong winds, the Stevens Screen appears to produce a slight delay in the temperature readings, in addition to the 45 minute difference between solar and civil time.

Following the heat island experiment, the Airport reported a continuing drop in temperature to -1° at midnight. It should be added that small ponds in the peripheral urban area remained frozen during the day of the heat island experiment, showing the prevailing temperatures.

Figure 10.8. Rio Gallegos winter urban heat island, measured at 9 pm, 1st June, 2001.
Reference: *Red circle*: starting and finishing point of the six simultaneous circuits.
Grey zone: central area of the city.
Source: Aerial photograph obtained from Google Earth (2006).

The estimated temperature range in the city centre is 6°, from +1 to + 7, with an average temperature of +4°C, while the temperature to the west of the city ranges from -2° to +4.5°C, with a swing of 6,5 degrees and an average temperature of 1,5°C. This difference, leads to a 16 % increase in the heating load of houses in the peripheral areas to the west, assuming an average daily indoor temperature of 18°C. This corresponds to a temperature of 20°C in living rooms during the day and 18°C in bedrooms, dropping to 18° and 16° respectively during the night.

Although the rise in the urban temperature can be considered favourable, it is only obtained at the expense of excessive heat losses from the building fabric. The saving of 16 % of the heating load is small, compared with the 60 % saving that could be obtained by improved insulation of buildings.

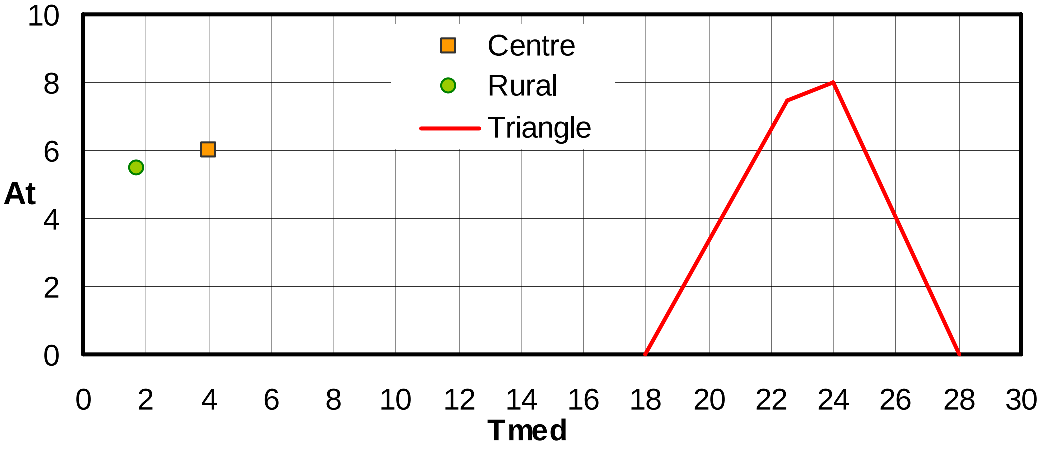


Figure 10.9. Temperature conditions in the urban centre and rural periphery of Rio Gallegos on the day of the heat island experiment.

10.6. URBAN HEAT ISLAND, TAMPICO, MÉXICO

This subsection presents the results of the heat island experiment for the City of Tampico, Tamaulipas, Mexico, with a warm and humid tropical climate. The measurements were made during a postgraduate course on Sustainable Architecture, given by Silvia de Schiller and the author at UAADU-UAT, the Architecture, Design and Urbanism Academic Unit of the Autonomous University of Tamaulipas, Mexico.

The general and specific conditions registered on the day of the experiment are described, together with the characteristics of the urban area and it's surroundings. The measurement method was summarised previously in Subsection 10.2.2, and reported in de Schiller, Evans and Katzschner (2001).

In this case, the process of data analysis was improved from previous experiments carried out in Argentina, and the results showed the phenomena which were not detected in the previous studies. These show the effect of specific geographical features such as green areas and stretches of water, as well as the formation of 'multiple islands' in different urban sectors. In this hot climate, the impact of extensive air conditioning in buildings is a major factor in the intensity of the urban heat island.

In an urban proposal developed by the author and de Schiller for a city in a warm humid climate, mitigation strategies were applied as an important measure (Evans and de Schiller, 1994). For this reason, the heat island measurements presented here provide an excellent opportunity to test the effectiveness of these measures. Additionally, this practical exercise allows the application of experimental techniques in postgraduate courses on planning and architecture in the framework of urban sustainability.

10.6.1. Location and climate.

The city of Tampico, latitude 21° N, located on the Gulf of Mexico, has long hot summers from May to September, with high relative humidity, small thermal swings typically ranging from 22 to 32° C, with relative humidity of 70-90 %. In winter, temperatures are lower, ranging from 8 to 16° C, with lower solar altitudes.

The rainfall is intense, and high temperatures combined with high relative humidity produce uncomfortable conditions, alleviated by the breezes coming from the sea. Therefore, cross ventilation is the typical traditional bioclimatic strategy, although in the urban centre, the dense compact built up fabric, together with noise and pollution reduce the effectiveness of this solution.

As a result, air conditioning installation is widely used, creating an important demand for electrical energy as well as heating the outdoor air, both factors which contribute to the intensity of the heat island in this climate. The heating of the outdoor air increases the cooling load, which in turn increases the electricity demand and heating in a vicious circle. This situation is stressed by current architectural design tendencies, influenced by global influences of large glazed surfaces with little or none solar protection. In this framework, the measurement of the heat island intensity provides clear evidence of this impact in order to promote the incorporation of bioclimatic design strategies in architecture and urban design as an alternative to this problem.

The city of Tampico, with a population of approximately 500,000 inhabitants, is located on the Panuco River, close to the Gulf of Mexico. In the city, not only there is evidence of the pre-Colombian civilization such as the Tuy Piramid, but also of the importance of the Spanish Conquest and subsequent colonial period. During the XX century, the city became a key centre of petroleum production. The Madero Refinery, within the metropolitan area, is the most important plant of PEMEX, the national petrol company. On the Panuco River, the construction and repair of drilling platforms for the off-shore petrol fields in the Gulf of Mexico has become an important industrial activity.

The metropolitan region contains three municipalities: the City of Tampico on the Panuco River, which forms the southern boundary of the urban area, Madero City, with the refinery and petrol industries bordering the Panuco River to the south and the Gulf of Mexico to the east, and Altamira to the north. To the west of Tampico and Altamira, the Caliel region is located, with lagoons and rivers flowing into the Panuco River.

To the south, crossing the Panuco River, a series of small settlements are related to the Tampico Metropolitan Area, although they are located in the neighbouring State of Veracruz. This region was not included in the present study due to the small size of the settlements and limited access across the river. The Municipality of Altamira was also excluded as it is separated from Tampico and Madero by a rural zone and the airport.

The variation of altitude within the study area is very limited, always ranging less than 30 m, though the ridges to the east and west affect the circulation of breezes. The Carpintero Lagoon, with an approximate diameter of 500 m is located within the urban area of Tampico and connected by a short branch leading to the Panuco River, although about half of the original area has been reclaimed with land-fill to form sports fields and rapid circulation routes.

The Historic Centre of Tampico covers 10 blocks along the river front and 5 blocks inland, with the typical colonial street grid. This area is now densely developed with a relatively compact building form, predominantly of 2 to 3 storeys, though a few reach 10 storeys. Around the two main squares, the traditional construction incorporates balconies with a cast iron structure similar to those found in New Orleans, as well as covered galleries and porticos.

Another dense urban area is the centre of Madero City, on the 1st of May Avenue, although the density is considerably lower than that found in the centre of Tampico. Towards the north, along the Suarez Avenue, a series of new commercial centres have been developed with no provision of shade in the large concrete parking lots near the wide and intense traffic motorway.

The general urban density is intermediate, with variations in height and land coverage. Though in most of the urban area trees only appear in private plots, vegetation in streets and public spaces is very limited, a microclimatic mitigation resource clearly underestimated at the urban scale.

Social housing developments are typically of high density and land coverage, especially those to the north of the study area. Figure 10.10. shows the principal geographic and urban features of the study area.

10.6.2. Measurements.

The measurements were obtained between 8 pm and 9 pm, on June 6th 2005, period of maximum intensity of the urban heat island (Oke, 1986), without the influence of the solar radiation. The data from the airport was used as the reference from a fixed station, and the temperature data at the initial and final stages of the circuits were compared to ensure that the temperature variation during the experiment was 29,5º-30º, considering the condition of a less than 1ºC variation. The wind velocity was limited, approximately 8 km/hr, from the NNE.

The circuits were planned to obtain the data within a one hour period and achieve a good coverage of the study area as well as the range of different characteristic areas of the urban area.

As in the previous studies, the circuits cross each other in order to verify the consistency of the data obtained in the different vehicles. In each vehicle, one of the occupants registered the location each 2 minutes, using the principle intersections as references. The morphology of the urban areas, including building heights, street widths, building set-backs and presence of vegetation was also recorded.

The data registered by the HOBO mini data loggers were transferred to an Excell spreadsheet for a rapid visualisation of the results, as shown in Figure 10.11. In this first stage, the principal temperature variations were noted, relating the increase and decrease of the temperature registers with urban zone with different characteristics.

With the data registered during the circuits, the location of the successive street intersections were located on a plan of the city to establish the relation between the observations and the time intervals with the corresponding temperatures measured in the principal street intersections of each circuit.

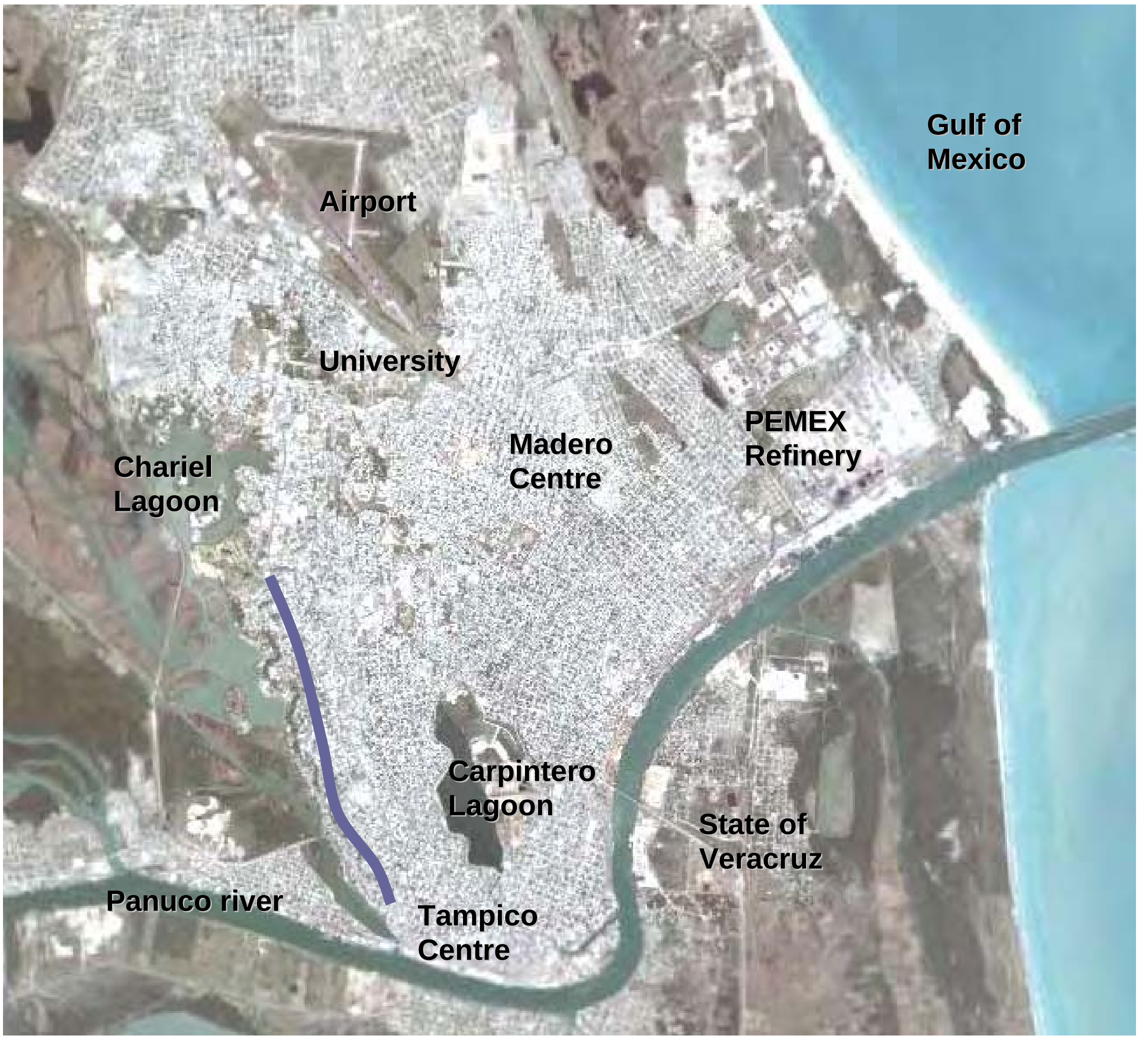


Figure 10.10. Main features of Tampico, Mexico

Table 10.2. Circuits of the mobile stations, vehicles with temperature data loggers, showing the time take to complete each circuit.

Circuit	Route	Time hrs
1. Coast	Centre, towards the coast by Fidel Velásquez Boulevard, Adolfo López Matéos Boulevard, Tamaulipas Av., Coastal Boulevard, Álvaro Obregón Av., Emilio Portes Gil Street, Centre.	1:25
2. River and Madero	Centre to Hidalgo Av., Ayuntamiento Av., Universidad Av., Adolfo López Matéos Boulevard, Monterrey Av., Centre.	1:05
3.Libramiento	Centre, Hidalgo Av., Loma Real Boulevard, Libramiento Av., Carr. Cd. Valles, Torreón Street, Centre.	1:00
4. Golden belt	Centre, Rosario Bustamante Street, Ejercito Mexicano Av., Faja de Oro, Prolongación Faja de Oro, Airport, Hidalgo Av., Centre	1:10
5. Circle	Centre, Monterrey Av., 1st of May & Francisco Sarabia Streets, Ejercito Mexicano Av., Hidalgo Av., Río Sabinas Street, Miraflores, Cairel Av., Reforma Av., Hidalgo Av., Centre.	1:05

Note: In all circuits, the Metropolitan Park parking entrance at the Liberty Plaza, in the centre of the city, was the point of departure and arrival of all circuits.

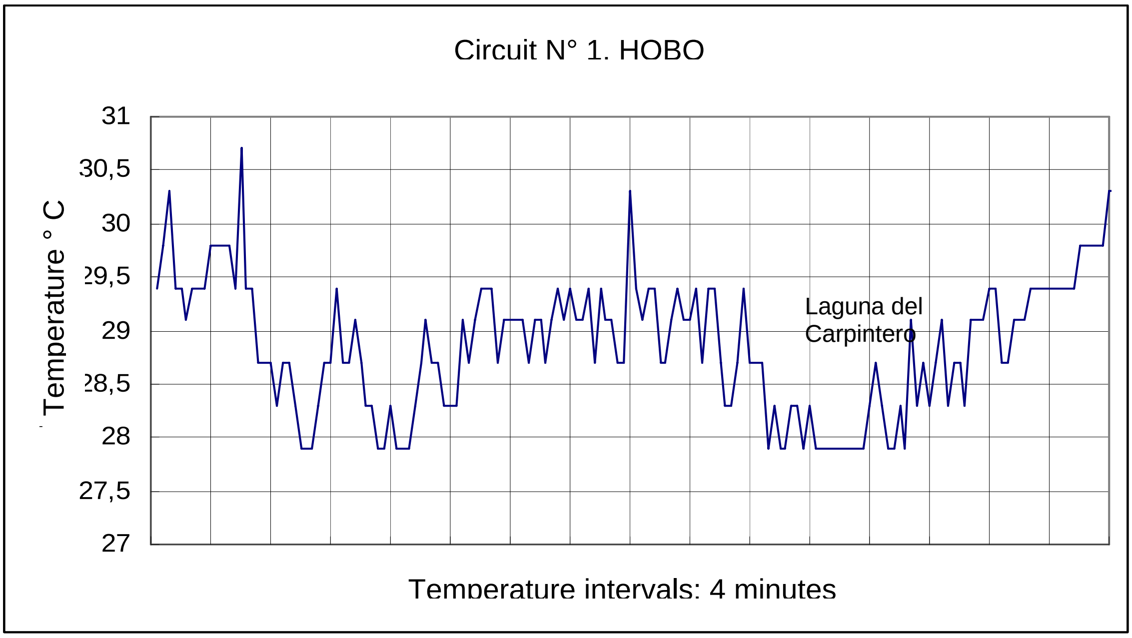


Figure 10.11. Example of temperature registers of a HOBO sensor.

In the second stage of analysis, the temperature data were prepared in an Excel file, according to the following procedure: an aerial photo of the study area was inserted as a background in an ACAD file, the circuits were then traced as a polyline to obtain the coordinates of intersections noted at two minute intervals. These coordinates were inserted in the Excel files in order to obtain a file with the temperature, time and coordinate of each register. The temperature data for preselected intervals could then be plotted automatially on a city map.

This procedure allows the plotting of all the temperature registers with different colours according to the temperature, with a total of 800 records in this case.

10.6.3. Results.

The Tampico heat island experiment showed a temperature variation of 4 degrees during the measurements with a minimum of 26° at the coast, 27° in the shores of rivers and lagoons, up to a maximum of 29° in the denser urban areas and zones with large asphalt and concrete surfaces. The densest zone in the city centre reached the maximum temperature of 30° C, Figures 10.12 and 10.13. The importance of air conditioning as a source of heat heat is shown in Table 10.3, based on measurements made in the university campus on the day of the experiment.

Table 10.3. Increase of outdoor air temperature with air conditioning at 11:30 am.

Measurement point	**Temperature**	**Difference**
Outdoor air temperature	31-32ºC	-
Indoor air temperature with A/C	25-26ºC	- 6 degrees
Outlet air temperature of the A/C equipment	37-38ºC	+ 6 degrees

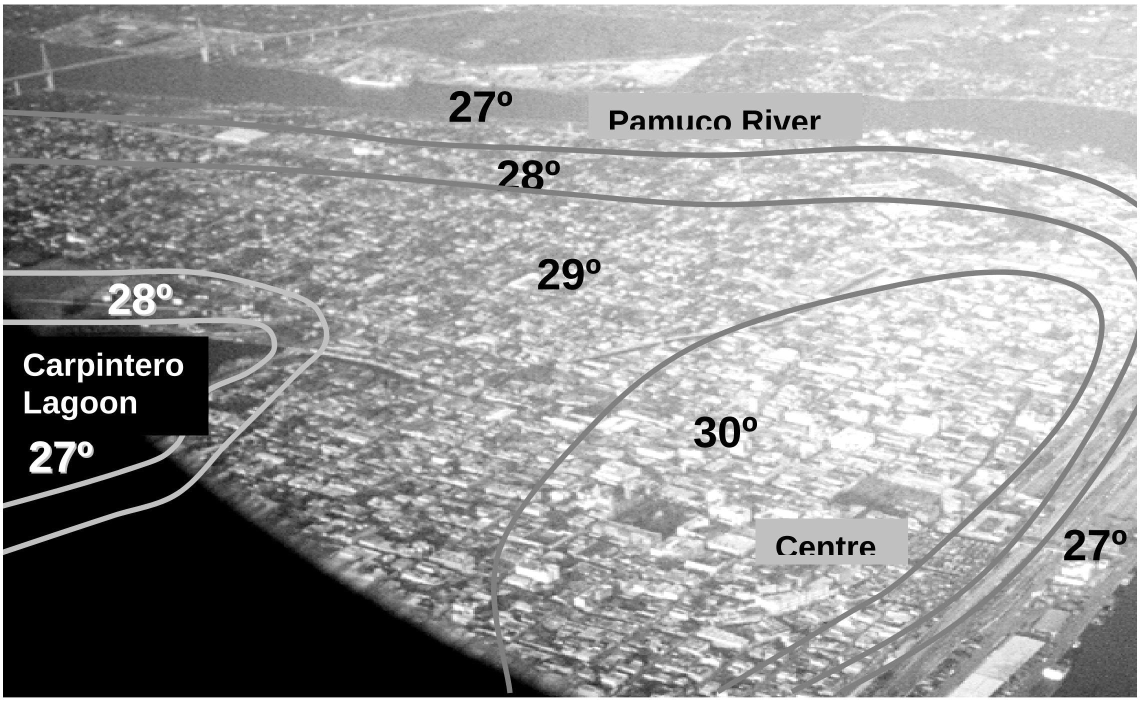


Figure 10.12. Isotherms of the urban heat island, Tampico, showing the moderating effect of the Pamuco River and the Carpintero Lagoon.
Source: Overview aerial photograph by the author.

The Tampico urban heat island, with a war-humid climate, presents a maximum temperature variation, similar to those measured in previous studies in temperate and cold climates of Argentina. The variation of 3 degrees C between the dense urban centre and the peripheral areas with water and vegetation clearly demonstrates the thermal impact of the built environment. In contrast to the previous studies, where only one heat island, based on the central area, was detected.

In this case, a series of zones with increased temperature were identified, coinciding with different centres in a polycentric urban structure.

Despite the low building density and building heights of the new commercial centres, it is concluded that the large extensions of dark unshaded asphalt in parking areas, without vegetation, is a major factor in the temperature increase registered in these areas, exacerbated by the heat emitted by vehicles. The zone of low rise but dense social housing developments located in the north of the study area also coincides with an area of high temperature.

The lagoons, within the urban area and adjacent to the study area to the west, coincide with significantly lower temperatures, while the moderating effect of the sea to the east is also apparent, with the lowest temperatures recorded.

Figure 10.13. The urban heat island of Tampico, Mexico.

These results confirm the following recommendations to contribute to the mitigation of the heat island effect:

- Conserve lagoons, stretches of open water and vegetation in the urban area.
- Avoid large surfaces of asphalt, especially extensive unshaded areas for parking.
- Control the maximum permitted ground coverage of buildings, Ground Occupation Factor, reducing the roof area.
- Promote tree planting in the urban area, both in streets and public areas, as well as private plots.

The results of the heat island experiment, carried out in the framework of a postgraduate master course, were very satisfactory and demonstrated the following points:

- The exercise was a strong motivation for the group of participants, allowing the detection of environmental impacts at the urban scale, without depending on sophisticated equipment.
- The preparation of the experiment and the planning of the circuits was undertaken in a period of a week with the active participation of the students.
- The experiment allowed the teaching and application of measuring techniques, including calibration, verification of registers obtained and the plotting of results.
- The detection of results was very rapid, with the first presentation of graphic results presented one hour after the circuits were completed.

10.7. CITY IMPACT ON AVERAGE TEMPERATURE AND SWING

For this thesis, the relevance of the heat island and the modifications of the thermal conditions in urban zones is the way in which the Comfort Triangles can show the changes of both the average temperature and the temperature swing produced by the built environment, compared with peripheral areas outside the zone of direct urban influence. In this section, the Comfort Triangles are applied to visualise the changes produce and demonstrate the value of this tool for analysing the environmental modifications.

10.7.1. Summary of results

Table 10.4 presents the results of measurements of the intensity of the heat island during the days of the experiments. Table 10.5 indicates the variation in the average temperature registered in the urban zone TMu, and the average temperature in the airport outside the area of direct influence on the urban area, with similar characteristics to the surrounding rural zone, TMr, together with the temperature swings ATu and ATr registered in both zones.

Table 10.4. Temperatures measured during the heat island experiment and maximum and minimum temperatures registered in the Met Station on the same day.

City	Date	Min temp		Heat island		Max temp	
		Tmin urban	Tmin rural	T, u	T, r	Tmax urban	Tmax rural
Buenos Aires summer	19/10/99	23,7	21,9	26,3	23,2	31,4	29,2
Buenos Aires, winter	22/06/99	12	10	13,7	10,7	21	18
Río Gallegos	22/06/01	1	-2	3,5	-1	4,5	0,5
Tampico, México	06/06/05	26	24	30,4	26,8	32	29

Table 10.5. Average temperatures and thermal swings in the four experiments.

City	Date	Average urban Temp	Urban thermal swing	Average rural swing	Rural thermal swing
Buenos Aires 1	19/10/99	27,6	7,7	25,6	7
Buenos Aires 2	22/06/99	16,5	9,0	14,0	8
Río Gallegos	22/06/01	2,8	3,5	-0,8	3
Tampico, México	06/06/05	29,0	6,0	26,5	5

10.7.2. Application of the Comfort Triangles at the urban scale.

Finally, the results of these studies are presented in the format of the Comfort Triangles, demonstrating the nature of the modifications registered both in temperature and environmental conditions, produced by the difference between the urban area and the surrounding natural habitat.

Although the increase in temperature and modification of the temperature swing are potentially favourable in the cold climate of Río Gallegos and the winter season in temperate Buenos Aires, it has been pointed out that this effect is the result of high energy use in the urban area, which also contributes to greenhouse gas emissions.

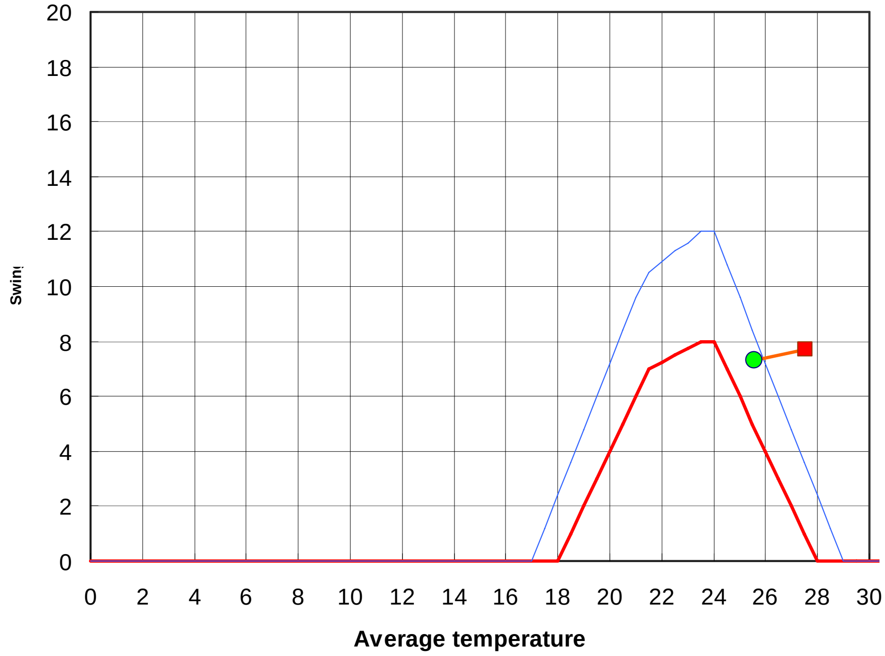


Figure 10.14. Difference between the environmental conditions in the central area (orange square) and the peripheral zone of the Federal Capital, Buenos Aires (green circle), in summer, with the mild temperature increase and the similar thermal swing.

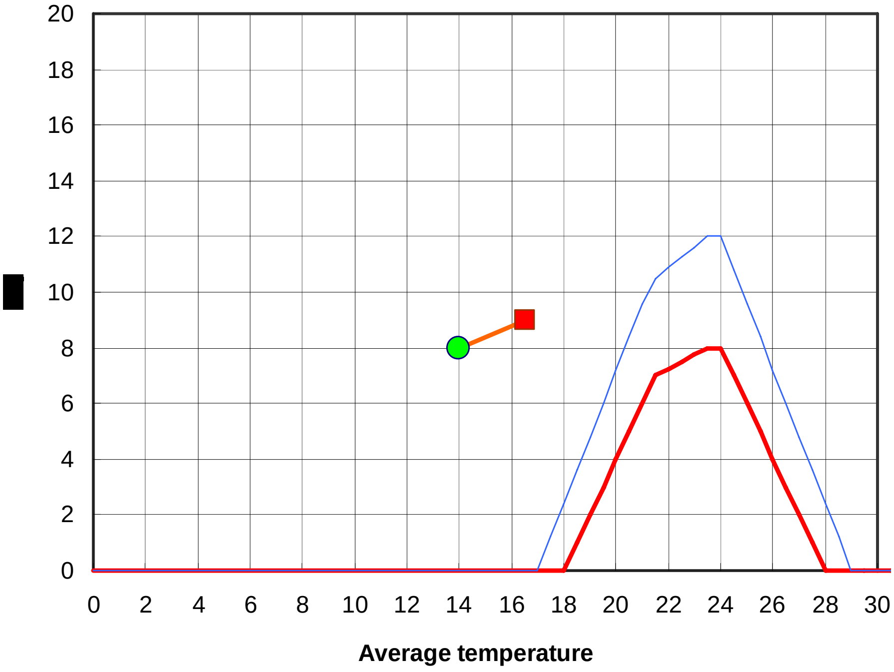


Figure 10.15. Difference between the environmental conditions in the central area (orange square) and the peripheral zone of the Federal Capital of Buenos Aires (green circle) in winter, with an increase in both the average temperature and the temperature swing.

It should be noted that the measurements in Buenos Aires corresponds to the Federal Capital area only, while the measurements in other cities covers the central area and the surrounding rural zone.

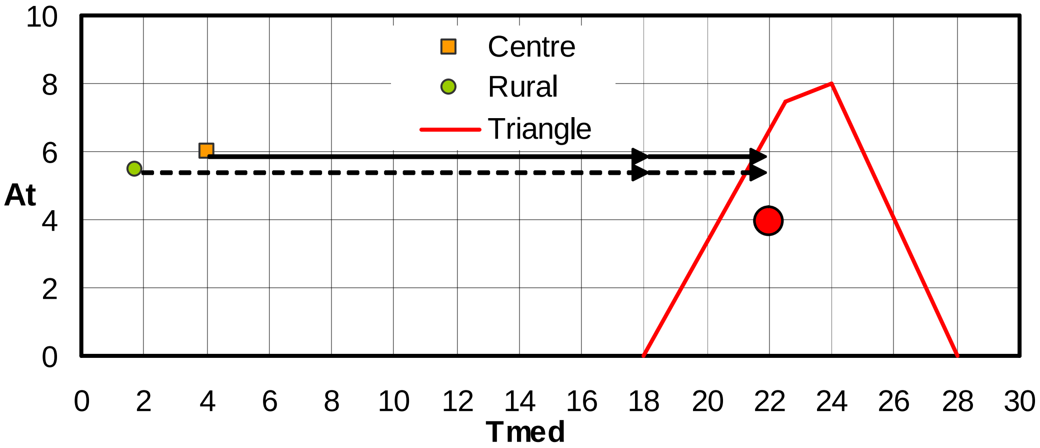


Figure 10.16. Difference between the environmental conditions in the urban centre and the peripheral areas of Río Gallegos, Argentina, in winter, with the temperature difference to achieve comfort (18°C) or to reach typical indoor temperatures.

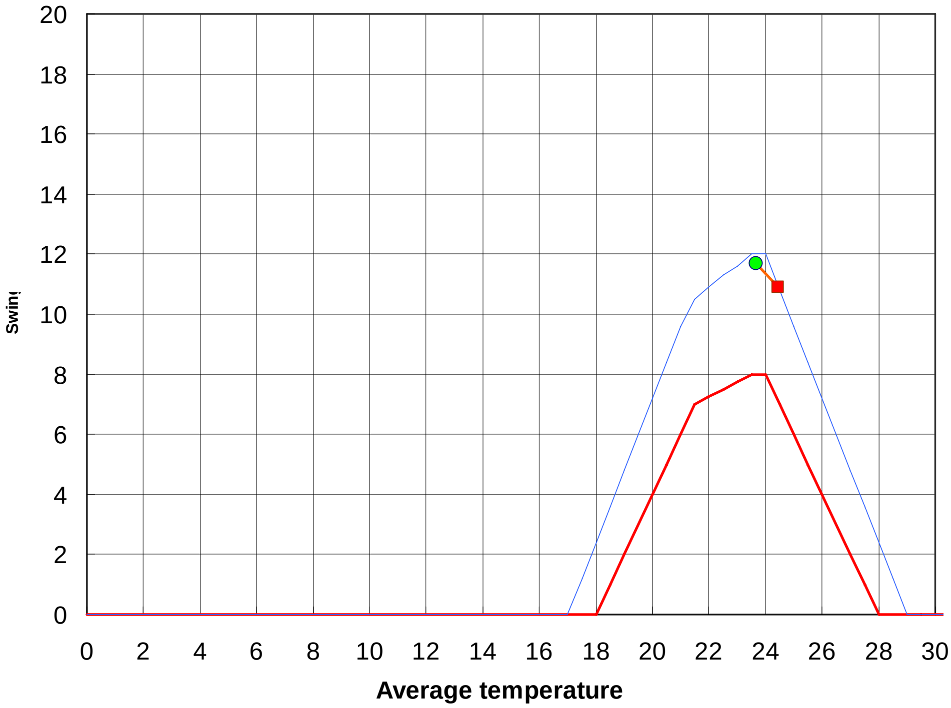


Figure 10.17. Difference between the summer environmental conditions in the urban zone (orange square) and the peripheral zone of Tampico, Mexico (green circle), with an increase in the average temperature and the temperature swing.

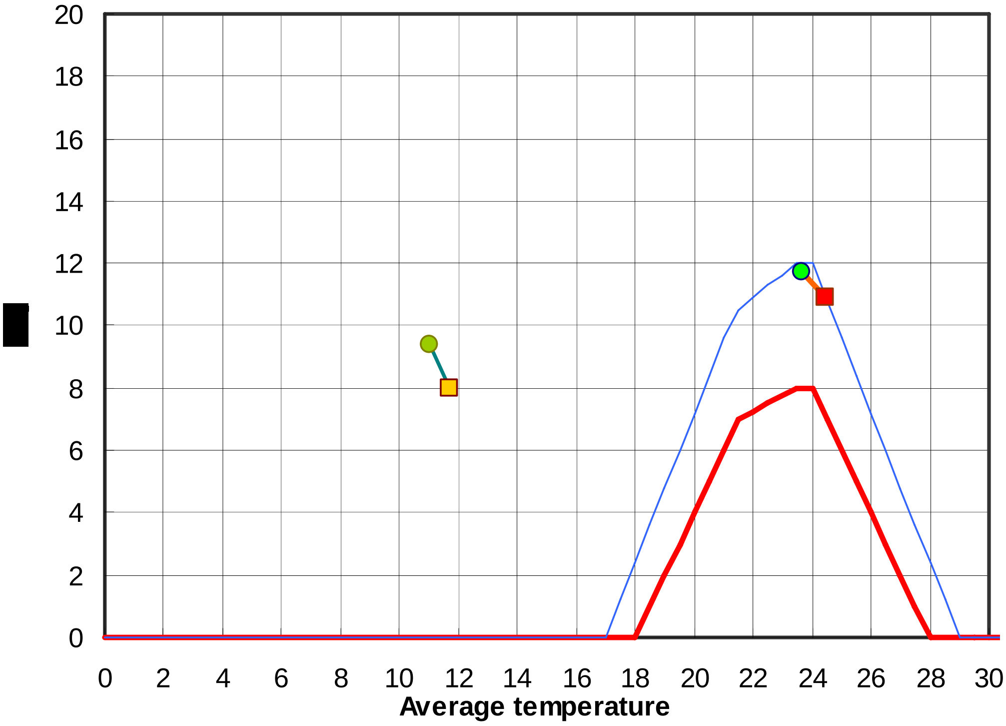


Figure 10.18. Comparison between the meteorological data from two stations in Buenos Aires, the Central Observatory (orange square) in the urban area and Castelar in the suburbs, further from the River Plate (green circle). Data for a 10 year period for the months of January, summer with orange line, and june, winter with blue line (Evans and de Schiller, 1991).

In the hot climate situation of Tampico and the hot summer season in temperate climates such as Buenos Aires, the increase of air temperature is highly unfavourable. In both cases the Comfort Triangle format indicates that the rural areas are more comfortable although at the upper limit of the comfort zone, while the conditions in the urban area are beyond the comfort zone. In contrast to the situation measured in cold climates, this variation is not due to heat losses from heated buildings, but rather from heat generated by vehicular circulation, heat from air-conditioning systems and the accumulation of heat in building materials exposed to the sun during the day

All of these heat island experiments indicate a clear impact of the built environment on the temperature distribution in the urban areas surveyed. Although the measurements presented here only represent a specific and not necessarily representative day, the values from urban and rural meteorological stations in the same area and for the same decade also show significant temperature differences. For example, Figure 10.18. compares the conditions in the central observatory in the Federal Capital, Buenos Aires, 4 km form the River Plate, with those of Castellar outside the Federal Capital, in a suburban area 21 km from the river (Evans and de Schiller, 1991).

In this case, the increased distance from the River Plate Estuary produces a larger temperature swing due to the lower heat capacity of the land, compared with the large surface of water moderating the temperature variation. The difference in average temperature is 1,2°C, while the difference in thermal swing is 0,8°C, small but significant variations affecting the energy demand for heating in winter as well as the cooling demand to achieve summer comfort.

10.8. CONCLUSIONS

This chapter demonstrates the significant effect that the built environment has on the modification of average temperatures and temperature swings. Although these differences are relatively small compared with the potential modifications achieved in indoor spaces which are analysed in the following chapter, they can have an important influence in the heating and cooling demand of buildings.

Indeed, the heating effect of cities can be equivalent to a latitude shift of 4°C; that is the temperatures in the urban area are similar to those found in rural areas 4°C closer to the Equator, applying the ‘latitude shift’ concept originally proposed by Olgyay (Cooke, 2004). The variation between urban and rural met stations in Argentina was studied by Camillioni and Barros (1991), who also reported a similar 3°C difference in the average temperatures for the two situations.

However, as the Comfort Triangle Graph shows, urban areas not only modify the average temperatures but also the temperature swing. This demonstrates the utility of the approach and enables the visualisation of important differences between meteorológical data recorded in airports outside the urban area and the conditions found arround buildings within urban centres.

In the next chapter, the even larger variations in the conditions produced by architectural design decisions, such as orientation, building form and design of the building skin, demonstrated by a series of examples and case studies.

CHAPTER 11. CASE STUDIES AT THE ARCHITECTURAL SCALE

11.1. INTRODUCTION

Following the sequence of different scales presented in Chapters 10, 11 and 12, this second chapter of Part 4 presents a series of studies of indoor temperatures in buildings, demonstrating the direct relationship between indoor and outdoor temperatures, with emphasis on the impact of architectural variables.

These variables are the features of the building that play an important role in the interaction with the environment according to the conditions found in different climates, particularly the location and orientation together with the building form and envelope, directly related to architectural design decisions.

Therefore, the object of this chapter is to test the Comfort Triangles as an analytical tool, demonstrate the application and verify the utility of this graphic bioclimatic design aid at the architectural scale, using measurements in existing buildings of different characteristics, as well as thermal simulations.

The case studies included in this chapter were specifically selected to analyse different architectural design features such as building form, morphology and orientation, glazing and solar protection. These variables are related to the occupancy and activities carried out in the buildings as well as the materials used, the specific theme of the next chapter.

The case studies in different climates are proposed to test the application of the Comfort Triangles in very different environmental situations, from the equator to the mid-latitudes, following a sequential rationale organised in Sections 11.2. to 11.5.

The sequence presented demonstrates the impact of design features, elements of solar control and covered courtyards on the thermal performance of buildings.

- **Section 11.2:** Impact of design features on thermal performance, shown by measurements in different spaces of a large building complex, the Faculty of Architecture and Urbanism of the Central University of Ecuador, at 2800 m above sea level and latitude 0º on the equator.
- **Section 11.3:** Role of solar control on thermal performance shown by temperatures registered in a building with favourable orientation, large glass surfaces and effective solar control, the Curutchet House, City of La Plata, Province of Buenos Aires, Latitude 34° S. In this case, simulations are compared with measurements.
- **Section 11.4:** The courtyard as a thermal modifier and microclimatic moderator is shown by measurements in a traditional patio with a well ventilated and shaded roof located in Colima, Mexico, latitude 10º N.
- **Section 11.5:** A second courtyard study located in Cuenca, Ecuador, latitude 3º S, shows very different temperature modification achieved by a glazed and ventilated roof. This example provides a valuable comparison with the previous study, considering the similar dimensions and building morphology, but different climate conditions and comfort requiements.

11.2. THERMAL PERFORMANCE OF DESIGN FEATURES, QUITO

With the purpose to demonstrate the role of design features in the thermal performance of buildings, a series of measurements were carried out in January-February 2006 in different indoor spaces of the Faculty of Architecture and Urbanism, Central University of Ecuador, located in the hills of the City of Quito at 2800 metres above sea level. They were made during a five day seminar for undergraduate students of architecture given by author. The temperature measurements were registered during the seminar, and the initial results presented to the participants on the final day.

11.2.1. Objective of the case study.

The objective of the experiment is to demonstrate the variation of thermal conditions according to the following architectural features:

- Orientation, compactness and building morphology.
- Overhangs, glazing areas and solar protection.
- Occupancy, activities and building use.
- Construction system, material characteristics and surface colour.

The typical temperatures of Quito are temperate during the day, dropping sharply at night to produce an important temperature swing. Due to the high altitude of the city, the average temperatures in February range between 8° C and 22° C, despite the location on the equator. The height above sea level also means that solar radiation is intense, though significant cloud cover and relative humidity moderate this impact, particularly in June and July.

Season variation is low as small seasonal differences in solar trajectories imply small season variations in radiation and temperatures. During the experiment, the outdoor temperatures ranged between 12° and 24° C, with generally sunny conditions, slightly higher than the average values for the month obtained from the National Meteorological Service.

11.2.2. Measurements.

A description of the selected spaces is given below, with the construction characteristics, orientation and solar protection of openings, activities undertaken in the spaces and location of the sensors, as follows:

Outdoor space: The HOBO recording instrument measured the air temperature in the central patio of the Faculty, an open paved space with a few trees, surrounded by buildings of two to four storeys. The sensor was placed on a thin metallic sheet, under a large concrete overhang, well protected from direct sun and rain in a well hidden location out of sight and reach of the students, as shown in Figure 11.1. It is possible that the concrete overhang in the form of a barrel vault with significant thermal inertia may have reduced the night-time temperature drop slightly.

Figure 11.1. Central square of the Faculty and location of the sensor.

Deans Office: This double height space with a concrete barrel vault and protected windows facing north and south, completely avoids the entry of direct solar radiation in this latitude on the equator. During the experiment, there were no meetings in the ample office, only occupied by the Dean with occasional presence of assistants, so the occupancy was low and intermittent and the internal gains were then negligible. The sensor was placed on the window sill, close to the window at a height of 1,40 m, close to the glass, as shown in Figure 11.2.

Figure 11.2. Exterior and interior view of the Deans Office.

Faculty Auditorium: The main Auditorium of the Faculty has a capacity for an audience of 250, with a very heavy construction consisting of a concrete roof slab, concrete block walls and a concrete floor without additional finishes. The space, totally internal without windows, has limited ventilation and no solar heat gains. During the experiment the auditorium was occupied by 200 students between 10 to 12 am. The HOBO was placed on the top of the projection cabin, well exposed to the indoor air, Figure 11.3.

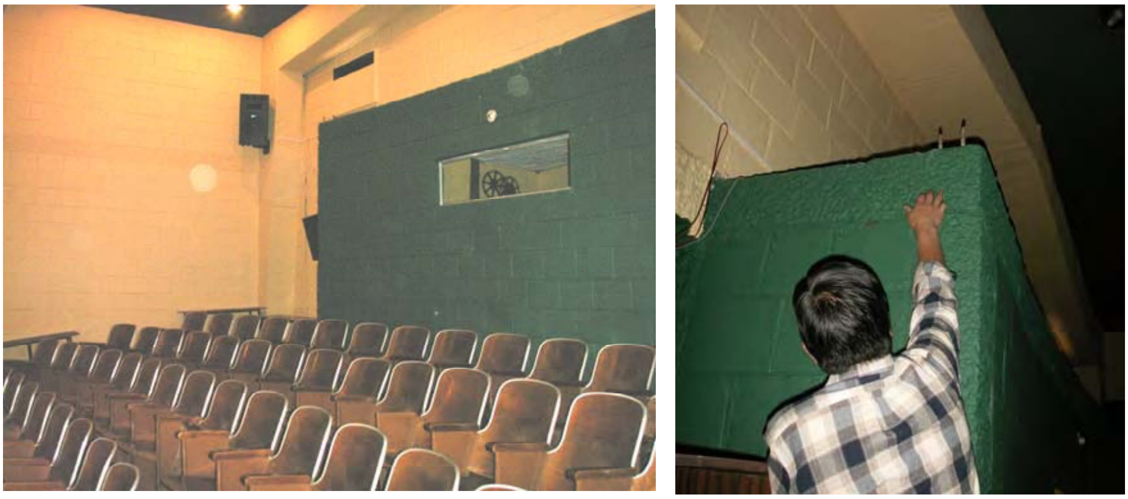


Figure 11.3. Interior of the Auditorium with the location of the HOBO on the roof of the projection cabin.

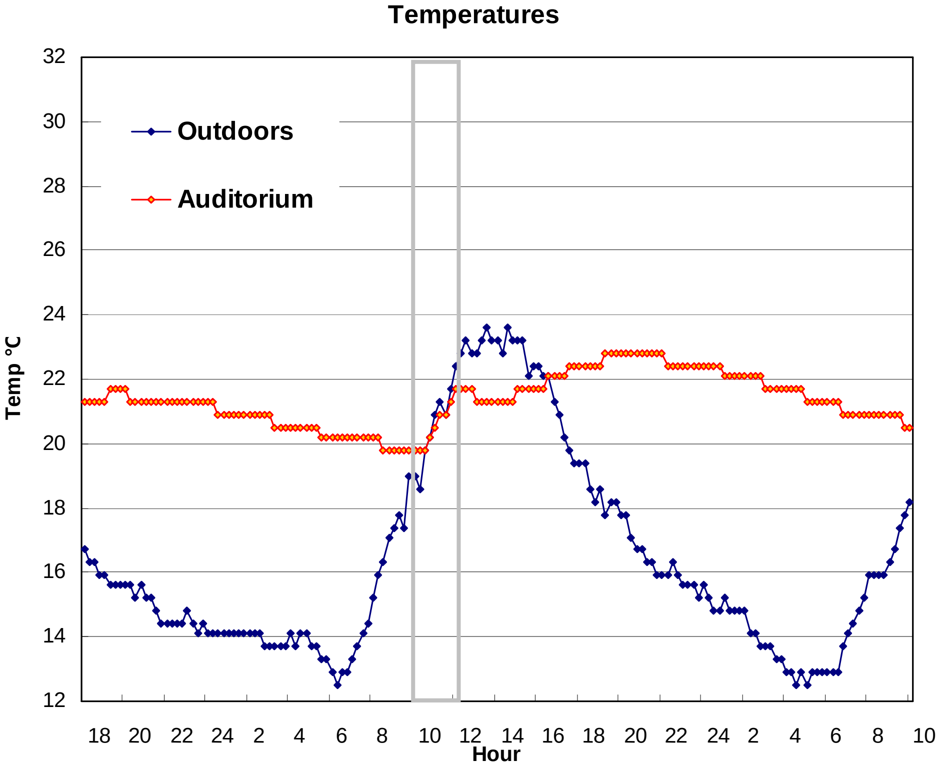


Figure 11. 4. Temperatures in the Auditorium, with the increase of temperature between 10 and 12 am, ranged from 19,8 C to 21,8° C, which coincides with the occupation of 200 students. The thermal inertia is about six hours, the time difference between the maximum outdoor peak (12 am-3 pm) and the indoor peak (8-10 pm).

Computer centre office: The sensor was located in the sill of the east facing window, seen in Figure 11.5., that the occupants considered to be out of contact with direct sunlight. However, the registers showed that the HOBOs are exposed to direct sunlight with a sharp rise in temperature between 7 and 9 am, reaching a maximum of 30,4° C. When analysing the average temperature and the temperature swing, this peak was compared with the estimated conditions without the impact of direct sunlight, considering that this variation was not typical of the air temperatures in the room. The internal gains are low, with one user occupying the office intermittently.

Figure 11.5. Window of the Computer Centre Office.

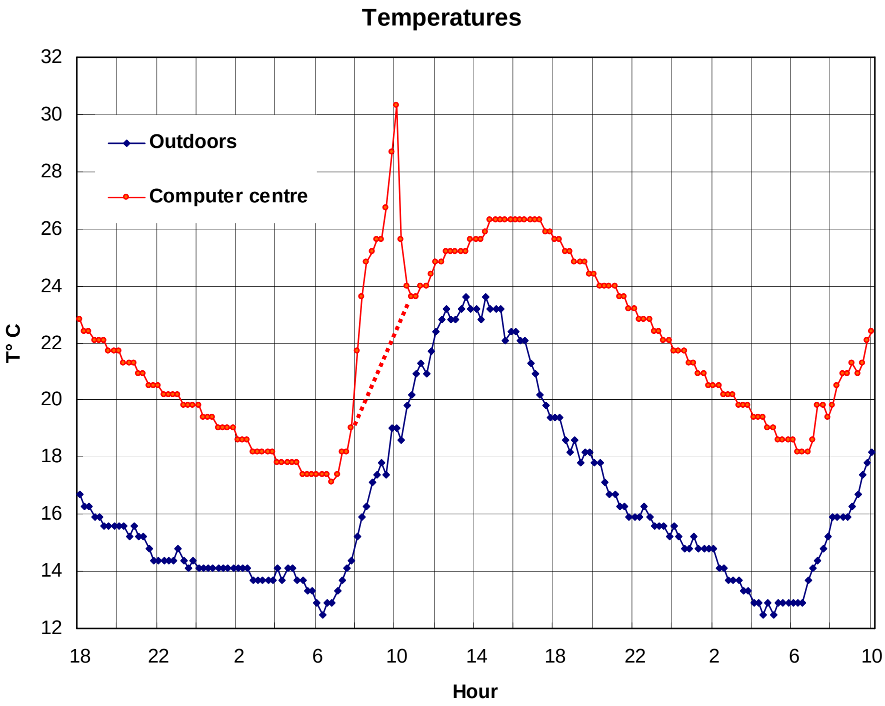


Figure 11.6. Temperatures in the Computer Centre Office, compared with the outdoor temperature, indicating the temperature with the HOBO exposed to direct sunlight at 8 am and the dotted line indicating the probable indoor air temperature, without the impact of direct sunlight. The thermal inertia is about three hours.

ISI Office, Advanced Research Institute (Instituto Superior de Investigaciones)**:** An internal space with very limited contact with the outdoors, with only occasional occupants during the measurements. The very small window, which opens onto the central patio was closed and totally protected from the sun. The sensor was located in the ventilation duct above the door, as shown in Figure 11.7.

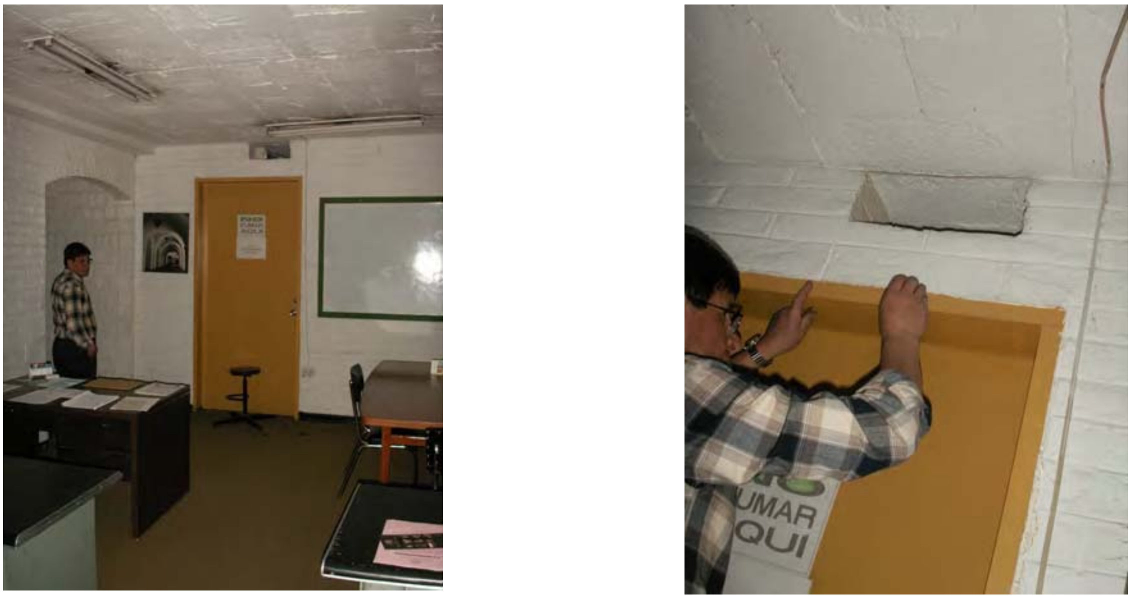


Figure 11.7. ISI Office, the Advanced Research Institute, showing location of HOBO.

11.2.3. Applying the Comfort Triangles.

In order to obtain temperature registers more representative of typical conditions and avoid possible irregular daily variations due to occasional cold winds or variation of sunshine, the average of the values obtained from the whole week were used. Figure 11.8. indicates the resulting variations of temperatures registered in the selected indoor and outdoor spaces. None of these spaces has artificial heating, cooling or ventilation.

Table 11.1. Maximum and minimum air temperatures, average temperatures and temperature swings in the spaces in the Faculty.

Space	T max	T min	T av	Swing	Inertia hs
Outdoor air temperature	23,8	12,3	18,1	11,5	-
Auditorium	22,7	19,8	21,3	2,9	6
Deans Office	24,0	18,7	21,4	5,3	4
Window to the East (without sun)	26,4	17,0	21,7	9,4	3
Window to East (with direct sun)	30,3	17,0	23,7	13,3	-
Advance Research Institute	17,6	17,3	17,2	0,3	23

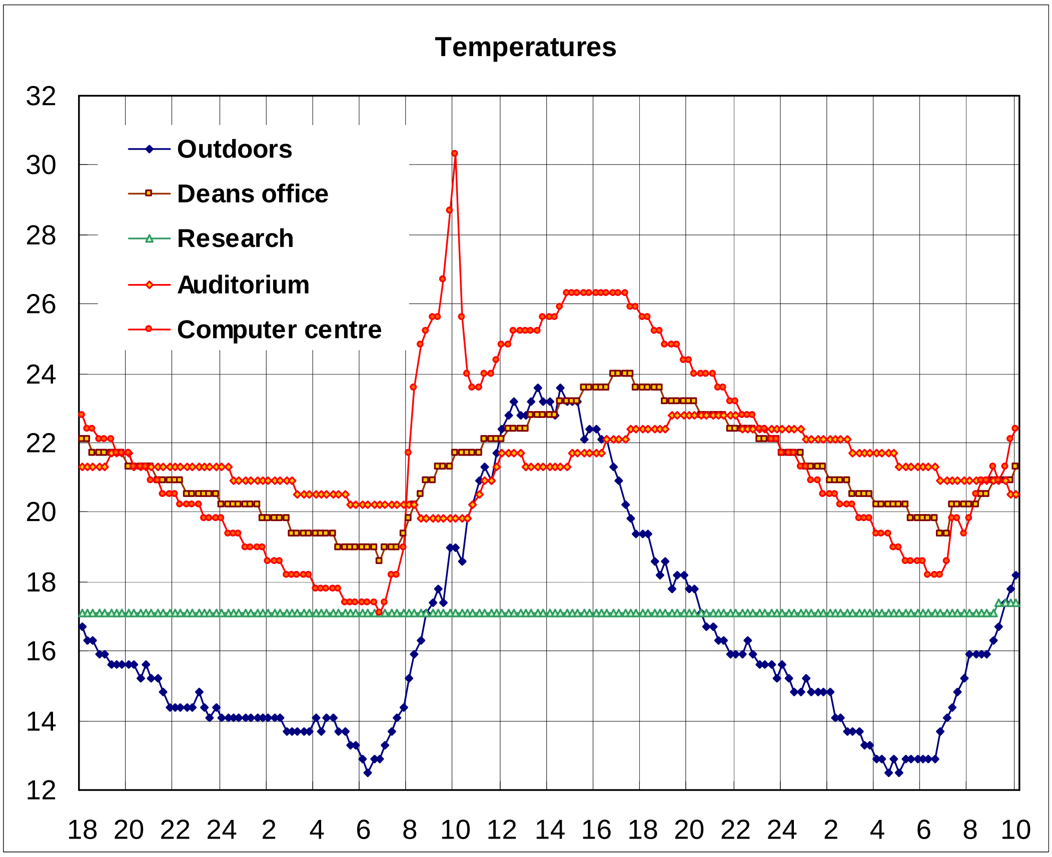


Figure 11.8. Comparison of air temperatures in the four different spaces selected for the experiment.

11.2.4. Conclusions.

This experiment, completed in a limited time period, provides a demonstration of the significant variations of thermal performance in different spaces of the building complex that houses the Faculty of Architecture and Urbanism, of the Central University of Ecuador, Quito.

The results identify the factors that produce these important modifications of average temperatures and temperature swings. The variables that affect the indoor temperature regime include:

- **Orientation and windows:** Direct solar gains (Computer Centre Office).
- **Overhangs and orientation:** Solar protection (Deans Office).
- **Construction:** Heat transmission through the dark coloured roof (Deans Office).
- **Occupants:** Internal gains due to occupants (Auditorium with 200 occupants over 2 hours).
- **Form:** Internal spaces with high thermal inertia (Advanced Research Institute).

As Figure 11.10. shows, the modification of the amplitude is related to the thermal inertia of the space. The dispersion of the points is in part the result of the difficulty to detect the thermal delay with precision as well as differences in ventilation and occupation.

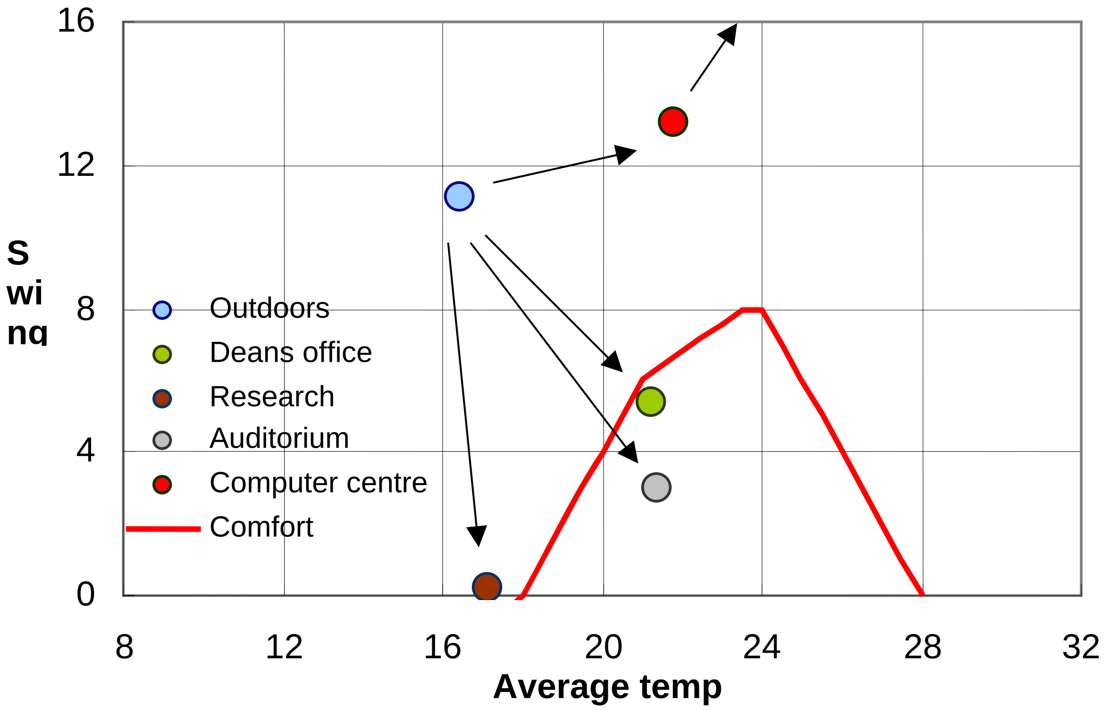


Figure 11.9. Average temperatures and temperature swings of the five spaces, and the increase in swing and average for the HOBO in the computer centre with direct sun.

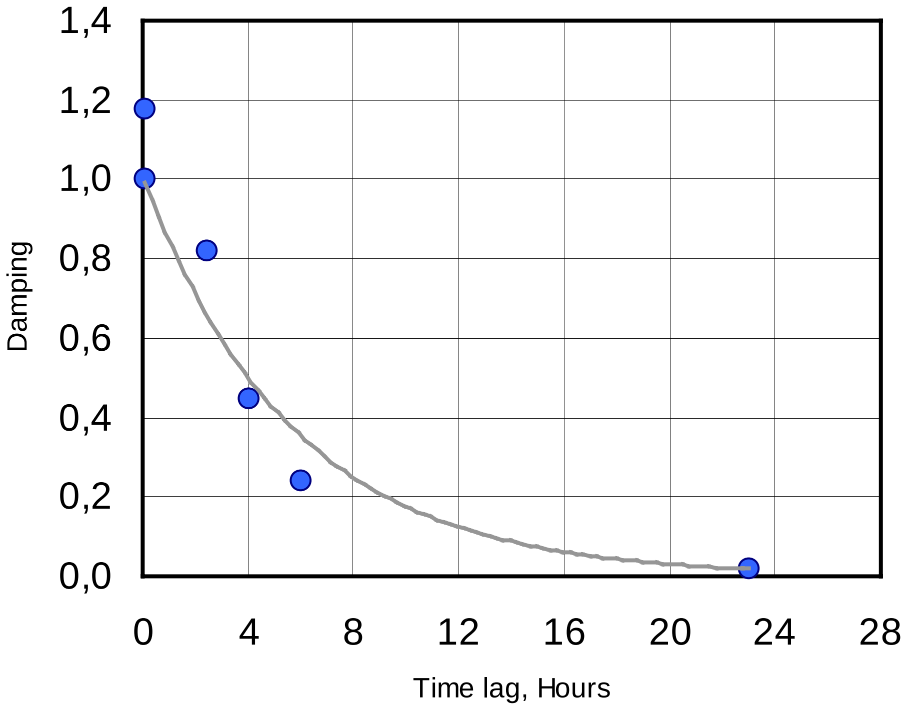


Figure 11. 10. The relationship between the reduction of temperature swing, indicated by the indoor temperature swing divided by the outdoor swing, and the time lag or thermal inertia, defined as the time difference between outdoor and indoor peak temperatures.

11.3. THERMAL PERFORMANCE OF SOLAR CONTROL

This Section presents the study of the thermal performance of the Curutchet House, designed by Le Corbusier and built in La Plata (1949-1955), capital of the Buenos Aires Province. The house incorporates several innovative features, integrated in this small master piece of architecture, shown in Figure 11.11. Measurements and numerical simulations were carried out in 2003 with the object of assessing the thermal performance of the house, both in winter and summer.

11.3.1. Introduction to the case study.

This building integrates innovative design strategies to achieve solar radiation in winter and solar protection in summer, through the *brise soleil*, as developed by Le Corbusier, one of the first examples of this element. Additionally, the house presents extensive glass surfaces and high thermal inertia incorporated in the building elements. In a previous study, the adequacy of the design of the solar protection elements was analysed (Evans and de Schiller, 1998) to show the excellent geometric performance according to the requirements for summer and winter.

In this study, the impact of these elements on the indoor temperatures was analysed. Indoor and outdoor temperatures were registered with portable mobile sensors, at 30 minutes intervals during a two week period, representative of the conditions in winter and summer. Results of the measurements were analysed with conventional diagrams and the Comfort Triangles.

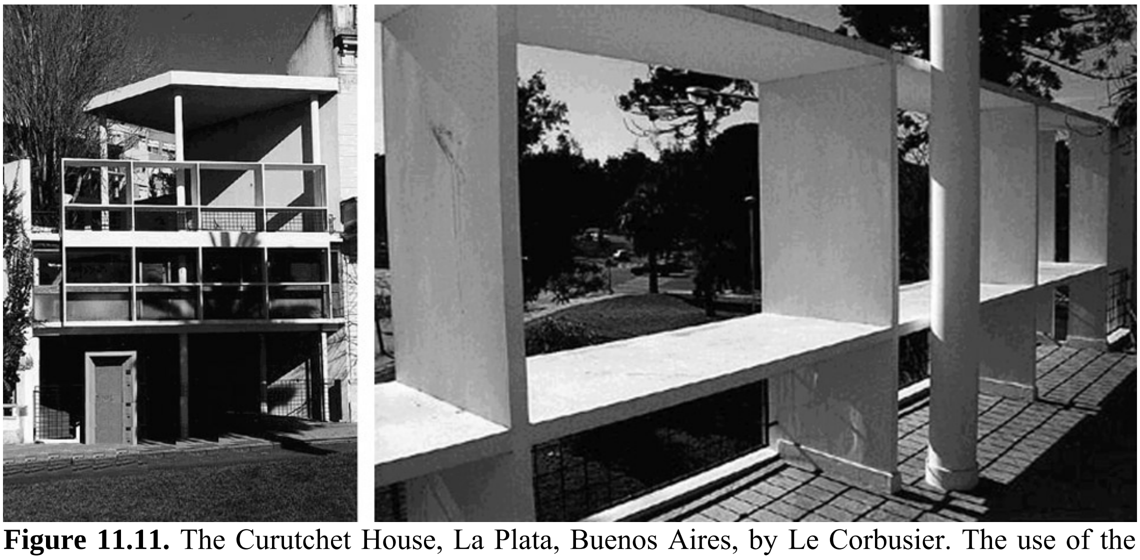


Figure 11.11. The Curutchet House, La Plata, Buenos Aires, by Le Corbusier. The use of the *brise soleil* in the front façade facing the park, and the covered terrace, perfectly calculated for solar control.

Additionally, an analysis of the thermal performance of the existing house was carried out simulating the use of new building technologies, but not available at the time when the house was design and built.

With this objective, a thermal simulation model was calibrated to verify the precision of the results, comparing the results obtained by simulations with the measurements of the rooms studied, considering the same outdoor conditions.

Afterwards, alternative building components were tested to evaluate their impact on the performance of the house. This exercise provided several conclusions drawn from the results obtained based on both measurements of the existing situation and simulations of possible alterntivas.

11.3.2. Technical data of the case study.

The house, built in a small plot facing north-west with views to the park across the road, is enclosed between party walls, shown in Figure 11.12., with the technical data as presented in Table 11.2.

Table 11.2. Technical data of the Curutchet House.

Architect:	Charles Edouard Jeanneret (‘Le Corbusier’, 1887-1965)
Site supervision:	Architect. Amancio Williams (1st stage) Architect. Simon Ungar (2nd stage) Ing. Alberto Valdes (3rd stage).
Owner	Dr. Pedro Domingo Curutchet.
Building use	House and medical consulting room.
Site area	180,00 m2
Building area	345,00 m2
Location	Boulevard 53 Nº 320, La Plata, Province of Buenos Aires.
Date of project	1947-1949.
Date of construction	1949-1955.
Building characteristics	Concrete structure and masonry walls. High thermal inertia and low insulation levels. Large openings of wooden frame and glass panels without frame, with high infiltration levels.

Due to the large glass surfaces facing north and north-west, the architectural design integrates two major bioclimatic strategies (Evans and de Schiller, 1998) for solar control at this latitude of 34° S; shading and thermal mass:

Winter solar gain with summer protection:

- The accurate design of the *brise soleil* allows maximum winter solar gain, with over 75 % of the glass surface exposed to the sun at midday, but protected from direct sun summer with only diffuse and reflected radiation.
- The deciduous tree in the inner courtyard further reduces the solar gains in summer.
- The floating roof, partially covering the terrace, provides a shaded and well ventilated outdoor area in the upper floor, with views to the park opposite, but still allowing solar penetration in the bedrooms in winter.

Thermal inertia: The concrete and masonry construction, both materials of high thermal capacity, moderate temperature variations indoors. Although this, combined with effective solar protection, minimises overheating risks in summer, it does not favour heating and energy conservation in winter. On the other hand, and in spite of the correct bioclimatic strategies implemented, the construction presents a series of thermal deficiencies, particularly during the cold season, such as:

- High thermal transmittance of the envelope, especially glass, concrete slab roof, and walls.
- High levels of infiltration in openings and sky lights roofs with limited hermetic performance

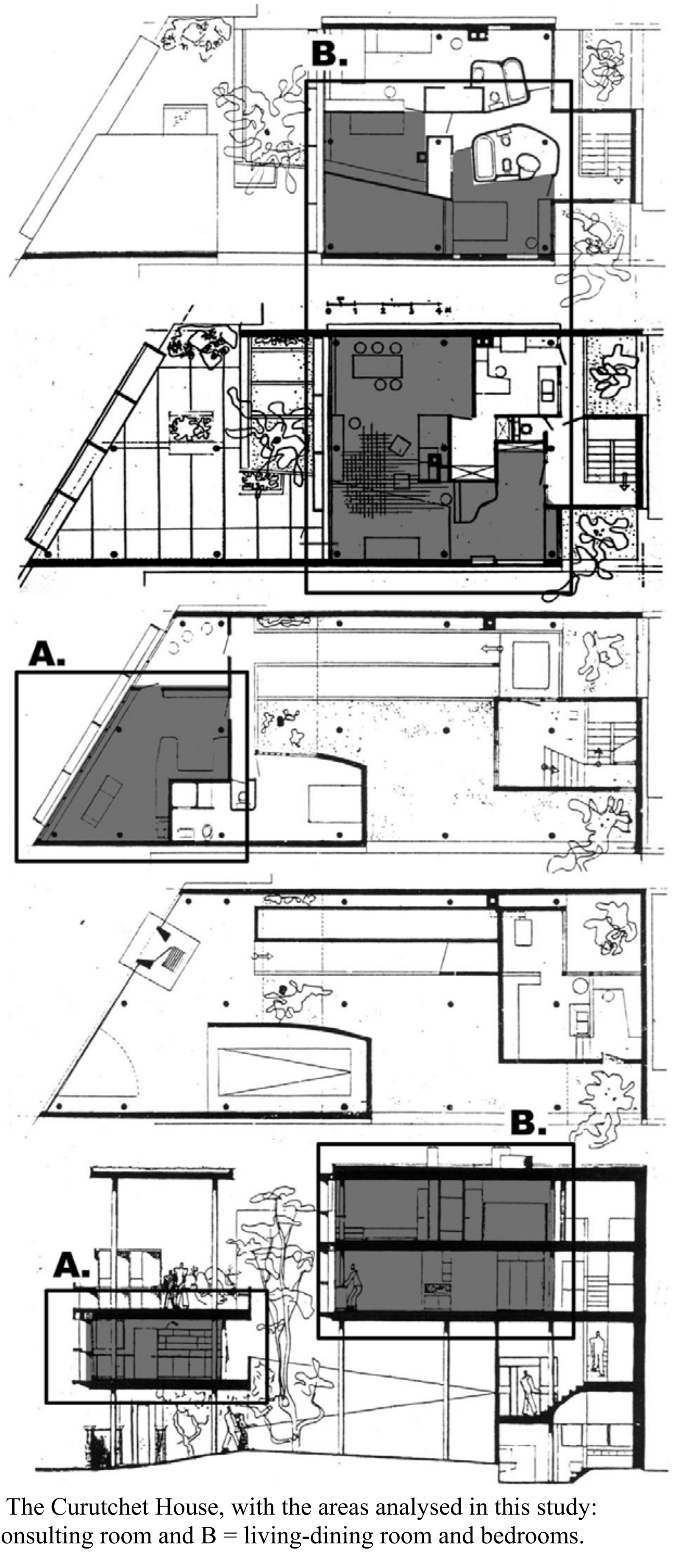


Figure 11.12. The Curutchet House, with the areas analysed in this study:
A = medical consulting room and B = living-dining room and bedrooms.

11.3.3. Objectives of the case study.

The main objective of this study is to carry out an empiric assessment on the efficiency achieved with the bioclimatic solutions adopted, analysed by temperature measurements and simulations of the thermal performance of the building, in both winter and summer. this procedure was developed to verify the results and the contributions made by the thermal characteristics of building elements and the design decisions adopted in the indoor conditions of the house, achieved in both cases by the original project and the simulated potential alternatives.

In the context of this exercise, it is relevant to take into account that the insulation materials on the market today were not available at the time of construction. Also, it is important to recognise the risks taken by le corbusier with the innovations proposed and built for this house, opposed to the conventional practice of that time. However, the this study provides the opportunity to test the potential performance of the house if new technologies actually available would have been used. for this purpose, simulation of light-weight insulation integrated in walls and roofs, together with hermetically sealed openings with double glass window panels.

11.3.4. Methodology.

The methodology adopted include the following stages:

- Measurements of indoor temperatures in a two week period in winter and equal period in summer with a reference outdoor temperature using portable sensors (Hobo and Tiny-Talk) and dry bulb measurements every 30 minutes. The house, in restoration process during the experiment, did not have significant internal gains, with the exception of occasional groups of visitors.
- Reference of solar radiation values were obtained from the CIHE Met Station, on the roof of the Faculty of Architecture, University of Buenos Aires, at a distance of 40 km from the house.
- Comparison of outdoor temperature were measured in the house with those obtained in the CIHE met station, Faculty of Architecture Design and Urbanism UBA and La Plata Observatory.
- Numerical simulation, using the program Quick (Matthews et al, 1997), incorporates the construction data of the house, with temperature and external radiation data corresponding to the measurement period. Two specific areas of the house were analysed: the medical consulting room and the double height living-dining room. Data of the air renovation were estimated based in the characteristics of the skin envelope, especially the quality of the openings.
- Assessment and evaluation of results, both simulated and registered, and adjustment of the simulation model.
- Simulation of the thermal performance considering higher insulation levels in walls and roofs, together with low infiltration openings and hermetic double glass in the consulting room.

The first measurements were carried out in winter (22/08/03 - 12/09/03), with 5 sensors, 4 indoors in different representative rooms and 1 reference sensor outdoors. In summer, temperatures were registered (12/12/03 - 29/12/03) with 8 sensors, 2 of them outdoors. It is relevant to mention that the location of the sensors used in winter was modified according to the results obtained, considering the following factors:

- The use of two thermometers outdoors allows possible identification of temperature rise due to the incidence of direct sun, detected in the winter measurements.
- Better covering of double height rooms where stratification was detected.
- Thermometers in indoor spaces, away from solar influence in main rooms.

.

11.3.5. Results.

In order to obtain a series of representative data, an hourly average of 6 similar consecutive sunny days were calculated both in winter and summer, shown respectively in Figures 11.13. and 11.14, summarised in Tables 11.6 and 11.7 .

In the winter measurements, the sensor outdoors, located in the terrace of the house, was exposed to the influence of the solar radiation between 3 and 5 pm approximately. Therefore, the values could be adjusted according to two independent techniques:

- Comparison with the data registered simultaneously in the CIHE Met Station, in Buenos Aires, distant 40 km.
- Interpolating data from the registers between 3 and 5 pm.

A small difference detected between the data registered in the house and the Met Station at the Faculty in Buenos Aires, could have resulted from the thermal inertia of the heavy concrete floor around the thermometer in the terrace of the house, Figure 11.13.

Additionally, the higher outdoor air thermal swing in La Plata, compared with the Met Station at the Faculty in Buenos Aires is probably due to the distance from the River Plate, a large surface of water which moderates the range of temperature variations.

Table 11.3. Measurements of maximum and minimum winter temperatures, Curutchet House.

Temperature	**Max.**	**Mín.**	**Tm**	**At**
Kitchen	10,7	9,0	9,8	1,7
Dormitory in double height	11,8	9,6	10,8	2,2
Dining room	10,5	9,6	10,0	0,9
Consulting room	18,5	12,0	15,2	6,5
Outdoors, terrace measured (with sun)	19,0	6,0	12,5	13,0
Outdoor, terrace estimated (without sun)	15,5	6,0	10,7	9,5
Outdoor, Faculty of Architecture, Bs As	15	6,5	10,7	8,5

Table 11.4. Maximum and minimum summer temperatures in different rooms, Curutchet House.

Temperature	**Max.**	**Min.**	**Tm**	**At**
Consulting room	26,8	23,6	24,2	3,2
Access hall	23,4	22,4	22,9	1,0
Outdoor, terrace	28	21	24,5	7,0
Double height bedroom	24,8	23,9	24,3	0,9
Outdoor, ground floor	27,0	21	24,0	6,0
Bathroom, 3rd floor	24,4	23,7	23,9	0,7
Kitchen	23,7	22,6	23,1	1,1
Dining room	23,9	22,7	23,3	1,2

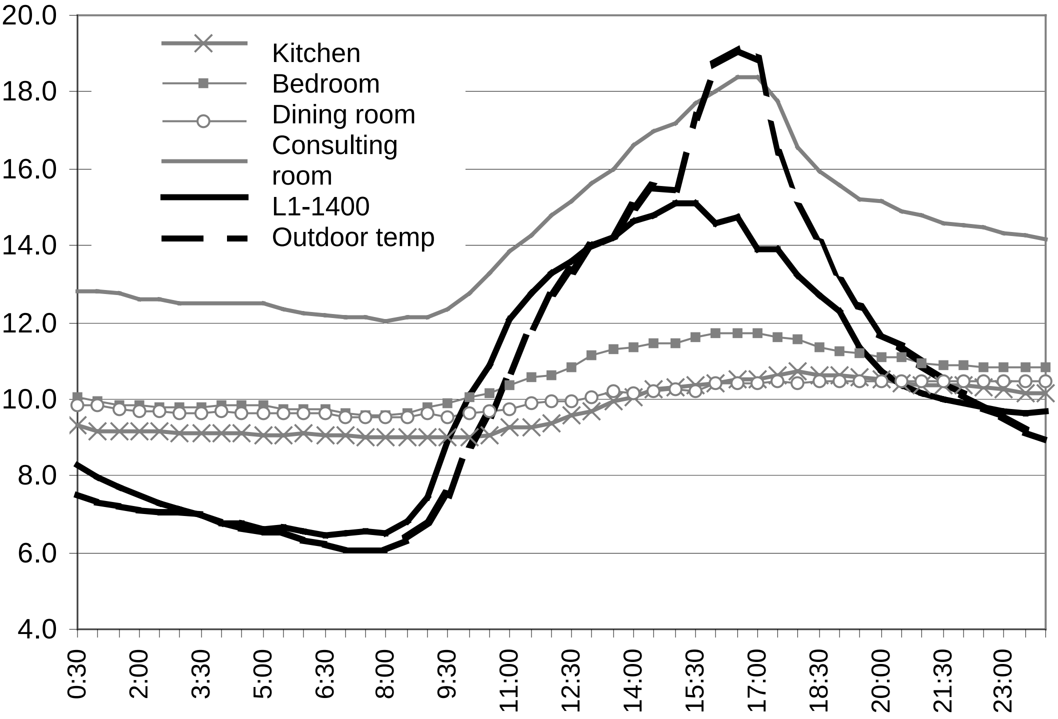


Figure 11.13. Average temperatures registered during the day in winter (29/08 - 03/09)

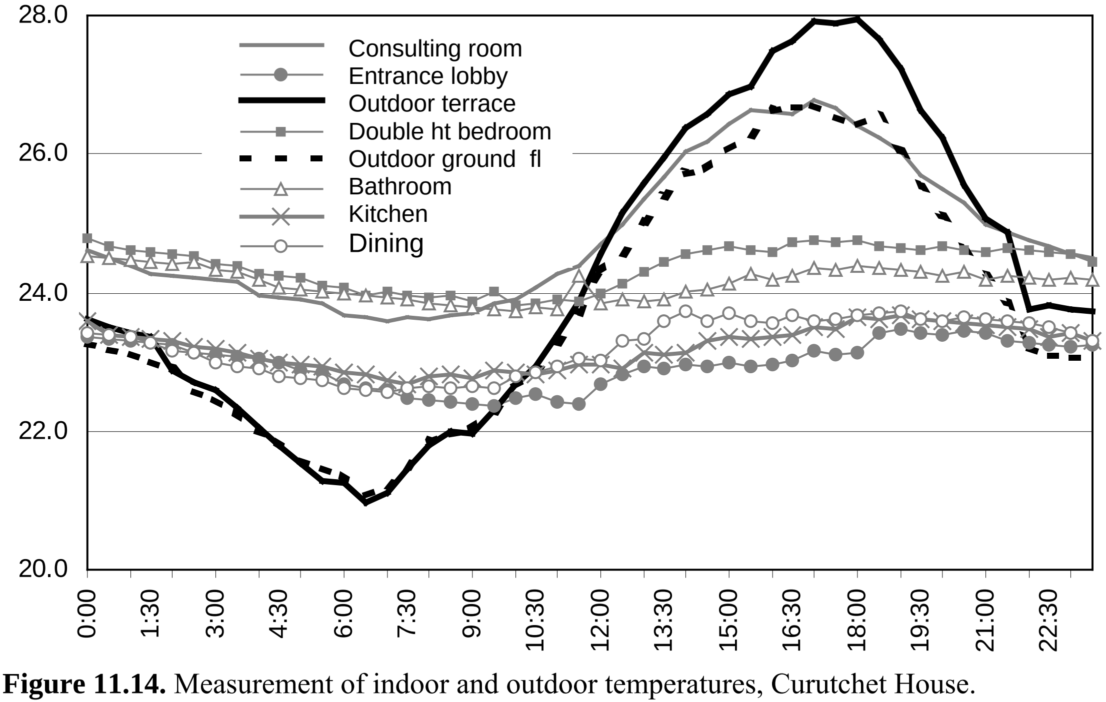


Figure 11.14. Measurement of indoor and outdoor temperatures, Curutchet House.

Consulting room,	1st floor	Outdoor temperature	ground floor
Access lobby	1st floor	Bathroom	3rd floor
Outdoor terrace	2nd floor	Kitchen	2nd floor
Double ht bedroom	3rd floor	Dining room	2nd floor

11.3.6. Thermal performance of the Curutchet House.

Winter: The results of both measurements and simulations show that, although the house has excellent solar gains in winter, the poor thermal insulation and low thermal inertia, together with high infiltration levels do not allow temperatures to reach the comfort zone. It is possible that the skylight system, designed to illuminate and ventilate the bathrooms of the upper floor, is a major cause of heat loss.

As a result of the important indoor thermal inertia, the variations of indoor temperature are very low, with a minimum value in the dining-living room of 3° C and a maximum of 6,5° C in the consulting room. The consulting room was also the space with the best thermal performance in winter as a result of the optimum orientation and limited volume. The average temperatures reached values of 16 to 17,5° in the consulting room, with maximum values within the comfort zone, while other rooms never achieve comfort.

Summer: The indoor temperatures of the consulting room are very acceptable, especially when the large areas of glazing is considered. The hottest room is the consulting room, which was also the warmest in winter. In the house on the second and third floor,

In the house on the second and third floor, the rooms on the upper floor had temperatures approximately 1º above those of the lower floor, with the lowest temperatures recorded in the access hall one floor below the living room. This shows the presence of stratification promoted by two important design features: the double height space on the one hand, acting in the cross-section, and the open plan on the other, acting in the plan configuration, both increasing temperatures on the upper floor.

11.3.7. Simulation results.

The thermal simulations made with Quick (Matthews and Richards, 1993) using the time constant method. This program was also tested in housing in tropical climates (de Schiller, 2002), with favourable results, shown by the small differences between measurements and simulations.

Figure 11.15 shows the data for the two key spaces of the house that are simulated: the living dining room and the consulting room In this case, as Figure 11.16. shows, the simulation of indoor temperatures in the consulting room is closely related to the measured data. As Table 11.8 shows, the maximum differences between the two data sets does not exceed 1º C.

Table 11.5. Temperature data for the medical consulting room in winter.

Measurements and simulations	Max.	Min.	Tm	At
Outdoor temperature	14,1	7,1	10,6	7
Measured temperature	18,2	12,0	15,1	6,2
Simulated temperature	18,1	11,7	14,9	6,4
Simulated with improvements	20,9	15,2	18,0	5,7

Table 11.6. Temperature data for the medical consulting room in summer.

Measurements and simulations	**Max.**	**Min.**	**Tm**	**At**
Outdoor temperature	28,0	21,2	24,5	6,9
Measured temperature	26,7	23,6	25,0	3,1
Simulated temperature	26,1	23,7	24,8	2,4
Simulation with improvements	25,2	23,4	24,3	1,8

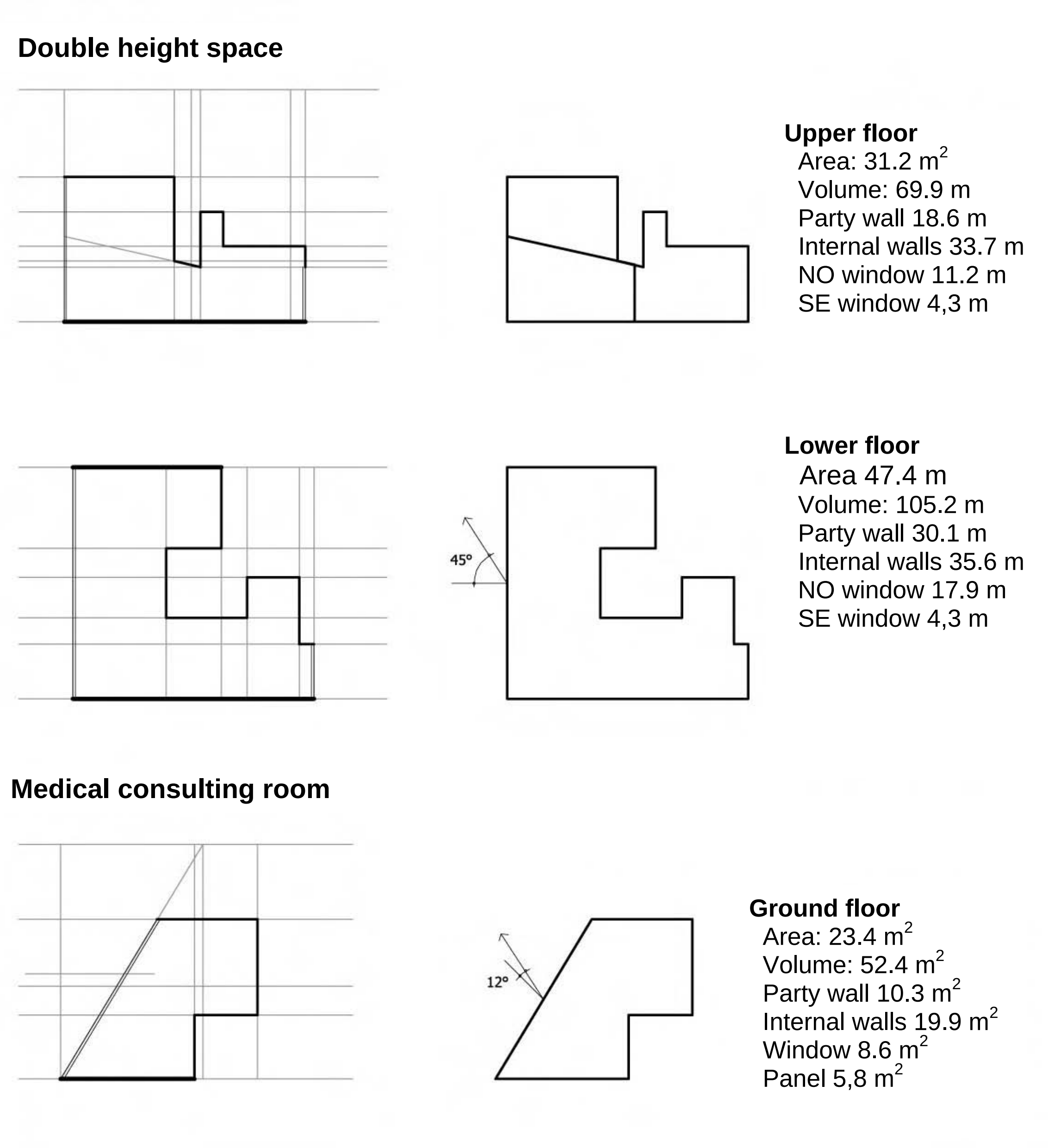
The simulation data for winter are considered to be more accurate, as well as being more useful, due to the poorer thermal performance in these months. In winter with low temperatures, ventilation rates are low and more predictable, while in summer higher and variavle ventilation is probable.

With this verification of the winter simulation results in the calibration process, modifications were introduced in the virtual model, to test the effect of improved thermal performance of materials.

However, in the living-dining room, the results of the simulations have greater differences with the measured data, as Table 11.7. and Figure 11.18 show, due to the flowing factors:

- The existence of stratification in the double height space, detected in the measurements, which cannot be simulated with accuracy in the computer program used in this case.
- The irregular shape of the space with large indoor wall surfaces and adjacent volumes that indirectly affect the results.

The partial shading due to the tree, which although deciduous, casts significant winter shadows.



Double height space

Upper floor
Area: 31.2 m^2
Volume: 69.9 m
Party wall 18.6 m
Internal walls 33.7 m
NO window 11.2 m
SE window 4,3 m

Lower floor
Area 47.4 m
Volume: 105.2 m
Party wall 30.1 m
Internal walls 35.6 m
NO window 17.9 m
SE window 4,3 m

Medical consulting room

Ground floor
Area: 23.4 m^2
Volume: 52.4 m^2
Party wall 10.3 m^2
Internal walls 19.9 m^2
Window 8.6 m^2
Panel 5,8 m^2

Figure 11.15. Synthesis of the data used in the simulation program (Raspall, 2003).

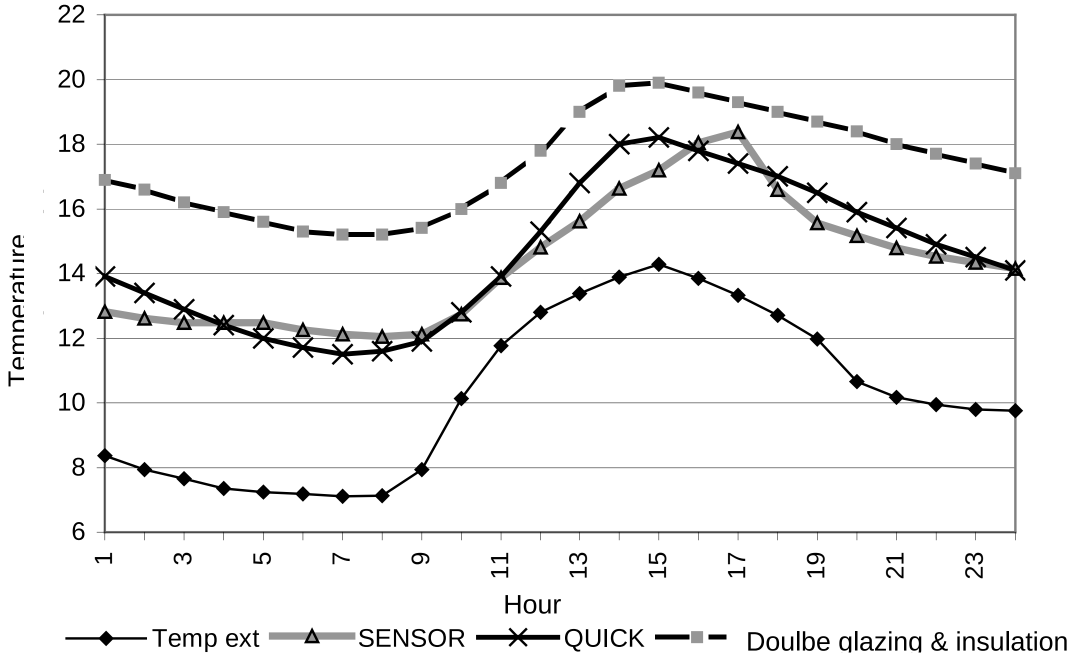


Figure 11.16. Measurements and simulations of the consulting room in winter. With external temperature, measured indoor temperature, simulated indoor temperature (Quick) and simulated indoor temperatures with double glazing and improved insulation.

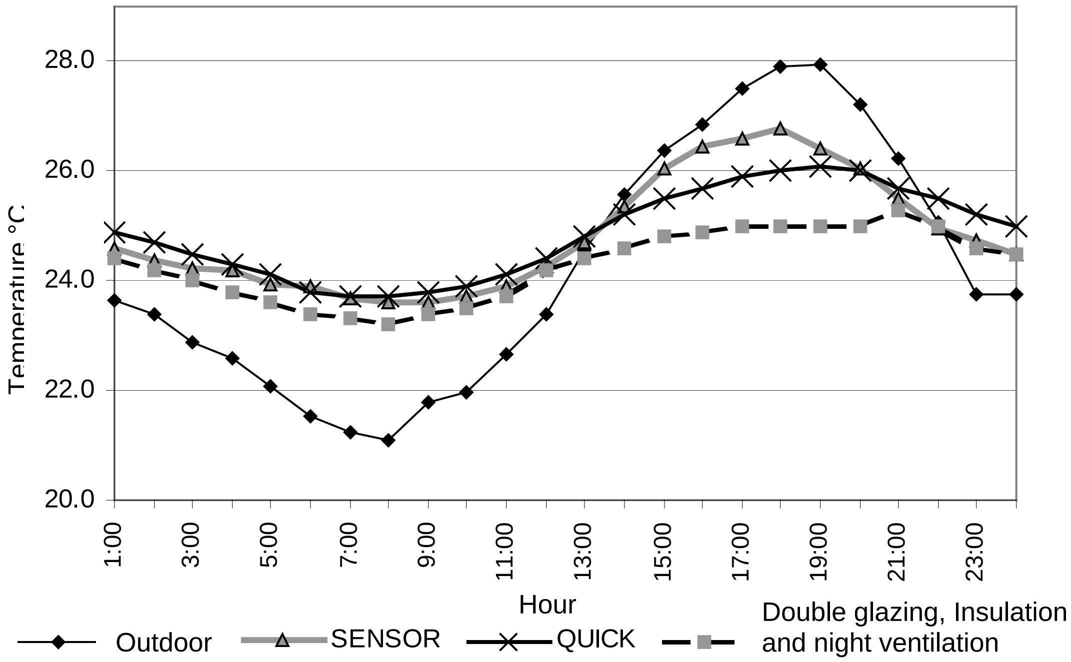


Figure 11.17. Results of measurement and simulations of summer indoor temperatures.

Table 11.7. Temperature data for the living-dining room in winter.

Measurements and simulations	**Max.**	**Min.**	**Tm**	**At**
Outdoor temperature	14,3	7,1	10,7	7,2
Registered temperature	11,8	9,7	10,7	2,1
Simulated temperature	12,3	9,7	11,0	2,5

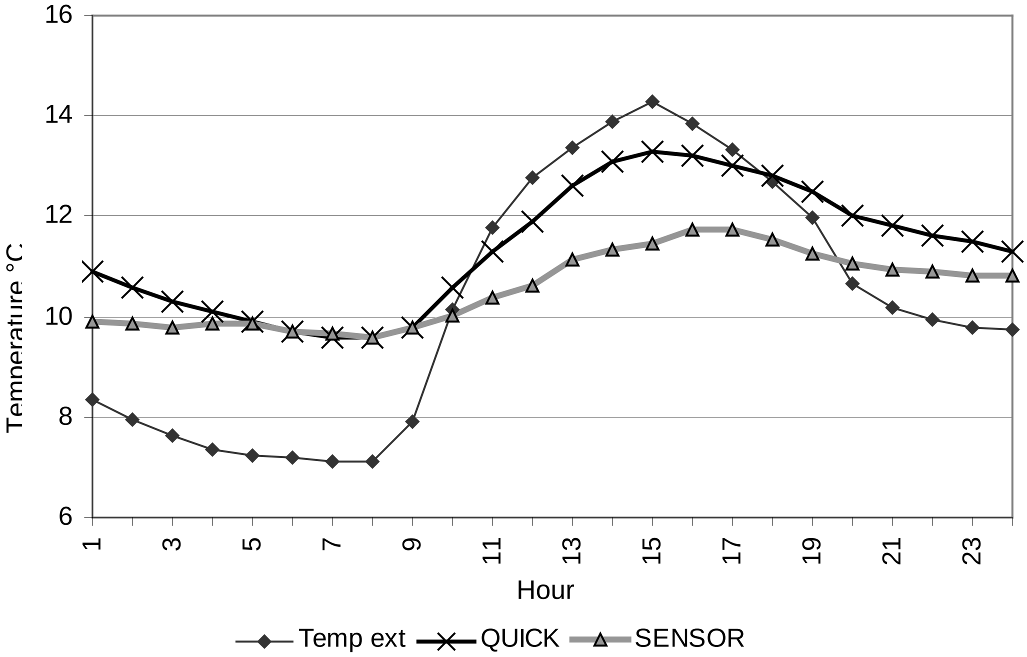


Figure 11.18. Results of measurements and simulations in winter, living-dining room.

In the simulation, the following changes were tested in the virtual model of the Curutchet House, using materials not on the market at the time of construction:

- use of sealed double glazing units in the windows.
- incorporation of 5 cm of expanded polystyrene in the external walls, roof slabs and floor slabs exposed to the outdoor air.
- improved control of infiltration through windows and sky-lights.

11.3.8. Conclusions of the case study.

The Comfort Triangles are applied to the results obtained to test the tool as a graphic analysis aid comparing the thermal performance of the selected spaces with different activities in the house, the differences between indoor and outdoor conditions and the comparison between measured and simulated values, both in summer and winter.

Summer: Results of the simulations confirm the good summer thermal performance, with sunshades that effectively control solar gains to avoid overheating, a considerable achievement considering the large glass areas. The results shown on the Comfort Triangle graph, Figure 11.19, confirm that average measured outdoor conditions are on the upper limit of the comfort zone, but the indoor conditions are much more favourable. The lower floor living space is more comfortable than the upper floor bedroom, while the consulting room shows intermediate performance in this season.

Winter: In the winter simulations, the results show that without movable or adjustable elements, the shading system allows good solar gains in winter, raising the average indoor temperature by about 4 degrees, improving comfort though without reaching optimum temperatures. The measurements and simulations are in good agreement, Figure 11.20. Finally, the simulations show that the average indoor temperature can increased by a further 3 degrees to 18º C when double glazing and improved thermal insulation are used, and the average temperature swing can also be reduced slightly.

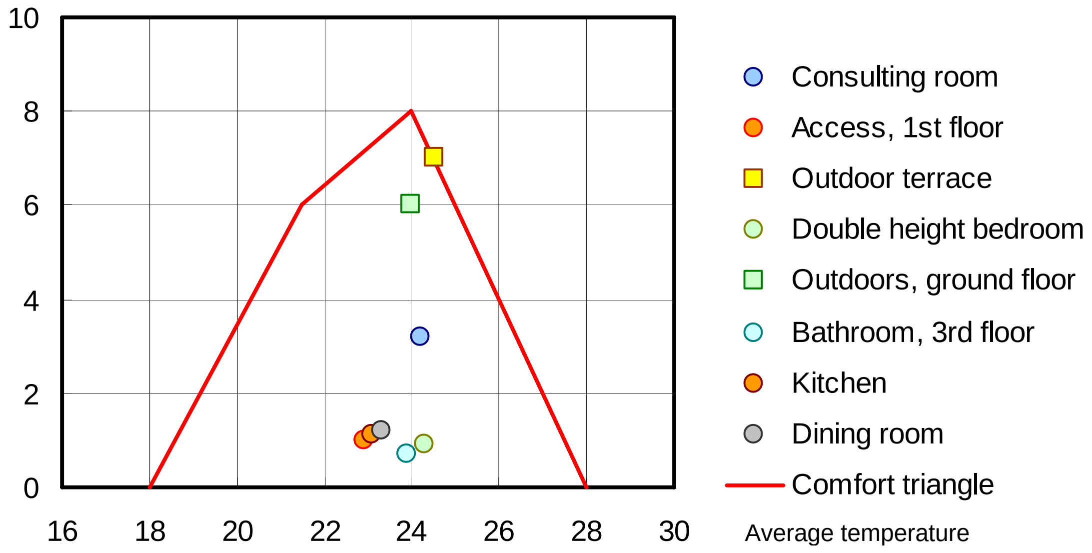


Figure 11.19. Measured conditions compared with the Comfort Triangles, the thermal performance of the Curutchet House in summer.

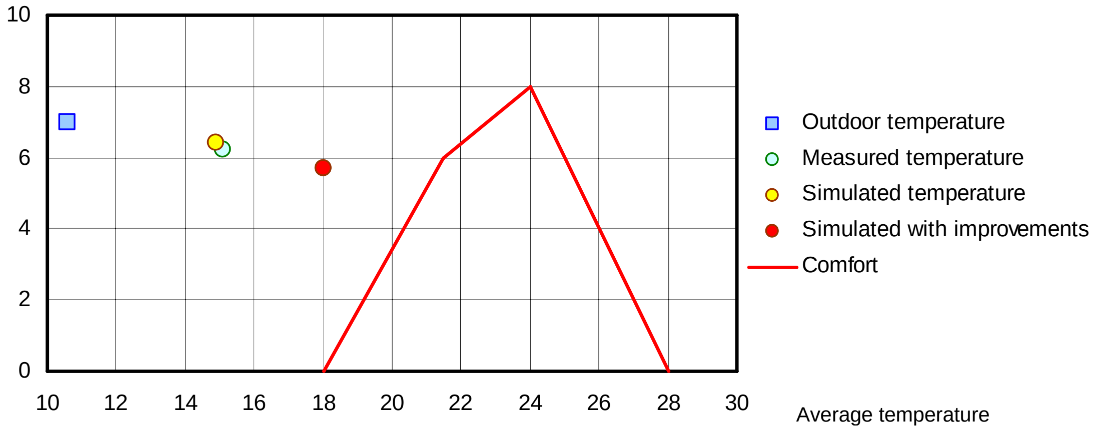


Figure 11.20. Measured and simulated winter temperatures in the consulting room, based on data from Table 11.5, showing the following features:

- The simulated and measured temperatures are very close
- Indoor temperatures are well below the comfort zone
- Simulated temperatures with double glazing and improved insulation are closer to the comfort zone.
- Indoor temperatures show high temperature swings.

During the test period, the existing design of the house achieves a 40 % reduction in the heating load, compared with outdoor conditions or a house without solar gains, while the improved insulation could have obtained a further 30 % reduction. With additional insulation thickness and Low-e glazing, the average temperature could be further increased, achieving indoor conditions very close to comfort without any heating, under the conditions in the test period.

It should be noted that the thermal improvements tested in the simulations do not affect the visual appearance of the architecture. However, the key architectural decisions of orientation, structural and construction system and the design of the shading device are vital to the thermal performance achieved.

11.4. THERMAL PERFORMANCE OF A GLAZED COURTYARD

The influence of the courtyard house as a microclimate moderator has been commented in Chapter 6. Al Azzawi (1993) has made comprehensive measurements of the conditions in the courtyard houses of Baghdad to show how the average temperature in the courtyard can be maintained 4 degrees below the average outdoor temperature. This is conformed by Hoffman et al (1994) who showed that deep courtyards are up to 4 degrees cooler than shallow courtyards and Geiger (1965) who describes similar cooling in coutyards in Vienna. In this section, a study of a traditional courtyard is presented to demonstrate the thermal performance of a courtyard with a glazed and well ventilated roof. The case study presents the results of measurements in a traditional courtyard with a glazed and well ventilated roof in the city of Cuenca, Ecuador.

11.4.1. Introduction to the glazed courtyard study.

The city of Cuenca, Ecuador, located in an equatorial upland climate, has a typically large thermal swing and low average temperatures, where protection is required from the low night temperatures and the high midday temperatures, often accompanied by strong solar radiation.

In this climate, the use of moderate solar gains to increase average temperatures, combined with thermal inertia to control temperature swings is recommended. These two variables form the two axes of the Comfort Triangles diagram so this study enables the utility of the tool to be tested.

The study also enables to effectiveness of the translucent glazed and ventilated roof placed over the courtyard to be evaluated as a passive bioclimatic design strategy for this climate. Specifically, the study can answer the question: in an equatorial upland climate with very high radiation levels on a horizontal plane, is it possible to capture these solar gains with a glazed roof, while simultaneously controlling the temperature swing in the courtyard?

The value and relevance of the study is to see if this solution can be applied to the many traditional courtyards, which do not provide the degree of comfort expected in today's buildings, due to extremes of temperature with high swings and ingress of rain.

The study was undertaken in a traditional building in the centre of Cuenca, Ecuador, at a height of about 2500 metres above sea level. The measurements were made in a hotel located in the central area of the city, 2 blocks from the central square, from 7th to 9th of February, 2006. The building, originally built as a large town house with three patios, was restored with excellent criteria and converted into a hotel. The traditional style has been maintained, with the spatial organization of the circulation and patios. These have been ventilated glazed roofs to increase the air temperature and avoid the entry of frequent seasonal rains, Figure 11.21.

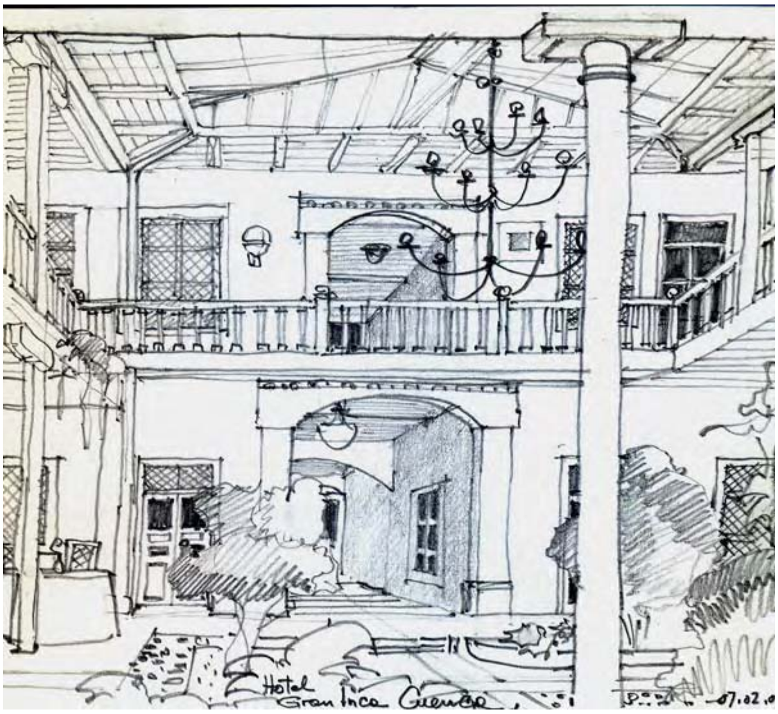


Figure 11.21. Main courtyard in Cuenca, Ecuador. Drawing by S. De Schiller.

11.4.2. Measurements.

The temperature data were obtained from HOBO sensors, placed in the following spaces and Met data:

- In one of 1st floor bedrooms, with a window onto the patio, on the window sill at a height of 90 cm above the floor, Figure 11.22.
- In the second patio, on the 1st floor, outside the bedroom, on a light bracket at a height of about 2 metres, well separated from the light bulb to avoid the possible heating effect, Figure 11.23..
- The data for the outdoor air temperature were taken from the local airport, at a distance of less than 3 km from city centre.

As expected, the glazed roof increases the average temperature by about 6 degrees, with a moderate increase in the temperature swing. However, as Figure 11.28 and Table 11.8 show, the temperature in the bedroom is much more stable due to the high thermal capacity of the adobe construction, typical of the city.

Figure 11.22. Bedroom with the location of the HOBO on the sill, close to the window looking onto the patio.

Figure 11. 23. Second patio with the HOBO location on the light bracket next to the bedroom window, shown in Figure 11.22.

The maximum patio temperatures reached 27 and 29° C on the two successive days, while the corresponding minimum temperatures were 15,5° and 17° C respectively. The indoor temperatures of the bedroom swung between 17.4 and 18.4, a very small variation compared with the patio or outdoor air. The heavy adobe construction achieves a total time lag of 6 to 7 hours, while the patio also has a time lag of 2 hours with respect to the outdoor air. Figure 11.24 shows the temperatures measured in the patio and one of the bedrooms during the period of the experiment.

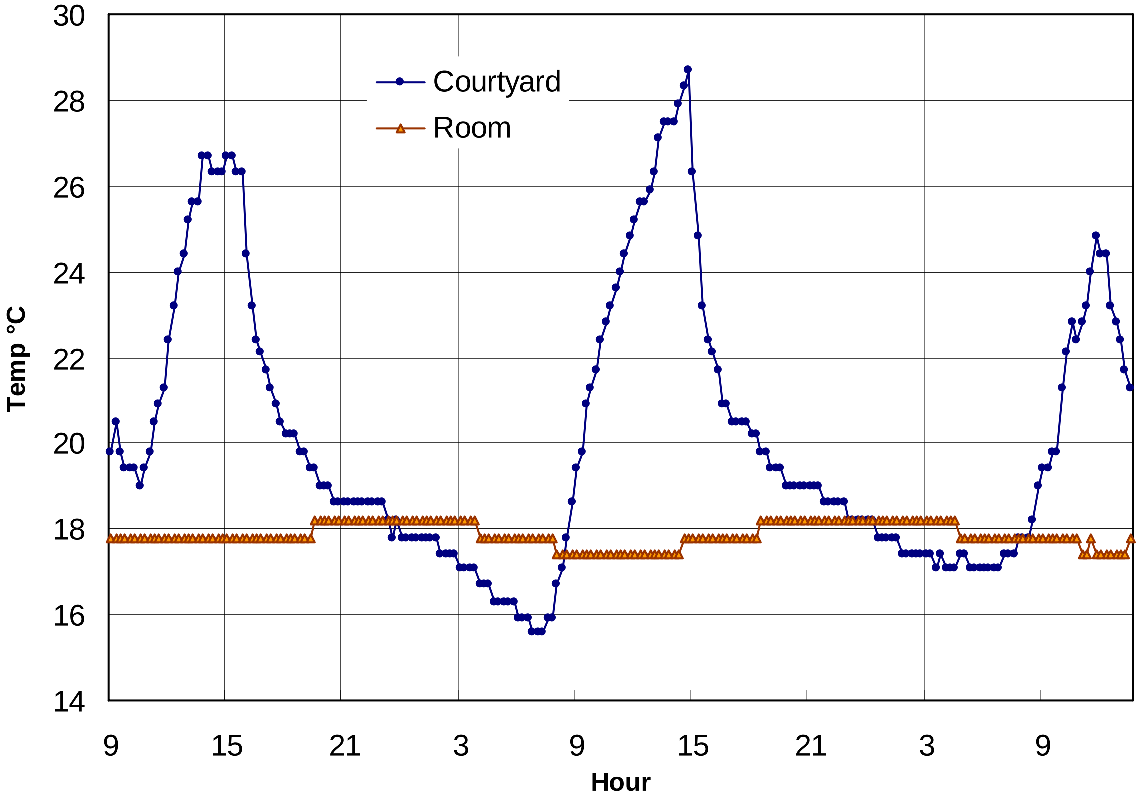


Figure 11.24. Temperature in the patio and bedroom. The time intervals in hours indicated in the horizontal axe are every 6 hours from 9 am of February 7th till 12 am two days later.

The ground floor of the main courtyard, now used as the hotel restaurant, was cool at breakfast time, 8:00 am, with a temperature of 16 to 17° C, although the temperature increases rapidly after 9:00. At the hour of the evening meal, between 19 and 22:00 hours, the temperatures of 18 to 20° C, close to the lower limit of the comfort zone are acceptable, though after 24:00 the temperatures were considered to low for sedentary activity.

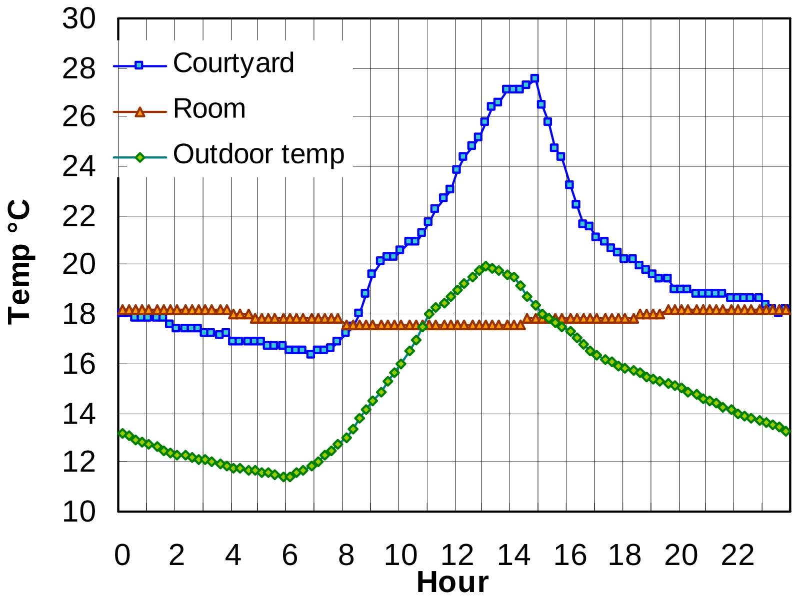


Figure 11.25. Indoor temperature of the room, patio temperature and the outdoor air temperature of Cuenca Airport, 3 km from the Centre, at the same height above sea level. Average of the two days of the experiment.

11.4.3. Conclusions of the case study

Table 11.8 shows the maximum and minimum values of the three locations, indicated in Figure 11.25.

Table 11.8. Maximum and minimum temperatures in the patio, Cuenca

	Courtyard	**Indoor air Bedroom**	**Outdoor air Airport**
Maximum temperature	27,5	18,2	20,0
Minimum temperature	16,4	17,6	11,4
Average temperature ((max + min) / 2)	21,9	17,9	15,7
Average temperature (of 48 hourly values)	19,9	17,9	14,9
Difference between the averages	2,0	-0,0	0,8
Thermal swing (maximum – minimum)	11,2	0,6	8,6

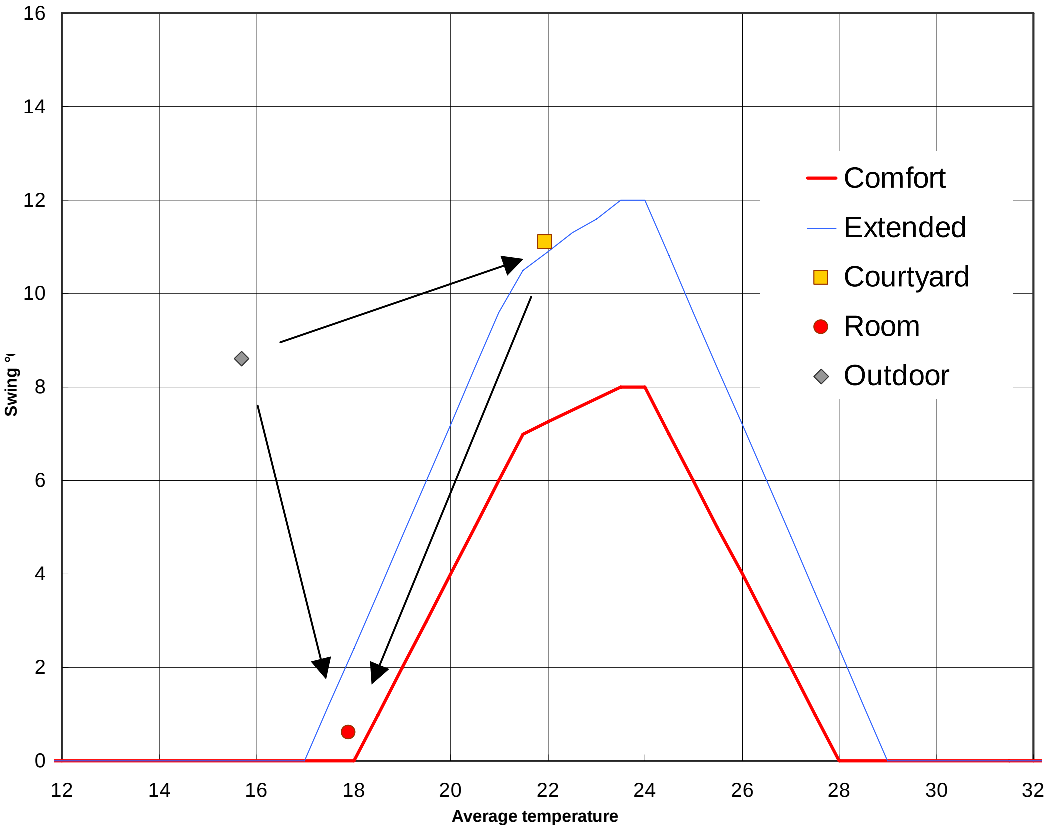


Figure 11.26. Comfort Triangles, glazed patio in Cuenca

The arrows in Figure 11.26. show the way in which the average temperature and the swing are modified. The glazed roof achieves an important increase in the average temperature with a difference of 6 degrees and a slight increase in the temperature swing, from 8.6º C to 11.2º C. The thermal inertia of the construction produces a room temperature below that one of the patio, with a dramatic decrease in the swing. In this case the Range Ratio of the indoor temperature compared with the courtyard temperature is only 5,4 %, while the Range Ratio of the bedroom compared with the outdoor air is also very low, at 6 %.

11.5. THERMAL PERFORMANCE OF A SHADED COURTYARD

The second example, presented in this section, shows another covered courtyard located in the warm humid climate of Colima, Mexico, Latitude 10º N. In contrast to the previous courtyard study of a ventilated glazed roof in Cuenca, Ecuador, in this case, although the proportions of the ventilation openings are similar, the solar transmission of the patio roof is very limited.

The measurements were made in the main courtyard of the Hotel Ceballos on the central square of the city of Colima, Mexico. The building is a historic monument listed by the National Institute for Arqueology and Historic Monuments. A specific characteristic of this building is the use of natural conditioning in the main public spaces, although the hotel rooms, especially the internal rooms, have artificial conditioning.

Figure 11.27. The facade of the Portal Medellin, now Hotel Ceballos, facing the central square of Colima, Mexico.

11.5.1. Objective

The object of this study is to evaluate the degree of thermal comfort achieved in courtyards in a warm humid climate, and to compare the indoor and outdoor temperatures. Two special aspects were incorporated in this study, the measurement of the stratification and the use of thermal inertia in a space with sensible air movement.

To respond to these issues, two studies were made using the measurements, considering the role of courtyards as climate modifiers:

- The effect of important high ventilation rates was analysed, considering the moderating effect of thermal inertia.
- The possible advantages of thermal mass in a warm humid climate, considering that bioclimatic design recommendations for this climate, presented in Chapter 3, normally propose light-weight materials to avoid heat storage and allow rapid cooling at night.

11.5.2. Building characteristics.

The principal space studied in this subsection is the two storey patio shown in Figure 11.30 and 11.31 consiting of the original courtyard space in the interior of the Hotel, converted with a translucent and ventilated roof with effective solar protection consisting of wooden slats that also moderate the natural light levels.

Figure 11.28. Lower and upper levels of the main patio.

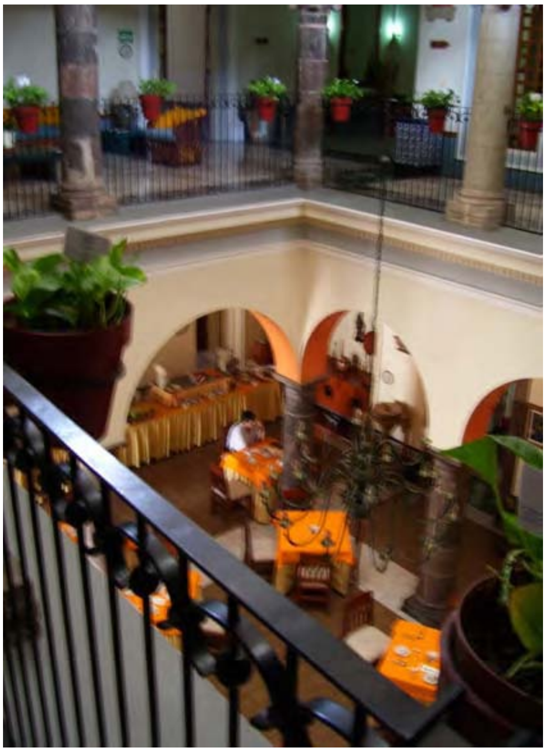


Figure 11.29. Lower level of the patio at breakfast, from the upper floor.

11.5.3. Method.

The measurement method adopted is similar to that used in the previous studies in this chapter. Temperature registers were made at 30 minute intervals with 5 HOBOs, model HO-001, at a hieght of 2 metres, above eye level to avoid detection.

Measurements were made during two days from 18th to 20th of September, 2006, in the following spaces:

- **Principal patio:** a two storey space, with the ground floor used for a restaurant and the ample upper gallery used for circulation and access to the rooms. Measurements were in the lower and upper floors. This space is used for a breakfast bar in the mornings, with heaters, occupants and artificial lighting from 8:00 to 11:00 with good ventilation provided by an open double door facing the street.
- **Secondary patio:** Measurments were made in the upper floor only, with limited occupancy and lower ventilation rates.
- **Outdoor air:** Placed on the south-west facade, exposed to the prevailing wind and proteccted from direct solar radiation. A further sensor was placed on the roof terrace, but stoped functioning due to heavy rain.

Additionally, complementary data of the outdoor air temperatures were obtained by manual measurements in the street and at Colima Airport. Figure 11.28 shows the measurements for the period of the experiment.

The following factors may have influenced the results of measurements:

- On the night of the 18-19th october, a severe storm produced an important drop in temperature.
- The experiment was limited in time.

- As the some of the senosrs were placed on stone shelves, the thermal mass may have reduced the temperature swing.
- The occupation and internal gains are unknown and variable

Figure 11.30. Roof of the patio. Location of the HOBO sensor placed on the capitel.

Figure 11.31. Moderation of the high light levels.

Figure 11.32. Roof of the patio with timber slats below translucent roofing sheets on an open structure to achieve good ventilation.

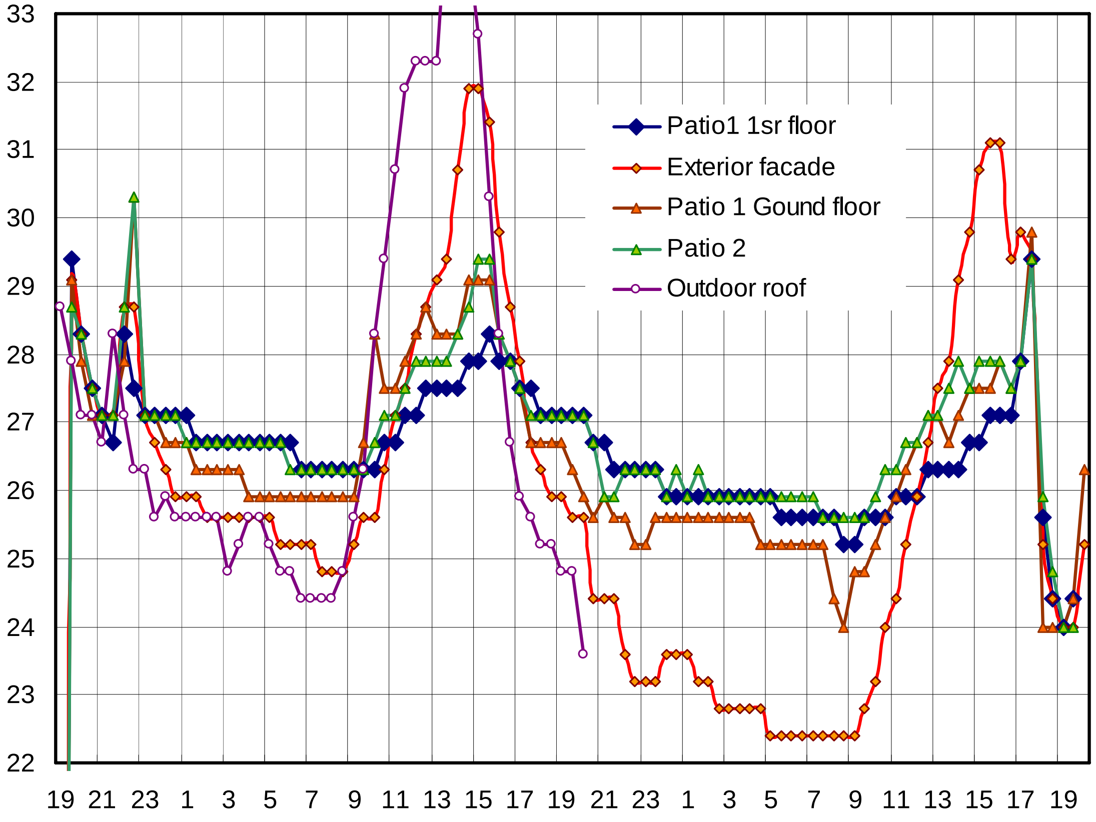


Figure 11.33. Temperatures measured in the patios and outdoor air.

Table 11.8. Average temperatures and temperature swings

Sensor location	Maximum	Minimum	Average	Swing
Exterior, facade	31.6	23,6	27,6	8
Patio 1, ground floor	28,5	24,9	25.7	3,6
Patio 1, 1st floor	28,2	25,7	26.9	2,5
Patio 2. 1st floor	28.6	25,8	27,2	2,8

11.5.4. Results

In response to the questions posed at the start of this subsection, the comfort triangles, Figure 11.34, show the following results:

- There is a noticeable effect of stratification as the average temperature on the ground floor of the patio is close to 1,5ºC less than the average temperature registered on the 1st floor.
- Although the patio is well ventilated, the indoor temperature swing is much smaller than the outdoor swing with a range ratio of 31 % on the upper floor and 45% on the ground floor, showing that the high thermal capacity has more effect than the ventilation.
- The average temperatures and temperature swings on the first floor of the 2 patios studied are very similar, confirming that the similar dimensions, design and ventilation levels produces similar thermal conditions.

- The combination of selective ventilation and thermal inertia produces a temperature reduction of 2 degrees. More importantly, the is nearly one degree of average temperature reduction for each two degree reduction in the temperature swing.

The roofed and shaded patio has modified the external conditions which are well outside the comfort limits to a comfortable environment on the ground floor, though slightly outside the limits on the upper floor which is warmer due to stratification.

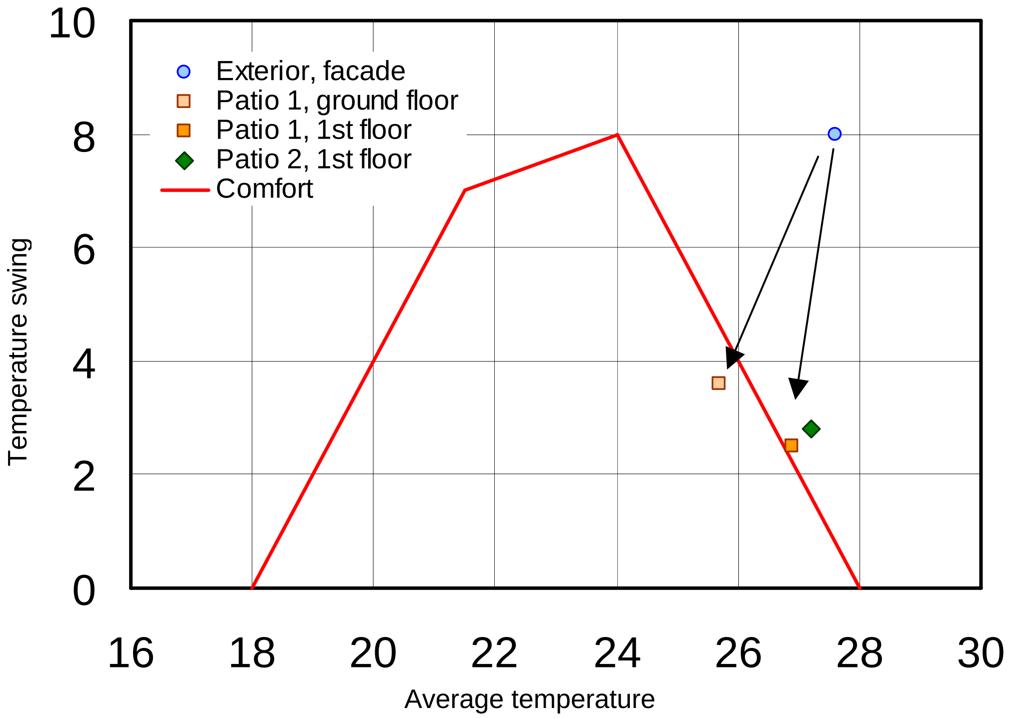


Figure 11.34. Comfort Triangle analysis of the performance of the shaded patio, Colima

11.5.5. Conclusions of the patio studies

The two traditional patios studied in this and the previous section have similar dimensions and construction, although the Colima patio has more thermal mass and the Cuenca patio has more timber incorporated in the construction.

- **Colima,** the combination of shade, ventilation and thermal mass achieves an average temperature decrease of 2 degrees.
- **Cuenca,** the solar gains through the glazed roof, moderated by ventilation increase the average temperature by 6 degrees.

In the first case the temperature swing is reduced by 45% while in the second the swing is increased by 15%. In both cases, the Comfort Triangles show the way in which the courtyard acts as a climate modifier, with different roofing systems producing completely different thermal results.

11.6. CONCLUSIONS

The studies presented in this section show that design decisions produce significant and favorable modifications of the daily indoor temperature variation, in comparison with the outdoor conditions. The first case shows the different impact achieved in spaces with different architectural characteristics. The second illustrates the modifications obtained with the same shading device in different seasons, showing how appropriate orientations assist bioclimatic control. The final case studies of patios in different climates illustrates the different results achieved with different roof treatments in spaces with similar proportions and architectural characteristics.

In all cases the Comfort Triangles enable the two modification vectors to the identified visually and independently:

- The change in average temperature obtained by natural heating or cooling
- The dampening effect of thermal inertia and other strategies.

The next chapter continues the series of case studies, emphasizing the modifications achieved with different construction alternatives and materials.

CHAPTER 12. CASE STUDIES AT THE BUILDING SCALE

12.1. Introduction.

This chapter presents a series of experimental studies with measurements in buildings with different construction methods and thermal characteristics. The buildings are situated in different climates, and measurements were made in different seasons, with special emphasis on warm and temperate conditions in equatorial, tropical and subtropical climates.

The objective of the studies presented in this chapter is to demonstrate the use of the Comfort Triangles to analyse the thermal performance of different types of construction, both light and heavyweight. The application of the Comfort Triangles shows how different materials and building systems can modify the impact of external conditions to achieve or approach indoor comfort.

The examples provided in this chapter include: :

- **Section 12.2.** Lightweight construction systems developed for low cost housing in Costa Rica, using thin panels of micro-cement.
- **Section 12.3:** Traditional construction in Amazonia, eastern Ecuador, with thatched roofs, thin masonry walls and high ventilation rates.
- **Section 12.4:** Experimental house constructed of compacted soil-cement in Florencio Varela, Buenos Aires.

12.2. LOW COST HOUSING IN COSTA RICA

The subject of this experimental study is a prototype low cost house, built with an earthquake resistant structure developed by CIVCO-ITCR, the Housing and Building Research Centre (Centro de Investigación en Vivienda y Construcción), of the Costa Rica Technological Institute (Instituto Tecnológico de Costa Rica). The study was made during a technical assistance mission in the framework of the Horizontal Cooperation Programme undertaken with financial support of OEA and the Argentine Foreign Ministry.

The housing project of about 50 dwellings was constructed in Carillos, Alajuela Province, Central Costa Rica, situated at latitude 10° N at a height of 800 metres above sea level. The climate is typical of equatorial uplands, with average minimum monthly temperatures between 14 and 17° C, and average monthly maximums reaching 35° C. The measurements were made in January-February, the dry season with clear skies and strong solar radiation due to the altitude. In general, the temperature seasonal variation is very limited due to the low latitude of 10° close to the equator (de Schiller, 2002).

The construction of the low cost houses responds to the following design objectives identified by CIVCO:

- Reduction of earth movement for access routes and foundations.
- Conservation of natural soil surfaces for absorption of rain water
- Building system that accommodates the important slopes, typical of many sites in a country with limited flat sites for urban development.

- Use of a timber structure with wooden sections from forest thinning of low commercial value.
- Lightweight construction to improve the resistance to earthquakes and allow self-help construction with limited equipment..
- Minimum use of materials to reduce costs and avoid imported products as well as limiting environmental impacts.

Although these guidelines did not include specific bioclimatic design requirements, this study was undertaken to detect the thermal performance of the construction system and analyse alternatives to improve indoor comfort.

The construction system developed in CIVCO and used in this project is shown in Figure 12.1, with the following characteristics:

Roof: Light coloured aluminium corrugated roofing sheets, air cavity and a aluminium foil on 5 mm of flexible polyethylene foam with an internal matt white plastic finish, supported on a timber structure.
Floor: Ceramic tiles on a bedding mortar of 10 mm, micro cement panel of only 35 mm supported on a timber structure, over an air cavity separating from the soil below the house, open to the outdoor air.
Walls: Panels of 35 mm thick reinforced vibrated micro-cement, precast in metal moulds with a reflective external colour.
Windows: Single glazing in an aluminium frame with opening lights, protected by 60 cm roof overhangs.

12.2.1. Objectives of the case study.

The study of the indoor temperatures in the house responds to a concern about the degree of comfort achieved with the construction system that was developed in response to requirements to achieve sustainable building. Although the housing reduces the environmental impacts significantly, due to the use of forest thinnings, reduction in building materiales used, conservation of absorbent terrain and adaptation to sloping sites, the question remained as to the adequacy of the living conditions provided by this non-conventional construction. The conditions of safety, heath and comfort for the occupants are an important ingredient of sustainable building, particularly related to social and economic factors in terms of durability and energy dependence, in addition to the use of sustainable materials and sustainable site planning.

In this context, the measurements of indoor temperatures provide evidence of the possible impact of the reduced quantities of materials and thin building sections on the comfort and living conditions, since the potential impacts on health and productivity of the occupants are important factors for the evaluation of sustainability.

In synthesis, the measurements allow a comparison between the degree of sustainability achieved by the design and materials on the one hand and the indoor environmental quality that contributes to the social sustainability of the project, on the other.

Figure 12.1. External and internal view of the house selected for temperature measurements, seen from the South.

12.2.2. Method.

The study of the thermal performance of the house was made with the following stages:

- **Initial Project evaluation:** analysis according to the climatic data for the site, the requirements for comfort with natural conditioning and the thermal characteristics of the building system used.
- **Measurements:** measurements of air temperature in different rooms of the house, and surface temperatures of external walls in different orientations and outdoor air temperature.
- **Calibration of a numerical simulation:** With a program of thermal simulation the indoor temperatures were simulated and compared with the measurements to verify the relation between the two data sets.
- **Evaluation of design alternatives:** With the program calibrated, a series of parametric studies were completed to evaluate design and construction alternatives in order to detect options that allow improved thermal comfort.
- **Application of the comfort triangles:** graphic presentation of the results to compare alternatives and define design recommendations for new housing projects.

The measurements were made in the completed house, without occupants but with the occasional entry of workers finishing internal details. The sensors were suspended from the ceiling in the middle of each room at a height of 1,65 m in order to reduce the risk of accidental damage. The surface temperature measurements were made with ‘HOBO’ sensors wit the thermo-couple in direct contact with the surface, fixed with adhesive tape. ‘Tiny-Talk’ sensors were used to measure the air temperatures.

In order to measure the outdoor air temperature, a sensor was suspended from the roof of the gallery used for washing clothes. This space, with an aluminium sheet roof, faces North with protection from direct solar radiation. The sensor was well exposed to the outdoor air and protected from the rain.

A total of 8 temperature sensors were used, to measure temperatures at 15 minute intervals during a period of the study which lasted 8 days, placed in the following locations:

- The indoor surface of the wall facing NE, partially protected from the morning sun with a roof overhang of 40 cm.
- The indoor surface of the SW wall, without an overhang or protection from the afternoon sun..
- The indoor surface of the SE wall exposed to the morning sun.
- The outdoor air temperature, measured with a sensor protected from direct solar radiation by a roof, without side walls.
- The indoor air temperature of the bedroom with a SE orientation. This data set was incomplete due to programming problems.
- The indoor air temperatures of the SW bedroom.
- The indoor air temperature of the living room facing NE and SW
- The indoor air temperature of the space immediately below the roofing sheet in the apex of the roof above the insulation. This sensor didn't record temperatures and was damaged, possibly due to the high temperatures..

12.2.3. Measurements.

Figure 12.2 indicates the surface temperatures recorded during the 8 days of the experiment. These data show that the conditions were stable with a series of days with similar conditions. In order to visualise the typical daily conditions in a 24 hour period, the average temperatures for the 6 complete days were calculated, omitting the first and last days with possibly incomplete or unrepresentative data before they were placed in position or after they were taken down. These results are shown in figure 12.6.

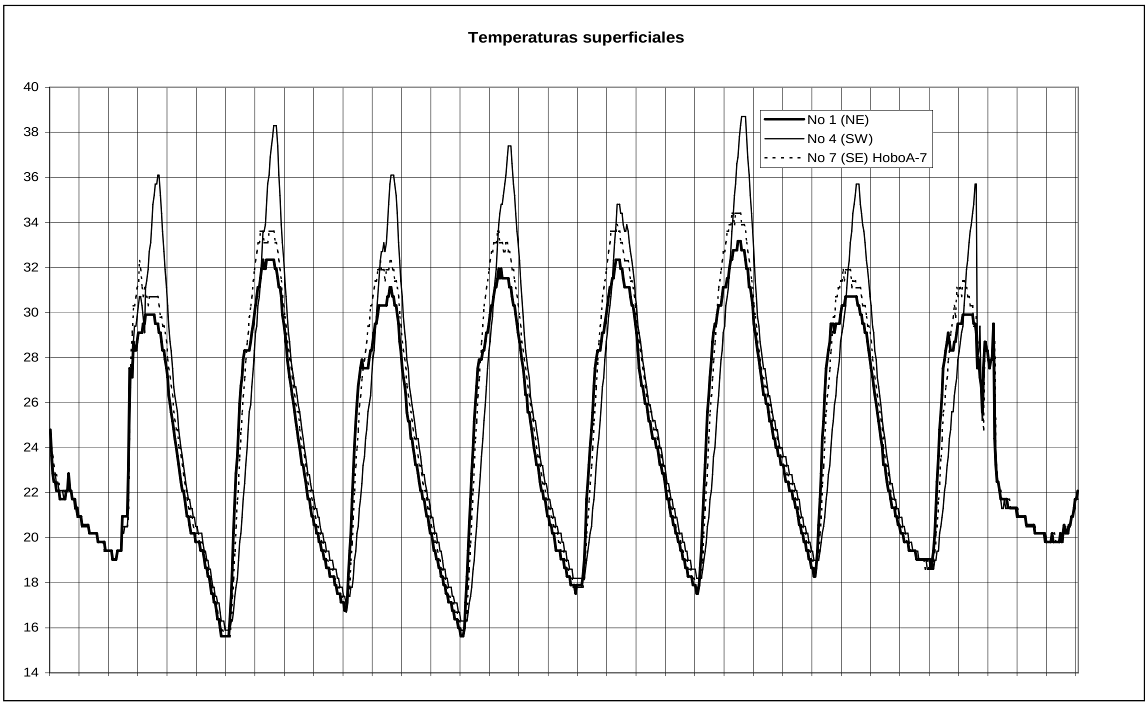


Figure 12.2. Registers of surface temperatures in the three rooms of the house.

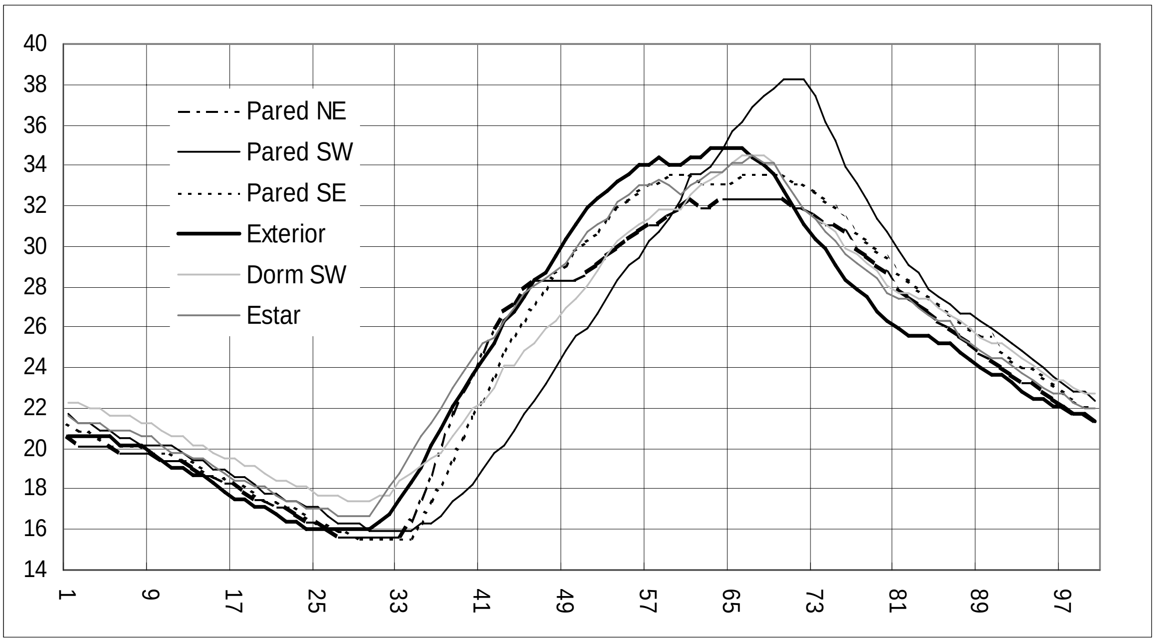


Figure 12.3. Average temperatures for a 24 hour period during the 6 days experiment.

12.2.4. Simulations.

With the data of the dimensions of each room of the house and the estimated thermal characteristics of the construction, a simulation of the thermal performance and indoor temperature was obtained and compared with the measured temperatures. For this simulation, the program Quick was used (Matthews, 1993).

For the simulation of indoor temperatures, the following data was used:

- The measured hourly outdoor temperatures.
- Estimated direct and global solar radiation values using a value of Kt, atmospheric clarity, of 0,71.
- Estimated thermal characteristics of building materials based on measured densities.
- No internal gains due to occupants or equipment.
- Average estimated ventilation rate of 5 air changes per hour.

Figure 12.4 allows a comparison between the simulated temperatures in the living room and the measurements made in the same space. The results are considered satisfactory with a reasonable relation between the simulated and measured values.

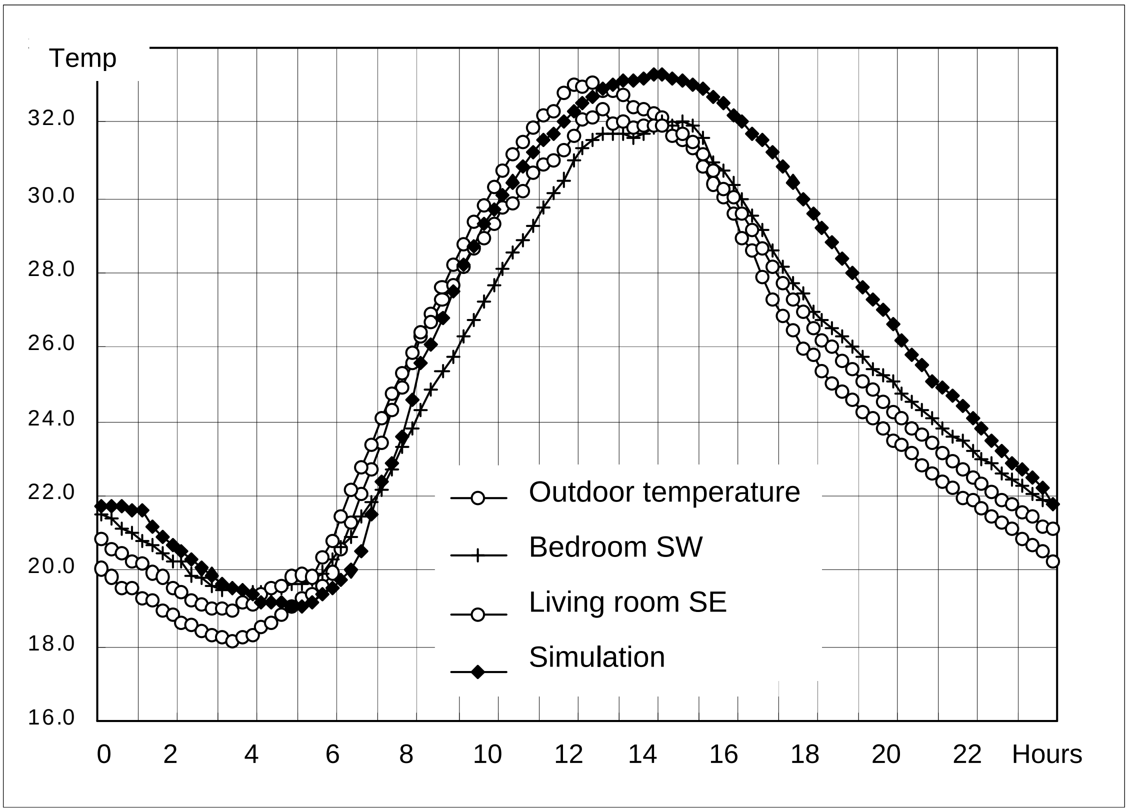


Figure 12.4. Measured indoor and outdoor temperatures, compared with the simulated indoor temperatures in the living room.

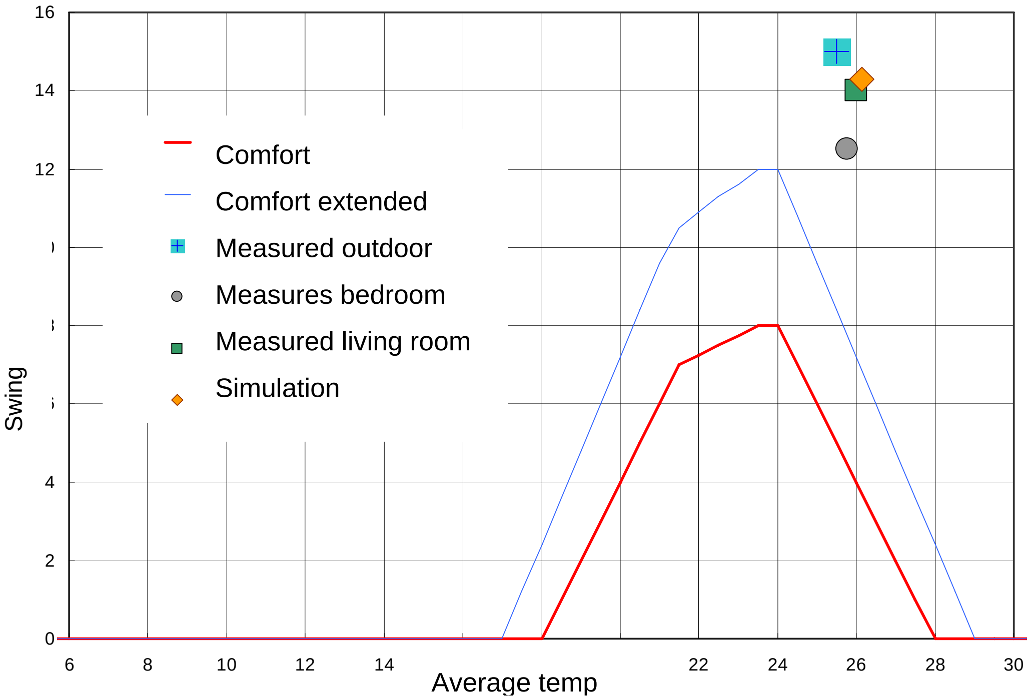


Figure 12.5. Indoor and outdoor temperature variations for different spaces, shown on the comfort triangle diagram.

Table 12.1. Measured and simulated temperatures in the study house.

Temperature	Max.	Min.	T average	ΔT°C
Existing, outdoor	33	18	25,5	15
Existing, bedroom	32	19,5	25,8	12,5
Existing, living room,	33	19	26,0	14
Simulation, living room	33,3	19	26,2	14,3

Notes:

- Thermal swing above the desirable limits (< 10°C)
- Indoor temperatures similar to the outdoor temperatures

As Table 12.1 shows, the indoor temperatures are similar to the outdoor temperatures, with a thermal swing well above the desirable limit for comfort. The difference between the average indoor and outdoor temperatures are negligible, indicating the internal gains and the gains form solar energy through windows are not significant. The ventilation rate, estimated in 5 air changes an hour with windows closed also contribute to the similitude between the two temperatures.

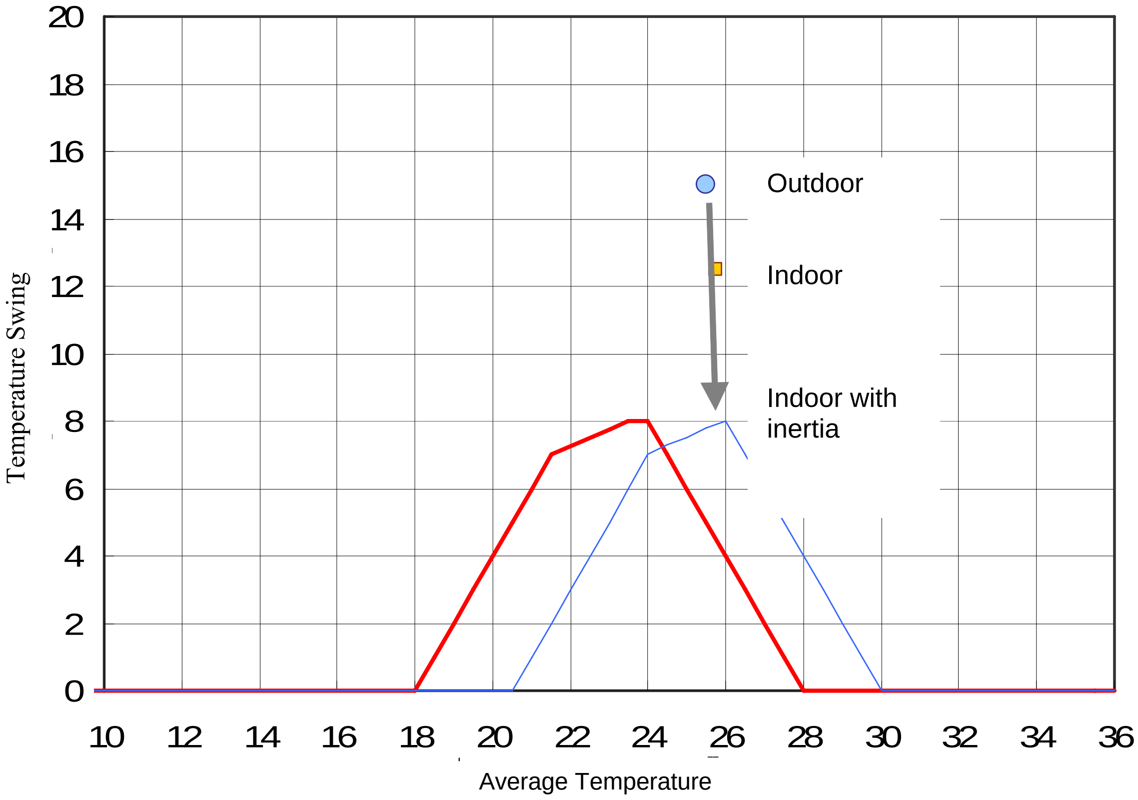


Figure 12.6. Indoor and outdoor temperatures, with simulation of indoor temperature when thermal inertia is added.

12.2.5. Results.

Despite the limitations of the building system with very low thermal capacity, limited thickness of thermal insulation and high rates of ventilation, the indoor conditions are not far from the desirable comfort requirements. The results of the calibrated simulations, based on measurements of limited duration, allow a direct evaluation of the thermal performance of the existing building.

The following simulations show the possible modifications of thermal performance for different design alternatives and building methods. The results of these simulations, shown in Table 12.2, are discussed below:

- **Increase in the thickness of the thermal insulation layer in the roof:** An increase from 5 mm to 50 mm achieves an increase in the minimum temperature of 0,4°C and reduces the maximum temperature by 0,6° C, also reducing the thermal swing by 1° C.
- **Shading walls with vegetation:** The provision of shade on the exposed SW wall, with a 50% shading factor, also reduces the maximum temperature by 0,3° C.
- **Light coloured roof:** The simulations also confirm the benefit of a light coloured roof, which reduces the indoor day temperatures, without noticeable variations at night. However, a dark coloured roof with an absorption of 60% increases the maximum indoor temperature by 1° C and the average indoor temperature by 0,5° C, as well as increasing the indoor swing by 1° C.
- **Orientation:** A favourable change in the building orientation of 45° towards the Equator (S) allows the maximum indoor temperature to be reduced by 0,8° C, while an orientation towards the north is also favourable, especially combined with a wall without windows orientated to the east, reducing the maximum temperature by 1,5° C. However, an unfavourable orientation towards the east and west produces a significant rise in the indoor temperatures up to 36° C, due to the direct solar gains in the afternoon.
- **Increase in ventilation rates:** Although an increase in the ventilation rate from 5 to 15-20 air changes per hour does not influence the indoor temperatures significantly, an increase in the sensible air velocity at body level can produce a favourable improvement in the thermal sensation equivalent to a 1 to 2° drop in air temperature.
- **Increased thermal inertia:** The thin concrete panels used in the building system do not incorporate significant thermal mass and increased thickness would imply additional costs and complications in the earthquake resistant structure. However, a floor directly resting on the ground instead of a raised floor with large air cavity would reduce the thermal swing to 8,5°C, a more acceptable variation with an average temperature of 26°C, close to comfort.

Table 12.2 tabulates the results of these simulations of both design and construction alternatives, with maximum and minimum temperatures with the corresponding average temperatures and daily temperature swings.

Table 12.2. Results of simulations.

	T max.	**T min.**	**T average**	**T Swing**
Outdoor (measured)	33	18	25,5	15
Indoor living room (measured)	33	19	26,0	14
Thicker insulation layer in roof	32,4	19,4	25,9	13
Vegetation (shade) SW wall	32,7	18,7	25,7	14
Dark external roof colour	34	19	26,5	15
Orientation North	32,2	19	25,6	13,2
Orientation South	31,5	19	25,2	12,5
Orientation West	36	19	27,5	17
More thermal inertia in floor	30,2	21,7	25,9	8,5

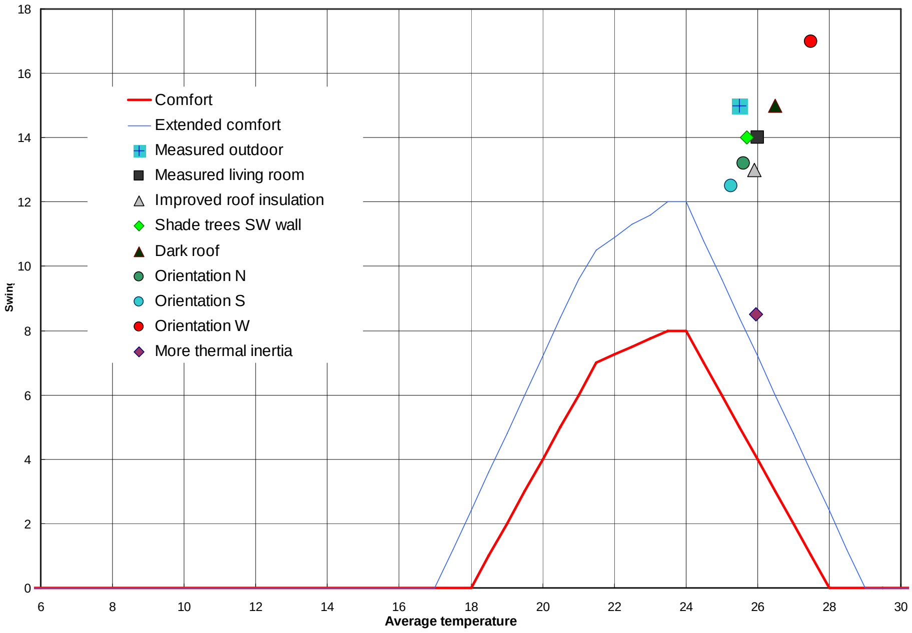


Figure 12.7. Variation in the comfort conditions with simulations of design alternatives compared with measured outdoor (+) and indoor conditions (☐).

12.2.6. Conclusions of the measurements and simulations in Costa Rica.

The majority of the alternatives evaluated in the simulations are of very low cost, indeed in this case the most important benefits have no cost. The changes in orientation in this housing site could have been achieved without changing the building design with a different site layout. The location of windows in the facades with different orientations can also be achieved at no cost.

The use of the Comfort Triangles, Figures 12.6 and 12,7, provides a useful visual tool to compare the thermal results of different alternatives, both measured and simulated.

12.3. LIGHTWEIGHT CONSTRUCTION IN AMAZONÍA, ECUADOR

12.3.1. Introduction.

This case study presents an evaluation of thermal performance of a lightweight construction with cross ventilation in a warm humid region of the Amazon Basin, Cotacocha, close to Tema, the Provincial Capital. The materials used respond to the traditional solutions found in the River Napo Region, with a thatched roof and timber structure. The example is located close to the equator, with hot and humid conditions typical of the equatorial zone at an altitude of about 500 metres above sea level. The relative humidity is high and the rainfall frequent and abundant, with predominantly cloudy skies. In this case, the aim of the experiment is to verify if the indoor conditions can be maintained close to the predominantly comfortable outdoor conditions, avoiding the heating impact of direct sun and the cooling effect of the rain.

The traditional constructions of Cotacocha have roofs of thatch made with leaves of the king palm, although the roof slopes are steeper than those found in traditional construction. The floor is made of hard-wood planks, suspended above and air cavity in direct contact with the outdoor air. The windows do not have glass, with a open weave fabric acting as an insect screen, without additional protection. The low walls are made with concrete blocks, Figure 12.8. The large eaves offer protection from the frequent and intense rainfall, while the surrounding vegetation surrounding the cabins provides additional protection.

Figure 12.8. Cotococha, Napo, Ecuador, traditional construction with cross ventilation.

12.3.2. Objective of the case study.

The aim of this study is to verify and demonstrate the limited difference that can be achieved between indoor and outdoor conditions in a warm humid climate with light-weight construction and good cross ventilation. In this climate, the most effective bioclimatic design strategy is the use of cross ventilation to improve evaporative cooling of the skin, combined with solar protection.

Figure 12.9. Covered expansions of the cabins used for measurements.

12.3.3. Method.

The temperatures were measured in three locations in the construction in a typically cloudy day during the rainy season:

- **Balcony:** HOBO exposed to the outdoor air in a balcony facing the Napo River, seen in Figure 12.9, protected from the rain and direct solar radiation.
- **Bedroom:** Located at a height of 1,5 metres in the large single room, well exposed to the air and protected from direct sunlight.
- **Floor:** Under the timber floor, in an air cavity of about 50 cm high, well exposed to the outdoor air.

The temperatures were recorded during a 30 hour period at 15 minute intervals.

Figure 12.10. The cabins set in traditional vegetation, on the shores of the Napo River.

12.3.4. Results.

The temperatures measured in three locations, shown in Figure 12.11., registered daily from 8 pm to 8 am, 2 days later, indicate a very low thermal swing of 1,9 to 2,3 degrees, with a variation between 21,3 and 23,6° C. The average temperature in the whole series of measurements is 22,5° C, with practically no difference between the series measured in different locations.

In this case, the main variation detected is the small reduction of temperature measured in the balcony at night, approximately 0,4 degrees less than the indoor temperature. There was also a small time lag in the measurement made under the floor, compared with the balcony and bedroom, a result of the thermal inertia of the earth in this space.

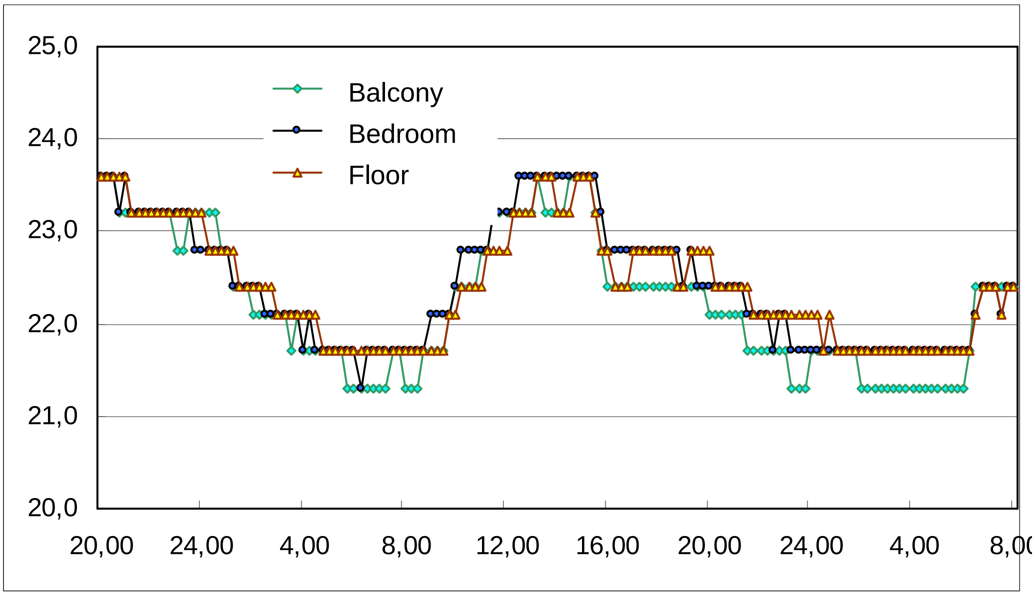


Figure 12.12. Measured temperatures in the balcony, bedroom and under the floor..

Figure 12.13 shows the same series, with a running average of the hourly values to obtain a smother curve without the abrupt jumps that are a result of the HOBO measurements at minimum intervals of 0,3 to 0,4° C. The bedroom, occupied at night between 23:00 and 7:00 by two people is slightly warmer than the outdoor spaces, without significant differences.

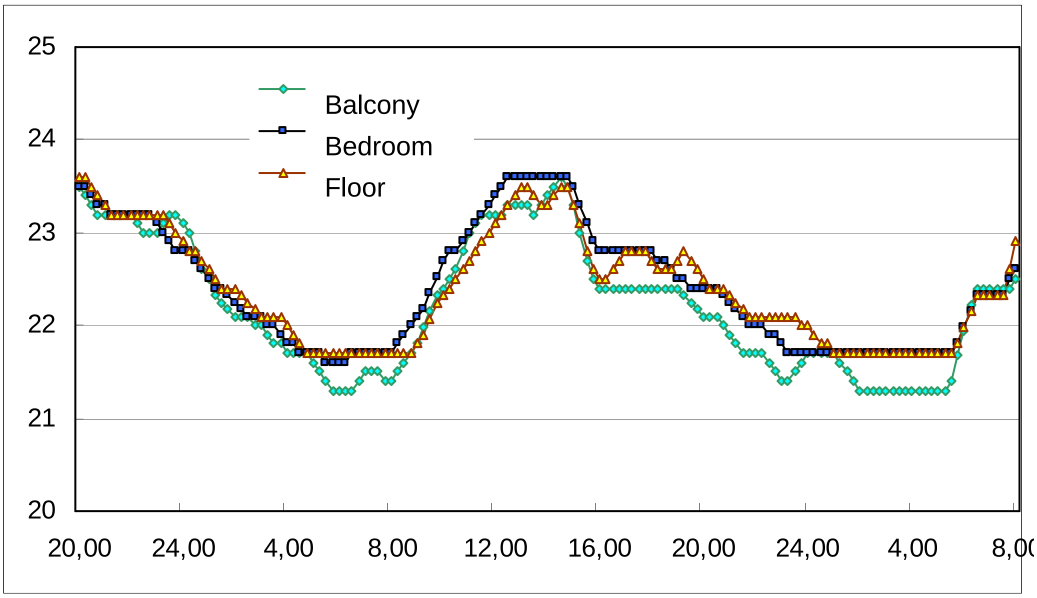


Figure 12.13. One hour running averages of the measured temperatures on the balcony, in the bedroom and under the floor.

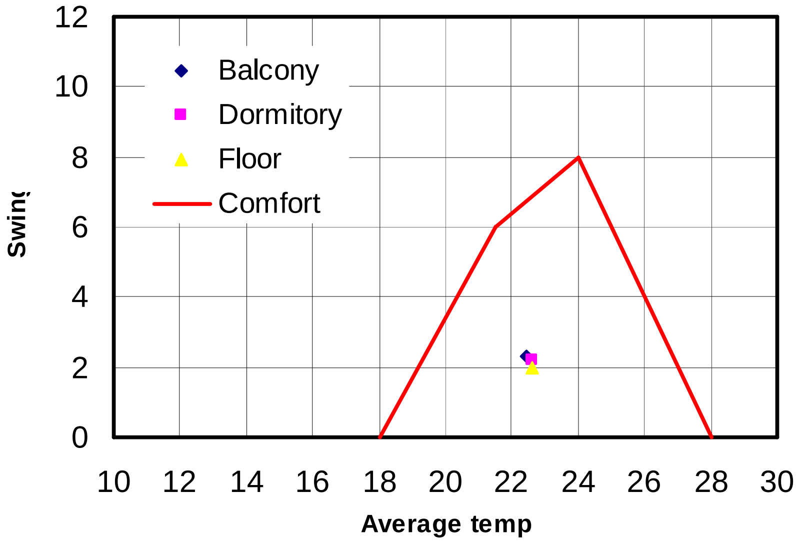


Figure 12.14. Indoor and outdoor temperatures at Cotococha, showing very limited variation and values within the comfort zone.

12.3.5. Conclusions of the measurements in Cotococha, Amazon.

This case study shows an example where the indoor and outdoor temperature maintain almost identical values during a 24 hour daily cycle. It is therefore possible to achieve indoor thermal comfort as the outdoor conditions are within the comfort range as indicated in the Comfort Triangles diagram, shown in Figure 12.14. In the previous example, the outdoor conditions showed larger daily temperature variation so more thermal mass is required to moderate the external variation. Additionally, in the previous example, solar radiation was an important variable, while in this case, the cloudy conditions avoid the impact of direct sun, favouring the low outdoor and indoor thermal swings

12.4. PERFORMANCE OF SOIL-CEMENT WALLS IN BUENOS AIRES

Compacted soil construction, stabilised with the addition of cement, achieves thermal characteristics completely different from the light-weight construction studies in the previous two cases.

This study aims to evaluate the thermal characteristics and the resulting comfort conditions. The case was selected to evaluate the construction with monolithic stabilised compacted soil, known as *tapial* in Spanish, as the economic, technological and bioclimatic characteristics can contribute to solve housing problems, with low cost and low impact construction, suitable for self-help construction.

The construction of a prototype house, undertaken by Patrone (2006), was supported by the Secretary of Public Works (Secretaria de Obras y Servicios Públicos) of the Municipality of Florencio Varela, Buenos Aires Province. The prototype not only provides an opportunity to test the construction method, but also to measure the thermal and environmental characteristics of the building with a view to obtain certificates of approval for low-cost housing (Patrone and Cabezón, 2004).

12.4.1. Objectives of the case study.

Although the principal objective of the research project was an evaluation of the building method and the structural properties of this non-conventional construction, the prototype building allows measurements and study of the thermal characteristics (Patrone and Evans, 2006).

The house, Figure 12.15, constructed with monolithic load bearing 20 cm thick walls of compacted soil cement has a total area of 36 m2, with a living, dining kitchen, a bedroom and bathroom, Figure 12:16. The floor and sub-floor is also soil cement with added lime. Two alternatives were tested for the roof construction:

- **Bedroom:** the roof is a non conventional layer of mud above and below a layer of straw with total thickness of 2,5 cm, supported on a ceiling of eucalyptus tongue and groove boarding, with an air cavity and galvanized roofing sheet.
- **Living room:** the roof is similar with a conventional 4 cm layer of expanded polystyrene replacing the straw and mud.

Figure 12.15. View of the prototype, Photo J. C. Patrone

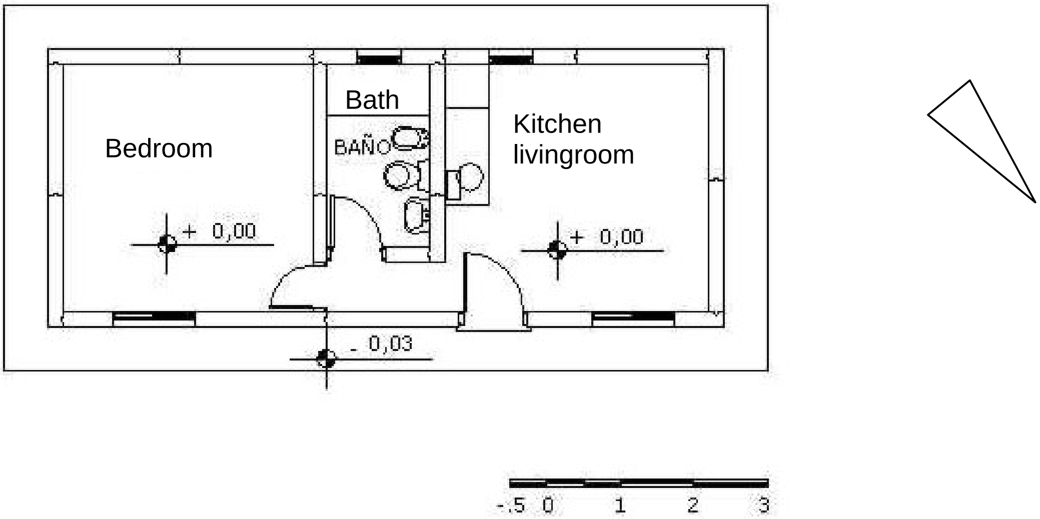


Figura 12.16. Plan of the prototype house (Patrone, 2006).

12.4.2. Standards requirements.

The IRAM Standard 11.605 (1996) indices the maximum allowable thermal transmission for winter and summer, with three different quality levels: A: Optimum, B Normal, C Minimum. The Secretary of State for Housing only requires level C for social housing projects. The previous version of the IRAM Standard 11.605 (1980) allowed increased thermal transmission for walls with increased heat capacity, according to the superficial density in kilogrammes per square metre.

However, in order to simplify the checking of the standards, the present version only considers a single value of thermal transmittance, irrespective of weight, density, thermal capacity or time-lag.

The object of the measurements presented in this study is to verify the environmental conditions of houses constructed of compacted stabilised soil in the climatic conditions of Buenos Aires, with emphasis on comfort in the hot season. Table 12.3 shows the maximum allowable values of thermal transmittance or ‘U’ value (known as the ‘K’ value in the standard) in order to comply with Level C of the IRAM Standard 11.605, for Buenos Aires, located in Bioclimatic Zone III b. The final row of the table shows the critical value, considering the lower value of both seasons.

Table 12.3. Maximum allowable values of Thermal transmittance (Watts/m^{2}K) for walls and roofs in summer and winter, IRAM Standard 11.605 (1996).

Conditions	**Roofs**	**Walls**
Winter (IRAM 11.605, Table 1)	1,00	**1,85**
Summer (IRAM 11.605, Table 2)	**0,76**	2,00
Critical Value (lower value of the two seasons)	**0,76**	**1,85**

The walls of compacted stabilised soil have an estimated density of 1900 kg/m^3. This corresponds to a thermal conductivity of 0,9 W/mK, based on a study of the relation between density and thermal performance. With a wall thickness of 20 cm, the thermal transmittance is 1,90 W/m^{2}K, according to a study of alternative earth construction (Evans, 2004). This value does no comply with the current requirements of the IRAM Standard 11.605, for this climatic zone, shown in Table 12.3.

This study therefore analyses the thermal characteristics and resulting indoor temperatures in order to evaluate the possible benefits of building materials with higher densities and greater thermal capacity, even if they do not achieve the required transmittance values

12.4.3. Measurements.

The automatic temperature data loggers, HOBO, were placed in the locations indicated in Table 12.4 The first period of measurements was made between the 10th and 16th of December, 2005, with temperature registers at 15 minute intervals, totaling 96 measurements in each 24 hour period. During the measurement period, the module was unoccupied, though the door was opened to store tools and materials, left in the living room. Figure 12.17 shows the graph of temperatures measured in the experimental module during the 6 day period. The same figure shows that the measurements were made during a period of increasing temperatures, with similar temperature variations on each day. The variation between the maximum and minimum temperatures is approximately 9 degrees, reaching a maximum of 26,5° C.

Table 12.4. Location of the measurements.

Reference	Location	Comments
S	Outdoor	Under the branches of a tree in leaf avoiding the impact of direct solar radiation.
D	Bedroom roof	In contact with the underside of the roof
F	Kitchen roof	In contact with the underside of the roof
R	Bedroom	In the centre of the room at a height of 1,5 m
T	Kitchen	In the centre of the room at a height of 1,5 m

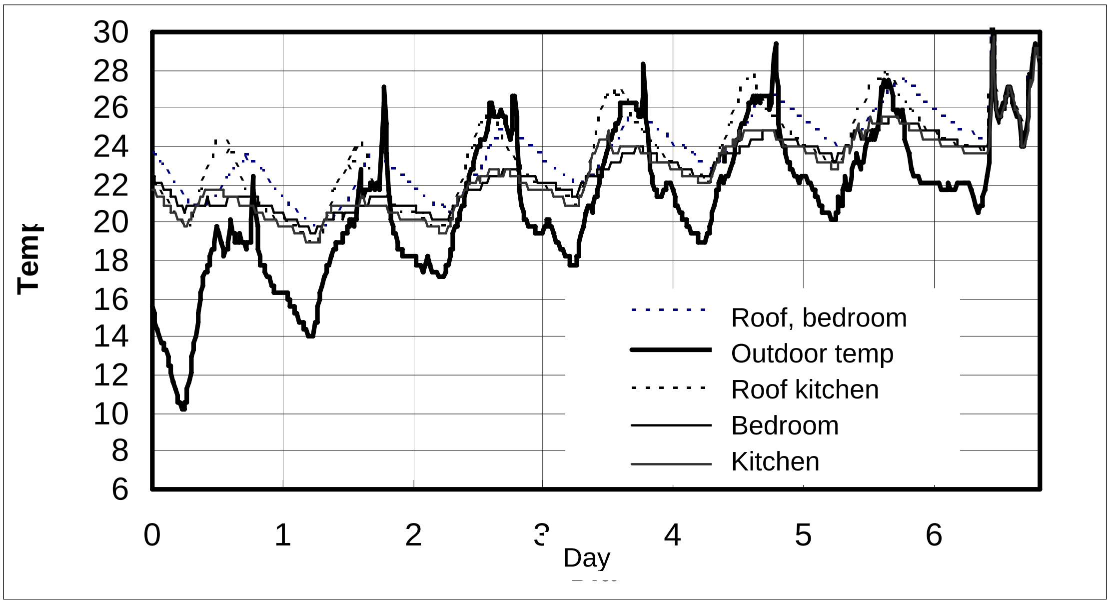


Figure 12.17. Temperatures registered automatically during a warm period, from 10th to 16th of December, 2005.

In order to visualise the thermal performance, and reduce the irregular variations due to passing clouds, Figure 12.18 shows the hourly average temperatures in the same 6 day period. The curves of the graph show the following thermal characteristics of the module:

- **Indoor temperatures:** The indoor temperatures in the kitchen and bedroom have a variation of 2,4 a 2,9 degrees C, while the outdoor temperature has a variation of 7,9 degrees, showing a favourable moderation of the indoor temperature variation.
- **Peak temperatures:** The indoor pick temperature was 23,7° C compared with a pick outdoor air temperature of 25,5° C, although with solar radiation, the comfort sensation outdoors is still less comfortable in hot summer days.
- **Minimum temperature:** The night minimum temperature was 20,8° C and 21,3° C respectively in the bedroom and kitchen, compared with an outdoor minimum of 17,6° C.
- **Outdoor temperature:** The outdoor temperature registers indicate a temperature peak in the afternoon, at exactly the same time each day, probably due to direct radiation penetrating the foliage. A comparison with the air temperatures measured in the local Buenos Aires airport, Aeroparque, and on the roof of the architectural

faculty do not show this peak, so the outdoor air temperatures were adjusted to eliminate the effect of this solar impact.

A comparison of roof alternatives requires a special analysis, considering the different rooms of the module, with the same walls and the different roof constructions described previously.

- **Kitchen roof:** galvanized corrugated iron roofing sheet, slightly ventilated air cavity, 25 mm of expended polystyrene thermal insulation with a density of 20 kg/m3, ceiling of 18 mm timber boarding. Calculated thermal transmittance: 0,50 and 0,53 W/m^{2}K in summer and winter, respectively. **Complies** with IRAM Standard 11.605.
- **Bedroom roof:** galvanized corrugated iron roofing sheet, slightly ventilated air cavity, layer of mud on 50 mm layer of straw on a second layer of mud. Calculated thermal transmittance: 0,97 y 1,07 W/m^{2}K in summer and winter respectively. **Does not comply** with IRAM Standard 11.605.

Therefore, the measurements allow a comparison between a lightweight roof with conventional insulation that complies with the standard and a heavier roof with non-conventional materials that does not comply with IRAM 11.605.

Figure 12.18 indicates that the maximum temperature of the internal surface of the bedroom roof with non conventional construction is more comfortable that the conventional roof of the kitchen. The maximum internal surface temperature of the kitchen is one degree less than the bedroom roof, which has a time lag of just over an hour, peaking at 14:00 hours, while the non conventional bedroom roof reaches its peak at 17:00 three hours later. Figure 12.18 also shows that the minimum temperatures, measured at 6:00 hours are 21º and 22º C in the bedroom and kitchen respectively. In summer, the non conventional construction which does not comply with the IRAM standard is more comfortable than the conventional roof with lightweight insulation.

.

The jump in temperature at 24:00 hours shown in Figure 12.18 is the result of the variation in temperature. As Figure 12:17 indicates, there was an increase of 4º C over the six day period of the experiment, approximately 0,7º C each day, the difference that occurs at 24:00 hours in the average values.

12.4.4. Simulations.

As in the case of the low cost house in Costa Rica, presented in the Section 12.2 of this chapter, the technique of calibrated simulations was used to compare the thermal performance of this non conventional construction with conventional alternatives. This process allows an evaluation of different construction techniques.

The first step is to compare the results of the measurements obtained with the HOBOs with a thermal simulation of the same building. Figure 12:19 presents the two sets of data, simulated and measures. For the simulation, the radiation data were obtained from the radiation measurement station, mounted on the roof of the Faculty of Architecture of the University of Buenos Aires. The ventilation data were estimated, considering the poor quality of doors and windows.

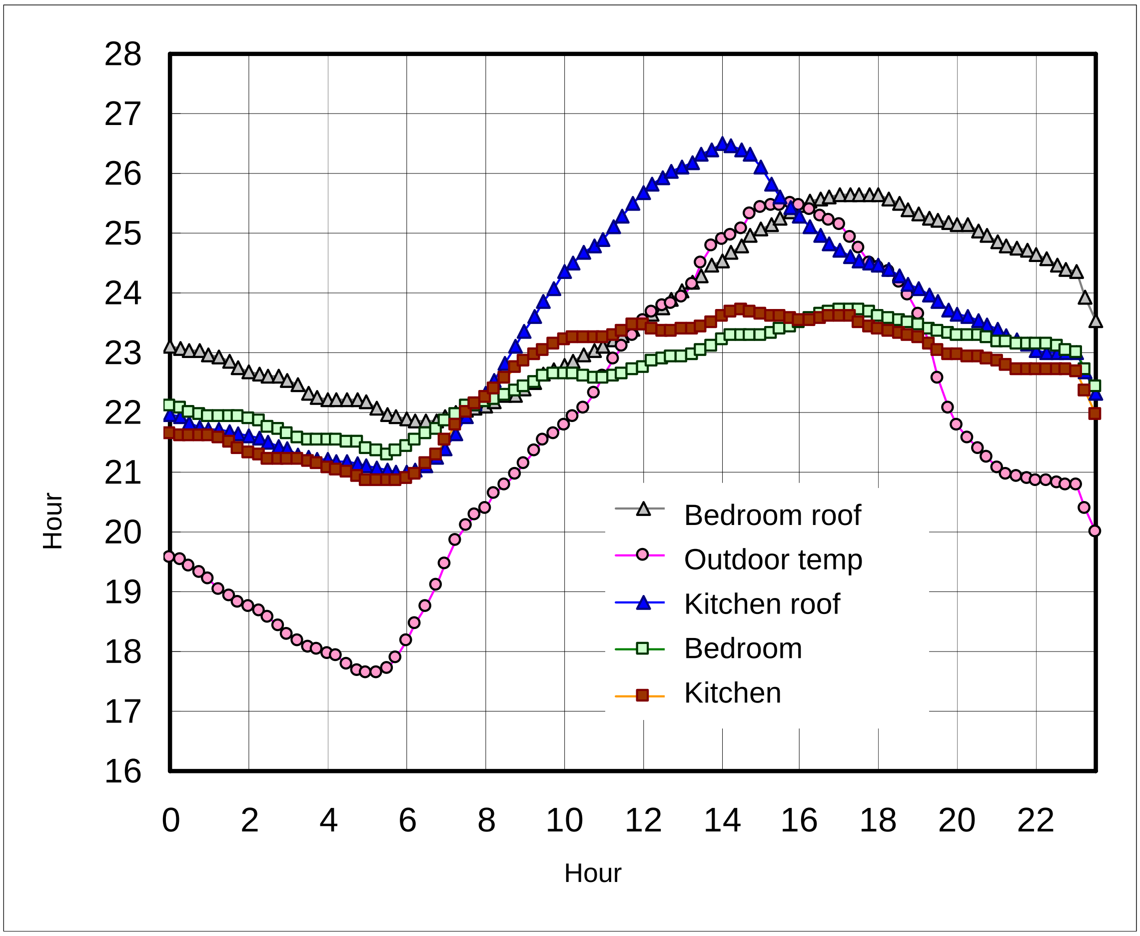


Figure 12.18. Average temperatures registered during the 6 day study period.

The program used in this case was the same as that used in the previous simulation, Quick, originally developed in South Africa for situations of natural conditioning in climates similar to those found in the Province of Buenos Aires (Matthews and Richards, 1993). The maximum difference between the two data sets is 0,5 degrees, a degree of precision that is considered very adequate considering the difficulty in estimating the ventilation rate and the solar radiation levels with accuracy.

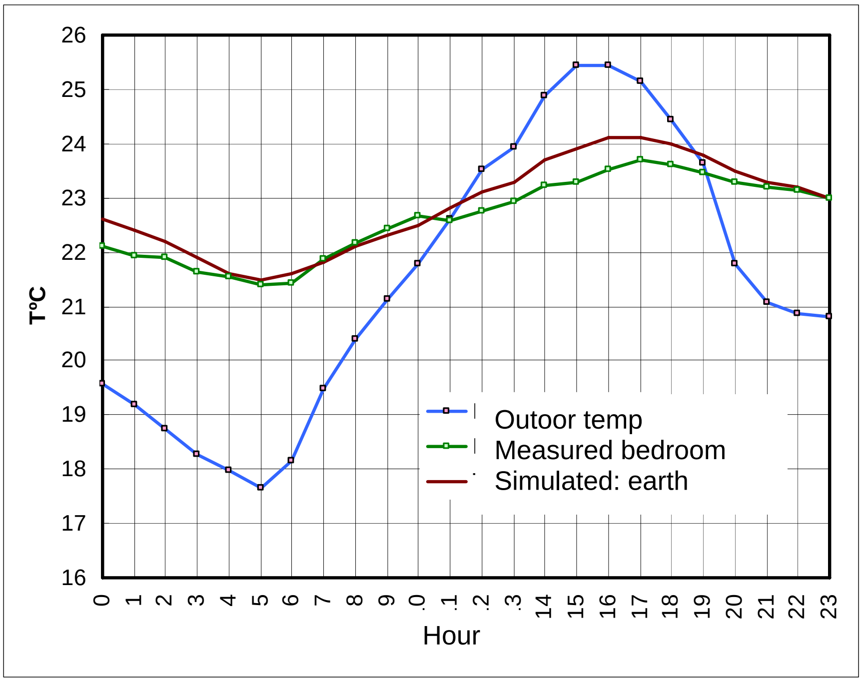


Figure 12.19. Comparison between the indoor temperatures registered in the bedroom with the HOBO and the indoor temperature obtained with the numerical simulation.

The second step is to compare the simulations of the rammed earth construction with the simulation results of other alternative constructions with conventional materials, selected for this study and listed in Table 12.5.

Table 12.5. Alternative wall constructions selected for comparison.

Construction	**Thickness mm**	**Construction layers**	**Thermal Transmittance K W/m^{2}K**
Soil-cement	200	Compacted stabilised soil	1,9 (Does not comply)
Block	200	180 mm hollow clay block with 4 rows of air spaces, rendered on both sides.	1,6 (Complies)
Brick	300	270 mm solid clay bricks, rendered on both sides.	1,8 (Complies)
Lightweight panel	200	Exterior cementicious panel, air cavity, 25 mm glass wool insulation, vapour barrier and internal plaster-board panel. .	0,8 (Complies)

12.4.5. Results.

Figure 12.20 shows the result of the simulations of the four alternative construction methods. In the simulations, the results correspond to the same ventilation rates, solar radiation intensities, external temperatures, building geometries and orientation. The thermal characteristics of the conventional materials were obtained from the IRAM

Standard 11.601(1996) based on results from tests in the laboratories of INTI, the National Institute of Industrial Technology in Argentina.

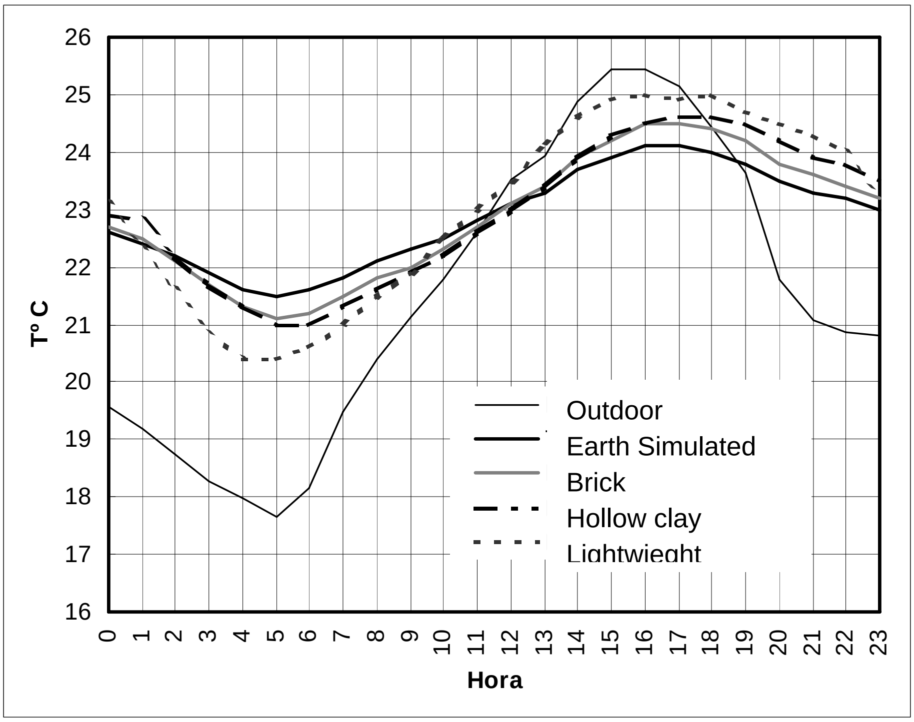


Figure 12:20. Simulated indoor temperatures with different constructions in summer. .

The results of the simulations, Figure 12:20 and Table 12.6, show the favourable thermal performance of the compacted soil in summer with the lowest temperature swing and lowest maximum temperature. The comfort triangle diagram, Figure 12.21, allows a clear visualisation of the relative thermal performance, based on the average temperature and temperature swing

Table 12.6. Measurements comparing conventional and non-conventional roof construction

	Maximum	Minimum	Tm	At
Outdoor temperature	25,6	17,6	21,6	8
Interior, roof of the bedroom: Straw and mud below roofing sheet	25,7	21,8	22,7	3,9
Interior, roof of kitchen: 5 cm PEX conventional lightweight insulation below roofing sheet	26,5	21	23,7	5,5

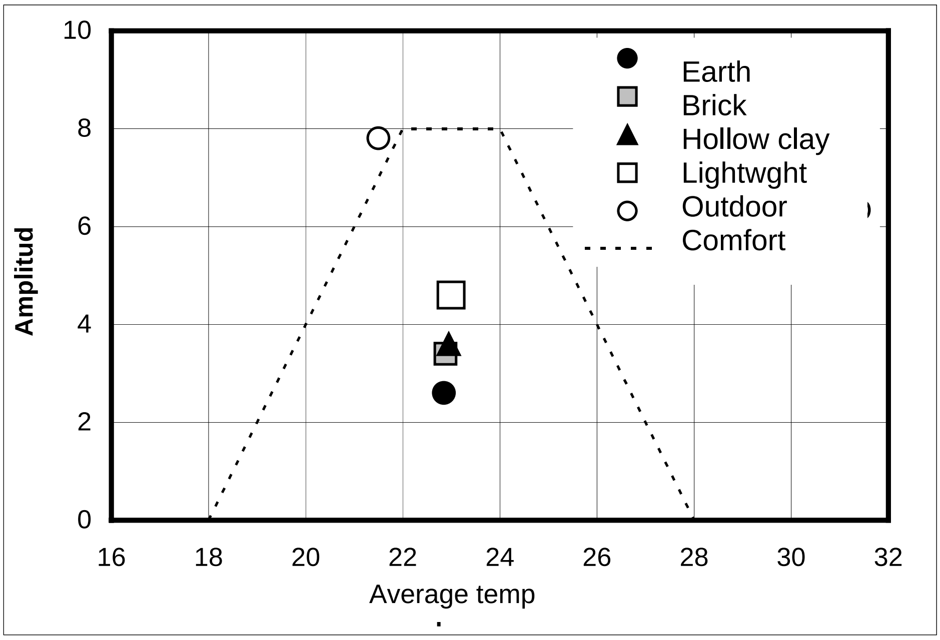


Figure 12.21. Simulated indoor average temperatures and temperature swings in the module compared with outdoor temperature conditions..

12.4.6. Thermal performance of soil cement: conclusions.

The results of the measurements in the soil cement house show clearly the favourable comfort conditions achieved in Buenos Aires during a typical summer period. The Measurements in winter In spite of the non-compliance with the requirements of the IRAM Standard 11.605 (1998), Level C, for the soil cement construction, the simulations show that the thermal behaviour of this alternative is better than that provided by solid bricks, hollow clay blocks or light insulated timber frame construction.

Another important result is the comparison of alternative conventional and non conventional roof constructions. Here again, the non-conventional roof construction with straw and mud, which does not comply with the IRAM Standard has a lower maximum temperature, though maintains higher temperature at night time. These results will be valuable for possible improvements of the IRAM Standard (1998).

12.5. CONCLUSIONS

This chapter presents three studies of the thermal performance of alternative construction materials, both lightweight and heavyweight. The thermal performance of three alternatives, studied in the previous sections of this chapter, were:

- **Section 12.2:** Very light construction in an equatorial upland climate are studied to show how the lack of thermal mass allows excessive thermal swings, though average temperatures were within desirable limits. The measurements allow the calibration of a numerical simulation, then used to test construction alternatives.
- **Section 12.3:** Traditional lightweight construction in a equatorial climate were presented to show that similar indoor and outdoor conditions can be maintained,

both average daily temperatures and swings. In this case the resulting temperatures were comfortable.

- **Section 12.4:** Non conventional soil cement construction is tested to determine the levels of comfort achieved. The results show that this heavyweight construction is comfortable in summer, even though this alternative does not comply with the thermal standard for insulation. Simulations show that conventional construction is less comfortable.

In two of the studies, thermal simulations were carried out to compare the measured results with alternative construction methods. This technique is more reliable than direct simulations as the measurements are used to calibrate the numerical model.

Although the materials studied in this chapter have an important impact on the thermal performance; the design, orientation, ventilation and use of the building are also vital to the results, indicating that materials must be chosen to contribute to the overall bioclimatic design strategies, which are clarified with the use of the Comfort Triangles.

PART 5
RESULTS AND CONCLUSIONS

CHAPTER 13. RESULTS OF THE CASE STUDIES.

CHAPTER 14. CONCLUSIONS.

Part 5 of this thesis presents the results and findings of the case studies, with the aim of assembling the evidence to prove the hypothesis:

Chapter 13 presents the results of the case studies used to develop and improve the Comfort Triangles, the new graphic tool to relate comfort, climate and habitat, the principal result of this thesis.

Chapter 14 argues that the thesis proves the hypothesis presented at the start of the thesis, considers the scope and application of the design tool and proposes lines of further research.

Part 1: Introduction

1. Introduction.
2. Background
3. History …

Part 2: State of the art

4. Thermal Comfort
5 Bioclimatic zones
6. Technology …

Part 3: Comfort triangles

7. Thermal Comfort
8. Analysis of Climate
9. Design Resources

Part 4. Case studies

10. Urban scale
11. Architectural scale
12. Building scale

Part 5: Conclusions

13. Results & case study evidence
14. Conclusions & ideas for further study

CHAPTER 13. RESULTS

13.1. INTRODUCTION.

This chapter summaries the results of the case studies presented in the previous chapters of Part 4, in order to show the degree and characteristics of climate modification that can be achieved, especially as a result of design decisions at the architectural and building scale, as indicated in Chapters 11 and 12 respectively. The case studies, together with the development of the Comfort Triangles graph in Part 3 are used to develop and adjust the Comfort Triangles as a tool for bioclimatic design.

The object of this chapter is to demonstrate the application of the Comfort Triangles for design, using the case studies as examples. This process contributes to the definition of the areas of the graph with given climate conditions of average temperature and swing in order to identify the zones where different bioclimatic design strategies are appropriate, according to their capacity to modify average temperature and temperature swing.

In all of the case studies presented in Part 4, the built environment is shown to modify the environmental conditions, especially the average temperature and the temperature swing. The only exception is the study of a light-weight construction in a warm humid climate where the indoor and outdoor temperatures are maintained at very similar levels. As is discussed in this chapter, this exception is a valuable finding as it shows that the modifications can be controlled to change, modify or maintain the conditions found in the outdoor thermal environment.

13.2. THERMAL MODIFICATION AT THE URBAN SCALE

The built environment produces changes in the urban temperature regime, especially the increase in temperature produced by the urban heat island. Examples of this phenomena are presented in Chapter 10, for different cities at varied latitudes. The typical results for large cities are an increase in the average evening temperature of 2 to 4 degrees, although other meteorological, topographical and urban development factors may produce variations in this change.

13.2.1. Urban variables

The following factors are show to affect the thermal conditions in urban areas.

Street canyons: Within the denser streets of the city, the shading effect of the street canyon can reduce the maximum temperatures, while the limited sky view factor can reduce heat loss to the night sky, reducing the nocturnal cooling to obtain higher minimum temperatures. Thus, in the city centre, measurements demonstrate increases of the average temperatures and decreases of the temperature swing.

Paved areas: However, in open but paved areas within the city, higher temperatures are recorded by day and the hard surfaces with higher heat capacity than the surrounding countryside can have both higher average temperatures and higher swings. This is shown by the local heat islands around the commercial centres in Tampico.

Green areas: On the other hand, parks, lakes and green areas within the city can reduce the average temperature due to the combined effect of evaporation, lower thermal heat capacity of vegetation as well as the higher heat capacity of lakes and lagoons. This produces lower average temperatures, compared with built-up areas as well as lower temperature swings.

Lakes and rivers: In the studies of Tampico, Mexico, Buenos Aires and Rio Gallegos, Argentina, the moderating effect of lakes and rivers are clearly shown. In the case of Buenos Aires, the effect of the River Plate can be detected at the local airport, *Aeroparque* on the shores of the wide estuary, compared with the Observatory in the urban area and the International Airport, Ezieza, surrounded by relatively open countryside.

The differences will also change in different seasons, as the temperature swing and the intensity of solar radiation tend to increase in summer and diminish in winter.

13.2.2. Impact of the urban climate modification

At the micro-urban scale, the modifications of average temperature and swing may be even more marked, producing greater modifications in more limited spaces. The variations at the micro urban scale, studied by de Schiller (2004) and Evans et al (2002) in Buenos Aires provide examples of this scale, where local impact in solar radiation and shade, as well as wind protection or acceleration are significant

The importance of these changes and climate modifications are considerable, affecting not only thermal comfort in outdoor spaces but also energy demand and comfort within buildings as quantified in the case studies of Buenos Aires, Rio Gallegos and Tampico, Mexico. The studies presented show the need to consider the significant variation between the climatic data obtained at local airports, normally located outside the urban centres and the conditions found in the built-up area.

This difference can produce significant variations in the levels of comfort in outdoor areas, the energy demand for heating, and the cooling load of buildings. The estimated differences in the heating load found in the Río Gallegos case study exceed 15 % .

13.2.3. Summary of the thermal modifications.

The different modifications of thermal conditions at the urban scale found in the case studies are shown in Figure 13.1., where the circular dot in each data set indicates the conditions in the city centre and the lines show the relationship to the ‘rural’ area on the same time. In general, the variation shows:

- Average temperatures: general increase of 1 to 3 degrees.
- Temperature swings: increase of 1 to 2 degrees.

However, in the case of Buenos Aires, there are two ‘rural’ conditions. Ezeiza international airport is situated in the open country inland with higher swings and lower temperatures, while the Aeroparque local airport on the shores of the river plate estuary has lower temperatures and lower swings.

As Figure 13.1. shows, below the average temperature of 18º C, the heat island effect always moves conditions towards comfort, with lower heating loads. Above the comfort zone, urban centre conditions become less favourable with increased cooling demand.

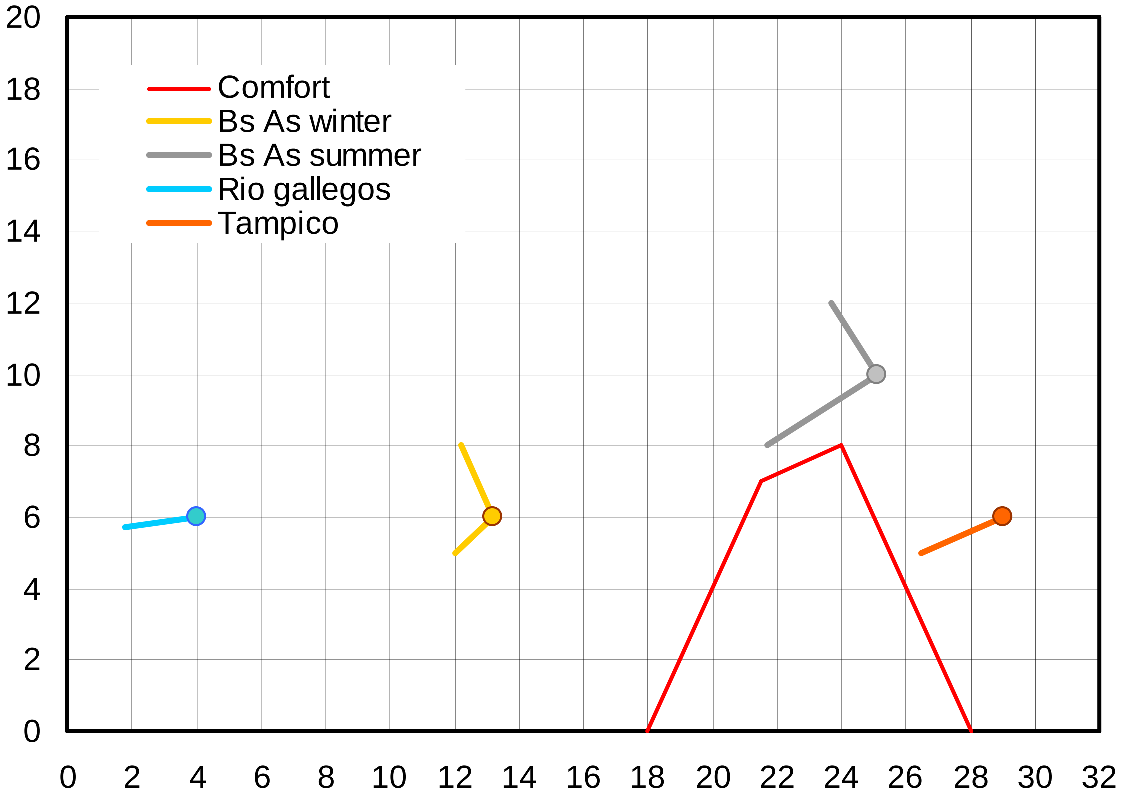


Figure 13.1. Variation between rural and urban conditions, shown by the circular dot.

13.3. MODIFICATIONS DUE TO DESIGN AND SELECTION OF MATERIALS

However, as Chapters 11 and 12 show, the variations in the outdoor conditions are small when compared to the modifications produced indoors. The Range Ratio at the urban scale is usually found to be more than 85 %, while within buildings, the measurements in the case studies produce values as low as 5 – 6 %. Also, the effect of solar heating can increase the temperature by over 6 degrees, even in well ventilated spaces as the glazed courtyard of Cuenca shows. Indeed, the Bioclimatic design diagram of Givoni (1976) shows that solar gains may be used to achieve a temperature increase of up to 8 – 10 degrees.

In this section the bioclimatic modifications achieved with different strategies are quantified using the results of the case studies and thermal simulations to show how different design decisions can modify temperature and comfort.

13.3.1. Solar gains.

Solar gains will raise the average indoor temperature, by up to 10 degrees, but will also tend to increase the indoor swing. The effect of two control mechanisms is demonstrated in the results of the case studies analysed in the next section of this chapter. With large indoor surfaces of high admittance, the swing is effectively reduced. Alternatively, the excess heat at midday may be eliminated by ventilation, reducing the indoor peak as well as the increase in average temperature.

Ventilation is a more effective strategy when the difference between indoor and outdoor temperatures are small, as in this case the 'dumping' of excess heat to the outside is not a problem. However, as outdoor temperatures decrease, it is important to conserve the solar gains to achieve the required difference in temperature.

So, to be effective, solar gains must be accompanied by selective ventilation and thermal mass, as well as thermal insulation incorporated in the external envelope. Figure 13.2 shows the combination of conditions where solar gains can improve comfort, considering that in cool conditions with small temperature differences between indoors and outdoors, internal gains can produce the required temperature increase. Internal gains are therefore considered in the next subsection.

Table 13.1. Effect of solar radiation on average temperatures and temperature swings

Variable	**Difference**	**Source**
Average air temperature	Up to 10 degrees	Evans de Schiller, 1987
Temperature swing	According to thermal mass	

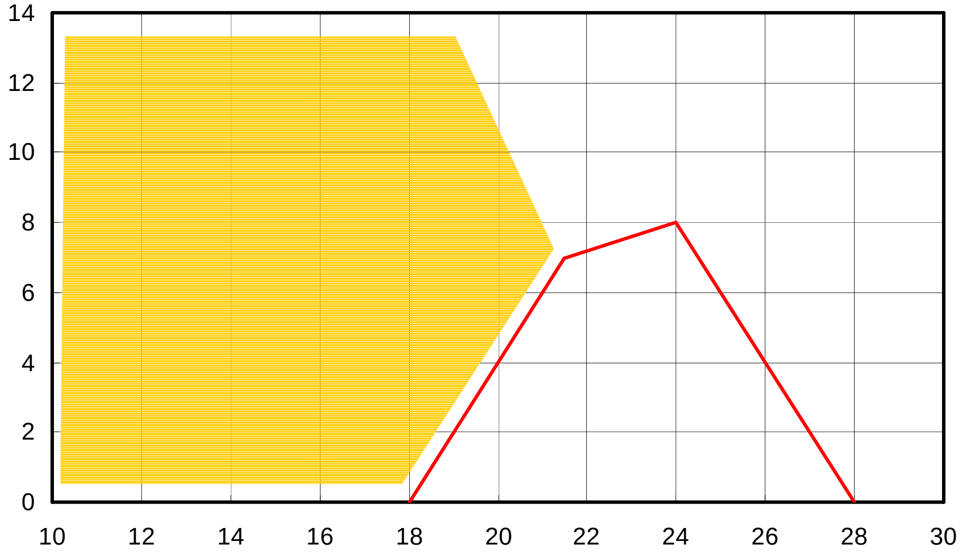


Figure 13.2. Combination of outdoor conditions for effective solar gains, combined with thermal mass in all cases.

13.3.2. Internal gains

Occupied buildings usually produce an increase in the indoor temperature with respect to outdoors, due to the metabolic heat and other internal gains, from lighting, electro-domestic equipment and other sources. Thus the average internal temperatures are usually comfortable when the average outdoor temperatures are up to three degrees below the comfort level. Indeed in well insulated houses, this difference increases to over 5 degrees. In offices with higher levels of occupancy and more equipment and lighting, the difference can be even higher.

Solar gains may therefore need controls to avoid indoor overheating when outdoor temperatures are comfortable or even cool, especially in buildings with high internal gains. High internal heat capacity, or high admittance can also be beneficial.

Internal gains may be highly variable over time, so good internal thermal mass will assist in moderating the indoor fluctuations and store excess heat from time of high internal gains, reducing the temperature drop later. Again, thermal insulation will increase the heating effect of internal gains in cool outdoor conditions. Figure 13.3 shows the combination of outdoor conditions which can provide comfort with internal gains for average and excellent levels of thermal insulation

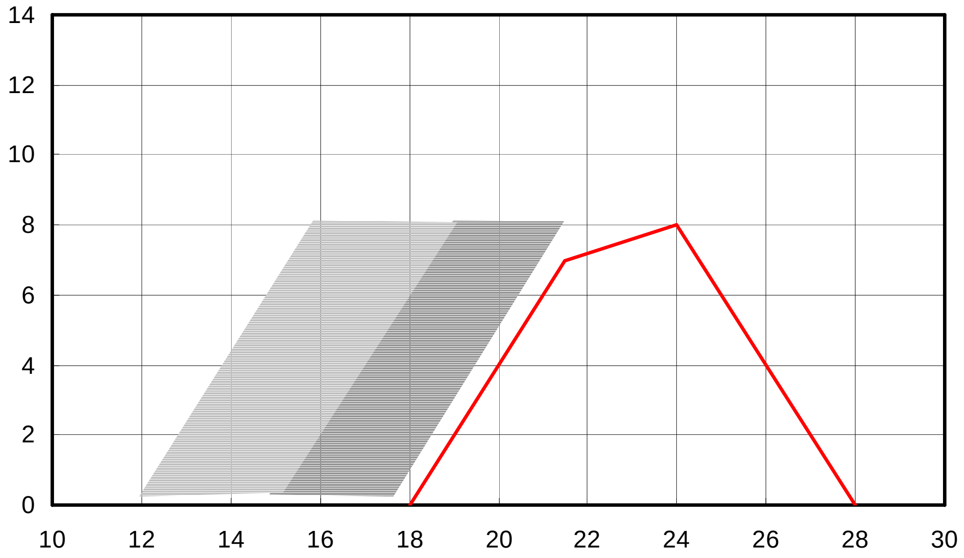


Figure 13.3. Combination of outdoor conditions for use of internal gains, with average and excellent thermal insulation. Higher temperature swings require more thermal mass.

13.3.3. Thermal inertia

Buildings with large indoor surfaces and materials with high heat capacity moderate the temperature swing very effectively, reducing the Range Ratio. In the case studies, values as low as 5 % have been recorded, although these very low levels may be influenced by the placing of the sensor close to dense high heat capacity surfaces.

As the next section shows, values of 15 – 20 % are readily achieved, allowing the high outdoor temperature swings of 24 degrees, the highest found in Argentina, to be reduced to comfortable levels of less than 5 degrees. The use of thermal inertia by itself does not influence the average temperature, but the potential to store solar gains or the cooling effect of night ventilation is clearly enhanced.

The effect of thermal inertia is reduced by high levels of ventilation, although the case studies show that spaces with high thermal capacity can reduce the indoor swing, even with high ventilation rates. External insulation also improves the dampening effect of thermal mass slightly.

Figure 13.4 shows the conditions where thermal inertia alone or in combination with night ventilation or day ventilation can achieve or improve comfort. Thermal inertia is also required when solar gains are used (figure 13.2.) or when internal gains are highly variable

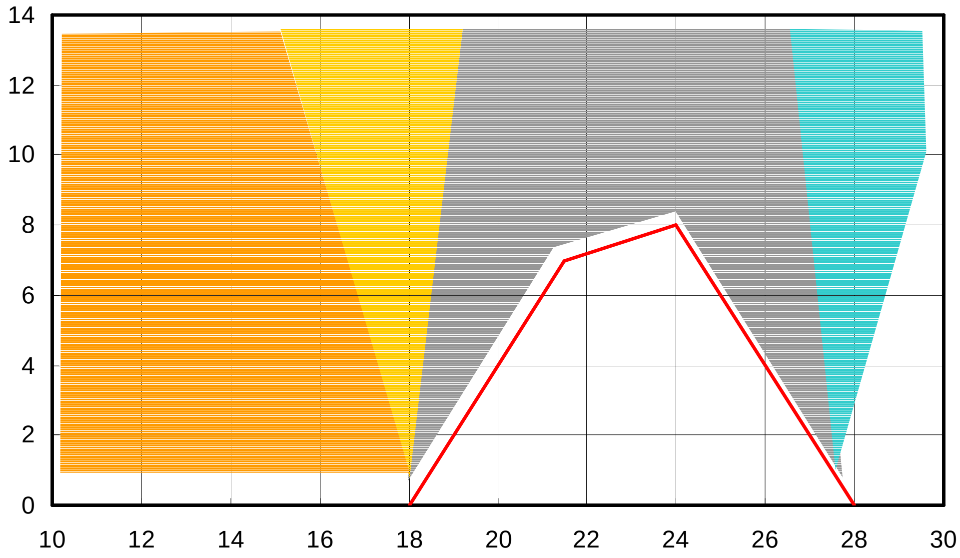


Figure 13.4. Conditions for the use of thermal inertia can be used to achieve comfort (grey), and with additional night ventilation (blue), day ventilation (yellow) or solar gains (orange).

13.3.4. Night ventilation.

Ventilation between sunset and sunrise enables the temperature of interior spaces to be reduced by the ingress of cool air and the evacuation of warmer air. Night ventilation is therefore an valuable cooling technique, especially in climates with high temperature swings.

Night ventilation is aided by high internal mass, solar protection of openings and external thermal insulation. Figure 13.4 shows the combination of conditions in which night ventilation will improve comfort, lowering the average temperature by half a degree for each 6 degrees of swing.

13.3.5. Sensible air movement

Sensible air movement is a special case as the movement of air does not create a difference in air temperature, but a cooling effect due to heat dissipation and evaporation at the skin surface. This can be described as ‘apparent cooling’ As the breeze that creates air movement normally increases at midday and diminishes at night, the use of natural breezes will produce more cooling at midday, reducing the apparent temperature swing. As the case study in Cotacocha shows, the use of natural breeze will produce indoor temperatures very close to the outdoor values, when internal gains are low and solar protection is effective.

When ceiling fans are used, there is sensible air movement, that is movement that can be sensed as it produces a cooling effect on the skin. However, unlike the movement induced by natural breezes, the ceiling fan does not necessarily produce ventilation air exchange between inside and outside air. So solar gains or internal gains, combined with limited ventilation and air movement produced by fans will tend to produce increases in the air temperature, slightly reducing the cooling effect of the air movement

In the warm humid climates where air movement is most effective, high ventilation rates are required to avoid an effect of stuffiness (Szokolay, 1999). So although night ventilation may be used to reduce the average air temperature, the requirement for ventilation in occupied rooms leads to the choice of sensible air movement as the preferable option. Figure 13.5 shows the range of conditions where selective ventilation is an effective bioclimatic strategy. At higher average temperatures, air movement will improve conditions, without obtaining conditions within the comfort zone.

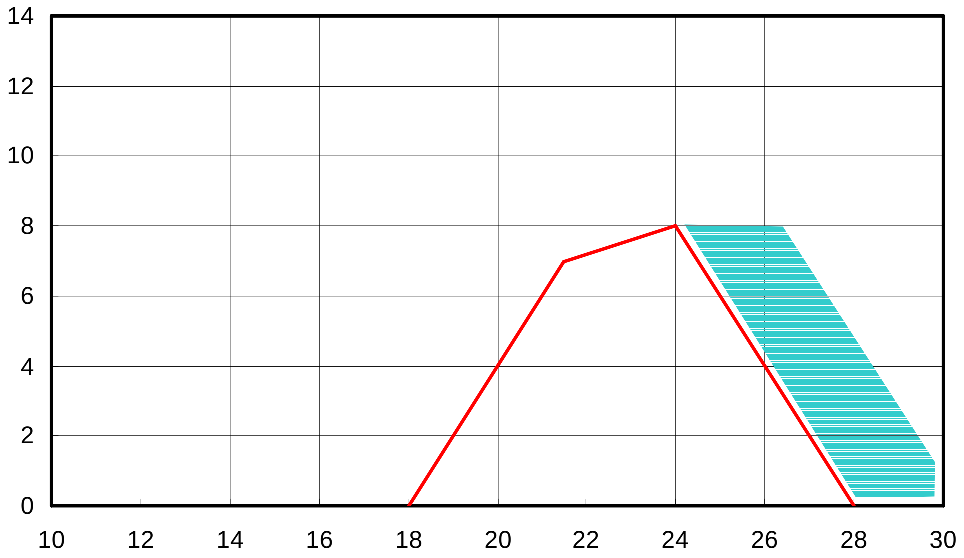


Figure 13.5. Conditions where air movement provides effective apparent cooling

13.3.7 Combinations of strategies

In all of the strategies considered in this section, combinations are required to achieve favourable modifications; solar gains with thermal mass, solar gains with selective ventilation, air movement with solar protection, internal gains with thermal insulation, etc. The discussion of different bioclimatic design strategies presented in Chapter 9 introduces this requirement, showing that strategies of favourable modification must be accompanied by strategies of avoidance of unfavourable modification. Many of the case studies show the need to adopt two or more strategies to achieve the desirable change in the internal conditions

13.4. STRATEGIES IN THE COMFORT TRIANGLES

This section presents a summary of the results of the cases studies presented in Part 3 of the thesis. The studies include the Comfort triangles, the variations of Average indoor temperature and Range Ratio as well as the relation between them.

13.4.1. Composite Comfort Triangles

The case studies demonstrate the way in which the buildings studied achieve a significant modification of the two key variables that form the axes of the Comfort Triangles. A composite diagram shows the different modifications of the thermal performance that have been recorded in Chapter 11, Figure 13.6.

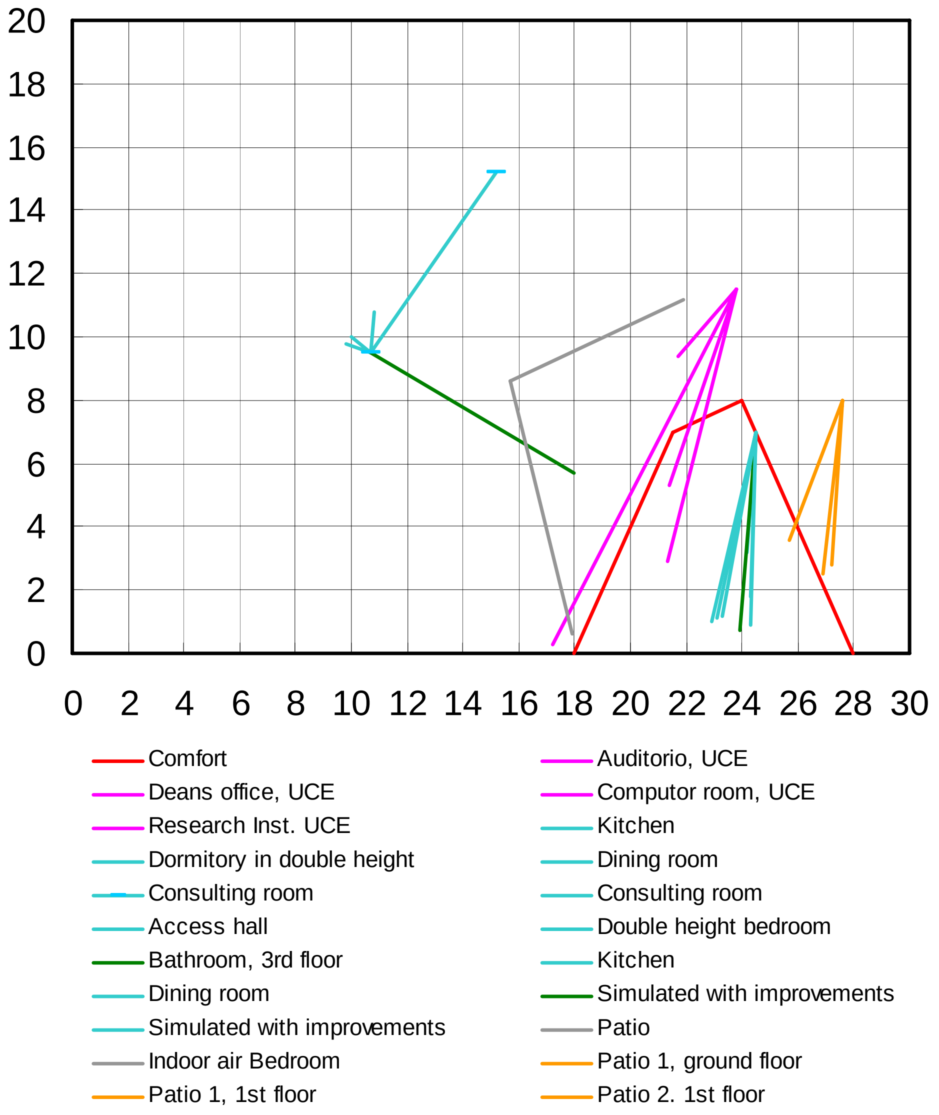


Figure 13.6. Bioclimatic modification achieved in the case studies

13.4.2. Changes in average temperature

Figure 13.7 shows the change of average temperature, or difference between average indoor and outdoor temperature. The highest value, 7,6ºC, is estimated for the simulation of the Curutchet house, with improved insulation, while the lowest value in the internal room of the Research Institute, UCE, Ecuador, with a very high thermal inertia.

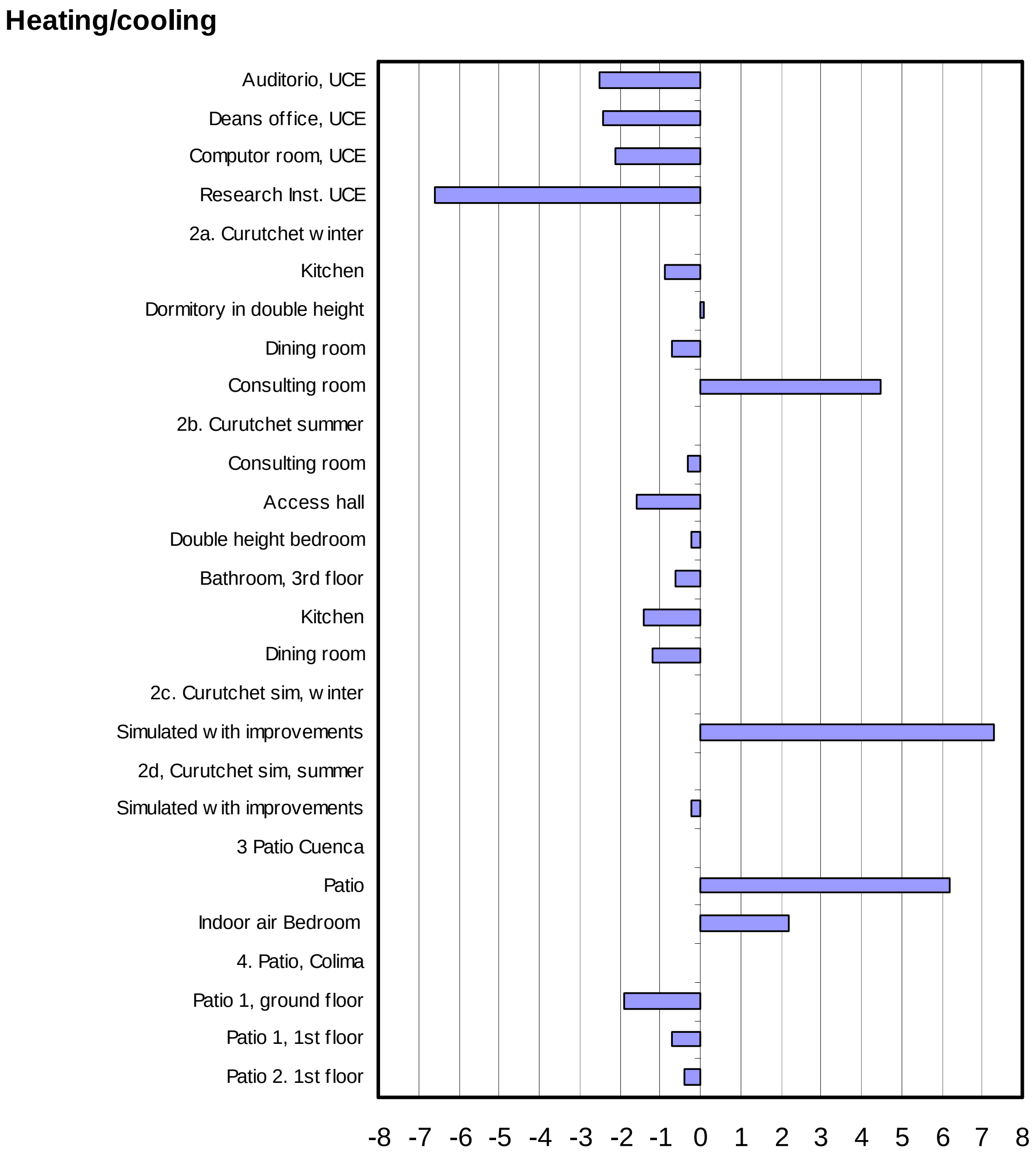


Figure 13.7. Heating and cooling measured or simulated in the case studies

The degree of heating or cooling found in the case studies is also related to the average outdoor temperature, as Figure 13.8 shows. With outdoor temperatures below 20º C, the temperature change tendency is positive, with a heating effect, while with temperatures above 20ºC, the average change is negative, producing a cooling effect.

The maximum heating effect corresponds to solar gains in a heavy, well insulated space, while the maximum cooling effect is a result of solar shading, night ventilation, high thermal inertia and moderation of temperature changes over a period of several days.

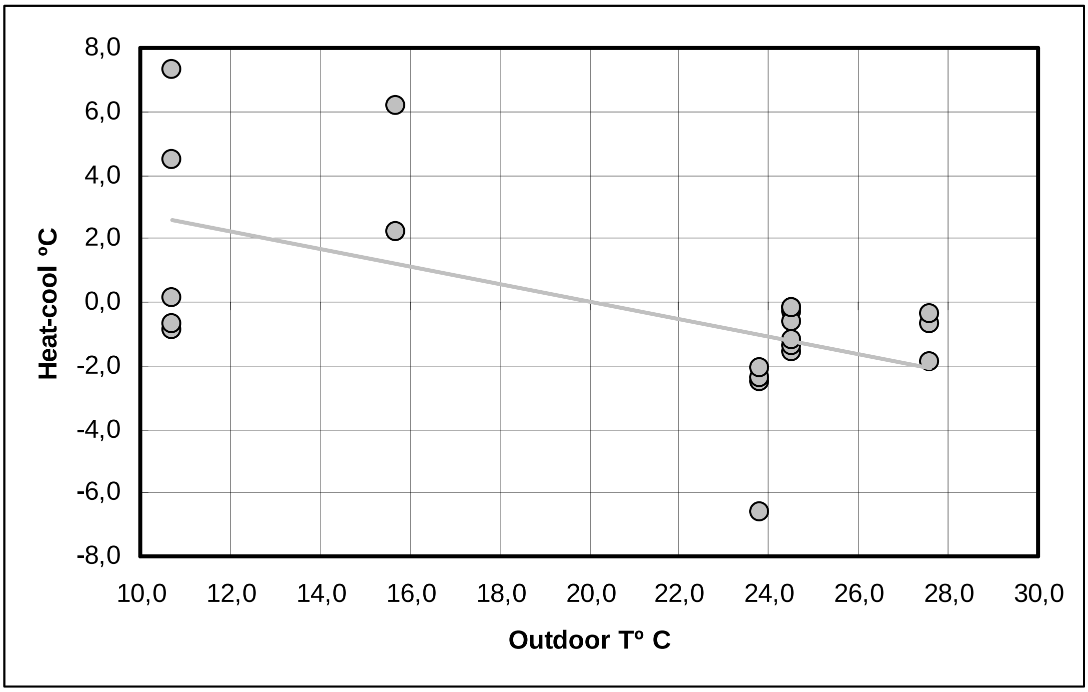


Figure 13.8. Relation between average outdoor temperature and average indoor-outdoor temperature change: negative values correspond to cooling and positive to heating.

13.4.3. Changes in Range Ratio

In the majority of the cases, the building reduces the thermal swing significantly. The measurements show a wide range of RR, Range Ratios, measured during the case studies, shown in Figure 13.9. The highest values of 125 % and 160 % correspond to spaces with high solar gains and poor thermal insulation, the Consulting room of the Curutchet House and the Glazed patio of Cuenca. The lowest values of 3 %, 7 % and 10 % are found in internal rooms with high thermal mass. For more conventional external rooms, values of 20 to 25 % are possible without special design measures. Poor insulation, large glazed surfaces and high ventilation rates increase the Range Ratio.

13.4.5. Links between Range Ratio and heating or cooling effect

Figure 13.10. shows the possible links between the two variables according to the bioclimatic strategies adopted. As discussed in Chapter 9, solar gains tend to increase the Range Ratio while increasing average indoor temperatures, Range Ratios below 70 % are only possible with high thermal mass. The figure shows other combinations such as poor insulation and high ventilation rates, internal rooms and night ventilation. The importance of combining strategies is evident.

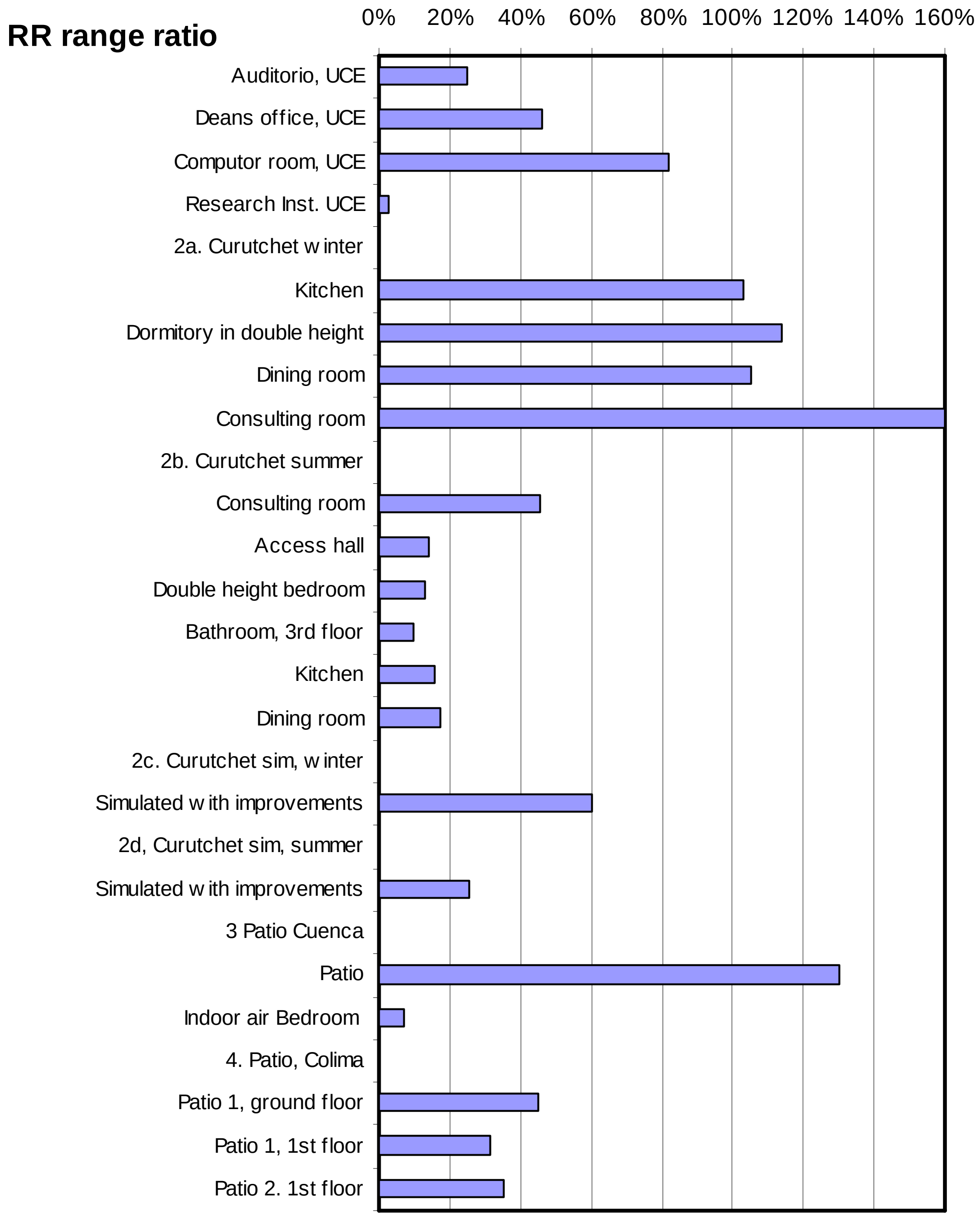


Figure 13.9. Values of RR the range ratio registered in the case studies.

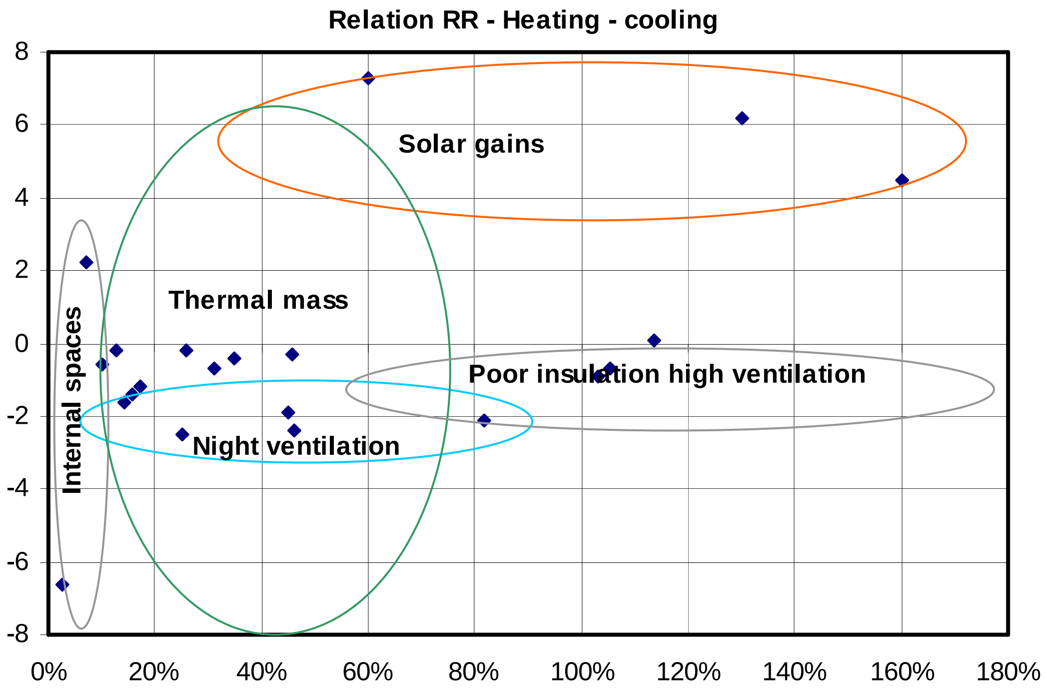


Figure 13.10. Relationship between RR, the Range Ratio (horizontal scale) and the heating or cooling effect (vertical scale), with corresponding strategies.

13.5. CONCLUSIONS.

The built environment modifies the external thermal conditions, changing the daily temperature swing and the average temperature. The Comfort Triangles show how these modifications are related to the external climate and the requirements for thermal comfort.

The case studies show that the thermal modification achieved by natural conditioning can produce differences between the average indoor and outdoor temperature of up to about 8º C in both the positive (heating) and negative (cooling) direction. The changes in the Range Ratio are also highly variable, from 5% to 160%.

The case study buildings do not incorporate materials with special thermal properties or adopt unconventional control strategies. The modifications are achieve principally through building design, including form, orientation, window size, solar protection and materials. In all the cases presented, the comfort triangles allow a clear visualisation of the way in which buildings achieve this modification.

CHAPTER 14. CONCLUSIONS

14.1. INTRODUCTION

This chapter summaries the argument presented in this thesis in order to show that the hypothesis presented in the first chapter has been confirmed by the series of case studies developed in the previous part of the thesis and the results.

The object of this chapter is to demonstrate that the Comfort Triangles, whose development is described in the third part of the thesis, are a valuable tool to analyse the function of bioclimatic design strategies. The chapter also considered the need for further studies to continue and perfect the comfort triangles and suggests various actions to continue this line of research.

As has been argued from the first part of the thesis, that two variables, average daily temperature and daily temperature swing, are key to the comprehension and application of most bioclimatic design strategies. The modification or moderation of the daily temperature swing is a variable that is not directly applied in other bioclimatic graphic design tools. In Appendix 1, the three main bioclimatic design graphs are presented to demonstrate this difference. The three graphic tools included in this Appendix are:

- The Original Bioclimatic design chart of Olgyay (1972)
- The Bioclimatic chart of Givoni (1982)
- The comfort triangles presented in Evans and de Schiller (1986)

14.2. THE ARGUEMENT

This section summaries the argument presented in the successive parts of this thesis.

14.2.1. Introduction to bioclimatic design.

In Part 1 of this thesis, the background to the thesis and the Comfort Triangles is presented in order to define the principles and concepts of bioclimatic design, and introduce a summary of developments over the past half century. The importance of the key variables of average daily temperature and temperature swing is introduced.

14.2.2. Background to the Comfort Triangles.

Part 2 covers specific aspects of the background, with chapters on thermal comfort, climatic variations with special reference to climatic zoning and bioclimatic design resources. These three chapters are relate to the three linked aspects of comfort, climate and habitat. It is argued that the study of climate in relation to comfort is the link to facilitate the ability to select and choose the appropriate bioclimatic design strategies, modifying the former, climate, in order to achieve the later, comfort..

14.2.3. Development of the Comfort Triangles.

Part 3 of the thesis shows how the concept of the Comfort Triangles was developed and perfected by the author over a period of nearly two decades, Chapter 7. The idea was suggested by two independent antecedents: studies of passive solar systems in order to control excessive temperature swings and studies of climatic zoning in the hot climates of Nigeria, where thermal swings were adopted as a key indicator for selecting bioclimatic design responses. This approach was later incorporated in the Mahoney Tables in which the author participated with Mahoney and Koenigsberger (Koenigsberger at al, 1970).

In Chapter 8, the same graphic format is used to show how climate variations can be compared with requirements for comfort. Studies with data from different climatic regions are provided to show this relationship. Finally, in Chapter 9, the different bioclimatic design strategies are analysed to show how they can be applied to modify the external conditions and achieve a more comfortable indoor thermal environment.

14.2.4. Case studies. Searching for evidence.

Part 4 of the thesis presents case studies of thermal performance at the urban, architectural and building construction scale, showing how the Comfort Triangles can be used to visualize and quantify the modifications in outdoor conditions achieved by different bioclimatic strategies.

14.2.5. Results and conclusions.

In this final part of the thesis, the results of the case studies are analysed to determine the appropriate conditions for different bioclimatic design strategies, improving the results developed in Part 3 of the thesis.

14.3. EVALUATION OF THE COMFORT TRIANGLES

This section evaluates the contribution of the Comfort Triangles as a method to relate comfort, climate and habitat, listing the innovations, advantages and limitations of this method, based on the development and application case studies presented in this thesis.

14.3.1. Innovations of the Comfort Triangles.

The following innovations are incorporated in the comfort triangles, emphasizing the contribution of this tool to the bioclimatic design process:

- **Daily temperature swing:** The main innovation is the use of this variable as a key indicator of the climate characteristics, the relation to comfort and the potential modification of conditions through bioclimatic design resources.
- **Average daily temperature:** The second innovation is the use of the daily average rather than the hourly values or the maximum and minimum values used by Olgyay and Givoni and other methods derived from these sources.
- **Bioclimatic graph:** The use of these two variables in the axes of a graph enable the daily variation in conditions to be identified with one point, rather than the length and direction of a line. No other bioclimatic graph summaries daily conditions so simply and directly.
- **Comfort Triangles:** The definition of comfort conditions on this graph with the two innovative variables produce a triangular form, showing that as temperatures approach the upper and lower limits of comfort, temperature swings must be

controlled to maintain comfort. No other study of thermal comfort shows this requirement so clearly.

- **Application of bioclimatic strategies:** The Comfort Triangles graph identifies the areas where bioclimatic strategies can be applied affectively. This is especially relevant with strategies that depend on periodic heat flow characteristics such as thermal inertial, solar gains and selective ventilation. For example, no other bioclimatic graph shows the combination of climate conditions where selective ventilation can achieve comfort. Olgyay (1963) mentions air movement due to indoor – outdoor temperature differences (pages 110-112) only to comment that they rarely produce adequate sensible air movement for comfort. Givoni's diagram (1976) also stresses conditions for sensible air movement, without indicating the area for selective or night ventilation. This area was covered on the later book on passive cooling (Givoni,1994) though not related to a bioclimatic chart or comfort diagram.

14.3.2. Potential limitations of the Comfort Triangles.

Like all bioclimatic diagrams, the comfort triangles also have limitations due to the need to stress two variables in a two dimensional representation. The potential limitations include:

- **Humidity:** The lack of humidity as a relevant variable for assessing comfort an be criticised, as high relative or absolute humidity will reduce the upper limit of comfort at high temperatures. However, two arguments are presented to justify the lack of humidity as an explicit variable. Firstly, the variable temperature swing is linked to humidity, with higher swings corresponding to lower relative humidity, especially when temperatures exceed 20º C. Secondly, the increase in the upper limit of the comfort zone is about 2º. This effectively increases the area of the night ventilation strategy with high temperature swings, without changing the comfort zone with low swings.
- **Average versus maximum temperature:** Givoni has proposed that his Bioclimatic chart is used with the average daily maximum temperature, as this value is likely to be critical, especially in hot climates. This temperature tends to coincide with normal indoor activities, while the minimum temperature corresponds to sleep. As shown in Chapter 7, comfort zones can be developed for different activities such as sleep or circulation, according to the time of day when they typically occur and the metabolic requirements.
- **Partial Comfort:** When climate conditions are outside the comfort zone, the comfort triangles indicate the strategies that can be used to approach desirable conditions. However, conditions outside the comfort triangles do not imply that conditions are always outside comfort. Indeed, temperatures may be comfortable most of the time or all of the time that a building is in use. For example, a school building may be comfortable while in use during the day, though the traingles may show partial discomfort at night. Additional more flexible comfort triangles could be developed to show conditions with specific proportions of the day when conditions are comfortable.
- **Calculating average temperatures:** The most widely available temperate data indicate the average maximum and minimum monthly temperatures so it is proposed that the arithmetic average of both values is used to obtain an approximate average. However, as was shown in Chapter 8, there is a difference between the average of the daily extremes and the hourly values, as the daily temperature variation is not

sinusoidal. The difference is not significant for this application and the method for calculating hourly values, recently developed by Roriz (2006) overcomes this difficulty as the only data required are the daily maximum and minimum, the latitude and the time of year.

- **Cold conditions:** When temperatures drop below about 8º C, auxiliary heating is usually required for comfort especially in housing and other buildings with limited internal heat gains. Under these conditions, the outdoor swing has less impact on the indoor variation. However, if solar gains are used, the comfort triangles provide a valuable insight into the important dampening effect of thermal mass.

14.3.3. Contribution of the Comfort Triangles.

The principle contribution of the Comfort Triangles is the emphasis on the dynamic nature of thermal performance of buildings and the control of daily temperature variations. They also allow a visual indication of the temperature modification with strategies that use periodic heat flow, such as night ventilation or solar gains. Indeed, the comfort triangles show specific combinations of conditions that other bioclimatic design diagrams do not usually show.

However, the Comfort Triangles are not proposed as a replacement of the existing design tools but rather as a complement to allow climate comfort and habitat to be related in a new visual relationship. A climate analysis spread sheet (Evans, 2004) follows this principle to show how the same basic climate data can be incorporated in different bioclimatic diagram formats to support design decisions.

14.4. PROOF OF THE HYPOTHESIS

In the first chapter of this thesis, the following hypothesis was postulated:

> **A new visual design tool, which incorporate and combine two key variables, average temperature and temperature swing, allows a better understanding and integration of bioclimatic strategies in the design process, as well as an improved application of energy efficiency in buildings, through the linking of indoor and outdoor environmental conditions with the requirements for thermal comfort and well-being, at the architectural and urban scale, to achieve environmental, social and economic benefits in the framework of sustainable development.**

Effectively, this thesis has introduced a new visual design tool based on two key variables: average daily temperatures and daily temperature swings. The use of this tool to explain the temperature modification found in the case studies demonstrates the value of this analytical approach to define appropriate bioclimatic design strategies and understand their functioning.

.

The thesis shows how the comfort triangles effectively link comfort, climate and habitat, at the urban, architectural and building construction scale. The selection of appropriate bioclimatic strategies can promote comfort through passive design measures, reducing the use of energy for artificial conditioning both for heating in cool conditions as well as for cooling in hot environments. This use of passive design strategies reducing energy use has environmental, social and economic benefits to support sustainable development. The research presented in this thesis therefore confirms that the hypothesis is proved

14.5. IMPLICATIONS OF THE COMFORT TRIANGLES

This section analyses current architectural trends and possible future developments in the light of the results of the comfort triangles. Climate change and global warming, the impact of urbanisation, design tendencies in building, and the need to achieve sustainable development, mentioned in the first part of this thesis are now analysed using the comfort triangles as a tool to detect possible consequences.

14.5.1. Climate change and the Comfort Triangles

The impact of climate change will tend to increase average temperatures, though the IPCC latest report (2006) indicates that certain regions will experience drier conditions with higher temperature swings while others may suffer from increased rainfall, higher humidities and lower swings. The comfort triangles show that climate change will have an undesirable impact on comfort in comfortable, warm and hot climates, as well as increasing the proportion of the world with these conditions.

14.5.2. Urban impacts

The case studies of urban impacts on the thermal environment show that urban concentrations increase average temperatures. This is in addition to the impact of global warming. However the warming of cities will have an important effect on energy demand, further fuelling global warming.

14.5.3. Architectural tendencies and comfort

Recent architectural projects in many regions of the world, regardless of climate differences, cultural traditions or available materials, tend to respond to the following tendencies:

- **Larger glazed areas:** The glazed proportion of the external envelope tends to increase, from values of 25 to 30% up to 60 to 80 % in residential and office buildings respectively. This additional area of glazing not only increase exposure to solar radiation, but also augment the night heat losses, with higher energy demand for both heating and cooling. The Comfort Triangles show the difficulty of achieving comfort in the face of this trend.
- **Less solar protection:** While traditional housing in Argentina and other regions of South America incorporated shutters or external roller blinds, modern housing often omits these necessary climate control components. Once again, the indoor temperature variation increases and comfort decreases.
- **Reduced thermal capacity:** Tradition construction in the South American region, as in many other regions used solid bricks, now replaced by hollow clay or hollow concrete blocks. These in turn are now giving way to lightweight construction of external panels, plasterboard internal finishes with air cavities. The use of less material may allow cheaper and more rapid construction but reduces the thermal mass and capacity to moderate indoor swings.

- **Deeper plan buildings:** Higher planning densities, lower building costs and real estate pressures all tend to favour deep plan buildings with higher internal gains due to artificial lighting, occupants and equipment. The evident difficulties to incorporate natural ventilation and extract heat from the internal zones all tend to increase average indoor temperatures.
- **Higher densities:** These higher densities also reduce solar access for natural heating in cooler seasons as well as limiting access to cooling breezes. Taller buildings may also reduce access to natural lighting, increasing internal heat gains and energy demand.

All these architectural tendencies produce increases in average indoor temperatures and temperature swings. In comfortable, warm and hot climates, these tendencies are therefore problematic, increasing indoor discomfort and the demand for artificial cooling, greater energy use and higher environmental impacts. The Comfort Triangles show the way in which these changes affect comfort.

14.5.4. Impact of current trends

Trends at the global, regional and local scale, especially in urban areas and buildings will all increase average temperatures, potentially increasing discomfort and energy demand for cooling. In large regions of the world, passive bioclimatic design strategies offer two benefits: they improve comfort as well as reducing energy demand. In this context, the Comfort Triangles can contribute to the reduction of environmental impacts and well as improved environmental conditions.

14.6. FINAL COMMENTS.

This final section suggests lines of future research, proposals for further testing and application in teaching and professional applications.

14.6.1. Lines of future research

It is considered that the comfort triangles, developed and tested in this thesis, still have considerable development potential and areas for further study. Suggested areas for specific study include:

- **Comfort and time:** The relation between thermal swing and time lag, detected in Chapter 11, Figure 11.3. shows that daily indoor variation in temperature can be related to the outdoor variation by three variables: change in average temperature, range ratio and time lag. This can better relate comfort conditions with the times of day when spaces are occupied.
- **Duration of discomfort:** The application of the comfort triangles presented in this thesis is based on achieving thermal comfort throughout the day. For some applications, a certain period of time outside the comfort zone may be acceptable, so adjustments in the triangles could be developed to respond to this situation.
- **Comfort for different activities:** The original version of the comfort triangles (Evans and de Schiller, 1994) proposed three different triangles for sedentary activities, circulation areas and sleeping. The version for sedentary activities has been stressed in this thesis, as it is the most widely applicable. However, studies of

the comfort zone for other activities such circulation, sleeping, and light work as could be perfected.

- **Costs of comfort alternatives:** The comfort triangles indicate alternative combinations of strategies to achieve comfort, The costs and impacts of these alternatives can be compared to find the most sustainable solution, considering the economic, social and environmental consequences.

14.6.2. Application in teaching and professional practice.

The comfort triangles have already been tested in the teaching of architecture, over a period of eight years at the graduate level, as well as in postgraduate seminars in Panama, Mexico, Ecuador, Chile and Argentina. The results of this experience has been positive, showing that the tool is an effective aid to design, that can be applied during design development.

The preparation of this thesis has incorporated new insights and examples that can improve the possibilities of transfer and application. It also allows a better potential for incorporation in professional practice.

In the final analysis, the proof of the hypothesis presented in this thesis will depend on the successful implementation in design. This will show the value and utility of the comfort triangles tool.

BIBLIOGRAPHY[1]

REFERENCES

ABNT (1998) *Desempenho térmico de edificaçoes, Parte 1, 2, 3, 4 y 5 (Projeto)* Asociacoa Brasileira de Normas Técnicas, Comité Brasileiro de Construçao Civil, San Pablo.

ABNT (2003) *Desempenho térmico de edificaçoes, Parte 3 Zonamento Bioclimatico (Projeto)* Asociacoa Brasileira de Normas Técnicas, Comité Brasileiro de Construçao Civil, San Pablo.

Ackerman. J. S., (1966) *Paladio,* Series The Architect and Society, Penguin Books, Harmondsworth.

Acosta, W. (1965) *Sol y Arquitectura*, Nueva Visión, Buenos Aires.

Ahmed, K. S. (1995) *Approaches to bioclimatic urban design for the tropics with special empasis to Dhaka, Bangladesh,* Doctoral, Thesis Architectural Association, London.

AIA Research Corporation, (1976) *Solar dwelling design concepts,* U.S. Department of Housing and Urban Development, Washington D.C.

Al Azzawi S. H. (1969) *Oriental houses in Iraq,* pp 91-102, in Oliver, P. (1969) Shelter and Society, Frederick A. Praeger, New York.

Aldersley-Williams, H. (2003) *Zoomorphic: New animal architecture,* Lawrence King Publishing Limited, London.

Alexandre A. and De Michelis N. (1996*) Environment and Energy: Lessons from the North*, pp 249-256, in Alberti, M. and Susskind, L., Eds, (1996) Special issue, Environmental Impact Assessment Review, Vol 16, Nros. 4-6.

Allen, A. and You, N. (2002) *Sustainable Urbanisation: Bridging the Green and Brown Agendas,* UN-Habitat, The Development Planning Unit, University College, London.

Alphen, Ed., (1994) *Sustainable urban development: research and experiments*, TU Delft, Delft University Press, Delft.

Andersson, H. E. B. and Setterwall A. K. Eds., (1996) *The energy book, A resumé of present knowledge and research,* The Swedish Council for Building Research, Stockholm.

Anink, D., Boonstra, C. and Mak, J, (1996) *Handbook of Sustainable building, An environmental Preference Method for selection of materials in construction and refurbishment,* James & James, London.

Anonimo, (1996) *La Casa Curutchet*, Editorial Syntaxis, Revista 3 N°8, Noviembre 1996, Buenos Aires.

Anstey, J., (1988*) Rights of light and how to deal with them*, The Royal Institute of Chartered Surveyors, London.

Archibugi, F. (1997) *The ecological city and the city effect: essays on the urban planning requirements for the sustainable city*, Studies in Green Research, Ashgate Publishing Ltd. Aldershot.

Architectural Institue of Japan (AIJ) Eds., (2005) *Architecture for a sustainable future: all about the hollistic approach in Japan,* Institute for Building Environment and Energy Conservation (IBEC) Tokyo.

---

[1] Numerical simulation programs and internet references are listed separately at the end of this bibliography

Aroztegui, J. M., and Negrin, G. (1996) *Propiedades térmicas de materiales y componentes de construcción corrientes in Uruguay*, Servicio de Climatología Aplicada a la Arquitectura, Universidad de la República, Montevideo.

Arvil, R. (1967) *Man and environment, crisis and the strategy of choice*, Pelican Books, Penguin Books, Harmondsworth.

ASHRAE (2004) *ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy* (ANSI Approved) ASHRAE, Washington D. C.

Atkisson, A. (1996) *Developing Indicators of Sustainable Community: Lessons from Sustainable Seattle*, pp 337-350, in Alberti, M. and Susskind, L., Eds., Special issue, Environmental Impact Assessment Review, Vol. 16, Nros. 4-6.

Auliciems, A. and Szokolay, S. V., (1997) *Thermal confort, PLEA Notes 3,* University of Queensland Department of Architecture, Brisbane.

Ayres, J. M., Haiad, J. C. and Lau, H., (1988) *Energy Conservation and climate control in Museums,* The Getty Conservation Institute, California.

Bach, B. and Pressman, N. (1992) *Climate sensitive urban space, Concepts and tools to humanize cities*, Publicatieburo, Delft.

Baker, N. (2000) *We are all outdoor animals*, in Steemers, K. and Yannas, S., *Architecture City Environment*, Proceedings of PLEA 2000, James & James, London.

Baker, N. and Steemers, K. (1998) *The LT Method 2.0*, Cambridge Architectural Research, Cambridge.

Baker, N. and Steemers, K., (1999) *Energy and Environment in Architecture: A Technical Design Guide,* E & FN Spon, London.

Baker, N. et al (1996). *The urban porosity model: simplified parameters as indicators of environmental performances*, pp 300-305, in *Proceedings of the Fourth European Conference on Architecture*, H. S. Stephens and Associates, Berlin.

Baker, N. V. and Standeven, M.(1994) *Thermal comfort in free running buildings, pp 25-32, in Ezion et al (Eds) (1994)* (Eds) 1994) Architecture of the Extremes, Proceedings of PLEA 1994, Ben-Gurion University of the Negev, Sede-Boker.

Baker, N. V., (1987) *Passive and low energy building design for tropical island climates,* Commonwealth Science Council, London.

Baldwin, R. et al, (1998) *BREEAM 98 for offices*, Construction Research Communications Ltd, London.

Banham, R. (1969) *The architecture of the well tempered environment*, Architectural Press, London.

Bardou, P. and Azoumanian, V. (1981) *Sol y Arquitectura,* Editorial Gustavo Gili, Barcelona.

Barker, T., Ekins, P. and Johnstone N., Eds, (1995) *Global Warming and Energy Demand*, Routledge, London.

Barros Frota, A., (2004) *Geometría da Insolaçoa,* Geros Ltda, San Pablo.

Behling, S. and Behling, S. (2000) *Solar Power, the evolution of sustainable architecture*, Prestel, Munich.

Belding, H. S. and Hatch, T.F, (1995) *Index for Evaluating Heat Stress in Terms of Resulting Physiological Strains.* Heating, Piping, Air Cond., 1955, Nº 8, 129-136.

Bell, C and Bell, R., (1972),*City Fathers, the Early historry of Town Planning in Britain,* Penguin Books, Harmondsworth.

Bell, S. and Morse, S. (1999) *Sustainability indicators: measuring the immeasurable*, Earthscan, London.

Bentley, I., et al (1985) *Responsive urban environments: A manual for designers*, Architectural Press, London.

Bermudez Lopez, J., (1987) *La Alambra y el Generalife,* Editorial En Su Mano, Madrid.

Bin Salleh, E. (1994) *Tropical outdoor environment and human thermal comfort,* Doctoral Thesis, Architectural Association, London.

Bitan, A., (Editor) (1991). *Urban climate, planning and building*. IFHP-CIB-WMO-IGU Proceedings of the International Conference Urban Climate, Planning and Building, Elsevier Sequoia, Lausanne.

Bittencourt, L., (1993). *Ventilation as a cooling resource for warm humid climates.* Doctoral Thesis, Architectural Association, London.

Blackmore, R. and Reddish, A. (1991) *Global environmental issues,* The Open University, Hodder and Stoughton Educational, London.

Blake, P. (1963) *Frank Lloyd Wright, Architecture and Space,* Pelican Book, Penguin Books, Harmondsworth.

Blaser, W., (1997) *Patios: 5000 años de evolución desde la antigüedad hasta nuestros días,* Editorial Gustavo Gili, S. A., Barcelona.

Borgato, J. and Tedeschi, E. (1953) Asoleamiento en Arquitectura, Facultad de Arquitectura y Urbanismo, Universidad Nacional de Tucumán, Tucumán.

Borja, J. and Castels, M. (1997) *Global y Local, La gestión de las ciudades en la era de la información*. UNCHS, Taurus, Grupo Santillana de Ediciones S. A., Madrid.

Boucher, K. (1975) *Global Climate*, English Universities Press, London

Bouwcentrum Argentina (1973) *Orientación de viviendas y radiación solar en Argentina,* Bouwcentrum Argentina INTI, San Martín, Buenos Aires.

Bouwcentrum Argentina (1975) *Protección solar: parasoles, Resumen de orientación 9*, Bouwcentrum Argentina INTI, San Martín, Buenos Aires.

Bouwmeester, W, (1995) Factsheet: Temperature & humidity, Scottish Museum Council, Edinburgh. (http://www.scottishmuseums.org.uk/pdfs/Factsheet_temperature_and_humidity.pdf)

Boyd, A., (1963) *Chinese Architecture*, pp 81-108, in:Lloyd, S., et al (1963) *World Architecture, an ilustrated history*, Paul Hamlyn, London.

Brager, S. G. and de Dear, R. (2000) *A Standard for natural ventilation,* Ashrae Journal, October 2000.

Brailovsky, A. E., (2006) *Historia ecológica de Íbero América: de los Mayas al Quijote,* Ediciones Le Monde, Buenos Aires.

Brandon, P., Lombardi, P. and Bentivegna, V. (1997) *Evaluation of the built environment for sustainability*, E & FN Spon, London.

BRE (2000) *BREEAM Rating System*, Building Research Establishment, Garston.

BRE (2002) *Eco-homes,* Building Research Establishment, Garston.

Bro, A. (1999) *Lekeberg: Sustainable Structure Plan by Public Consultation*, Swedish Building Research 3/99, Estocolmo.

Brunskill, R. W. (1970) *Illustrated handbook of vernacular architecture*, Faber & Faber, London.

BS (2000) British Standard 5454, *Recommendations for the storage and exhibition of archival documents,* British Standards Institute, Teddington.

Buckingham-Hartfield, S. and Evans, B. (Eds.) (1996) *Environmental planning and sustainability,* John Wiley & Sons, New York.

Burberry, P. (1968) *A. J. Handbook: Building Environment*, Architectural Press, London.

Burberry, P. (1983) Ahorro de energía: Manuales A. J., Hermann Blume, Madrid.

Burgess, R., Carmona, M. and Kolstee, T. (1997) *Cities, the State and the market*, in Burgess, Carmona and Kolstee, (Eds.) (1997) *The challenge of sustainable cities: neoliberalism and urban strategies in developing countries,* Zed Books, London - New Jersey.

Burgess, R., Carmona, M. and Kolstee, T. (Eds.) (1997) *The Challenge of Sustainable Cities, Neoliberalism and urban strategies in developing countries*, Zed Books, London.

Burgess, R., Carmona, M. and Kolstree, T. (1998) *Neoliberalismo y estrategias urbanas,* FLACSO, San José, Costa Rica.

Burton, E., Williams, K. and Jenks, M. (1996) *The compact city and urban sustainability: conflicts and complexities,* in Jenks, M., Burton, E. and Williams, K., Eds (1996) *The Compact city: A sustainable urban form?* E & FN Spon, London.

Burton, S. (Ed.) (2001) *Energy efficient office refurbishment*, James & James, London.

Button, D and Pye, B. (Eds.) (1994) Glass in buildings Butterworth, Architecture. London

Calvert, J. B, (1999) *M. Vitruvius Pollio and the Analemma,* (downloaded 2006) http://www.du.edu/~etuttle/classics/analemma.htm

Camilioni, I. A. and Barros, V.R. (1991) *Analysis of thermal effects of urbanization*, pp 47-52, in Alvarez, S., Lopez de Asiain, J., Yannas, S. and Oliveira Fernandes, E., Eds., (1991) *Architecture and Urban Space, Proceedings PLEA-91,* Kluwer Academic Publishers, Dordrecht.

CAPBA, (2006) *Sede del Consejo Superior del Colegio de Arquitectos de la Provincia de Buenos Aires*, http://www.capba.org.ar/index.cfm/s.9.nro.38.htm

Capeluto, I, and Shaviv, E. (2000) *SustArc – a model for the design of urban fabric with solar rights considerations,* pp 655-659, in Maldonado, E. and Yannas, S., (Eds.) *Environmentally Friendly Cities, Proceedings of PLEA 1998*, James & James, London.

Carden, A. (1963) Japanese architecture, pp 109-127 in: Lloyd, S., et al (1963) *World Architecture, an ilustrated history*, Paul Hamlyn, London.

Carley, M. and Christie, I. (1992) *Managing Sustainable Development*, Earthcan Publications Ltd., London.

Casabianca, G., Evans, J. M. and de Schiller S. (1991) *Solar Rights and Planning Codes,* pages 61-66, in Alvarez, S., Lopez de Asiain, J., Yannas, S. and Oliveira Fernandes, E., Eds., (1991) *Architecture and Urban Space, Proceedings PLEA-91,* Kluwer Academic Publishers, Dordrecht.

Castell, R. (Ed.) (1988) *Diccionario de la lengua española,* Castell, Madrid.

CAVIPLAN, (2005) Manual del Vidrio Plano, Cámara del Vidrio Plano and sus Manufacturas de la Republica Argentina, Buenos Aires.

CEC (1990) *Green paper on the urban environment,* Commission of the European Community, Brussels.

Chan K. J. K. (1998) *Plot ratio and site coverage* (selected parts of an article) pages 186-187, in MVRDV, Maas, W. van Rijs, J. and Koek, R., Eds., (1998) *Farmax: Excursions on density*, 010 Publishers, Rotterdam.

Chandler, T. J. (1965) *The climate of London,* Hutchinson, London

CIB (2000) *Agenda 21 on sustainable construction*, CIB Report Publication 237, Rotterdam.

CIBSE, (1980) Manual CIBSE, Volume A, Building Services Engneers, London

Ciudad de Buenos Aires (1999) *Evaluación de Impacto Ambiental*, Ley 123, Boletín Oficial de la Ciudad de Buenos Aires N° 622, Buenos Aires.

Cofaigh, E. O. et al, (1996) *The climatic dwelling: an introducción to climate-responsive residential architecture,* James & James on behalf of the European Comission, London.

Cole, R. J. and Larsson, N. (1997) *A General Framework for Building Performance Assessment,* Green Building Challenge ’98, Natural Resources Canada, Ottawa.

Cole, R. J. and Larsson, N. (1998) *Green Building Challenge ’98, Assessment Manual*, Vancouver.

Cole, R. J. and Mitchel, L. (1999) *Customizing and Using GBTool: Two case study projects*, Building Research and Information, Vol. 27, Number 4/5, July-Oct 1999, Ottawa.

Collinder, P. (1970) *Swedish Astronomers 1477-1900* , Acta Universitatis Upsaliensis, Ser. C. 19, Uppsala.

CONAE (1999) *Anteproyecto de NOM-020-ENER, Eficiencia energética en edificaciones, norma para la envolvente de edificios residenciales hasta tres niveles,* CONAE, México.

CONHABIT, (1977) *Documento de Base sobre Regionalización Ambiental de la República Argentina, Reunión Nacional de Regionalización Ambiental.* Programa Nacional Conhabit - Buenos Aires.

Cook, J and Prowler, D. Eds. (1978) *Passive systems '78, a selection of the leading solar papers of the year,* Publications office American Section of the International Solar Energy Society, Inc., Delaware.

Coppock, J.T. (1974) *Environmental Quality: an Introduction*, in *Environmental Quality,(1974)* Scottish Academic Press, Edinburgh.

Coppock, J.T. and Wilson, C.B. Eds, (1974) *Environmental Quality*, Scottish Academic Press, Edinburgh.

Corbella, O., and Llanas. S. (2003) *Em busca de uma Arquitetua Sustenável para os tropicos: conforto ambiental,* Editorial Revan, Rio de Janiero.

Correa, C. (1985) *The new landscape*, The Books Society of India, Bombay.

Cowan, H. J. (Ed) (1980) *Solar energy applications in the design of buildings,* Applied Science Publishers Ltd, London.

Crespi, M. A. (1980) *Acondicionamiento ambiental en arquitectura y Urbanismo: acondicionamiento higrotermico de la calidad del aire y acústico,* Colegio Oficial de Arquitectos de Madrid, Madrid.

Croiset, M. (1976) *Humedad y temperatura en los edificios, condensaciones y confort en verano y invierno*, Eds Técnicos Asociados, Barcelona.

Cutropia, M. A., Figueroa, H. O., and Nonino, J. C. (sin fecha 1968 aprox.) *Diseño con Clima,* Facultad de Arquitectura y Urbanismo Universidad de Mendoza

de Jong, T. M. & van de Voordt, D. J. M. (2002) *Ways to study and research, urban, architectural and technical design,* DUP Science, Delft.

de Schiller et al, (2003) *Relevancia de proyectos demostrativos de bajo impacto y eficiencia energética,* pp 21-36, Edição Especial, Conforto e Energia, Ambiente Construido, Revista de ANTAC. ISSN 1415-8876.

de Schiller, S (2004) *Sustainable urban form: environment and climate responsive design,* Tesis doctoral, Oxford Brookes University, Oxford.

de Schiller, S and Evans J. M. (1978) *Nuevos asentamiento en los Países Bajos, 'Ciudades bajo en nivel del mar'*, Summarios 23, Ediciones Summa, Buenos Aires.

de Schiller, S and Evans J. M. *(2001) Environmental strategies in patrimonial buildings,* Open House, 2001.

de Schiller, S. (1998) *Managing the urban microclimate: the link between climatic environment and architectural design*, in Proceedings of Second International Conference on Human-Environment System, Yokohama National University, Japón.

de Schiller, S. (2000) *Sustainable cities: contribution of urban morphology*, in Steemers, K. and Yannas, S. Eds, Proceedings of PLEA 2000, Architecture-City-Environment, Cambridge, James & James Ltd, London.

de Schiller, S. (2000) *Towards sustainable architecture: the relevance of design in evaluation methods*, Sustainable Building 2000, Maastricht, Países Bajos.

de Schiller, S. (2001) *Forma edilicia y tejido urbano sustentable,* Serie Difusión 15, pags. 61-74, Capitulo 4, SICyT, Facultad de Arquitectura, Diseño y Urbanismo, Universidad de Buenos Aires, Editorial La Colmena, Buenos Aires.

de Schiller, S. (2002*) Morphological transformation and environmental impact: planning legislation and sustainable urban form in Buenos Aires*, in Carmona, M. and Schoonraad, M Eds, (2002) *Globalization, Urban Form and Governance,* Fifth International Conference, Alfa-Ibis Proceedings, TU Delft, Delft University Press, Delft.

de Schiller, S. (2002a) *Argentina, social and living conditions become the starting point.* Sustainable Building, pp32-35, 2-2002,

de Schiller, S. (2002b) *A renewed focus on the design process,* Sustainable Building, pp 5, 4-2002.

de Schiller, S. (2004) *Sustentabilidad en vivienda social. Desarrollo y aplicación de un método de evaluación* Actas, NUTAU, Universidade do Sao Paulo, Sao Paulo

de Schiller, S. and Evans, J. M. (1979) *Nuevos Asentamientos en Gran Bretaña, 'New Towns en el tiempo*' Summarios 37, Ediciones Summa, Buenos Aires.

de Schiller, S. and Evans, J. M. (1991) *Design of outdoor spaces: Socio-political tendencies and bioclimatic consequences,* pp. 99-108 in Alvarez, S., Lopez de Asiain, J., Yannas, S. and Oliveira Fernandes, E., Eds., (1991) *Architecture and Urban Space,* Kluwer Academic Publishers, Dordrecht.

de Schiller, S. and Evans, J. M. (1992). *Integración de Arquitectura y Energía Solar: proyecto demostrativo,* Actas 7 SENESE, Seminario Nacional de Energía Solar y Eólica, Universidad de Playa Ancha, Valparaíso, Chile.

de Schiller, S. and Evans, J. M. (1995) *Teaching energy efficient and bioclimate architecture: reflections of the experience in Buenos Aires University, in* Sala, M. Ed. (1995) Proceedings of the Florence International Conference for Teachers of Architecture, Alinea, Florencia.

de Schiller, S. and Evans, J. M. (1998a) *Sustainable development: Design Guidelines for Warm Humid Cities,* Urban Design International, 3(4) 165-184.

de Schiller, S. and Evans, J. M. (1998b) *Rediscovering outdoor living space: design from the outside in,* in Maldonado, E. and Yannas, S. Eds., (1998) *Environmentally Friendly Cities, Proceedings of PLEA 1998,* James & James, London.

de Schiller, S. and Evans, J. M. (2000) *Urban climate and compact cities in developing countries*, pp 117-124 in Jenks, M. and Burgess, R. (2000) Eds., *Compact cities. Sustainable Urban forms for Developing Countries,* Spon Press, London.

de Schiller, S. and Evans, J. M. (2002) *Evaluación del impacto ambiental de proyectos urbanos. El caso del Boulevard ExAU3, Buenos Aires,* Avances en Energías Renovables y Medio Ambiente, Vol, 6. N° 1.

de Schiller, S., Evans, J. M. and Katzschner, L. (2001) *Isla de calor, microclima urbano y variables de diseño: estudios en Buenos Aires y Río Gallegos, pp 1.45-1.50,* Avances en Energías Renovables y Medio Ambiente, Vol. 5, 2001.

de Wit, M. H. (Ed) (2004) *Proceedings, Built environments and environmental buildings, 21st International Conference PLEA*, Technical University Einhoven, Endhoven.

Diez, F. E. (1996) *Buenos Aires y algunas constantes en las transformaciones urbanas,* Editorial de Belgrano, Buenos Aires.

du Plessis, C. (1998) *The meaning and definition of sustainable development in the built environment*, Tesis de Maestría, University of Pretoria.

du Plessis, C. Ed. (2002) *Agenda 21 for sustainable construction in developing countries.* CIB-UNEP, supplement distributed with 'Sustainable Building', 2002-3.

Du Pont, P., and Morrill, J. (1989) *Residential indoor air quality and energy efficiency,* American Council for an Energy Efficient Economy. Washington D. C.

Dudley Stamp, L. (1964) *The Geography of Life and Death,* Collins Fontana Library, London.

Dunham, D. (1978) *The courtyard house as a temperature regulator*, The New Scientist, Vol 8, 663-666.

Dunster, B. (2006) *Mass uprising,* Viewpoint, RIBA Journal, July, 2006, Brick Bulletin, pp 06.

Echechurri, H. A. (1997) *Evaluación de impacto ambiental*, Centro de Estudios Ambientales, Facultad de Arquitectura, Urbanismo y Diseño, Universidad Nacional de Mar del Plata, Mar del Plata.

Echenique, M. (1972) *Models: a discussion*, pages 164-174, in Martin, L and March, L. Eds., Urban Space and Structures, Cambridge Urban and Architectural Studies, Cambridge University Press, London.

Edén M. and Jönsson, Å. Eds, (2002) A. *MISTRA, Sustainable building, Experiences from a cross disciplinary research programme,* Chalmers University of Technology, Gothenburgo.

Edholm, O. G. (1967) *The biology of Work,* World University Library, Weidenfeld and Nicholson, London.

Ellis, P (1989) *Rights to light,* Estates Gazette Ltd, London.

Elsom, D. (1995) *Air and Climate*, Chapter 8, in Morris, P. and Therivel, R., Eds, (1995) *Methods of environmental impact assessment*, The natural and built environment series 2, UCL Press, London.

ENEA (1983) *Bioclimatic Architecture,* De Luca Editore, Roma.

Etzion, Y, Erell, E, Meir, I. and Pearlmutter, D, (Eds) 1994) *Architecture of the Extremes, Proceedings of PLEA 1994*, Ben-Gurion University of the Negev, Sede-Boker.

Evans y de Schiller, 2004, *La isla de calor en Ciudades con clima cálido-humedo: el caso de Tampico, Mexico,* Avances en Energías Renovables y Medio Ambiente, Vol 6.

Evans, J. M. (1980) *Housing, Climate and Comfort,* Architectural Press, London.

Evans, J. M. (1981) *La problemática de la zonificación ambiental,* Actas de ASADES, Catamarca.

Evans, J. M. (1983) *Education for responsive climatic design*, Habitat International, Vol. 7, N° 5/6, pp 347-355.

Evans, J. M. (2000). *The Environmental Laboratory: Experiences and Applications in Teaching Architecture,* in Proceedings TIA, Oxford Brookes University, Oxford.

Evans, J. M. (2001) *Bioclimatic Traditions in South America: Lessons form the past and pointers for the future*, in F. Pereira et al Eds., Proceedings of the PLEA 2001 Conference, Florianopolis, Brasil.

Evans, J. M. (2001) *Las Tablas de Mahoney y los Triángulos de Confort*, Actas, COTEDI, Maracaibo.

Evans, J. M. (2003) *Evaluation comfort with varying temperatures: a graphic design tool*, Energy & Buildings, vol. 35, pp 87-93.

Evans, J. M. (2003) *Herencia y Vigencia de la arquitectura bioclimatic en América del Sur,* in Rodríguez Viqueira, M., Ed (2003) *Estudios de Arquitectura bioclimática, Anuario 2003,* Vol V, Limusa Noriega Editores, México.

Evans, J. M. (2004a) *Construcción en tierra, aporte a la habitabilidad,* 1 Seminario Taller, Construcción en Tierra, FADU UBA, Buenos Aires.

Evans, J. M. (2004b) *Clean Development Mechanism for building: potential in different climatic regions of Argentina,* pp 909-914 in Wit, M. H. (Ed) (2004) Proceedings, Built environments and environmental buildings, 21st International Conference PLEA, Technical University Einhoven, Endhoven.

Evans, J. M. (2004c) *Zonificación bioambiental y arquitectura sustentable: ampliación de conceptos y nuevas respuestas, Anuario Bioclimático,* UNAM, México.

Evans, J. M. (2006) *Simulación de temperaturas internas en el proceso proyectual: e-temp.xls, un nuevo enfoque para evaluar comportamiento térmico,* Avances en Energías Renovables y medio Ambiente, Vol 10, INENCO, Salta.

Evans, J. M. and de Schiller, S. (1991) *Bridging the gap between climate and design at the urban and building scale: research and application*, in Bitan, A., Ed., *Urban climate, planning and building.* IFHP-CIB-WMO-IGU Proceedings of the International Conference on Urban climate, Planning and Building, Elsevier Sequoia, Lausanne.

Evans, J. M. and de Schiller, S. (1994) *Diseño Bioambiental y Arquitectura Solar*, EUDEBA Ediciones Previas, Buenos Aires, 1ra. edición.

Evans, J. M. and de Schiller, S. (1994) *Sustainable urban development for Haikou: design guidelines for a warm humid coastal city*, pp. 165-184, in Wiesman, B., Xiaowei, L. and Xiang, L., Eds. (1994) *Urban design: Tropical Coastal Cities,* China Architecture and Building Press, Haikou.

Evans, J. M. and de Schiller, S. (1996) *Diseño Bioambiental y Arquitectura Solar*, (2da. edición) SEUBE-FADU-UBA, EUDEBA, Buenos Aires.

Evans, J. M. and de Schiller, S. (1997). *Two Competition Projects in Different Climates: Applying Bioclimatic Design Methods*, in Proceedings, Florence International Conference for Teachers of Architecture, Universita Degli Estudi di Firenze, Florence.

Evans, J. M. and de Schiller, S. (1998) *The friendly city, the sun and Le Corbusier: Form, function and bioclimatic response*, in Maldonado, E. and Yannas, S., *Environmentally and Friendly Cities*, Proceedings of PLEA 98, James & James, London.

Evans, J. M., de Schiller, S., Casabianca, G., Fernández, A. and Murillo, F. (2001) *Ambiente y Ciudad,* Serie Difusión 15, SICyT, Facultad de Arquitectura, Diseño y Urbanismo, Universidad de Buenos Aires, Editorial La Colmena, Buenos Aires.

Fahey, M., (2005) The care and preservation of oil paintings, The Henry Ford Museum, Greenfield Village. (http://www.hfmgv.org/explore/artifacts/paint.asp#1b)

Fanger, P. O., (1973) *Thermal Comfort: analysis y aplications in environmental engineering,* McGraw Hill Book Company, New York

Fathy, H. (1969) *Architecture for the poor: an experiment in Rural Egypt,* The University of Chicago Press, Chicargo.

Fathy, H. (1972) *The arab house,* Longmans, London.

Foley, G. and Nassim, C. (1981) *The energy question*, Penguin Books, Harmonsworth.

Fossdal S, and Huovila, P. (2001) *Update: development of sustainable building indicators*, Sustainable Building pp 33-36, 4-2001.

Fuentes Freixanet, V. A., (2004) *Clima y Arquitectura,* Universidad Autónomo de México, Azcapolzalco, México D. F.

Fundación Antorchas (1997) *Imagenes de Buenos Aires, 1915 – 1940, Fotografias de la Dirección Municipal de Paseos and de Otras Colecciones*, Ediciones Fundación Antorchas, Buenos Aires.

GCBA (1999) *Ley 123, Determinase el procedimiento técnico administrativo de evaluación de impacto ambiental (EIA) conforme a los términos del articulo 30 de la constitución de la Ciudad de Buenos Aires,* Boletín Oficial de la Ciudad de Buenos Aires, Buenos Aires.

GCBA (1999) *Ley 71, Establece que el organismo encargado de la formulación y actualización del plan urbano ambiental será el consejo del plan urbano ambiental,* Boletín Oficial de la Ciudad de Buenos Aires, Buenos Aires.

GCBA (1999) *Plan Urbano Ambiental*, Gobierno de la Ciudad de Buenos Aires, Buenos Aires.

Geddie, W. (1968) *Chambers twentieth century dictionary*, W. R. Chambers, London.

Gibbs, S. (1976) *Greek and Roman Sundials*, Yale University Press, Yale

Gieger, R. (1965) *Climate near the ground,* Harvard University Press, Cambridge, Massachusetts.

Givoni B. (1969) *Man, Climate and Architecture*, Elsevier, London (1st edition).

Givoni B. (1976) *Man, Climate and Architecture*, Elsevier, London (2nd edition).

Givoni, B. (1992) *Comfort, climate analysis and building design guidelines,* Energy and Buildings, V 18, July 1992, pp 11-23.

Givoni, B. (1994a) Effectiveness of mass and night ventilation in lowering the indoor daytime temperatures, pp 151-156, in Yair et al, (Eds) 1994) Architecture of the Extremes, Proceedings of PLEA 1994, Ben-Gurion University of the Negev, Sede-Boker.

Givoni, B. (1994b) *Passive and low energy cooling of buildings,* John Wiley & Sons, INC. New York .

Glasson, J., Therivel, R. and Chadwick A., 1994. *Introduction to environmental impact assessment*, The natural and built environment series, UCL Press Ltd, London.

Glaumann, M. and Westerberg, U. (1999) *Environmental assessment of buildings: the problem of comparing apples and pears*, in Szokolay, S., Ed. (1999) *Sustaining the future: energy – ecology - architecture*, Proceedings of Passive and Low Energy Architecture, PLEA '99, Brisbane University, Brisbane.

Gloyne, J.T. (1974) *Urban Climates and Micro-Climates*, in *Environmental Quality*, (1974) Scottish Academic Press, Edinburgo.

Golany, G. (1980) *Housing in arid lands: design and planning,* Architctural Press, London.

Gómez Azpietia and Elizondo Mata, M., (2003) *El desarrollo sustentable y la dimensión ambiental como detonantes de mercados alternativos para los arquitectos.* In Rodríguez Viqueira, M., Ed (2003) *Estudios de Arquitectura bioclimática, Anuario 2003*, vol V, Limusa Noriega Editores, México.

Gonzalez, G. (1998) *Diseño bioclimatico*, Nabuco, Buenos Aires.

Goodburn, R. (1972) *The roman villa, Chedworth,* The National Trust, Curwin Press, London. ,

Goodwin, G., (1990) *Islamic Spain,* Viking, London.

Goulding, J. R., Lewis, J. O. and Steemers, T. C (1993) *Energy conscious design, a primer for architects*, Batsford, for the Commission of European Communities, London.

Green Building Challenge (2000) *GBC2k Building Performance Rating System: Version 0.9g.2000 1:31*, Natural Resources Canada, Ottawa.

Gropius, W (1931) *Rationelle Bebaungsweisen,* Julius Hoffmena Verlag, Stuttgart. Referred to in March, l. (1972) *Elementary models of built forms.* Also in Gropius, W. (1956) *Scope of Total Architecture*, Allen and Unwin, London.

Gropius, W (1935) *The new architecture and the Bauhaus* Faber and Faber, London.

Grundstrom, K., Johnasson, E. and Rosenlund, H., (1999) *A more agreeable climate in Moroccan housing areas,* pp 10-12, Swedish Building Research, Swedish Council for Building Research 4/99, Stockholm.

Guadagni, A., (1985) *Energía para el crecimiento,* Ediciones El Cronista Comercial, Buenos Aires.

Hagan, S. (2001) *Picture this: conceptual models and sustainable cities*, pp 7-14, in Hewitt, M. and Hagan, S. (2001) *City fights; debates on urban sustainability*, James & James, London.

Hall, K. (2005) The green building bible (2nd Edition) The Green Building Press, London

Hancock, T. (1996) *Health and Sustainability in the Urban Environment*, pp 259-277 in Alberti, M. and Susskind, L. Eds, Special issue, Environmental Impact Assessment Review, Vol 16, Nros. 4-6.

Haughton, G. and Hunter, C., (1996) *Sustainable cities; regional policy and development*, University of Cambridge Press.

Hawkes, D. et al, (Eds) (1987) *Energy and Urban Built Form*, Butterworths, London.

Hawkes, J. (1973) *A guide to the prehistoric and roman monuments in England and Wales*, Sphere Books, London.

Haynes, E.E. L. (1965) *An Archeeological and histroical guide to the pre-islamic antiquitoes of Tripolotania,* The Antiquities, Museums and Archives of Tripoli, Libya.

Hayward, R. and McGlynn, S. (Eds.) (1993) *Making better places, Urban design now*, Joint Centre for Urban Design, Butterworth Architecture, London.

Heap, D. (1973) *An outline to planning law*, Sixth Edition, Sweet and Maxwell, London.

Heinen, J. T. (1994) *Emerging, diverging and converging paradigms on sustainable development,* International Journal of Sustainable Development and World Ecology, Vol.1, pp 22-33.

Hendricks, Ch. F. Nijkerk, A. A. and van Koppen, A.E. (2000) *The building cycle,* Æneas Technical Publishers, Best.

Hermes, J. C., (1995) *Hatching small numbers of eggs,* Pacific Northwestern Extension Publication, Oregon.

Heschong, L., (1996) *Thermal delight in architecture,* The MIT Press, Cambridge, Massachussetts.

Hewitt, M. (2001). *Emerging city shapes: energy at the urban scale*, pp 100-108, in Hewitt, M. and Hagan, S. (2001) *City fights; debates on urban sustainability*, James & James, London.

Hewitt, M. and Hagan, S. (2001) *City fights, debates on urban sustainability*, James & James, London.

Hewitt, M. et al (2000). *Using design imagination to develop sustainable urban strategies*, pp 702-707, in Proceedings of PLEA 2000 Conference, James & James, Cambridge.

Hillier, B. et al (1993) Natural movement: or, configuration and attraction in urban pedestrian movement, in Environment and Planning, section B: Planning and Design, Vol. 20, pp 29-66.

HMSO (1958) *Tables of temperature, relative humidity and precipitation for the world,* (6 Volumes) HMSO, London.

Hodgson, P., 1997. *Energy & environment*, Bowerdean Publishing Company Ltd, London.

Hoffman, M, Mosseri, A, De-Urrutia, O and Wertheim, I. (1994) The courtyard a a climate design element, a quantitative approach, pp 392-389, in Etzion et al, (1994) *Architecture of the Extremes, Proceedings of PLEA 1994,* Ben-Gurion University of the Negev, Sede-Boker.

Hoinville, G. (1974) *Evaluating Community Preferences*, in *Environmental Quality*, (1974) Scottish Academic Press, Edinburgh.

Holan, J., (1990) *Norwegian wood: a tradition of building,* Rizzoli, New York.

Holdgate, M., 1996 and 1997. *From care to action, making a sustainable world*. Earthscan Publication Ltd, London.

Houghton, F. C and Yaglou, C. P. (1923) Determination of the Comfort Zone, American Society of Heating and Ventilation Engineers, Transactions, Vol. 29, p 361, Also in ASHVE Research Report 673, cited by Olgyay (1963).

Houghton, J. (1997) *Global Warming, the complete briefing*, Cambridge University Press, Cambridge.

Howard, E. (1965) *Garden cities of tomorrow,* Faber & Faber, London. First published as *Tomorrow, a Peaceful Path to real reform* in 1898.

Humphreys, M. A. (1981) *The dependence of comfortable temperatures upon indoor and outdoor climates.* Chapter 7 in Cena, K and Clark, S. A. Eds. (1981) *Bioengineering, Thermal Physiology and Comfort,* Elsevier, Amsterdam.

Huntingdon, Ellsworth (1945) *Mainsprings of Civilization: Heredity, Geography and Climate*, Mentor Books, New York.

IAE, (1999) Anuario 1999, *Sector Energético, Sector Hidrocarburos, Sector Energía Electrica, Republica Argentina*, (CD) Instituto Argentino de la Energía 'Gral Mosconi', Buenos Aires.

IIV, (1969) *Tipos predominantes de vivienda rural en la República Argentina*, Instituto de Investigaciones de la Vivienda, Facultad de Arquitectura y Urbanismo, Universidad de Buenos Aires, Buenos Aires.

IIV, (1972a) *Tipolog1a según materiales de acuerdo al censo nacional 1960. Tipos predominantes de vivienda natural en la República Argentina,* Instituto de Investigaciones de la Vivienda. Facultad de Arquitectura y Urbanismo - Universidad de Buenos Aires - Editorial Universitaria de Buenos Aires 1972.

IIV, (1972b) *Tipos predominantes de vivienda natural en la República Argentina*, Instituto de Investigaciones de la Vivienda, Facultad de Arquitectura y Urbanismo, Universidad de Buenos Aires, Buenos Aires.

INEN, (1978) *Asoleamiento y aplicaciones para el diseño climatológico de la vivienda en Ecuador,* (Nienhuys, S, Autor) Instituto Ecuatoriano de Normalización, Quito

Instituto de Investigaciones de la Vivienda (sin fecha) Tipos Predominantes de vivienda natural en la Republica Argentina, VR.2, IIV.4, IIV, Facultad de Arquitectura y Urbanismo, UBA, Buenos Aires.

INTI, (1976) Regiones climáticas en la República Argentina, Resumen de Orientación 10, Bouwcentrum Argentina INTI, San Martin, Buenos Aires.

IPCC (1990) *Climate change, Intergovernmental Panel on Climate Change*, Naciones Unidas. New York.

IPCC (2000) *Climate change, Intergovernmental Panel on Climate Change*, Naciones Unidas. New York.

IPCC (2001a) *Climate change: the scientific basis,* Cambridge University Press, Cambridge. (Also available from http://www.grida.no/climate/ipcc_tar/wg1/pdf/WG1_TAR-FRONT.PDF)

IPCC (2001b) Climate change 2001: Mitigation, United Nations Environmental Program, New York, (also available from http://www.grida.no/climate/ipcc_tar/wg3/index.htm)

IPCC (2001c) Third assesment report, Climate change 2001, Cambridge University Press, Cambridge.

IPCC (2006) *Working Group II, Climate change Impacts, Adaptation and vulnerabilitiey, Fourth Assessment Report,* UNEP, United Nations, New York.

IRAM, (1970) *Norma IRAM 11.605 Acondicionamiento térmico de edificios: transmitancia térmica de paredes y techos,* Instituto Argentino de Normalización, Buenos Aires.

IRAM, (1970) *Norma IRAM 11549, Acondicionamiento térmico de edificios: definiciones,* Instituto Argentino de Normalización, Buenos Aires.

IRAM, (1971) *IRAM Norma 11559 Método de ensayo: conductividad de los materiales de construcción mediante el aparato de placa caliente,* Instituto Argentino de Normalización, Buenos Aires.

IRAM, (1972) *IRAM Norma 11564 Método de ensayo: transmitancia térmica de elementos de construcción mediante el aparato de la caja caliente,* Instituto Argentino de Normalización, Buenos Aires.

IRAM, (1978a) *Norma IRAM 11605, Acondicionamiento térmico de edificios, condiciones de habitabilidad para verano,* Instituto Argentino de Normalización, Buenos Aires.

IRAM, (1978b, 1981 and 1996a) *Norma IRAM 11.603, Acondicionamiento térmico de edificios: Clasificación Bioambiental de la Republica Argentina*, Instituto Argentino de Normalización, Buenos Aires.

IRAM, (1980 and 1996b) *Norma IRAM 11.605, Acondicionamiento térmico de edificios: condiciones de habitabilidad en viviendas, valores máximos de transmitancia térmica en cerramientos opacos,* Instituto Argentino de Normalización, Buenos Aires.

IRAM, (1998) *Norma IRAM 11.603, Zonificación Bioambiental de la República Argentina*, Instituto Argentino de Racionalización de Materiales, Buenos Aires.

Irwin, R., (2004) *The Alhambra,* Profile Books, London

ISO (1994) *Standard ISO EN 7730 Moderate thermal environments, determination of PMV and PPD indices and specifications of the conditions for thermal comfort,* International Standards Organization, Geneva.

Izard, J-L and Guyot, A., (1980) *Arquitectura bioclimática,* Editorial Gustavo Gili, Barcelona.

Jacobs, J. (1964) *The Death and Life of Great American Cities: the Failure of Town Planning.* Penguin Books, Harmondsworth, Middlesex.

Jauregui, E. (1986) *Tropical urban climates: review and assessment*, in Oke, T.R. (ed) *Urban climatology and its applications with special regard to tropical areas*, Publ. N. 652, World Meteorological Organization, Geneva.

Jauregui, E. (1999) *Bibliography on Urban Climatology. Period 1996-1998,* Centre Atmospheric Sciences, National University, Mexico D. F.

Jenks, M. and Burgess, R. (2000) Eds., *Compact cities. Sustainable Urban forms for Developing Countries,* Spon Press, London.

Jenks, M., Burton, E. and Williams, K, (1996) Compact cities ans sustainability, An Introduction, in Jenks, M., Burton, E. and Williams, K, Eds (1996) *The Compact city: A sustainable urban form?* E & FN Spon, London.

Jenks, M., Burton, E. and Williams, K, (1996) *The Compact city: A sustainable urban form?* E & FN Spon, London.

Jenks, M., Burton, E. and Williams, K, (1999) *Achieving sustainable urban form,* Routledge, London.

Johnasson, E., (2007) *Urban Design and outdoor thermal comfort in warm climates, Studies in Fez and Colombo,* Thesis 3, Housing development and Management, Lund University, Lund.

Katzschner, L, 2000, *Urban climate maps – a tool for calculations of thermal conditions in outdoor spaces*, in Koen Steemers and S. Yannas Eds (2000) *Architecture City Environment*, Proceedings of PLEA 2000, James & James, London.

Kaya, Y. and Yokobori, K., Eds., (1997). *Environment, energy & economy*, The United Nations University Press, UNUP-11, Tokyo.

Kendrew, W. G.(1961) *The climates of the continents*, Oxford University Press, London.

King, S., (1992) *Building for conservation, appropriate design for environmental control in the tropics,* Proceedings of the regional symposium on the preservation of cultural property in tropical environments, 1991, The Getty Conservation Institute, Marina del Rey, Los Angeles

King, S., (1993) Design for conservation, Appropriate design and alternative technologies, Proceedings, Expert Workshop, 1992, The Getty Conservation Institute, Marina del Rey, Los Angeles.

Kisilewicz, T., (2005) *The significance of thermal energy storage for efficient energy use, pp 289-294,* de Wit, M. H. Ed (2005) *Built environments and environmental buildings, Proceedings 21st International Passive and Low Energy Architecture Conference,* Vol 1, Technische Universiteit Eindhoven, Eindhoven.

Knowles, R. L. (1974) *Energy and Form, an Ecological Approach to Urban Growth*, The MIT Press, Cambridge, Massachussetts.

Knowles, R. L. (1981) *Sun Rhythm Form,* The MIT Press, Cambridge, Massachussetts.

Knowles, R. L. (2000) *The solar envelope: Its meaning for urban growth and form, pp 649-654, in* Steemers, K and Yannas S. Eds (2000) *Architecture, City, Environment,* Proceedings of PLEA 1998, James & James, London.

Koenigberger et al., (1977) *Viviendas y edificios en zonas cálidas y tropicales*, Editorial Paraninfo, Barcelona

Koenigsberger, O. H, Mahoney, K and Evans, J. M. (1970) *Climate and house design,* United Nations, New York

Koenigsberger, O. H, Mahoney, K and Evans, J. M. (1973a) *Clima y el diseño de casas,* United Nations, New York (Spanish translation of Koenigsberger et al, 1970)

Koenigsberger, O. H, Mahoney, K and Evans, J. M. (1973b), *Climat y Habitat,* United Nations, New York, (French translation of Koenigsberger et al, 1970).

Koenigsberger, O. H. and Lynn R., (1965) *Roofs in the warm humid tropics,* Lund Humphreys, London.

Koenigsberger, O. H. Ingersoll, T. G. Mayhew A. and Szokolay S. V. (1974) *Manual of Tropical Housing and Building, Part 1. Climatic Design,* Longmans, London.

Konya, A. (1985) *Handbook of Tropical Architecture*, Architectural Press, London.

Kullock, D. Editor (1993) *Planificación participativa y hábitat popular*, Cuaderno de Posgrado 2, Facultad de Arquitectura, Diseño y Urbanismo, Universidad de Buenos Aires, Buenos Aires.

Labeur, A. (1999) *Estudios de Morfologia urbana y su relación con aspectos ambientales* unpublished study CIHE, FADU-UBA.

Labeur, A. and Tessandori, F. (1999) *Estudio de los efectos de clima en grupos de torres,* unpublished study, CIHE, FADU-UBA

Lacy, R. E. (1977) *Climate and building in Britain*, Department of the Environment, Her Majesties Stationary Office, London.

Lam, J. O. (1986) *Energy in Physical Planning; a method for developing the municipal master plan with regard to energy criteria,* Swedish Council for Building research, Document D14:1986, Stockholm.

Lamb, L. H., (1982) *Climate, History and the Modern World,* Methuen, London.

Lazarus, M et al (1993) *Towards a fossil free energy future, the next transition, a technical análisis for Greenpeace International,* Stockholm Environmental Institute, Boston Centre, Greenpeace International, Amsterdam.Lee, N, and Colley, R. (1990) *Reviewing the Quality of Environmental Statements*, Occasional Paper N° 24, EIA Centre, Department of Planning and Landscape, University of Manchester, Manchester.

Le Corbusier, (1947) *Plan Director para Buenos Aires*, La Arquitectura de Hoy, Año 1, No 4., Buenos Aires.

Le Corbusier, translated by Etchells, F. (1965) *Towards a new architecture,* Architectural Press, London. (The original version in French (1923) was entitled '*Vers un Architecture' [Towards an architecture].)*

Lele, S. M. (1991) *Sustainable development: a critical view*, World Development, vol. 19, pp 607-621.

Leveratto, M. J., de Schiller, S. and Evans, J. M. (2000) *Buenos Aires urban heat island intensity and environmental impact,* in Steemers, K. and Yannas, S. Eds, *Architecture-City-Environment*, Proceedings of PLEA 2000, Cambridge, James & James Ltd, London.

Leveratto, M. J., Gonzalez Matterson, M, L. and de Schiller, S. (2000) *Assessing methodologies for environmental performance of office buildings in Buenos Aires*, in Sustainable Building 2000, Maastricht.

Ley 1827 (1985) *Ley de Uso de Suelo*, Provincia de Buenos Aires, La Plata.

Lloyd Jones, D., (2002) *Arquitectura y entorno, el diseño de la construcción bioclimatica,* Blume Art, Barcelona

Lloyd Jones. D., (1998) *Architecture and the Environment*, Lawrence King Publishing, London.

Lloyd, S., (1963) *Ancient and Classical Architecture*, pp 15-80 in:Lloyd, S., et al (1963) *World Architecture, an ilustrated history*, Paul Hamlyn, London.

Longmore, J. (1968) *BRS Daylight Protactors,* Her Majesties Stationary Office, London.

Loterstain I., (1970) *Condensación de humedad en viviendas,* Instituto Nacional de Tecnología Nacional, San Martín, Buenos Aires.

Lovelock,, J. (2007) *La venganza de la Tierra, la teoría de Gaia y el futuro de la humanidad,* Planeta, Buenos Aires

Lynch, K. (1960) *The image of the city,* The MIT Press, Cambridge, Massachusetts.

Maas, W. and van Rijs, J, with Richard Koek, (MVRD) (1998) Eds., *FARMAX, Excursions on density*, 010 Publishers, Rotterdam.

Macfarlane, A., and Martin , G., (2003) *The glass bathyscaphe,* Profile Books, London.

Mangosio, J. E., (1980) *Fundamentos de higene y seguridad en el trabajo,* Editorial Nueva Libreria, Buenos Aires.

March, L (1967) *Homes beyond the fringe,* Architects Journal 146, pp 156-158.

March, L. (1972) *Elementary Models of built forms,* pp 55-96 in Leslie Martin and Lionel March Eds, *Urban Space and Structures,* Cambridge Urban and Architectural Studies, Cambridge University Press, London.

Markus, T. A. and Morris, E. N., (1980) Buildings, climate and energy, Pitman, London.

Marsh, A. (2007) *The PMV Tool,* http://squ1.com/downloads

Martin, L, et al (1972b) *Speculations,* pp 28-54, in Martin, L and March, L. Eds, (1972) *Urban Space and Structures,* Cambridge Urban and Architectural Studies, Cambridge University Press, London.

Martin, L. and March, L., Eds., (1972) *Urban Space and Structures,* Cambridge Urban and Architectural Studies, Cambridge University Press, London.

Martin, L., (1972a) *The grid as a generator,* pp 6-27, in Martin, L and March, L. Eds, (1972) *Urban Space and Structures,* Cambridge Urban and Architectural Studies, Cambridge University Press, London.

Martinotti, G., (1997) *Perceiving, Conceiving, Achieving, The sustainable city, A Synthesis Report.* European Foundation for the Improvement of Living and Working Conditions, The European Communities, Luxemburg.

Matthews, E. H. and Richards, P. G., (1993) *An efficient design tool for future building design,* Building and Environment, 28:409-417.

Mazria, E. (1979) *The passive solar energy book,* Rodale Press, Emmaus PA.

Mazria, E., (1983) *El libro de la energía solar pasiva,* Tecnología y Arquitectura, Ediciones G. Gili S. A. Barcelona.

Mazzeo, N. and Camillioni, I. (1991) Buenos Aires urban meteorological data analysis of a 5 day period, in Bitan, A., (Ed.) *Urban climate, planning and building.* IFHP-CIB-WMO-IGU Proceedings of the International Conference Urban Climate, Planning and Building, Elsevier Sequoia, Lausanne.

MCBA (1925) *Código de la Comisión de Estética Edilicia,* Municipalidad de la Ciudad de Buenos Aires, Buenos Aires.

MCBA (1925) *Proyecto Orgánico para la Urbanización del Municipio*. El Plan Regulador y de Reforma de Capital Federal, Municipalidad de la Ciudad de Buenos Aires, Buenos Aires.

MCBA (1928) *Ordenanza 2736/28, Remate de fachadas, Cuerpos salientes y Retiradas*, Municipalidad de la Ciudad de Buenos Aires, Buenos Aires.

MCBA (1938) *Recopilación de ordenanzas, decretos reglamentos y otras disposiciones referentes a Obras publicas y seguridad*, pp 308, in Terrot, A. E. (1938) Anuario de Arquitectura y Técnica, Editorial Arte y Técnica, Buenos Aires

MCBA (1968a) *Informe Preliminar Etapa 1956-60,* Municipalidad de la Ciudad de Buenos Aires, Buenos Aires.

MCBA (1968b) *Descripción Sintética del Plan Regulador*, Municipalidad de la Ciudad de Buenos Aires, Buenos Aires.

MCBA (1972) *Plan de Renovación de la Zona Sur de la Ciudad de Buenos Aires.* Municipalidad de la Ciudad de Buenos Aires, Buenos Aires.

GCBA (1999) *Plan Urbano Ambiental*, Gobierno de la Ciudad de Buenos Aires, Buenos Aires.

McCaig, E. and Henderson, C. (1995) *Sustainable development: what it means to the general public,* Central Research Unit, Secretary of State for Scotland, Edinburgo.

McMichael, A. J, Haines, A., Slooff, R. and Kovats, S. Eds (1996) *Climate change and human health,* World Health Organisation, Geneva.

Meadows, D. H. et al, (1972) *The limits to growth,* University Books, New York.

Measurementas Standards Laboratory (2005) History of Thermometry, Industrial research Ltd, New Zealand (http://msl.irl.cri.nz/training_&_resources/History/history_thermometry.html)

Mehta, P. (1996) *Local Agenda 21: Practical experiences and emerging issues from the south*, pp 309-335 in Alberti, M. and Susskind, L., Eds, Special issue, Environmental Impact Assessment Review, Vol 16, Nros. 4-6.

Meteorological Office (1997) *Observers Handbook*, HMSO, London

Michelson, W. Ed, (1975) *Behavioural Research Methods in Environmental Design*, Community Development Series, Halstead Press, New York.

Ministerio de Infraestructura y Vivienda (2000) *Estándares Mínimos de Calidad para Vivienda de Interés Social (Versión Preliminar)* Ministerio de Infraestructura y Vivienda, Secretaría de Obras Públicas, Buenos Aires.

MINVU (2006) *Manual de aplicación reglamentación térmica, Ordenanza General de Urbanismo y Construcciones, Articulo 4.1.10,* Ministerio de Vivienda y Urbanismo, Santiago de Chile.

MIT (1971) Inadvertent climate modification, MIT Press,

MOHLG, (1964) *Planning for daylight and sunlight.* Planning Bulletin 5, Ministry of Housing and Local Government, HMSO, London.

Morris, P. and Therivel, R., Eds, (1995). *Methods of environmental impact assessment*, The natural and built environment series 2, UCL Press, London.

MOSP (1972) *Estudio preliminar del transporte de la Región Metropolitana,* Ministerio de Obras y Servicios Públicos, Tomos I y II, Buenos Aires.

Mukhtar, Y. A., (1978) *Roofs in hot dry climates, with special reference to Northern Sudan,* Overseas Building Notes, N° 182, Overseas Building Division, BRS, Watford.

Mumford, L., (1966) *The city in history* Penguin Books, Harmondsworth.

Murillo, F. and de Schiller, S. (2000) *Evolving approaches to evaluate sustainable housing projects*, SB 2000, Maastricht.

Murillo, F. and de Schiller, S. (2001) *Calidad ambiental y costos de desarrollo urbano*, pages 39-60, Capitulo 3, in Ambiente y Ciudad, Serie Difusión 15, Eds., Evans, J. M., de Schiller, S., Casabianca, G., Fernández, A. y Murillo, F., SICyT, FADU, Universidad de Buenos Aires, Editorial La Colmena, Buenos Aires.

Murrain, P. (1993) *Urban Expansion: look back and learn, in* Hayward, R. and McGlynn, S. Eds, *Making better places, Urban design now*, Joint Centre for Urban Design, Butterworth Architecture, London.

Murrey, P and Stevens, M. Eds (1998) *New Urban Environments*, British Architecture and its European Context, Royal Academy of Arts, London.

NCh (2007) Norma Chilena NCh 853 Acondicionamiento térmico - Envolvente térmica de edificios - Cálculo de resistencias y transmitancias térmicas,MINVU, Santiago de Chile.

Ne'eman, E. and Light, W. (1975) *Availability of sunlight,* British Research Establishment Current Paper 75/75, Watford.

Newman, O. (1976) *Defensible space, people and design in the violent city,* Architectural Press, London.

Nicol, F. (2000) *International standards don´t fit tropical buildings: what can we do about it*, in Gonzalez, E. et al, Eds, Memorias, COTEDI 2000, Maracaibo.

Nicol, F. and Humphreys, M. (2001) *Adaptive comfort and sustainable standards for Building, Proceedings*, Moving Comfort Standards into the 21st Century, Oxford Centre for Sustainable development, Oxford.

Nijkamp, P. and Perrels, A. (1994) *Sustainable cities in Europe*, Earthcan Publications, London.

NOM (2001) *Norma Oficial mexicana NOM-008-ENER-2001, Eficiencia energética en edificiaciones, envolventes de edificios no residenciales,* NOM, México D.F.

OECD (1976) *Economic measurement of environmental damage*, Organisation for Economic Co-operation and Development, Paris.

OECD (1979) *Environmental Impact Assessment Analysis of the Environmental Consequencies of Significant Public and Private Projects*, Organisation for Economic Co-operation and Development, Paris.

Oke, T. R. (1982) *Boundary layer climates,* Academic Press, London; and Oke, T. R. (1987),Cambridge University Press, Cambridge.

Oke, T. R. et al, (1991). *Simulation of nocturnal surface urban heat islands under 'ideal' conditions: model validation and use as a diagnostic tool*, in Bitan, A., (Ed.) *Urban climate, planning and building*. IFHP-CIB-WMO-IGU Proceedings of the International Conference Urban Climate, Planning and Building, Elsevier Sequoia, Lausanne.

Oke, T. R., Taesler, R. and Olsson, L. (1991) *The Tropical Urban Climate Experiment (TRUCE)* in Bitan, A, (Ed.) (1991) *Urban climate, planning and building*. IFHP-CIB-WMO-IGU Proceedings of the International Conference Urban Climate, Planning and Building, Elsevier Sequoia, Lausanne, también Energy and Buildings, 15-16 (1990-1991) pp 67-73.

Olgyay, V. (1963) *Design with Climate, bioclimatic approach to architectural regionalism,* Princeton University Press, Princeton, N.J

Olgyay, V. (1998) *Arquitectura y Clima, Manual de diseño bioclimático para arquitectos y urbanistas*, GG Barcelona, 1998.

Olgyay, V. and Olgyay, A. (1957) *Solar protection and shading devices*, Princeton University Press, Princeton N.J.

Oliver, P. (1987) Dwellings: the house across the world, University of Texas Press, Austin

Oliver, P. (Ed) (1969) *Shelter and Society,* Frederick A. Praeger, New York

Oliver, P. (Ed) (1971) *Shelter in Africa,* Barrie and Jenkins, London

Owens, S. (1986) *Energy, Planning and Urban Form*, Pion, London.

Owens, S. (1993) *The good, the bad and the ugly, dilemmas in planning for sustainability*, Town Planning Review, 64 (2) iii-vi.

Owens, S. (1994) *Land, limits and sustainability: a conceptual framework and some dilemmas for the planning system*, Trans. Inst. Br. Geoggr, NS. 439-456.

Owens, S. (1997) *Giants in the path: Planning, sustainability and environmental values*, Town Planning Review, 68 (3) 293-304.

Owens, S. (1997) *Interpreting sustainable development: the case of land use planning*, pp 88-97, in Jacobs, M. (1997) *Greening the Millenium: The new politics of the Environment*, The Political Quarterly, London.

Palladio, A., (2005) *Los cuatro libros de la arquitectura, (Translated to Spanish by Pérez Infante), C.* Editorial Limaza, Mexico.

Papanek, V., (1993) *Prologo,* in Pearson, D., (1994) El libro de la arquitectura Natural: en busqueda de un hogar sano y ecologico, Integral, London.

Pardano, C. A., (1969) Nuestro clima y la Arquitectura, Departamento de Diseño Arquitectónico, Facultad de Arquitectura y Urbanismo, Universidad Nacional del Nordeste, Publicación 3, Resistencia, Chaco.

Patrone J. C. and Cabezón M, (2004) *Tierra Estabilizada Apisonada en el Gran Buenos Aires,* 1er. Seminario Taller, Construcción con Tierra, FADU UBA, Buenos Aires.

Patrone J. C., (2005) *Gestión y Desarrollo en la Construcción de la Vivienda de Interés Social con empleo de suelo estabilizado,* Construcción con Tierra 1, FADU UBA, Buenos Aires.

Pearce, E. A. and Smith, C. G. (1990) *The world weather guide*, 2nd Edition, Hutchinson, London.

Pearson, D., (1994) *El libro de la arquitectura Natural: en busqueda de un hogar sano y ecologico*, Integral, London.

Pearson, D., (1995) *The natural house book: creating a healthy, harmonious and ecologically sound home,* Conran Octopus, London.

Peet, J. (1992) *Energy and the ecological economics of sustainability*, Island Press, Washington.

Pereyra, D. (1997) *Notas criticas sobre la globalidad y la globalización*, Oficina de publicaciones del CBC, Universidad de Buenos Aires, Buenos Aires.

Petroni, C. A and Kratz de Koenigsberg, R (1966) *Diccionario de urbanismo,* Cesarini Hnos Editores, Buenos Aires.

Pevsner, N., (1968) *The sources of modern architecture and design,* The World of Art Library, Thames and Hudson, London.

Pilatte, A., Nicolas, P. (1980) *Meteorological data: Treatment of radiation data, test reference year,* Heat Exchange and Solar Energy, Vol. 1 29 p (SEE N81-18499 09-44)

Poler, M. (1968) *Clima y arquitectura,* Banco Obrero, Caracas.

Potvin, A, (1996) *Movement in the architecture of the city: a study in environmental diversity*, Doctoral Thesis, Cambridge University, Cambridge.

Prakash, S., (1991) *Solar architecture and earth construction in the northwest Himalaya*, Har-anand Publications, New Delhi.

Pressman, N. (1991) *Quality for public urban space and pedestrian movement* , Pages 99-108 in PLEA-91, Architecture and Urban Space, Edited by Servando Alvarez, Jaime Lopez de Asiain, Yannas, S. and E. De Olivera Fernandez, Kluwer Academic Publishers, Dordrecht.

Pressman, N. (1995) *Northern Cityscape, linking design to climate*, Winter Cities Association, Yellowknife, Canada.

Puppo, E., Puppo G and Puppo E, (1976) *Sol y Diseño, Indice Térmico Relativo,* Marcombo Boixaren Editories, Barcelona.

Purbeck District Council (1997) *Purbeck District Local Plan, deposit draft*, Purbeck District Council, Wareham, Dorset.

Rabinoovich, G, (2006) Estado de Situación del Sector Energético Nacional, Instituto Argnetina de la Energía Gral Mosconi, Buenos Aires.

Ramírez, C. F. (2006) *Confort térmico,* Revista BIT, BIT 50, pp 18-27, Santiago de Chile.

Rappoport, A., (1969) *House form and culture,* Prentice Hall, New Jersey.

Ratti, C, Robinson, et al, (2000) *LT Urban: The energy modelling of urban form,* pp 660-665, in Maldonado, E., E. and Yannas, S., Eds., Environmentally Friendly Cities, Proceedings of PLEA 1998, James & James, London.

Rees, W. and Wackernagel, M. (1996) *Urban Ecological footprints: Why Cities cannot be sustainable – and why they are the key to sustainability*, pp 223-248 in Alberti, M. and Susskind, L., Eds., Special Issue, Environmental Impact Assessment Review, Vol 16, Nros. 4-6.

Reynolds, J. S., (2002) *Courtyards: aesthetic, social and thermal delight,* John Wiley & sons, Inc., New York.

Richards, P. G. and Matthews, E. H. (1994) *A thermal design tool for buildings in ground contact* Building and Environment, 29:73-82.

Rivero, R. (1985) *Acondicionamento térmico natural, Arquitetura e clima,* D. C. Luzzatto Editores, Porto Alegre.

Roaf, S. (2001) *Ecohouse,* Architectural Press, London

Roaf, S. (2003) *Ecohouse 2,* Architetural Press, London.

Rodríguez Viqueira, M., (2003) *Las macro-regiones climáticas y los criterios de diseño de la arquitectura prehispánica en México,* in Rodríguez Viqueira, M., Ed (2003) *Estudios de Arquitectura bioclimática, Anuario 2003*, vol V, Limusa Noriega Editores, México.

Roe, D., Dalal-Clayton, B. and Hughes, R. Eds, (1995) *A Directory of Impact Assessment Guidelines,* Environmental Planning group, International Institute for Environment and Development, London.

Rogers, R. (1997) *Cities for a small planet*, Faber & Faber. London.

Rogers, R. and Power, A. (2000) *Cities for a small country*, Faber & Faber. London.

Rolen, C. (1998) *Environmental evaluation of buildings – knowledge in demand*, Swedish Building Research 3/98, Stockholm.

Roriz, M, (2006) Um algoritmo para determinar os valores horários das temperaturas do ar em função das normais climatologicas, Avances en Energías Renovables y medio Ambiente, Vol 2006, INENCO, Salta.

Ryan, P., (1969) *The invasión of the moon: the storey of Apollo 11*, Penguin Books, Harmonsworth.

Saini, B. S., (1987) *Construcción en climas cálidos secos,* Editorial Limusa, Mexico, D. F. (translation of Saini, B. S., (1987) *Building in hot dry climates,* Wiley, New York.

Salama, A. (1998) *Human Factors in Environmental design, An introductory approach to architecture*, The Anglo-Egyptian bookshop, Cairo.

Samaja, J. (1993) *El proceso de la ciencia, Serie Difusión 1,* Secretaria de Investigación y Posgrado, FADU-UBA, Buenos Aires.

Samuels, R. and Prasad, D., (1994). *Global warming and built environment*, Span.

Santamouris, M and Asimkopoulis, D., Eds, (1996) *Passive Cooling of Buildings*, James and James, London

Santamouris, M. (2001). *Energy and environmental quality in the urban built environment*, pp 80-87, in Hewitt, M. and Hagan, S. (2001) *City fights; debates on urban sustainability*, James & James, London.

Santamouris, M. Ed. (2001) *Energy and climate in the urban built environment,* James & James, London.

Sarin, M. (1982) *Urban Planning in the Third world: The Chandigarh Experience*, Mansell Publishing Ltd. London.

Schellen, H., (2004) *Tools to evaluate and or design heating systes for monumental churches*, pp 789-984, in Wit, M. H. (Ed) (2004) *Proceedings, Built environments and environmental buildings, 21st International Conference PLEA,* Technical University Einhoven, Eindhoven.

Scoffham, E. and Vale, B. (1996) *How compact is sustainable – how sustainable is compact,* pages 66-73, in Jenks, M., Burton, E. and Williams, K, (1996) *The Compact city: A sustainable urban form?* E & FN Spon, London.

Scott, A. (1998) *A time for change and innovation*, Introduction to *Dimensions of sustainability*, (1998) E & FN Spon, London.

Secretaría de Energía (2007) Balance Energetico Nacional 1970-2006, Secretaría de Energía de la Nacion, Buenos Aires

Selman, P. (1996) *Local Sustainability, Managing and planning ecologically sound places,* Paul Chapman Publishing, London.

Short, A. (1998) *The evolution of a naturally conditioned building*, in *Dimensions of sustainability*, (1998) E & FN Spon, London.

Slessor, C. (1997a) *Eco-Tech, Sustainable Architecture and High Technology*, Thames and Hudson, London.

Slessor, C. (1997b) *Eco-Tech, Arquitectura High-Tech y Sostenibilidad*, Editorial Gustavi Gili, S. A, Barcelona.

Smith, P. (2001) *Architecture in a climate of change, a guide to sustainable design*, Architectural Press, Oxford.

SMN, (1984) *Datos meteorologicos 1970-1980,* Servicio Meteorologico Nacional, Buenos Aires.

SRNDS, (1999a) *Inventario de gases de efecto invernadero de la Republica Argentina,* Secretaría de Recursos Naturales y Desarrollo Sustentable, Buenos Aires.

SRNDS, (1999b) *Revisión de la primera comunicación del Gobierno de la Republica Argentina, según la convención marco de las Naciones Unidas sobre cambio climático,* Secretaría de Recursos Naturales y Desarrollo Sustentable, Buenos Aires.

Stamp, D, (1964) *The geography of life and death,* Fontana, London.

Stanners, D. and Bourdeau, P., Eds, (1995) *Europe's environment, the Dobris Assessment,* European Environmental Agency, Denmark.

State of Minnesota (2003) *The State of Minnesota sustainable building guidelines, Beta version,* State of Minnesota, (www.csbr.umn.edu/B3, 15th January, 2003).

Steemers, K. (1992) *Energy in Buildings, the urban context*, Tesis Doctoral, Cambridge University, Cambridge.

Steemers, K. (1998) *Assessing the Urban Microclimate: Introducing innovative modelling techniques.* Pages 157-158, in Maldonado, E. and Yannas, S. Eds, Environmentally Friendly Cities, Proceedings of PLEA 1998, James & James, London.

Steemers, K. et al, (1998) *Project ZED: Towards Zero Emission Urban Development*, The Martin Centre, Cambridge.

Steemers, K., Baker, N., Crowther, D., et al, (1997). *City texture and microclimate.* Journal of Urban Design Studies, Vol. 3, University of Greenwich, London.

Steiner, R. (2003) *Architecture – an introductory Reader,* Rudolf Stainer Press, Dornach.

Strickney, B., (1978) *The home owners guide for evaluating passive solar heating,* pp 153-160, in Cook J. and Prowler, Eds., (1978).

Suarez, O.E. (1986) *Planes y Códigos para Buenos Aires, 1925-1985,* Serie Ediciones previas, N° 1, SEU, Facultad de Arquitectura y Urbanismo, Universidad de Buenos Aires, Buenos Aires.

Summerson, J. (1966) *Inigo Jones,* The Architect and Society, Penguin Books, Harmondsworth.

Szokolay, S. V., (1995) *Bioclimatic design: strategy to details*, pp 71-83, in Sattler, M, A., and da Costa Silva, H., Eds. (1995) Anais, III Encontro Nacional y I Encontro Latino Americano de Conforto no Ambiente Construído, Gramado, ANTAC, Porto Alegre.

Tedesci, E. (Editor) (1976) *Arquitectura + Energía solar, Summario 2,* Ediciones Summa, Buenos Aires.

Teygeler, R., (2001) *The preservation of Archives in Tropical Climates, An anotated bibiliography,* International Council on Archives and National Archives of Indonesia, Jakarta (http://palimpsest.stanford.edu/byauth/teygeler/tropical.pdf)

Thayer, B (2006) *The LacusCurtius Resources on Roman Britain*, http://penelope.uchicago.ed /Thayer/E/Gazetteer/Places/Europe/Great_Britain/_Periods/Roman/_Texts/WARRBE/6*.html

The Martin Centre (Coord.) (1997) *Towards Zero Emission Urban Development*, The Martin Centre for Architectural and Urban Studies, University of Cambridge, Cambridge.

Thompson, I. H. (1999) *Ecology, community and delight, sources of value in Landscape architecture,* E. & FN Spon, London.

Thornthwaite C. W., *An approach towards the rational classification of climates*, Geog. Rev, 33., 233-55, 1948.

Tinbergen, J. (Ed.) (1976) *RIO, Reshaping the International order, A report to the Club of Rome,* Dutton & Co, New York.

Trewartha, T., *An approach to climate*, McGraw Hill, New York, 1968.

Trinius, W. and Borg, M. (2002) *Allocation of environmental loads,* in Edén M. and Jönsson, Å. Eds, (2002) A. *MISTRA, Sustainable building, Experiences from a cross disciplinary research programme,* Chalmers University of Technology, Gothenburg.

Turner, D. P. (ed) (1977) *Window Glass Design Guide,* Architectural Press, London.

U. S. Green Building Council (1998) *LEED Buildings, Green Building rating System Criteria*, U. S. Green Building Council, San Francisco.

UGYCAMBA, (2000) *Gobernabilidad en la región Metropolitana de Buenos Aires,* Unidad de Gestión y Coordinación para el Área Metropolitana de Buenos Aires. Facultad de Arquitectura, Diseño y Urbanismo, Universidad de Buenos Aires, Buenos Aires.

United Nations, Economic Commission for Latin America and the Caribbean (1991) *Sustainable development: changing production patterns, social equity and the environment*, Santiago, Chile.

University of Saskatchewan (1987) *Guide to farm practice,* Saskatchewan Agriculture and the University of Saskatchewan, Saskatchewan.

van de Ryn and Calthorpe (1986) cited in CIB (1999) Agenda 21 on sustainable construction. CIB, Rotterdam.

van Ettinger, J. & Sittig, J. (1965) *More… through quality,* Bouwcentrum Quality Centre, Rotterdam.

van Hal, A, de Vries, G. (2000) *Opting for change, sustainable building in the netherlands,* Aeneas Technical Publishers, Best, Netherlands

van Hal, A. (2000) *Beyond the Backyard. Sustainable housing experiences in their national context*, Aeneas Technical Publishers, Best, Netherlands.

van Hal, A. (2000) *Beyond the Demonstration Projects*, Netherlands.

van Heerden, E. and Matthews, E. H., (1996) A new simulation model for passive and low energy architecture, pp 223-228, in de Herde, A. (ED) Building and urban renewal, Proccedings, PLEA 1996, Architecture et Climat, Louvain-la-Neuve.

van Rijs, J. (1998) *Far East: Hong Kong Tower typologies,* pages 230-247, in MVRDV, Winy Maas and Jacob van Rijs with Richard Koek, Editors., Farmax: Excursions on density, 010 Publishers, Rotterdam.

Van Straten, J. F. (1967) *Thermal performance of buildings,* Elsevier, London.

Vitruvius, (Tranlated by Morgan M. H.) (1914) *The ten books of architecture*, Harvard University Press, Cambridge, Massachussetts.

Wakely, P. Et al. (2001) *Implementing the Habitat Agenda. In Search of Urban Sustainability.* The Development Planning Unit, University College London, London.

Wall R. with Seidle R. (1998 Re-edited by MVRDV) pages 230-247, MVRDV, Winy Maas and Jacob van Rijs with Richard Koek, Eds, Farmax: Excursions on density, 010 Publishers, Rotterdam.

Ward, B. (1976) *The home of man,* Penguin Books, Harmondsworth.

Ward, B. and Dubos, R. (1972) *Only one Earth, the care and maintenance of a small planet*, Penguin Books, Harmondsworth.

Ward, J. (1911) *Romano-British Buildings and Earthworks,* Methuen & Co. Ltd, London.

Ward, P., (1970) *Sabratha: a guide for visitors,* The Oleander Press, New York.

Webb, C. G., (1960) *Ventilation in warm climates,* BRS Overseas Building Notes, N° 66, BRS, Gaston.

Weibel, P. (2001). *The city in the post-industrial information society: transforming from place of production to a place of consumption,* pp 2-6, *in* Hewitt, M. and Hagan, S. (2001) City fights; debates on urban sustainability, James & James, London.

Wernley, J., (1975) *Los problemas del clima: factor de diseño,* Facultad de Arquitectura y Urbanismo, Universidad Nacional del Nordeste, Resistencia.

Wikipedia, (2007) *Petroleum*, http://en.wikipedia.org/wiki/Petroleum

Wilson, D. (1972) *The Anglo-Saxons,* Penguin Books, Harmonsworth

Wilson, E. (1996) *The precautionary principle and the compact city, in* Jenks, M., Burton, E. and Williams, K, Eds (1996) *The Compact city: A sustainable urban form?* E & FN Spon, London.

World Meteorological Organization (1994*) Report on the Technical Conference on Tropical Urban Climates*, WCASP-30, WMO/TD N, Geneva.

World Meteorological Organization (1995) *Climate information and prediction services*, WMO, N° 832, Geneva.

World Meteorological Organization (1996a) *Climate and urban development*, WMO, N° 844, Geneva.

World Meteorological Organization (1996b) *Climate and human health*, WMO, N° 843, Geneva.

Zold, A. and Szokolay, S. V., (1997) *Thermal Insulation, PLEA Notes 2,* University of Queensland Department of Architecture, Brisbane.

Numerical Simulation Programs and Electronic Spreadsheets

Evans, J. M., (1992) *isol.exe,* Centro de Investigación Hábitat y Energía, Facultad de Arquitectura, Diseño y Urbanismo, Universidad de Buenos Aires, Buenos Aires. Executable programme in Quick Basic. Calculation of Solar radiation using the method of Lui and Jordan

Evans, J. M., (1991) *Comfort.exe,* Centro de Investigación Hábitat y Energía, Facultad de Arquitectura, Diseño y Urbanismo, Universidad de Buenos Aires, Buenos Aires. Executable programme developed in Quick Basic based on the method of Fanger (ISO, 2001).

Evans., J. M. (2005) *e-clim* Centro de Investigación Hábitat y Energía, Facultad de Arquitectura, Diseño y Urbanismo, Universidad de Buenos Aires, Buenos Aires. Electronic speadsheet developped in Microsoft Excel for climate analysis.

Evans, J. M. (2006) *e-temp.* Centro de Investigación Hábitat y Energía, Facultad de Arquitectura, Diseño y Urbanismo, Universidad de Buenos Aires, Buenos Aires. Electronic speadsheet developped in Microsoft Excel, for simulating indoor temperature.

Evans, J. M. (2006) *e-dia,* Centro de Investigación Hábitat y Energía, Facultad de Arquitectura, Diseño y Urbanismo, Universidad de Buenos Aires, Buenos Aires. Electronic speadsheet developped in Microsoft Excel, based on the algorithms of Roriz (2006) for estimating hourly outdoor temperatures.

Matthews et al (1997) *Quick II,* Centre for Heat and Mass Transfer, University of Pretoria, (Matthews and Richards, 1993) simulating indoor temperatures in naturally conditioned buildings.

Microsoft Word 2000 (1999) word processing.

Microsoft Excel 2000 (1999) electronic spreadsheets and preparation of climate and comfort graphs.

Marsh, A. J. (2007) *Predicted Mean Vote Tool* available on the internet http://squ1.com/downloads

World Wide Web pages

Wunderground (2006) *http://www.wunderground.com/* provided daily data for Met stations: Quito, Buenos Aires, Rio Gallegos, Colima and Tampico, in addition to the published data obtained from the respective Meteorological Services.

Google Earth (2005) *http://earth.google.com/* Used for Aerial photographs and checking heights and orientation for the case studies. (oblique aerial photos of Tampico by the Author)

Onsett Data loggers (2006) *http://www.onsetcomp.com/* provides data on the HOBO data loggers : H-08-001 with one internal temperature channel and H-08-002 2 channel models were used.

Tinktalk data loggers (2006) *http://www.geminidataloggers.com/* were used for the earlier heat island studies.

Wikipeadia (2007) *http://en.wikipedia.org/wiki/Main_Page* has been used for general references and definitions, although the open editing of this source may produce some contentious content

The Engineering Tool Box (2007) *http://www.engineeringtoolbox.com/* has been used to obtain and check technical data.

APPENDIX 1. ABBREVIATIONS, SYMBOLS, GLOSSARY & DEFINITIONS

A1.1. ABBREVIATIONS

ABNT	Asociacão Brasileira de Normas Técnicas, *Brazilian Association of Technical Standards* http://abnt.org/
AIA	American Institute of Architects http://www.aia.org/
AIJ	Architectural Institute of Japan http://www.aij.or.jp/
AMR	Annual mean range
AMT	Annual mean temperature
ANSI	American National Standards Institute http://www.ansi.org/
ANTAC	Asociação Nacional de Tecnología do Ambiente Construido, *National Association for Technology of the Built Environment* Organizes ENCAC and ELACAC http://www.antac.org.br/
ASADES	Asociación Argentina de Energías Renovables y Medio Ambiente, *Argentine Association for Renewable Energy and the Environment,* http://www.asades.org.ar/
ASHRAE	American Association of Heating, Refrigeration and Air conditioning Engineers http://ashrae.org/
BRE	Building Research Establishment (formerly BRS) http://www.bre.co.uk/
BREEAM	Building Research Establishment Environmental Assessment Method
BRS	Building Research Station (name changed to BRE)
BS	British Standards
CEN	Standard of the European Community http://www.cenorm.be/cenorm/index.htm
CET	Corrected Effective Temperature
CIB	International Council for Research and Innovation in Building and Construction, *Formerly Conseil International du Bâtiment* http://www.cibworld.nl/website/
CIBSE	Chartered Institute of Building Services Engineers, Professional Institute in the United Kingdom http://www.cibse.org/
CIHE	Centro de Investigación Hábitat y Energía, *Habitat & Energy Research Centre(FADU-UBA)*
CIVCO	Centro de Investigación de Vivienda y Construcción, *Housing and Construction Research Centre, Costa Rica Technological Institute* http://www.itcr.ac.cr/investigacion_extension/index.aspx
CLO	Scale for thermal insulation of clothing
COTEDI	Confort Térmico en Edificios, *Thermal Comfort in Buildings (Regional Congress in Latin America)*
CZ	Comfort Zone
E	East
ELACAC	Encontro Latino-Americano do Conforto no Ambiente Construido, *Latin American Meeting on Comfort in the Built Environment* (Regional Congress in Brazil)

Abreviations (Continued)

ELACAC	Encontro Latino-Americano do Conforto no Ambiente Construido, *Latin American Meeting on Comfort in the Built Environment* (Regional Congress in Brazil)
EN	European Standard see CEN
ENCAC	Encontro Nacional do Conforto no Ambiente Construido, *National Meeting on Comfort in the Built Environment* (National Congress in Brazil)
ET	Effective Temperature (see also CET).
FADU	Facultad de Arquitectura, Diseño y Urbanismo; *Faculty of Architecture, Design and Urbanism (UBA).*
GBC	Green Building Challenge (International network for Sustainable Building assessment, using the GBTool) http://greenbuilding.ca/
GBC	Green Building Council; see WGBC and NGBC
GBTool	Green Building Tool (Spread-sheet for sustainable building evaluation)
GHG	Green House Gases
GCBA	Gobierno de la Ciudad de Buenos Aires, *Government of the City of Buenos Aires, now Government of the Autonomous City of Buenos Aires (GCABA)*
iiSBE	International Initiative for Sustainable Built Environments (International network promoting sustainable building, applying assessment methods) http://greenbuilding.ca/
IIV	Instituto de Investigación de la Vivienda, *Housing Research Institute (FADU-UBA)* (no longer in existance)
INEN	Instituto Nacional Ecuatoriano de Normalización, *National Ecuatorian Standards Institute* http://www.inen.gov.ec/
INTI	Instituto Nacional de Tecnología Industrial, *National Institute for Industrial Technology (Argentina)* www.inti.gov.ar/
ITCR	Instituto Tecnológico de Costa Rica, *Technological Institute of Costa Rica* http://www.itcr.ac.cr/
IPCC	Inter-governmental Panel on Climate Change http://www.ipcc.ch/about/about.htm
IRAM	Instituto Argentino de Racionalización de Materiales, *Argentine Institute for Materials Standards* http://www.iram.com.ar/
ISO	International Standards Organization http://www.iso.org/iso/en
K	Thermal transmittance value, more commonly know as U (See page xx.)
LEED	Leadership in Environmentally Efficient Design (Certification method for green building assessment by the U.S. Green Building Council); see WGBC
LT	Light and Thermal (energy prediction method, see Baker, 1998)
MCBA	Municipalidad de la Ciudad de Buenos Aires, *Municipality of the City of Buenos Aires*
MET	Scale for the rate of metabolic activity
N	North
NGBC	National Green Building Council
PLEA	Passive and Low Energy Architecture http://www.plea-arch.org/
RH	Relative Humidity
RR	Range Ratio (see Chapter 6)

Abreviations (Continued)	
S	South
TIA	Teaching in Architecture (International Conferences)
TIM	Transparent Insulating Material
U	‘U’ Value or thermal transmittance
UBA	University of Buenos Aires http://www.uba.ar/homepage.php
W	West
WGBC	World Green Building Council (International organization promoting sustainable building, using the LEED certification system) http://www.worldgbc.org/
WHO	World Health Organization http://www.who.int/en/
WMO	World Meteorological Organization http://www.wmo.ch/

A1.2. SYMBOLS

A_t	Average daily temperature swing
A_{ti}	Average indoor daily temperature swing
A_{to}	Average outdoor daily temperature swing
R_{si}	Indoor surface thermal resistance
R_{so}	Outdoor surface thermal resistance
T_i	Indoor temperature
T_m	Average daily temperature
T_{max}	Maximum daily temperature or average of daily maximum temperatures
T_{min}	Minimum daily temperature or average of daily minimum temperatures
T_o	Outdoor temperature
T_{mr}	Mean radiant temperature
T_{sa}	Sol air temperature
T_{si}	Indoor surface temperature
T_{so}	Outdoor surface temperature

A1.3. GLOSSARY AND DEFINITIONS

Term	Definition	Units	Symbol	References
Absolute humidity	Water vapour mass per unit volume of dry air.	gm/Kg: gm of water per Kg of dry air	*X*	IRAM 11.549 (1993)
Absolute maximum temperature	Highest temperature recorded in the period under study; usually a month, year or decade.	°C	t_{maxab}	
Absolute minimum temperature	Lowest temperature recorded in the period under study; usually a month, year or decade.	°C	t_{minab}	
Absolute sunshine duration	Average number of hours of direct sun in the period under study.	hours	*N*	
Absolute zero	Minimum value in the Kelvin scale of temperature, occurring at -237,16 in the Celsius scale.	°K	*t*	Crespi, 1980
Absorbent glass	Body coloured glass, which absorbs a significant proportion of the visible light and solar radiation in order to reduce solar heating of indoor spaces.			
Absorber surface	Surface with high absorptivity used to receive solar radiation in a solar heating system.			
Absorbtivity	Capacity of a material or surface to absorb radiant energy. The sum of reflectivity and absorbtivity of an opaque surface is unity	%	A	Crespi, 1980
Absorption	Proportion of light or radiation incident on a surface not reflected or transmitted.	%	α	Evans, 1979
Accumulator wall	Wall with a dark outside surface, with an external glass performing as a passive solar heating system, variant of the Trombe-Michel passive solar system.	-		
Admittance	Heat flow between the surface of a building element and the air, per unit of surface area and per unit of variation in temperature around the average when subject to periodic air temperature variation. Capacity of a building element surface to absorb or return heat to the air when subject to periodic temperature variations.	W/m2K	*Y*	CIBSE, 1980
Aerogel	Low density translucent material with high solar radiation transmission and very low thermal conductivity (see TIM).	-		

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Aerosols	Very small liquid or solid particles suspended in the air that absorb part of solar radiation; diameters range from 0.01 to 100 microns.	-	-	Crespi, 1980
Air change	See Ventilation.	h^{-1}	*N*	
Air gap	Sealed, un-ventilated or slightly ventilated air space between two construction layers, incorporated to increase the thermal resistance.	-		
Air velocity	Speed of air movement.	m/s	*v*	See relative
Albedo	Proportion of reflected light or solar radiation from the Earth's surface.	%	A	
Altitude	See Height above sea level or Solar altitude.			
Argon	Inert gas with low thermal capacity used in double glazing cavities to reduce thermal transmittance.	-	Ar	
Artificial sky	Equipment used to simulate light distribution from an overcast sky for illuminating building interiors.	-		
Artificial ventilation	Exchange of indoor and outdoor air using extract fans or other mechanical ventilation devices.			
ASHRAE	American Association of Heating, Refrigeration and Air-conditioning Engineers.	-		
ASHRAE Comfort scale	Seven point scale used by ASHRAE to define subjective comfort sensation, where 0 = thermal neutrality.			See Bedford
Atmospheric clarity	Coefficient of radiation transmission through the Earth's atmosphere. The intensity of solar radiation received at the Earth's surface, compared with the simultaneous extra-terrestrial radiation.	non dimensional	Kt	
Atmospheric pressure	Pressure resulting from the atmosphere. In normal conditions at sea level, equivalent to a column of mercury of 76 cm.	kPa		Crespi, 1980
Auxiliary system	Equipment used to supplement renewable energy systems when they cannot supply sufficient energy, for example, passive solar systems on cloudy days.			
Average temperature	Mean of outdoor or indoor temperatures in a given period.	°C	Ta	
Average thermal transmission	Mean heat flow per unit area of a heterogeneous building element subject with different air temperatures on either side.	W/m^2K	K, U	U Value or K Value

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Azimuth	Orientation of the sun, indicated on a horizontal plane by the intersection of the vertical plane intercepting the sun's rays. Normally measured in a clockwise direction with 0° North, 90° East, 180° South and 270° West.	°	φ	
Bedford's comfort scale	Seven point scale proposed by Bedford to define subjective comfort sensation where 0 = Comfort.			See ASHRAE
Bioclimatic architecture	Building design offering protection from the unfavourable impact of climate and taking advantage of favourable aspects.	-		See Chapter 2
Bioclimatic design	Architectural process for specific climate conditions that aims to improve human thermal comfort by natural conditioning with minimum use of conventional energy, by appropriate building form, orientation, materials and openings, reducing or eliminating artificial conditioning.	-		See Chapter 2: 2.2.2
Bioclimatic design resources	Alternative methods of indoor climate modification used in natural conditioning.			See Chapter 2
Bioclimatic indicators	Values of climate variables defining conditions of potential discomfort, which can be avoided by specific and related design strategies.	-		See Chapter 4.
Bioclimatic strategies	Ways to achieve favourable modifications of the external climate conditions applying combinations of design resources for natural conditioning.			
Bioclimatic zone	Geographical region defined by meteorological variables related to the interaction between man, climate and architecture, to achieve natural conditioning with specific design recommendations.			IRAM Standard 11.603, also Chapter 5
Bio-environmental design	Translation of the Spanish term Diseño Bioambiental, implying a response to environmental factors in addition to climatic factors considered by bioclimatic design.	-		Evans & de Schiller, 1988
Brise soleil	Fixed external shading device, normally made of reinforced concrete, term coined by Le Corbusier.	-		See Chapter 11
Built environment	Man-made habitat, encompassing regional, urban, local and building design scales.			
Calorific value	Quantity of heat generated by a mass or volume of a fuel.	KJ/m3 or KJ/kg	q	

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Candela	Unit of luminous intensity produced in a direction perpendicular to a surface of 1/600000 m2 of a black body at the temperature of solidification of platinum at a pressure of 325 Newtons per square metre.	Cd	c	AJ Matric Handbook, 1985.
Celsius	Scale of temperature based on the freezing (0° C) and boiling point (100° C) of water at normal pressure.	° C	*t*	
CIBSE	Charted Institute of Building Services Engineers, based in the United Kingdom.			
Clear sky	Sky vault without clouds or with less that 2 eights of cloud cover.	-		Met Office, 1997.
Clearstory windows	Glazed openings at high level.	-		
Climatic variables	Temperature, humidity, rainfall, wind, cloud cover and other meteorological data.			Met Office, 1997.
Clo	Scale to indicate the thermal insulation value of clothing.	-	Clo	ISO 7730
Cloudiness	Proportion of the sky vault covered by cloud, normally expressed in eights, and obtained by visual inspection.	Eighths		Met Office, 1997.
Coefficient of efficiency	Relation between the energy supplied and the useful energy delivered or extracted by equipment, for example, for heating or cooling.	non dimensional		Crespi, 1980
Comfort scale	Seven point scale to define subjective comfort sensation.			See Bedford & ASHRAE
Comfort triangles	A tool to visualise the daily temperature variation of a space, compared with comfort requirements.			Presented in this thesis. Chapter 7.
Comfort zone	Combination of environmental conditions of temperature, relative humidity, mean radiant temperature and air movement, which a high percentage of subjects consider to be thermally neutral, without sensation of cold or heat.			See Chapter
Computa-tional fluid dynamics	Numerical simulation of the behaviour of fluids to estimate speed and low direction.	-	CFD	
Concentrat-ing solar collectors	Surface to receive solar energy from a curved reflector, designed to increase the intensity of the sun's radiation.	-		
Conductivity	Capacity of a homogeneous material to transmit heat according to the unit thickness, per unit area and per unit temperature difference between the airs on two opposing sides.	W/mK	λ	IRAM 11549, 1993

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Condensation	Process of transforming water vapour into liquid produced by reducing the temperature.	-		Crespi, 1980
Control of thermal swing	Use of bioclimatic resources, such as high admittance surfaces, high heat capacity materials and thermal inertia, to reduce thermal swings in indoor spaces.	non dimensional		
Convection	Heat transfer mechanism by natural or forced ventilation.			
Cooling strategies	See Passive cooling strategies.			
Corrected effective temperature	Scale of thermal comfort, equivalent to the dry bulb temperature at 100% relative humidity that produces the same thermal sensation as a combination of temperature, relative humidity, air movement and mean radiant temperature.	°CET	*t*	Evans, 1980
Cross ventilation	Air movement in buildings to achieve sensible cooling of the occupants, produced by breeze through openings in opposing facades.			
Curtain	Woven fabric or flexible vertical element used to achieve solar protection, privacy or control of light levels.			
Data logger	Instrument to measure and record a time series of data.			See Hobo
Daylight factor	Light level on a horizontal plane at a point in a boiling interior, expressed as a percentage of the light available from the sky on an outdoor horizontal plane without obstructions.	%	DF	
Decibel	Measure of noise level, with a logarithmic scale that relates approximately to the subjective sensation of the human ear.	dB	I	
Solar declination	Angular coordinate of the sun at midday measured to the North or South of the equatorial plane.	°	Dec, δ	Wikipedia, 2007.
Density	Mass of material in a unit volume.	kg/m^3	d	
Design recommendations	Specific guidelines at different design scales to select architectural and construction decisions.			
Dew point, Dew point temperature	Temperature at which the air, with a known absolute humidity, becomes saturated when cooled at constant pressure.	°C		
Diffuse solar radiation	Energy received from an overcast sky or a clear sky, excluding direct solar gains.		I_{dif}	

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Diffuse reflection	Scattering phenomena produced by a rough, matte or uneven surface, that distributes light or radiation evenly in different directions.			
Thermal diffusivity	Ratio of thermal conductivity to volumetric heat capacity in heat transfer analysis.	m^2/s,	α	CIBSE, 1980, Wikipeadia
Direct gain	Radiation intensity received directly from the sun. See directo solar radiation	W/m^2		
Direct sky component	Portion of natural light received without reflections from an overcast sky on the working plane.	-	SC	
Direct solar radiation	Intensity of electro-magnetic waves received directly from the sun.	W/m^2	I_{dir}	
Double facade	External wall with two separate layers and a wide ventilated air gap between them to achieve a favourable moderation of climatic impacts, especially solar protection and controlled ventilation.	-		
Double glazing	Two parallel sheets of glass with a small air space between them incorporated in windows to reduce heat transfer in comparison with single glazing.	-		
Dry bulb temperature	Register of the air temperature without the influence of humidity or radiation.	°C	t_{db}	
Dry bulb thermometer	Thermometer used to obtain the air temperature without the influence of humidity or radiation.			
Effective temperature	Scale of thermal sensation, based on wet bulb and dry bulb temperature.	°C	ET	Markus & Morris, 1980
Embodied energy of materials	Amount of energy use to extract, produce and transport building materials, expressed as kilojoules per cubic metre or kilogram.	KJ/m3 or KJ/kg		
Energy	Capacity of a system to do work.			Wikipedia, 2007.
Environmental impact	Effect of the physical context on human health, ecological sustainability and the capacity of nature to absorb changes without detrimental consequences.			
Equation of time	Difference between average time, based on a 24 hours day, and solar time, based on the sun's position. This difference, due to eccentricities in the Earth's trajectory around the sun, can reach up to 16 minutes.			Wikipedia, 2007.

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Equiangular projection	Projection of the sky vault on a flat plane, considering that equal distances represent equal angles.			
Equinnox	Date when the sun is directly above the equator.			
Evaporative cooling	Reduction of temperature achieved by the latent heat of water changing state from liquid to gas.			
External surface resistance	Ability of the outdoor building surface and air layer close to the surface to resist the heat flow, including the effects of convection and radiative heat emission.	$m^2 K / W$	R_{se}	
Externally reflected component	Portion of natural light received on the working plane from diffuse light of an overcast sky and reflected by external ground and building surfaces.	-		
Extraterres-trial radiation	Solar radiation intensity at the outer limit of the earths atmosphere, about 1366 W/m^2			See solar constant
Flat plate solar collectors	Devices for transforming solar radiation into heat by water circulating through copper tubes fixed to a black surfaced metal plate with a thermally insulated backing and a glazed cover.	-		
Float glass	Glass produced by a patented process using a sheet molten glass floating on a tank of liquid tin to achieve a surface totally free of visual distortions.			
Forced convection	Air movement to transfer heat produced by the application of external energy, such as a fan.			
Fossil fuels	Energy resource in the form of liquid, solid or gaseous materials, produced by the decomposition of organic materials by heat and pressure over long periods of time, such as coal, tars, tar shale, petrol and gas.	-		
Frosts	Climatic conditions producing freezing of water, with temperatures below 0° C.			
G	Volumetric coefficient of building heat loss, in Watts per cubic metre of heated building per degree temperature difference.	W/m^3K	G	IRAM 11504
Greenhouse Gases, GHG	Gasses that reduce the outgoing radiation from the Earth's surface, producing global warming.			

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Givoni's Bioclimatic Chart	Graph of Baruch Givoni (1978) with a horizontal axis of dry bulb temperature and a vertical scale of absolute humidity, showing comfort and zones where different bioclimatic strategies are applied.	-		Givoni, 1978, see Appendix 2.
Glass thickness	Nominal dimensions of glass thickness, for float glass 3, 4, 5, 6, 8, 10 and 12 mm.	mm	e	
Glass, monolithic	Homogeneous glass, excludes laminated glass.			
Global warming	Increase in the Earth's average temperature produced by the increased concentration of green house gasses in the atmosphere.			
Globe or black bulb temperature	Measurement of a mercury in glass thermometer with the bulb in the centre of a black metal sphere, to obtain an index of combined temperature and mean radiant temperature.	°C		
Globe thermometer	Mercury in glass thermometer with the bulb in the centre of a black metal sphere, used to measure the temperature increase due to radiation from surrounding surfaces.			
Gnomic projection	Projection of the sky vault according to the length of shadow produced by a light ray of given angular altitude.			
Greenhouse gases	Gaseous components of the Earth's atmosphere that reduce the low temperature radiation from the Earth's surface to space, affecting the thermal equilibrium of the planet.		GHG	
Greenhouse	Glazed space used to cultivate plants requiring temperatures higher than the outside air. Glazed spaces acting as a passive solar system to heat adjacent spaces.			
Greenhouse effect	Heating phenomena caused by materials with different transmission of radiant energy emitted by surfaces at different temperatures.			
Heat	Form of energy that is transferred due to difference in temperature.	J, Joule	Q	Crespi, 1980
Heat capacity	Quantity of thermal energy needed to raise a unit mass of material by one unit of temperature.	J/kgK		
Heat loss coefficient	Volumetric coefficient of heat transfer from building interiors to the external air.			IRAM 11605

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Heat losses	Transfer of thermal energy from indoors to outdoors by transmission or ventilation, during the season when outdoor temperatures are below comfort level.			
Heat pump	Machine or device to move heat from one location to another.	-		
Heat storage	The capacity of material to incorporate heat energy when it's temperature increases.	-		
Heating	Systems used to raise indoor temperatures, by natural design strategies or artificial conditioning.	-		
Heating degree days	The annual sum of the differences between the average daily outdoor air temperature and the reference temperature, normally 18° C, when the outdoor air temperature is below the reference temperature; index indicating the duration and severity of the heating season.	DD	*n*	IRAM 11549: 1993, 11603: 1996
Heating strategies	See passive heating strategies.			
Heavyweight construction	Building components with a density of over 1400 kg/m^3 and a surface mass over 300 kg/m^{2,} used to achieve high admittance and heat capacity.			
Heliodon	Equipment to simulate solar impact on buildings, construction details and urban spaces, using scale models, according to time of day, latitude and season.	-		
Height above sea level	Vertical distance between average sea level and the site under study.	m		
Horizontal shading angle	Angle defining the extension of a vertical element that provides shade to an opening.	°		
Horizontal sun shade	Horizontal external element to provide solar protection.			
Hot box	Equipment to measure thermal transmittance of a homogeneous or heterogeneous building element or component.	-		ASTM, C 236: 1989
Hot plate, Guarded hot plate	Equipment to measure thermal conductivity of homogenous materials.			ISO 8302: 1991

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Hot wire anemometer	Instrument to measure low velocity air movement, consisting of two thin wires, an electrical resistance to heat the wire and a thermocouple to measure the temperature. The cooling effect of air movement depends on the air velocity.	-		
Hybrid solar system	Systems for the provision of energy that use solar and conventional sources.			
Hygroscopic material	Material use to absorb the humidity in the air.	-		
Illuminance	Intensity of electromagnetic radiation in the visible spectrum on a surface.	lux		
Illumination	Provision of visible light on working surfaces and building interiors.			
Incidence angle	Formed between the ray incident on a surface and the normal, perpendicular to the surface plane.	°		Evans, 1979
Indoor air quality	Composition and state of air inside buildings that can affect the health, well being and satisfaction of occupants.	-	IAQ,	
Infiltration	Air passing through gaps or cracks in building construction elements that contributes to heat losses and ventilation.			
Infrared radiation	Radiation with wavelengths less than the visible spectrum that transfer heat: wavelengths between 750 nm and 1 mm approximately.			Wikipedia, 2007.
Insulation value of clothing	Scale of the degree to which different clothing assemblies reduce heat loss from the body. 1 Clo = 0.155 m2K/W. An overall insulation or Clo value can be calculated by simply taking the Clo value for each individual garment worn by the person, adding them together. The mean surface area of the human body is 1.70 m2 approximately.	Clo		
Internal gains	Heat produced by occupants, equipment, lighting, etc., that contributes to satisfy the heating demand or increases the cooling demand.	W		
Internal surface resistance	Ability of the indoor building surface and air layer close to the surface to resist the flow of heat, including the effects of convection and radiative heat emission.	m^2 K / W	Rsi	

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Internally reflected component	Portion of natural light received on the working plane from diffuse light from an overcast sky and reflected by internal building surfaces, principally ceiling, floor and walls close to windows.	-		
Interstitial condensation	Transformation of water vapour to liquid due to cooling in the inner layers of building components.	-		IRAM 11625
Irradiance	Intensity of electromagnetic radiation on a surface.			
Kata thermometer	Alcohol in glass thermometer with a large silvered bulb and two indicators, used to determine air movement according to the time taken for the heated bulb to cool between two temperature intervals.			
Kelvin	Scale of temperature based on minimum temperature (absolute zero or -273°C) using the intervals of the Celsius scale from the freezing (0° C) and boiling point (100° C) of water at normal pressure.	K		
Laminated glass	Two or more sheets of glass joined by a transparent or translucent film of PVB in order to achieve a security glass, highly resistant to breakage.			
Latent heat	Change of enthalpy during a change of state of a material.	J/kg	Q	Crespi, 1980
Latent heat of evaporation	Heat required to change a material from the liquid to the gaseous state.	J/kg		Crespi, 1980
Latent heat of solidification	Heat required to change a material from the solid to the liquid state.	J/kg		Crespi, 1980
Light meter	Instrument used to measure levels of incident light.			
Lightweight construction	Building component with low surface mass (< 100 kg/m^2) to achieve low admittance.			
Longitude	Angle to describe the geographical location East or West of the prime meridian or the Greenwich meridian.	°	λ	Wikipedia, 2007.
Low emissivity	Surfaces with a low capacity to transfer heat in the form of radiation at normal temperatures found in buildings.	-	Low e	
Low-e	Superficial treatment of glass surface to reduce the emissivity of heat transmission in the form of radiation from the surface to the air.	-	Low-E	
Lumen	Unit of luminance.	l		

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Lux	Unit of illuminance; one lumen per square metre.	lx	i	
Mahoney Tables	Tables developed by Carl Mahoney to provide guidance on bioclimatic design strategies according to basic climatic data.	-		Koenigs-berger et al, 1970.
Maximum relative humidity	Average value of the maximum relative humidity recorded during a series of days, normally a month, a year or a decade.	%	HR	
Mean maximum temperature	Average of the maximum temperatures recorded during a month.	°C		
Mean minimum temperature	Average of the minimum temperatures recorded during a month.			
Mean radiant temperature	Weighted average temperatures of the building surfaces.	°C		
Mean thermal transmittance	Average heat transfer through heterogamous building components per unit area and unit difference in temperature between the air on both sides of the component, under steady state conditions.			
Medium weight construction	Building components with average superficial density of 100 to 300 kg/m2.			
MET	Scale of the production of metabolic heat, according to physical activity, expressed as a proportion of the metabolic heat produced at rest per unit surface area of the body. 1 Met = 58 W/m^2 the nominal surface area of the human body or Dubois area is considered to be 1,80 m2.			ISO 7730, 1995
Metabolic heat	Heat produced by the human body as a result of muscular activity.		MET	
Microclimate	Local climate conditions, with specific features differing from the general climate of the region, produced by vegetation, buildings and topography.	-		
Minimum relative humidity	Average value of the minimum relative humidity recorded during a series of days, normally a month, a year or a decade.	%	HR	
Minimum ventilation	Minimum renovation of indoor air needed for the health and well-being of the occupants.			
Monolithic glass	see Glass, monolithic.			

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Natural conditioning	Total or partial control of indoor conditions resulting from bioclimatic strategies applied to building design, without recourse to heating or cooling installations with conventional energy.	-		
Natural convection	Air movement to transfer heat produced by the difference in temperature between two masses of air.			
Natural illumination	Lighting of indoor spaces using direct or diffuse solar energy.	-		
Night radiation	Heat emission to the low temperature clear night sky from ground and building surfaces achieving natural cooling.			
Night ventilation	Increase of ventilation during nocturnal hours when the lower outdoor air temperature allows cooling of indoor spaces.			
Non conventional energy	Energy from sources not normally used in conventional applications.			
Olgyay's Bioclimatic Chart	Graph proposed by Olgyay (1970) with a horizontal axis of relative humidity and a vertical scale of dry bulb temperature, showing comfort conditions and zones where different bioclimatic strategies are recommended for application in design.	-		Olgyay, 1970. See Appendix 2
Operative temperature	Weighted average between the air temperature and the mean radiant temperature, used as a simplified scale of thermal comfort.			
Overcast sky	Sky vault covered with clouds or with more than six eights coverage.	-		Evans, 1979
Overhang	External horizontal element that protects openings from direct solar radiation, specially from high angles, rain or snow.	-		
Overheating	Excessive indoor temperatures, usually resulting from high solar gains, and/or internal gains produced by people and equipment.			
Passive architecture	Buildings that achieve comfort through design decisions rather than dependence on active mechanical plant with high energy demand.	-		See Chapter 2 (2.2.2)
Passive cooling strategies	Use of bioclimatic design resources to lower the indoor temperature, or apparent temperature, such as evaporative cooling, air movement, selective night ventilation, and radiant cooling to a cold night sky.			

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Passive heating strategies	Use of bioclimatic design resources to raise the indoor temperature, or apparent temperature, such as direct and indirect solar gains, use of internal heat load, complemented by thermal insulation and incorporation of thermal mass and reduction of ventilation rate.			
Passive solar architecture	Buildings designed to optimise the use of energy from the sun, using natural heat transfer mechanisms, of convection, conduction and radiation.	-		See Chapter 2 (2.2.2)
Passive solar systems	Energy devices that transform energy from the sun without additional conventional energy sources.			
Periodic heat flow	Variable energy flow through a construction component subject to a sinusoidal variation in the external air temperature.			
Permeability, Moisture permeability	Quantity of water vapour in unit time, passing through a unit surface area of a building element or construction layer with unit difference in water vapour pressure between the two opposing parallel surfaces.	gm/m.h.kPa	δ	IRAM 11.601 & 11549
Permeance	Quantity of water vapour in unit time, passing through a unit surface area of a building material of unit thickness with unit difference in water vapour pressure between the two opposing parallel surfaces.	Gm / m^2 . h . kPa	Δ	
Phase change materials	Substances used to store large quantities of heat energy with small temperature changes using latent heat of fusion.			
Photometer	Instrument use to measure levels of incident light.	-		
Photovoltaic, Photovoltaic panels	Chemically prepared surfaces in panels used to produce electricity from solar radiation.		FV (PV en ingles)	
Plain glass	see Glass, plain.			
Polyvinyl Butiral	Plastic film used to join to glass sheets to form laminated glass.		PVB	
Predicted Mean Vote	Subjective sensation index likely in a sample population, measured on a scale from -3 Cold, 0 thermal neutrality, +3 hot.	non dimensional	PMV	ISO 7730
Predicted Percentage Dissatisfied	Proportion of the population considered to be dissatisfied with the thermal conditions.		PPD	ISO 7730

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Psychometric diagram	Graph showing the physical and thermodynamic properties of gas vapour mixtures, especially water vapour and air mixtures.			
Pyranometer	Instrument for measuring the intensity of solar radiation.	-	-	
R value	Total thermal resistance of a building element, equal to the sum of the resistances of each layer.			
Radiative cooling	Temperature reduction of a surface due to outgoing radiation; for example, to a 'cold' night sky.			
Rainfall	Precipitation of water on the Earth's surface, including rain, snow and hail.			
Reflection, solar radiation	Fraction of solar radiation incident on a surface not absorbed or transmitted. The sum of reflected, absorbed and transmitted light is unity.	%	*r*	
Reflection, visible light	Fraction of visible light incident on a surface not absorbed or transmitted. The sum of reflected, absorbed and transmitted light is unity.	% (fraction)	*r*	
Reflective glass	Glass with metallic particles in the body or with surface treatment to reduce solar heat gains.			
Reflective glass	Glass with surface treatment to achieve high reflectivity of visible and near infrared radiation.			
Reflectivity	Surface property indicating the proportion of electromagnetic radiation not absorbed.			
Relative air velocity	Speed of air movement relative to the movement of an object. For a stationary object this is the air velocity, for a person walking it is the speed of the air relative to the movement of the person.	m/s		See air velocity
Relative humidity	Quantity of water vapour in a given air volume, compared with the maximum possible water vapour content at the same temperature and pressure.	%		See absolute humidity
Relative sunshine duration	Daily hours of direct sun, as a proportion of the maximum possible number of hours.	%		See hours of sunshine
Renewable energy	Power sources that avoid depletion of fossil or non-renewable fuels, specially sun, wind, water and geothermal resources.			
Renovation of indoor air	See air changes.	non dimensional	n	Crespi, 1980

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Resistance of air cavity	The capacity of an air gap in a multiplayer building element to reduce the heat flow.	m2K/W	Rc	
Resistivity	The reciprocal of conductivity.			
Rock bed heat storage	Large stones used to store heat from a flow of warmed air and release the heat later, for example, in solar heating systems storing daytime heat for night time.	-		
Safety glass	Laminated or tempered glass used to avoid breakage or dangerous splinters.			
Sea breeze	Air movement at regional scale produced by the difference in surface temperature between sea and land.	-		
Sealed double glazing units	Two glass panes with a sealed low absolute humidity air space between them, in order to achieve a low thermal transmittance.		DHV	
Selective surface	Material with significant difference between absorption of high temperature solar radiation and low temperature emission from the same surface.			
Selective ventilation	Controlled and variable ventilation to take advantage of favourable differences between indoor and outdoor air temperature to cool or heat buildings.			see night ventilation
Shading coefficient	Fraction that allows a comparison between the transmission of solar radiation of different glass systems: the total solar radiation transmission divided by the total transmission of a clear 3 mm glass sheet.	Non dimensional	CS	
Silk screen printing (on glass)	Ceramic pigment baked onto the surface of glass to reduce solar transmission, provide privacy or control light levels.			
Sol-air temperature	Air temperature producing the same heat transfer through a building element as a given air temperature and intensity of incident solar radiation.	°C	t_e	CIBSE
Solar altitude	Angle formed by the direct solar ray and the horizontal plane. With higher angles, the atmospheric absorption is reduced.	°		
Solar architecture	Buildings designed to optimise the use of energy from the sun, both ‘active’, requiring additional energy to transfer heat, and ‘passive’, using natural heat transfer mechanisms.	-		see Chapter 2 (2.2.2)

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Solar constant	The incoming radiation energy from the sun per unit area, measured at the other extreme of the earths atmosphere totalling about 1366 W/m^2, about half of which is in the visible spectrum.	-		
Solar energy	Radiant electromagnetic power emitted by the sun.			
Solar envelope	Maximum extent of a building form that allows a defined degree of solar access to adjacent buildings and ground surfaces.			
Solar factor	Coefficient between the total solar radiation incident on the surface of a translucent or transparent material and the energy transmitted through the material.	%	FS	
Solar heat factor	Proportion of radiant energy from the sun transmitted through a glazing system.	%	SF	
Solar incidence	Direct radiation received on a surface in urban spaces, on facades or through window openings.	-		
Solar radiation	Electromagnetic radiation form the sun.			
Solar radiation transmission	Proportion of solar radiation transmitted through a translucent or transparent material.	non dimensional	τ	
Solar trajectory	Path of apparent sun movement across the sky.			
Specific heat	Energy needed to raise the temperature of a given amount of a substance by one degree.	J/kgK	Q	Crespi, 1980
Specific heat capacity	Measure of heat energy required to raise the temperature of a given amount of a substance by one degree.	J/Kg k	C	
Spectrum of visible radiation	Wavelengths of between approx. 400 to 700 nm producing a sensation of light when falling on the retina of the human eye.			
Specular reflection	Mirror like change of direction of light in which the incoming light is reflected in a single outgoing direction, making the same angle with respect to the surface normal, a line perpendicular to the surface.			
Stack effect	Vertical air movement as a result of pressure differences between two air volumes at different temperatures.			

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Standard overcast sky	Overcast sky with a luminance distribution that varies with altitude according to the standard of CIE, the Comisión Internacionale de L'Eclairage. This distribution is established for daylight calculations.	-		
Steady state heat flow	Constant energy transfer through a building element due to a constant temperature difference between the indoor and outdoor temperature.			
Stereographic projection	Projection of the sky vault onto a two dimensional horizontal plane in such a way that circular arcs on the sky vault are projected as arcs of circles on the projection plane.			
Stevenson's screen	Small space with white painted louver walls, and insulated white roof, raised on 1,25 m high columns for measurements at meteorological stations.			
Summer solstice	Date of the year when the sun is over the tropic closest to the latitude of the location under study.			
Sun path diagram	Two-dimensional figure that represents a projection of the suns path across the sky, usually for specific latitude.			
Sundial	Device to obtain the hour of day according to the solar azimuth and altitude in different seasons of the year. Also used to obtain the angular impact of the sun on scale models of buildings.			
Sunshade	External element, partially or totally intercepting solar radiation on glazed openings.			
Sunspace	Glazed room or gallery facing winter sun performing as a passive solar system to heat adjacent rooms, suitable for intermittent use and plant cultivation.			
Superficial condensation	Liquid produced from water vapour on cold surfaces below the dew point of air.	-		IRAM 11625
Surface identification (glass)	Numbering system to identify the surfaces of glazing systems, starting from the outside to the inside.			
Sustainability	Concept referring to responsible management based on resource efficiency and ecological principles. Quality of processes and procedures used to minimise future environmental, social and economic impacts.			de Schiller, 2004

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Sustainable architecture	Architecture aiming to reduce or minimise environmental, social and economic impacts.	-		See Chapter 2 (2.2.2)
Sustainable development	Development that meets the needs of current generations without compromising the ability of future generations to meet their needs and aspirations.			WCED, 1987, Bruntland Report
Temperature	A physical property of a system that indicates the degree of coldness or heat.	°C		
Tempered glass	Security glass with a high temperature treatment to achieve resistance to breakage four times higher than common glass, as well as reducing the danger of sharp splinters.			
Thermal balance	Temperature level at which heat losses and heat gains of a building are equal.			
Thermal bridge	Section of the building envelope that transmits a high proportion of heat when subject to a indoor-outdoor temperature difference, increasing heat losses in cold seasons and possible surface condensation.			
Thermal capacity	Quality of materials to store or emit heat energy when subject to temperature change.	J/KgK		
Thermal characteristics	Physical properties of a building material that determine the energy transfer performance and temperature variations.	-		
Thermal comfort	Environmental conditions that favour the thermal equilibrium of the human body and create a sensation of neutrality while promoting user satisfaction and well-being.	-		ISO7730
Thermal inertia	Physical analogy relating the volumetric heat capacity to the temperature change resistance of a building material.			
Thermal load	Energy needed to raise or lower the temperature of a space to the design value.	T (tons)		
Thermal resistance	Reciprocal of conductance.			
Thermal resistivity	Reciprocal of the conductivity.	m K / W	R	
Thermal sensation	Subjective evaluation of the degree of heat or cold of environmental conditions.			
Thermal swing, thermal amplitude	Difference between maximum and minimum temperatures of a space in a period of temperature variation.	Kelvin		

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Thermal transmittance	Heat flow per unit area of a building element with a unit difference in temperature between the air on opposing sides.	W / m^2 K	K	
Thermal zoning	Division of buildings in sectors with similar thermal characteristics in order to calculate, design and/or install artificial conditioning systems.			
Thermo-syphon	Heat flow produced by natural convection currents with ascending warm fluids and descending cooler fluids.			
Time constant	Difference in time between an instantaneous change in air temperature on one side of a building element and a change of temperature of 63.2% of the step change. A first order frequency response.	hours	Q/C	
Time lag, thermal delay	Difference in time between peak sinusoidal variation on one side of a building element and the resulting peak on the other side.			
Transmission of solar radiation	Proportion of incident solar radiation transmitted through a translucent or transparent material.			
Transparent Insulation Material, TIM	Thermally insulating and translucent or transparent material that allows incident solar energy to be transmitted to an absorbent surface of solar collectors while reducing heat losses from the heated surface to the outside air.	-		
Transpiration, sweat	Secretion of liquid on the skin surface to improve cooling by evaporation.			
Trombe wall	Passive solar system consisting of a high-density wall with outer dark coloured surface, air gap and external glazing. The system absorbs and stores heat which is transferred to the indoor surface with a time lag, while the air gap and glazing reduce heat loss to the outside air.	-		Wikipedia, 2007.
U value	Thermal transmittance of an external building component, indicating the steady state heat flow through each square metre according to the temperature difference between indoor and outdoor air.	W/m2K	U	

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Ultraviolet radiation	Electromagnetic energy with a wavelength shorter than visible light between 400 nm and 1 nm. Can degrade organic materials and fade colours.		UV	Wikipedia, 2007.
Ultraviolet transmission	Proportion of incident electromagnetic energy in the spectrum between 400 and 1 nm passing thorough a translucent or transparent material.			
Urban heat island	Area of increased temperature in cities caused by energy use in buildings and transport and the storage of heat in building materials and urban surfaces.			de Schiller, 2004
Useful solar energy	Heat received from the sun replacing conventional energy for heating, hot water and other applications.			
Vane anemometer	Instrument to measure air velocity, consisting of a freely rotating propeller and a revolution counter.	-		
Vapour barrier	Film or sheet of very low permeability material in a building component that reduces or prevents transmission of water vapour from warmer to colder layers, reducing or eliminating internal condensation.	-		Mazria, 1978
Vapour break	Film or sheet of low permeability material in a building component that reduces the transmission of water vapour from warmer to colder layers, reducing or eliminating internal condensation.	-		Norma IRAM 11.601
Ventilation	Exchange of indoor and outdoor air using natural or forced air movement.	non dimensional	n	
Vertical cylindrical projection	Projection of the sky vault onto a vertical cylinder.			
Vertical projection	Projection of the sky vault on a flat plane, where distances from the centre of the diagram are proportional to the cosine of the angular altitude.			
Vertical shading angle	Angle defining the extension of a vertical element that provides shade to an opening.	°		
Vertical sunshade	Element of solar protection in the vertical plane.			
Visible light transmission	Proportion of visible light incident on the surface of a translucent or transparent material that passes through the material.	non dimensional %	T %	
Visible radiation	Light in the spectrum between about 380 to 780 nm, which can be detected by the human eye.			

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Visual comfort	Control of contrast and adequate levels of illumination to favour user satisfaction and productive working conditions.	-		
Volumetric heat capacity	The ability of a given volume of a substance to store or release heat when undergoing temperature change. Amount of thermal energy needed to raise the temperature of a unit volume of a material by a unit interval of temperature.	J/m3K		IRAM 11549
Volumetric heat loss coefficient	Coefficient of heat loss of a building expressed as the flow of heat per unit volume of the building.	W/m3		IRAM 11605
Waterproof breather fabric	Film or fabric that is impermeable to water in the liquid state, while permeable to water vapour. Used in roofs and walls to avoid ingress of water, while allowing water vapour to escape, avoiding interstitial condensation.			
Watt	Unit of energy flow, produced by a joule in one second.	W	q	
Wet bulb temperature	Temperature of mercury in glass thermometer with the bulb covered by a wetted fabric indicating the depression of temperature due to evaporation.	°C		
Wet bulb thermometer	Mercury in glass thermometer with the bulb covered by a wetted fabric used to indicate the depression of temperature due to evaporation.			
Wind break	Rows of trees, or other preferably partially permeable obstacles, designed to provide protection from high winds.	-		
Wind frequency	Number of observations of air movement in a specific direction in a specified period such as a month or year, usually expressed as a proportion of 1000 observations.	‰		
Wind tunnel	Equipment for simulating air movement around buildings, vehicles or aircrafts.			
Wind velocity	Speed of air movement over the earth's surface, usually measured at a height of 10 metres above the ground.	km/hr	V	
Winter solstice	Instant of the year when the altitude of the sun at midday is at the lowest angle and vertically above the latitude of the tropics in the opposing hemisphere.			

Glossary and definitions (continued)

Term	Definition	Units	Symbol	References
Wired glass	Glass with a wire mesh incorporated in the mass of the glass during manufacture used to retard the propagation of flame.			
Working plane	Horizontal surface, 75-80 cm high, which requires natural or artificial lighting.			
Zenith	Point in the sky vault directly above the observer, corresponding to an angular altitude of 90°.	-		

Notes on the glossary

- In order to facilitate comprehension, many of the definitions refer to applications in buildings rather than the general use of the terms in physics.
- The Wikipedia, 2007. http://en.Wikipedia, 2007..org/wiki/Main_Page has been extensively used as a source to verify definitions, despite the possibility of contentious material. It is also recommended as a source of further information, in the cases noted specifically in this glossary.

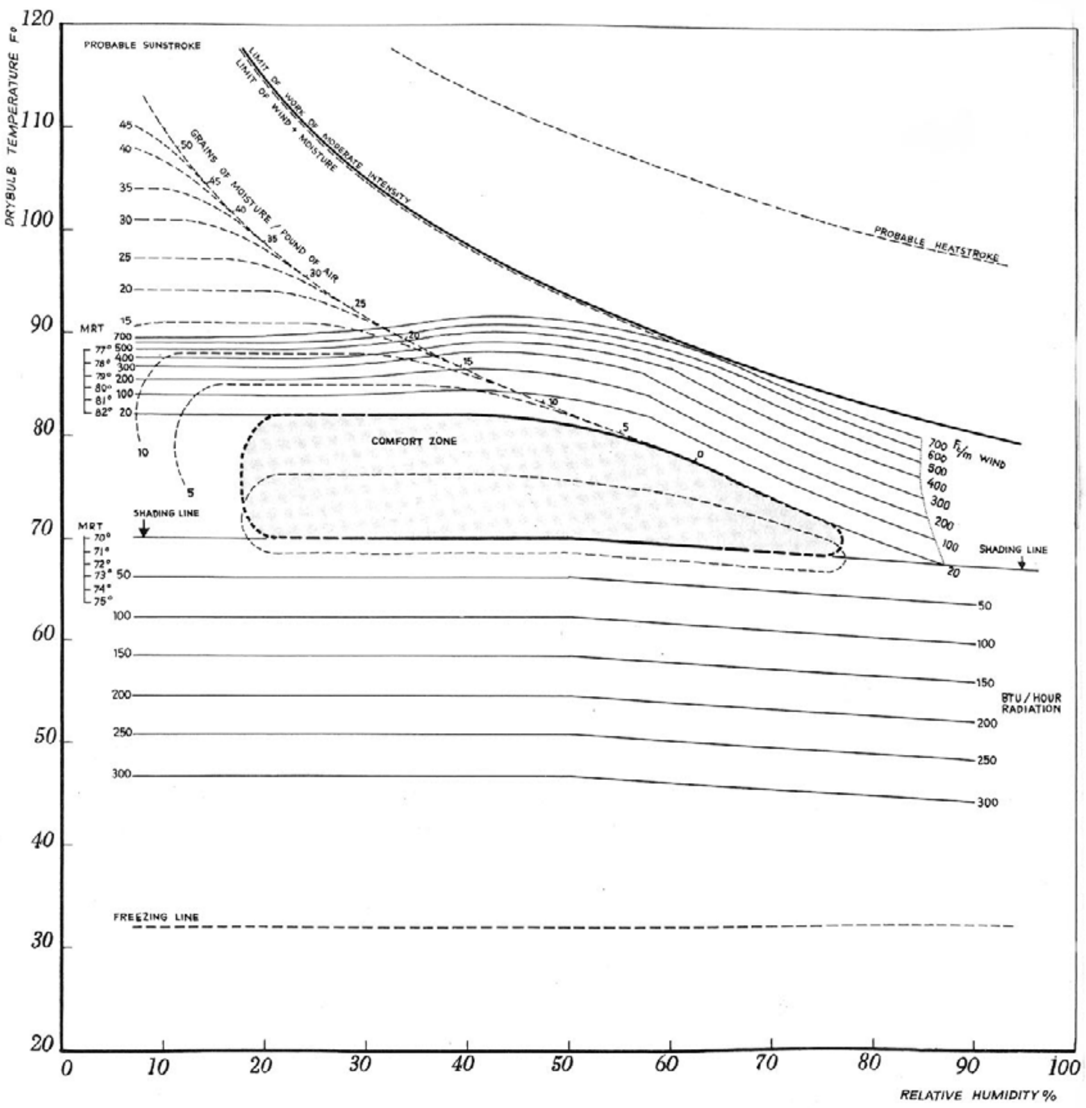
APPENDIX 2

2A. BIOCLIMATIC CHARTS AND GRAPHS.

2A.1 INTRODUCTION.

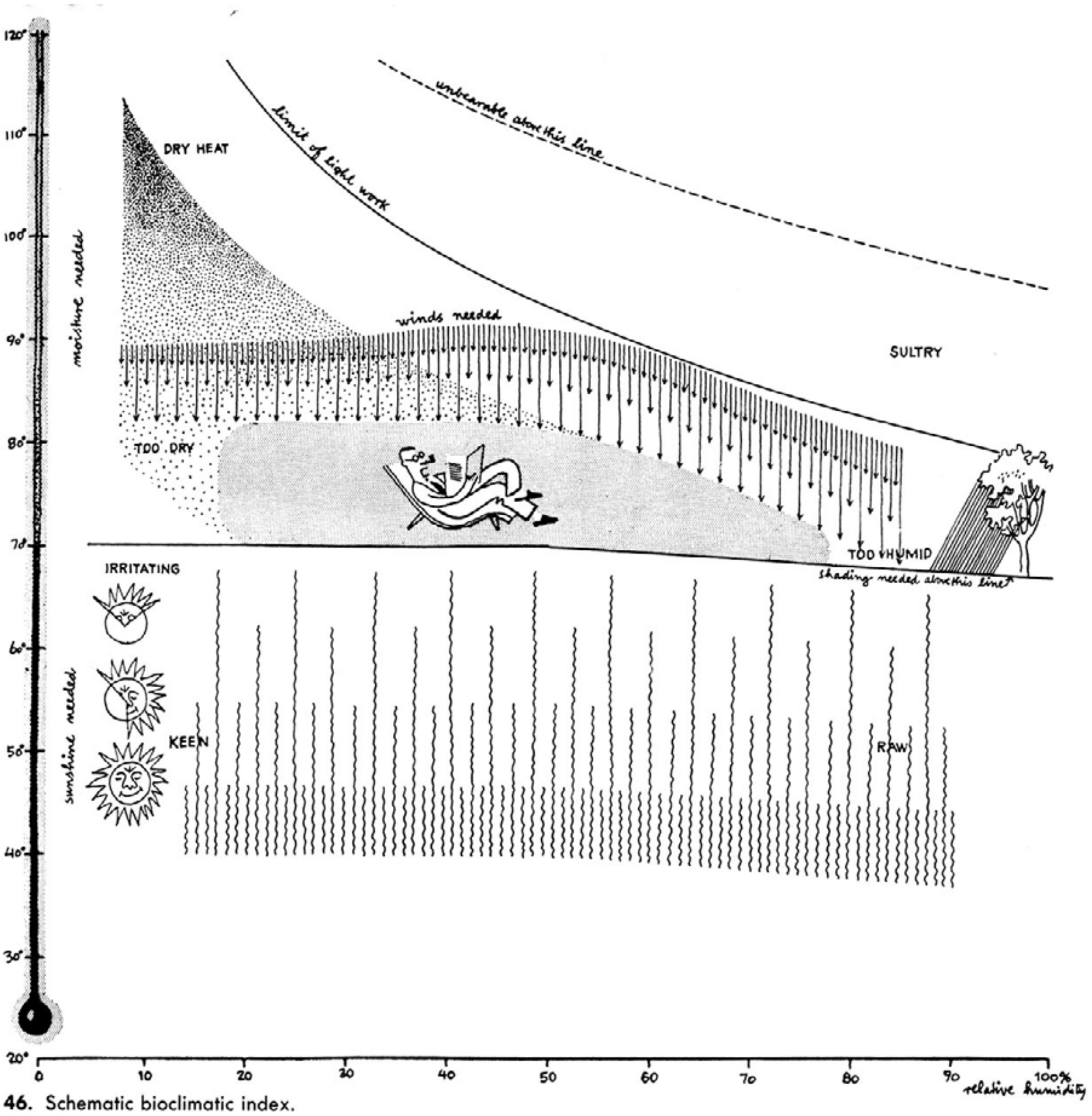
This appendix presents and compares the principle comfort graphs and charts mentioned in the text, in order to provide a comparative context for the comfort triangles developed in this thesis.

2A.2 OLGYAY'S BIOCLIMATIC CHART



45. Bioclimatic Chart, for U.S. moderate zone inhabitants.

Figure A2.1. Olgyays Bioclimatic chart scaned from Design with Climate Figure 45 (Olgyay, 1967)



46. Schematic bioclimatic index.

Figure A2.2. Schematic version of Olgyays Bioclimatic chart scaned from Design with Climate Figure 46 (Olgyay, 1967)

Olgyay's Bioclimatic chart, with relative humidity on the horizontal scale and temperature on the vertical scale, combines climate data, comfort conditions and bioclimatic design recomendations. This text also relates extreme sectors of the diagram to incidence of health problems such as sunstroke and frostbite. The scope and presentation of this chart contributed to it's position as one of the first and most influential of bioclimatic charts.

2A.3 GIVONI’S BIOCLIMATIC CHART

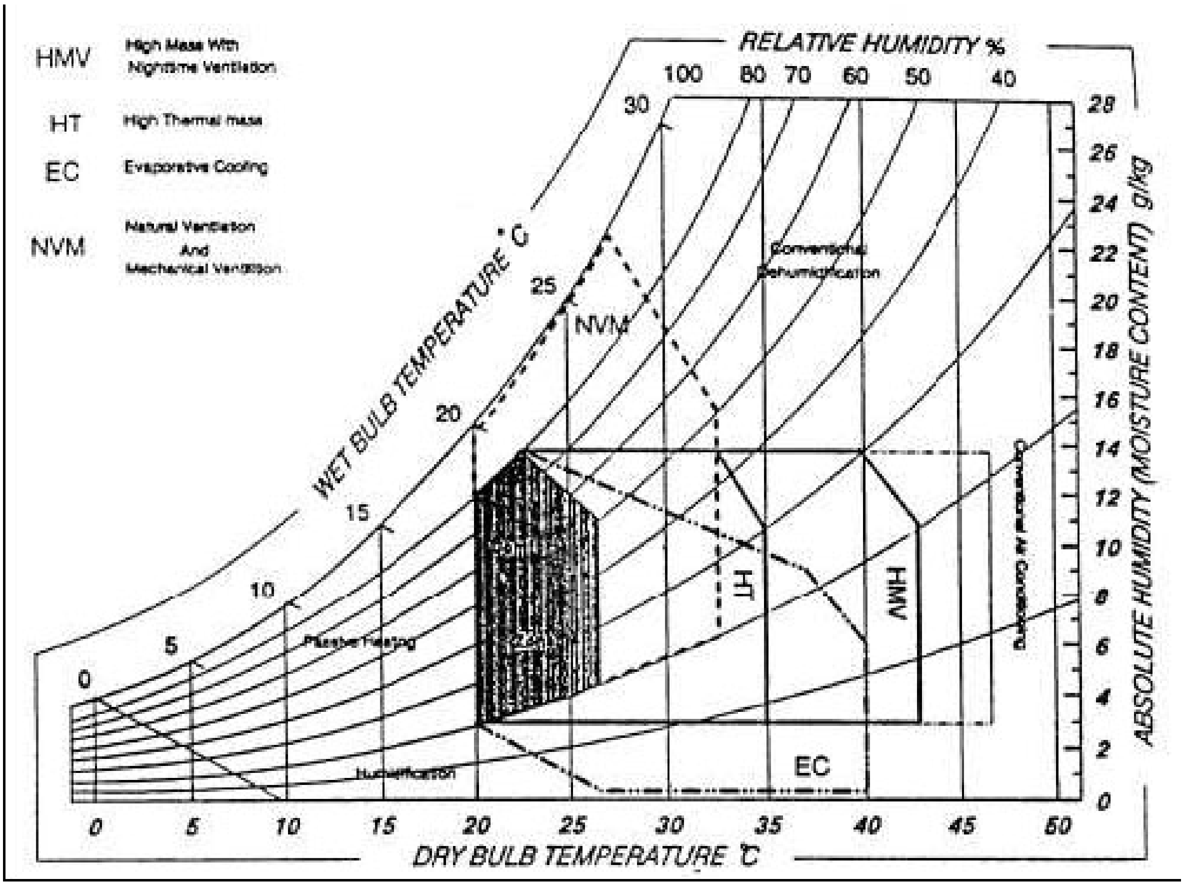


Figure A2.3. Givoni’s Bioclimatic chart scaned from Man, Climate and Architecture Figure XX (Givoni, 1969)

This graph, with dry bulb temperature on the horizontal scale and absolute humidity on the vertical scale, provides more detailed design recomendations in specific environmental zones.

2A.4 COMFORT TRIANGLES

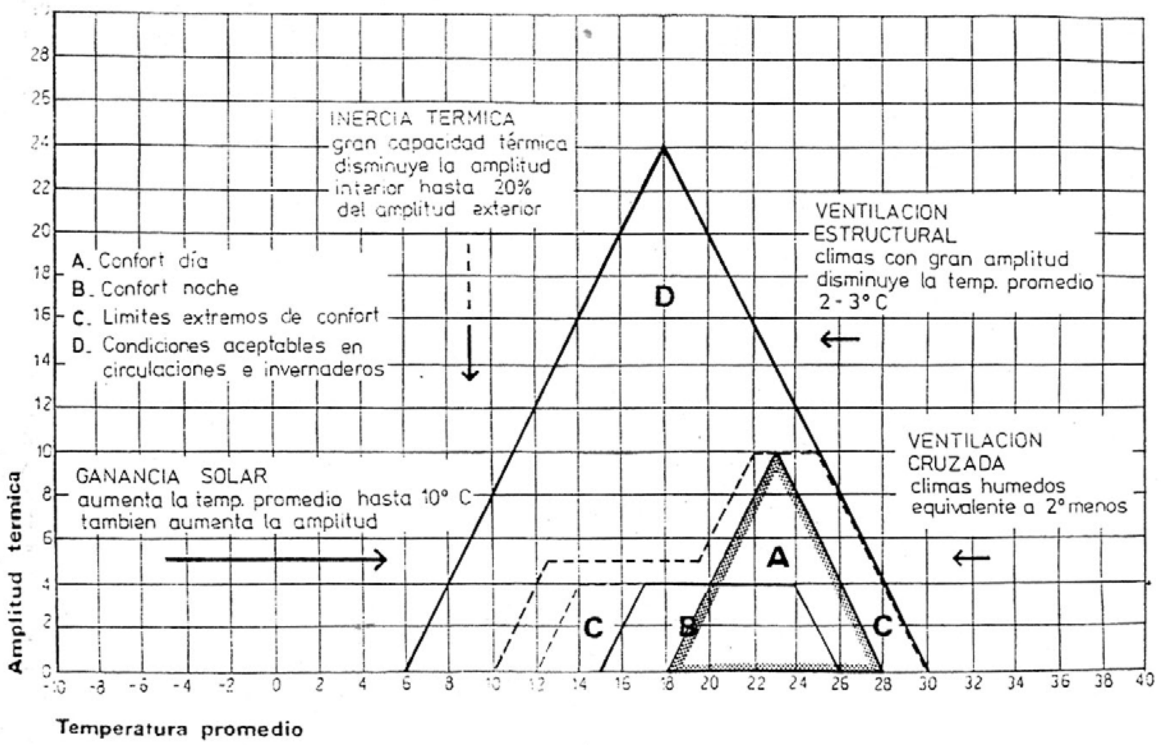


Figure A2.4. The first version of the comfort triangles scaned from Diseño Bioclimatico y Arquitectura Solar, Figure 3.3 (Evans & de Schiller, 1988)

Translation of the spanish comments:

A. Confort día: Day comfort
B. Confort noche: Night comfort
C. Limites extremos de confort: Extreme comfort limits
D. Condiciones aceptables en circulaciones e invernaderos: acceptable copnditions for circulation and sunspaces

Ganancia solar: Solar Gains increase in average temperature up to 10°C also increases the swing.
Inercia térmica: large internal thermal mass reduces the swing to less than 20% of the outdoor swing.
Ventilación estructural: 'Structural ventilation' (better called selective ventilation) Climates with large swings, reduces the average temperature by 2- 3° C.
Ventilación cruzada: Cross ventilation 2° C temperature reduction in humid climates.

2A.5 FANGER'S SCALE OF THERMAL COMFORT

The scale developed by Fanger (1973) and incorporated in ISO Standard 7730 (ISO, 1994) is based on a formula to indicate PPD, Predicted Percentage Disatisfied and PMV, Predicted Mean Vote, using the 7 point ASHRAE scale. These are related by a graph, Figure 2A.5, showing the minimum percentage disatisfied at 5 %, with a PMV of 0, neutral thermal sensation, while at +3 and -3, hot and cold respectively, the PPD is 100%. However this is not a bioclimatic chart, as the Fanger scale does not directly relate climate and comfort to bioclimatic design strategies

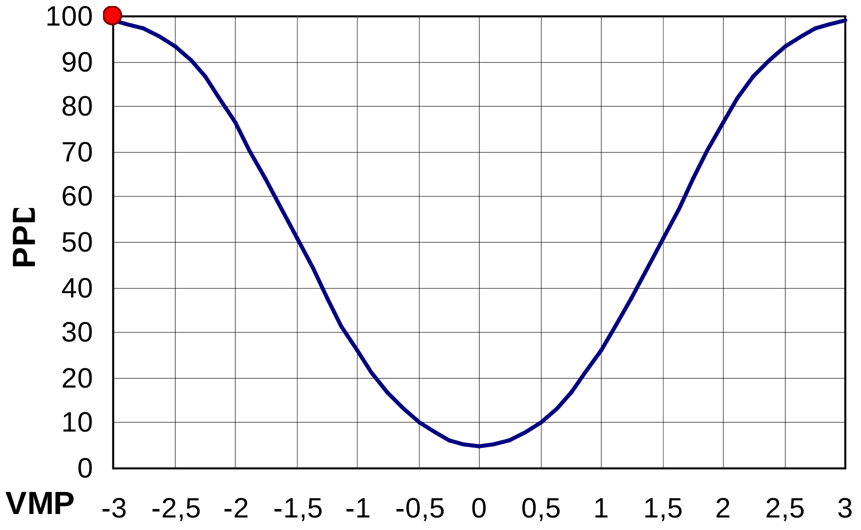


Figure 2A.5. Relation between PMV and PPD, ISO standard 7730 (1994).

Based on the graphs presented in the PMV Tool (Marsh, 2007), it is posible to show the relation of each of the environmental variables with the PMV. In this case, the base values and range of variables used in the analysis are shown in Table 2A.1.

Table 2A.1. Variable used to develop the PMV graphs in this section of Appendix 2

Variable	Base value	Maximum	Mínimum	Units
Dry bulb temperature	25	15	35	° C
Mean radiant temperature	25	15	35	° C
Relative humidity	50	0	100	%
Air movment	0,5	1	1	m/s
Clothing	0,84	Without variation		Clo
Activity level	1,09	Without variation		Met

The base values are chosen to represent comfortable indoor conditions, while the range shows possible variations, considering probable extremes of indoor conditions. Velocities of over 1 m/s are considered undesirable indoors, while the range of relative humidity includes values below 30% and above 85%, likely to be percieved as uncomfortable.

Figure 2A.6 to 2A.9 show respectively the effect of air temperature, mean radiant temperature, relative humidity and air movement on PMV.

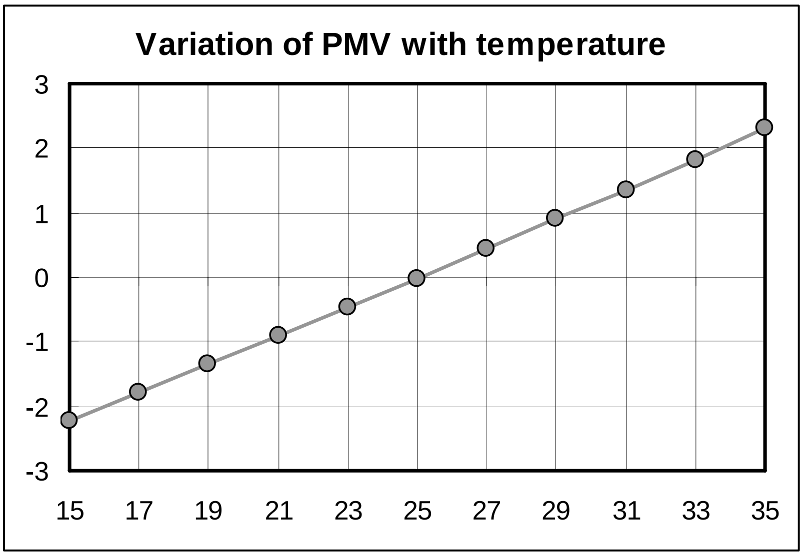


Figure 2A.6. Effect of changes in air temperature from 15 to 35°C, horizontal scale, on the PMV from -3, cold to +3 hot on the vertical scale.

Figure 2A.6 shows that the variations in air temperature within the range found in buildings has an important and primary impact of the PMV.

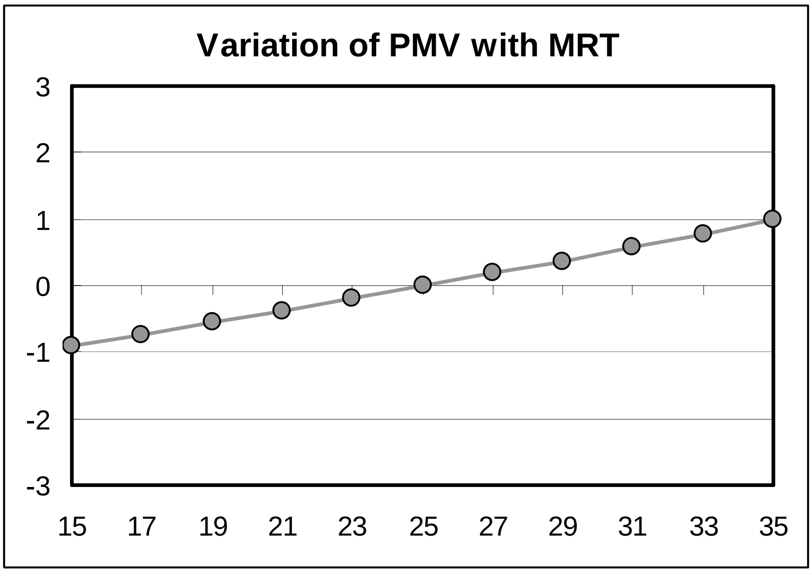


Figure 2A.7. Effect of changes in mean radiant temperature from 15 to 35°C, horizontal scale, on the PMV from -3, cold to +3 hot on the vertical scale.

As Figure 2A.7 shows, the variation in mean radiant temperature has less effect than the same variation in air temperature.

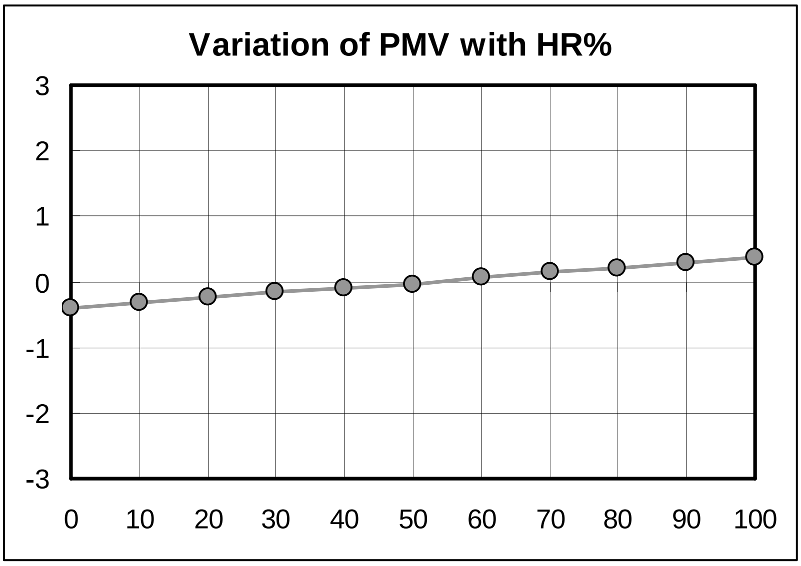


Figure 2A.8. Effect of changes in relative humidity from 0 to 100 %, horizontal scale, on the PMV from -3, cold to +3 hot on the vertical scale.

Figure 2A.8 shows the relatively small impact of relative humidity on PMV, which ranges within the range of +0,5 to -0,5, considered thermally neutral or comfortable.

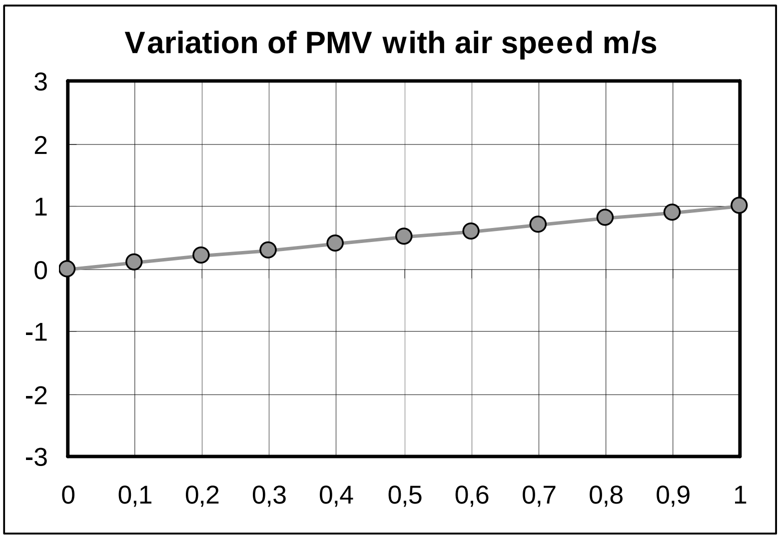


Figure 2A.9. Effect of changes in air movement from 0 to 1 m/s, horizontal scale, on the PMV from -3, cold to +3 hot on the vertical scale.

Air speeds within the limits appropriate for indoor conditions also have little effect on the PMV, with a range of values similar to those found for relative humidity variations, as Figure 2A.9 shows.

Conclusions: The analysis of environmental variables using PMV presented here supports the assumption implicit in the comfort triangles that relative humidity has little direct impact on thermal comfort. This conclusion is also valid for different values of clothing insulation and metabolic activity. The indirect relation between humidity and thermal swing is also important, with low humidity related to higher swings, as explained in Chapter 7. The effect of humidity on the sensation of dryness or high humidity is a separate factor that affects the sensation of well-being, related to non thermal aspects such as water loss due to sweating, discomfort from wet skin, dry throat and sore eyes.

Curriculum Vitae

Name:	**John Martin Evans**
Date of birth.	29th February, 1944,
Place of birth:	Sutton and Cheam, Surrey, United Kindom
Secondary education:	St Johns School, Leatherhead, Surrey, United Kingdom 1957-1961.
Tertiary education	Full time recognised course of architecture, Architectural Association School of Architecture, London. 1961 – 1966 Including: 1 year student exchange programme, Kumasi University of Science and Technology, Kumasi, Ghana, Africa. 1964-65 . 1 year full time specialization course leading to the Certificate of Tropical Architecture, Department of Tropical Studies, AA School of Architecture, London. 1965-66 Diploma of the Architectural Association, awarded 1966.
Profesional activities	Chartered Architect, member of the Royal Institute of British Architects, registered with the Architects Registration Board, United Kingdom since 1976. Life member of the Architectural Association, London. Profesional activities in architecture and planning carried out in the United Kingdom, Libya, Kuwait, Saudi Arabia and Argentina. Consulting activities in the field of bioclimatic and energy efficient design for projects in Argentina, Armenia, Costa Rica and Spain.
Academic activities	Professor of Architecture, Faculty of Architecture, Design & Urbanism, University of Buenos Aires since 1984. Co-founder of the Research Centre Habitat and Energy, University of Buenos Aires and Director since 1987.

PROPOSITIONS
John Martin Evans

1. The current trend of architectural education, which uses the project as a medium for integration, with difficulties in the transfer and incorporation of technical expertise, particularly in energy and environmental issues, requires new integration techniques to apply this knowledge in the design process.
2. Architectural training places a strong emphasis on three dimensional manipulation of form, visual comunication and graphic skills, however special techniques are required to explain non-visual phenomena such as thermal performance, heat flow and air movement, and promote the use of these resources in design.
3. The global impact of architectural and urban design trends, originating in developed countries, requires special and selective interpretation to provide the necessary incentive to achieve energy efficiency and passive design for thermal comfort, especially in warmer climates of tropical and sub-tropical zones in the less developed regions.
4. Conventional bioclimatic charts define comfort zones according to temperature and humidity in steady state or instantaneous conditions; however, the use of the daily temperature swing as a variable introduces dynamic thermal performance and temporal factors, also illustrating the potential moderating effect of periodic heat flow in explicit form, overcoming the limitations of conventional approaches.
5. The development of a graphic design tool that combines average temperature and daily temperature swing as variables, in the form of the Comfort Triangles, provides design guidance to improve the dynamic thermal performance of buildings in relation to climate impact and comfort requirements during the design process.
6. Successful application of the bioclimatic design process integrates the cumulative thermal performance of the built environment at three scales: urban, building and detail design.
7. Passive and low impact architecture, which incorporates bioclimatic design strategies using periodic heat flow, will become more important in the future as a consequence of accelerating climate change and increasing global warming.
8. The origins of building science were based on conditions found in the cool and cold climates of Northern Europe, especially the thermal and lighting conditions; the application of this body of knowledge in the warm and hot climates of the developing world still demands a change of emphasis to respond to the different environmental requirements.
9. The visual properties of glass, with a high level of transparency to radiation in the visible spectrum, which promote natural daylight and indoor - outdoor spatial integration, have a strong appeal in design, while the impact of transparency to high temperature thermal radiation and limited transmision of low temperature radiation, the original ‘green-house effect’, has little influence on design decisions.
10. The development of powerful, user friendly, integrated and accessable numerical simulation models for predicting and improving thermal, lighting, and energy behaviour of buildings, provide effective evaluation tools, but the expected improvement in the environmental performance of architectural design has still not been acheived.

Stellingen

John Martin Evans

1. De tegenwoordige trend in de architectuuropleidingen, waarbij het project als middel van integratie wordt gebruikt, maakt het moeilijk om technische expertise vooral op het gebied van energievraagstukken en milieu over te dragen. Een nieuwe integratietechniek is nodig om deze kennis in het ontwerpproces toe te passen.

2. Bij ontwerpoefeningen wordt een grote nadruk gelegd op de drie dimensionale bewerking van vormen, op visuele communicatie en op grafische vaardigheden. Echter, speciale technieken zijn vereist om niet-visuele fenomenen zoals thermische prestaties evenals warmte en luchtstromingen te tonen en in het ontwerp te gebruiken.

3. De globale impact van stromingen in architectuur en stedenbouw die uit de industrielanden voortkomen, vraagt om een specifieke en selectieve interpretatie om de nodige stimulans voor energiebezuiniging en passieve thermische ontwerpconcepten te genereren, vooral in het warmere klimaat van tropische en subtropische zones in minder ontwikkelde landen.

4. Conventionele representaties van het bioklimaat bepalen comfort zones op basis van temperatuur en luchtvochtigheid onder stabiele omstandigheden. Echter, het gebruik van de dagelijkse temperatuurverschillen als variabele introduceert dynamische thermische prestaties en tijdelijke factoren, toont expliciet het in potentie matigende effect van periodieke warmtestromingen en overwint de beperkingen van conventionele benaderingen.

5. De ontwikkeling van een grafisch ontwerpinstrument, dat gemiddelde temperatuur en dagelijkse temperatuurverschillen in de vorm van een comfort driehoek met elkaar combineert, maakt het mogelijk om de dynamische thermische prestaties van gebouwen gerelateerd aan klimaatcondities en aan comfort eisen tijdens het ontwerpproces te verbeteren.

6. De succesvolle toepassing van het bioklimatisch ontwerpproces integreert de cumulatieve thermische prestaties van de gebouwde omgeving op drie niveaus: op het niveau van het stadsontwerp, het gebouwenontwerp en het detailontwerp.

7. Passieve en minder milieu belastende architectuur die op dynamische bioklimatische ontwerpstrategieën gebaseerd is, zal in de toekomst steeds belangrijker worden onder de condities van versnelde klimaatveranderingen en toenemende opwarming van de aarde.

8. De oorsprong van de bouwfysica is gebaseerd op condities die in het koele klimaat van Noord Europa bestaan. Dit geldt in het bijzonder voor de thermische en de lichtcondities. De toepassing van deze kennis in het warme klimaat van ontwikkelingslanden vraagt om aanpassingen aan andere milieueisen.

9. De visuele eigenschappen van glas met zijn hoge graad aan doorzichtigheid die daglichttoetreding en de integratie van binnen en buiten ondersteund, spelen een grote rol in het ontwerpproces. Echter, de transparantie voor hoge temperatuurstraling en de isolerende werking bij lage temperaturen (het bekende ‘glashuis effect’) hebben nauwelijks invloed op ontwerpbeslissingen.

10. De ontwikkeling van krachtige, gebruikersvriendelijke, geïntegreerde en toegankelijke numerieke simulatie modellen voor de voorspelling en de verbetering van eigenschappen van gebouwen ten aanzien van warmte, licht en energiegebruik heeft tot effectieve evaluatie instrumenten geleidt. De verwachte verbetering van de milieuprestaties van het architectonische ontwerp is echter nog niet bereikt.