INSTITUTO DE ARQUITECTURA TROPICAL

THE COMFORT TRIANGLES: A NEW TOOL FOR BIOCLIMATIC DESIGN

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Chapter 12

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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 selfhelp 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.

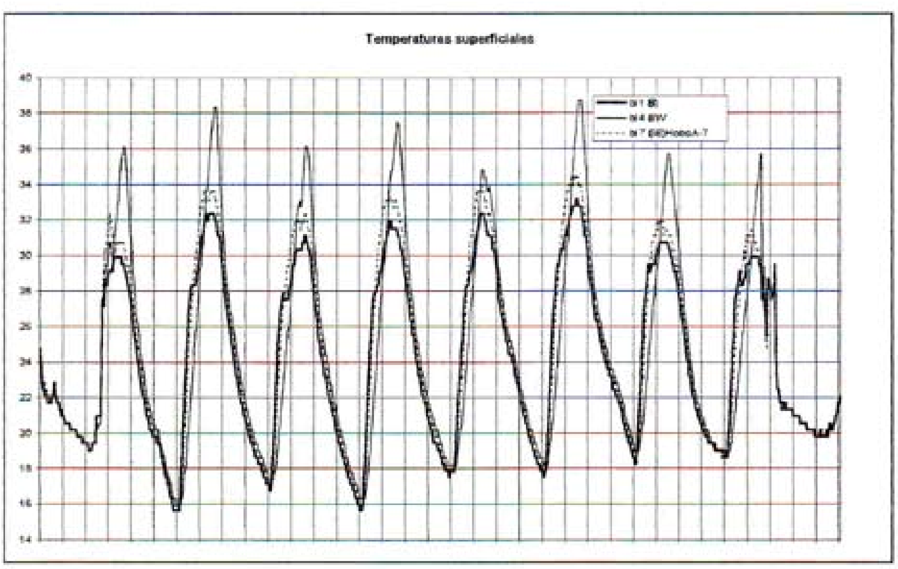

Figure 12.2. Registers of surface temperatures in the three rooms of the house.

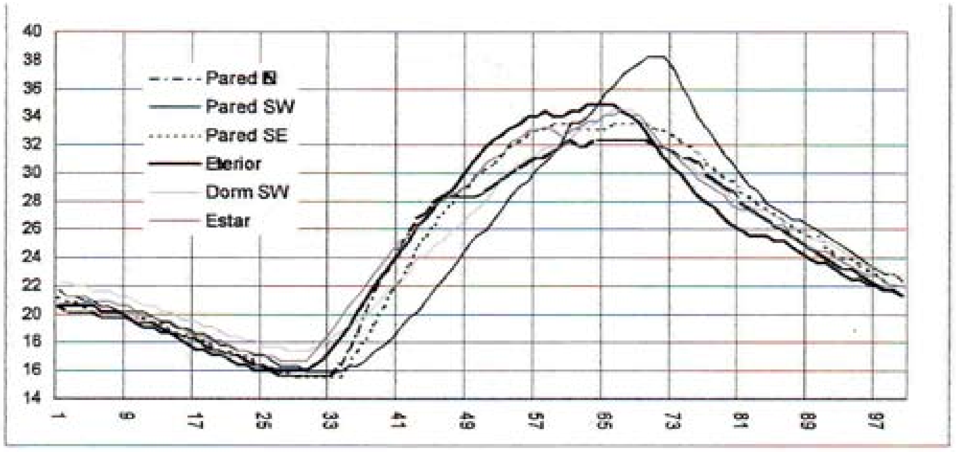

Figure 12.3. Average temperatures for a 24 hour period during the 6 days experiment.

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.

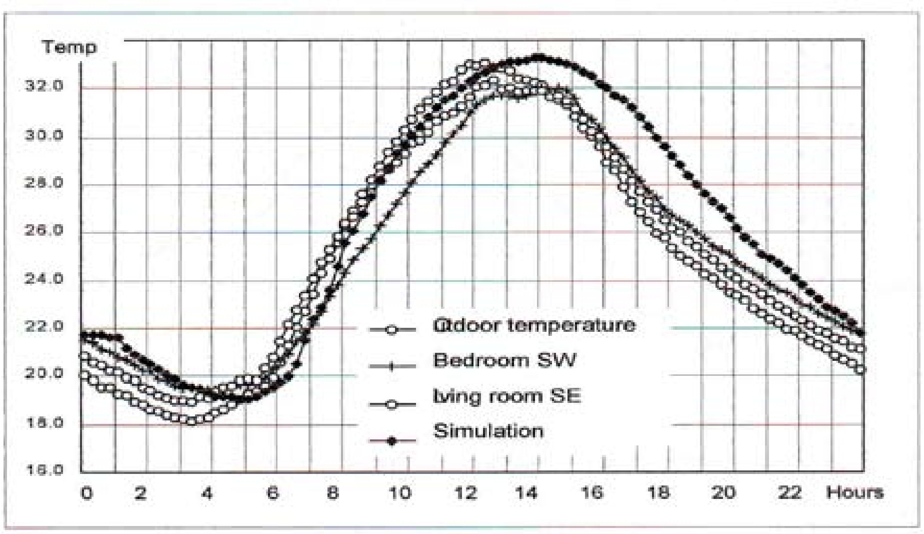

Figure 12.4. Measured indoor and outdoor temperatures, compared with the simulated indoor temperatures in the living room.

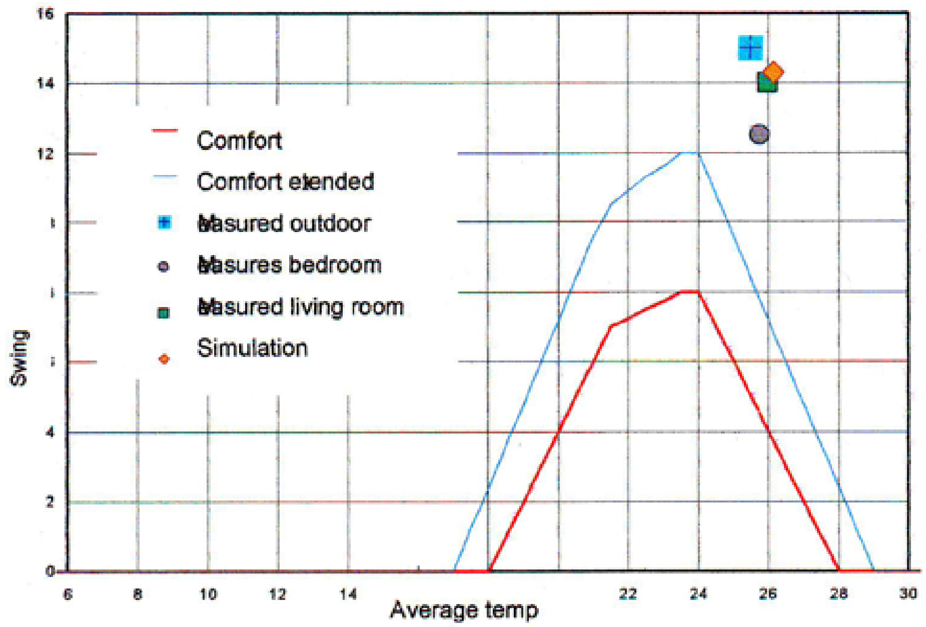

Figure 12.5. Indoor and outdoor temperature variations for different spaces, shown on the comfort triangle diagram.

Table 12.1. Measured and simulated temperatures in the study house.

Temperature	Max.	Min.	T average	ATºC
Eisting, outdoor	33	18	25,5	15
Eisting, bedroom	32	19,5	25,8	12,5
Eisting, livin 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

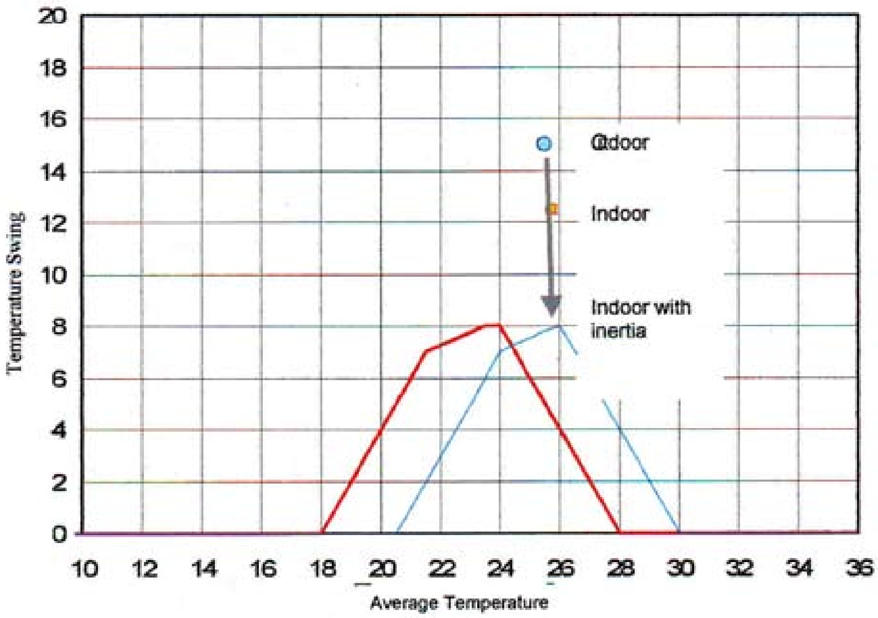

Figure 12.6. Indoor and outdoor temperatures, with simulation of indoor temperature when thermal inertia is added.

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 eternal 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

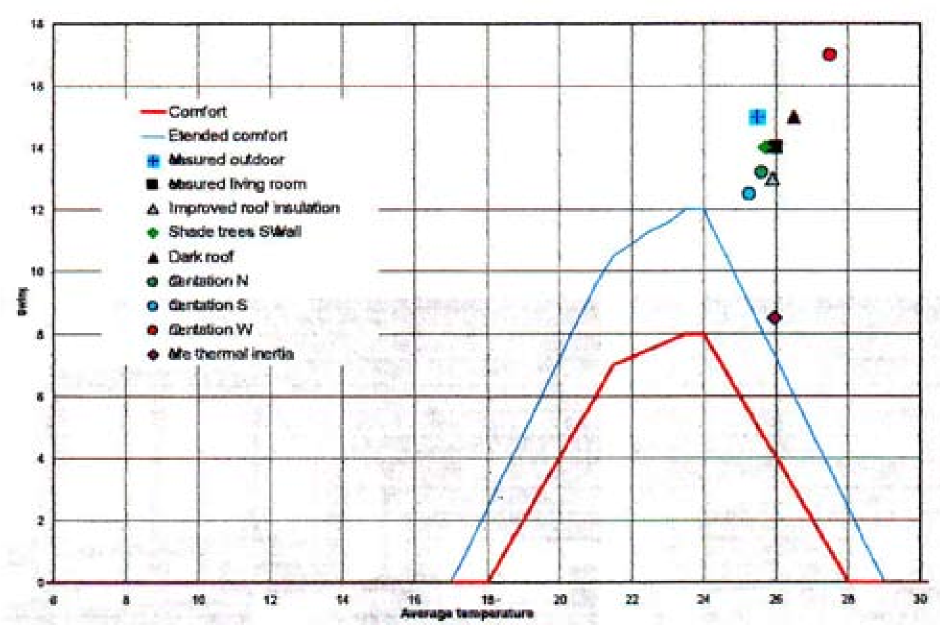

Figure 12.7. Variation in the comfort conditions with simulations of design alternatives compared with measured outdoor (+) and indoor conditions (□).

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 lightweight 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.

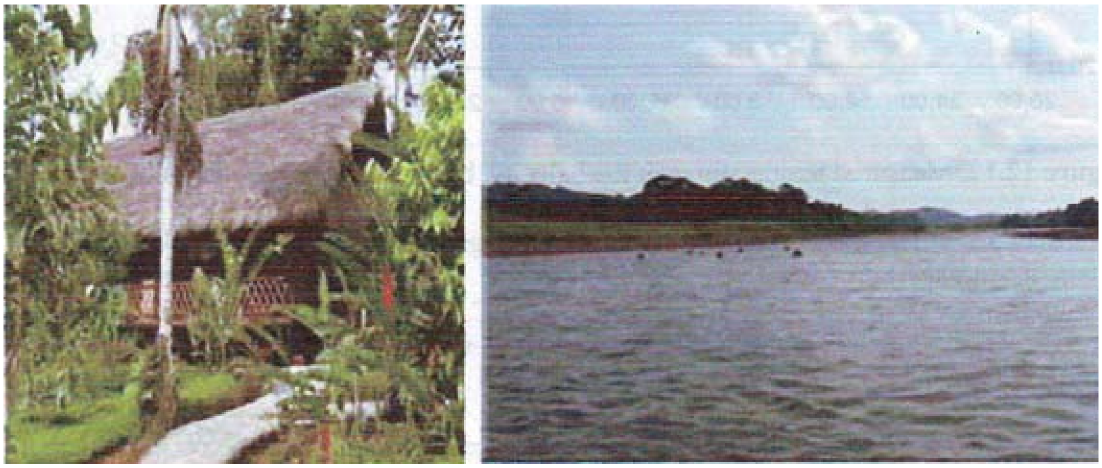

Figure 12.10. The cabins set in traditional vegetation, on the shores of the Napo River.

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.

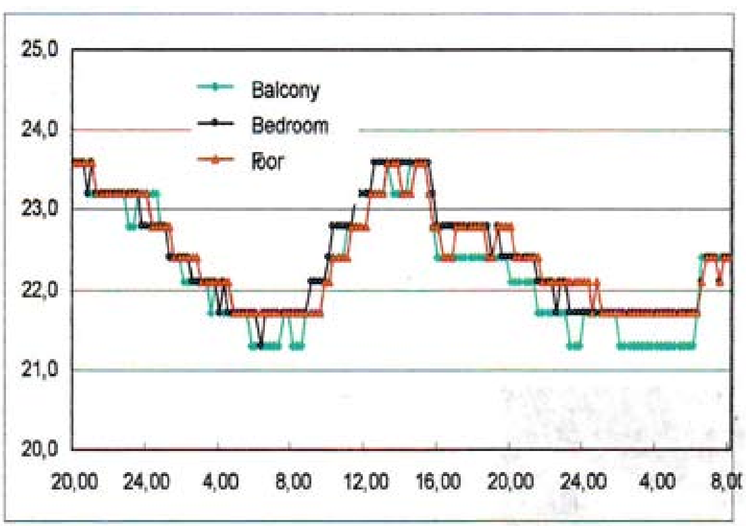

Figure 12.12. Measured temperatures in the balcony, bedroom and under the floor.

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.

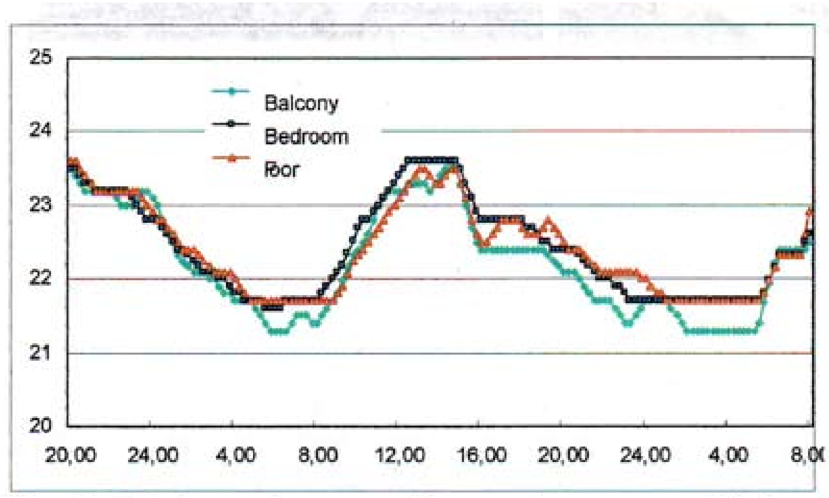

Figure 12.13. One hour running averages of the measured temperatures on the balcony, in the bedroom and under the floor.

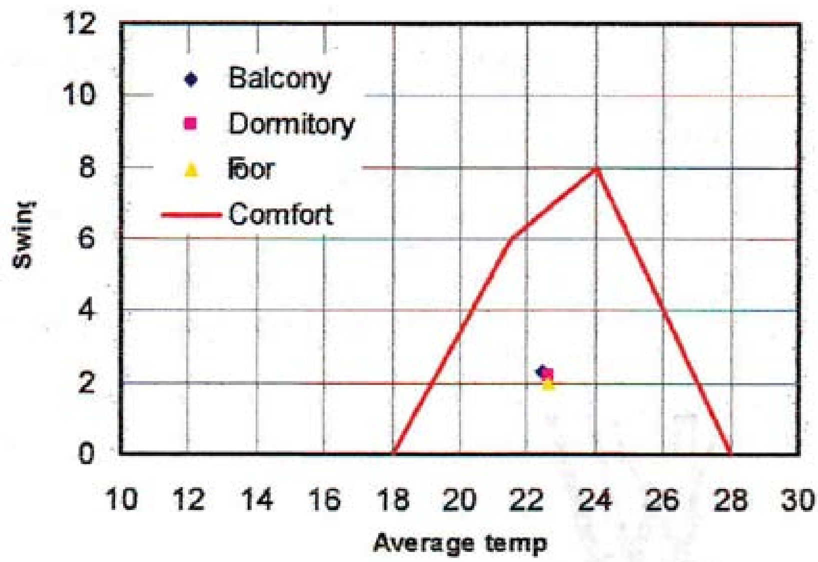

Figure 12.14. Indoor and outdoor temperatures at Cotococha, showing very limited variation and values within the comfort zone.

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.

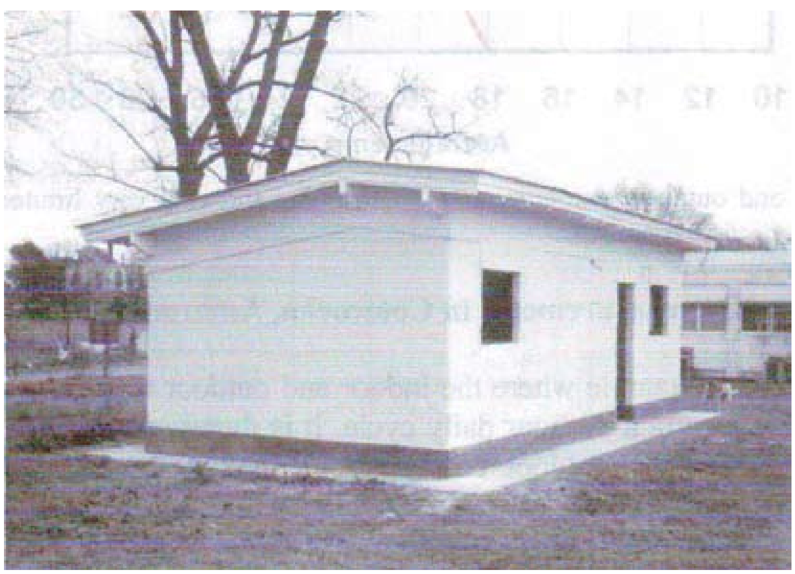

Figure 12.15. View of the prototype, Photo J. C. Patrone

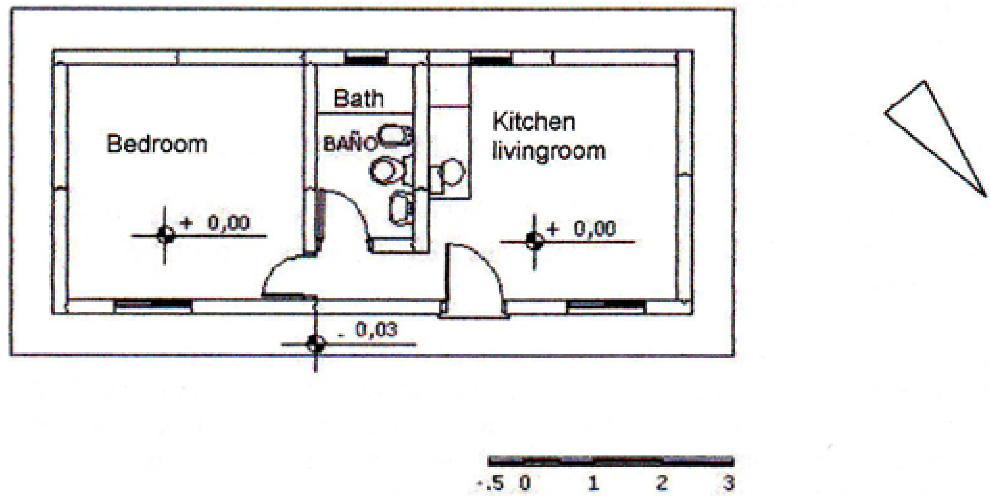

Figura 12.16. Plan of the prototype house (Patrone, 2006).

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/m2K) for walls and roofs in summer and winter, IRAM Standard 11.605 (1996).

Conditions	Roofs	Walls
Winter (IRAM 11,605, table 1) 1,00	1,00	**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/m3. 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/m2K, 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 center of the room at a height of 1,5 m
T	Kitchen	In the center of the room at a height of 1,5 m

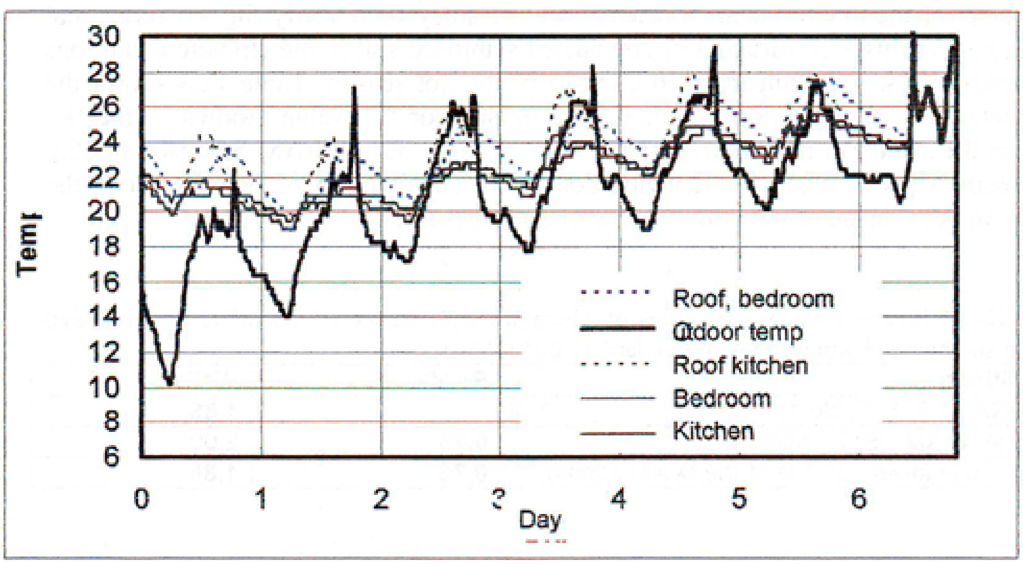

Figure 12.17. Temperatures registered automatically during a warm period, from 10th to 16th of December, 2005.

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 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/m2K 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/m2K 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 nonconventional 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.
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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.

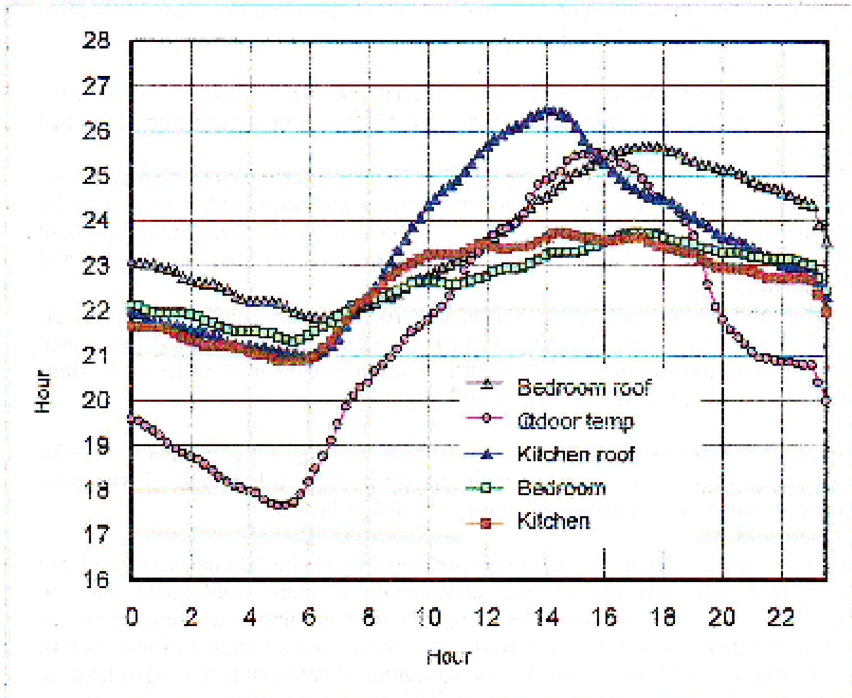

Figure 12.18. Average temperatures registered during the 6 day study period.

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.

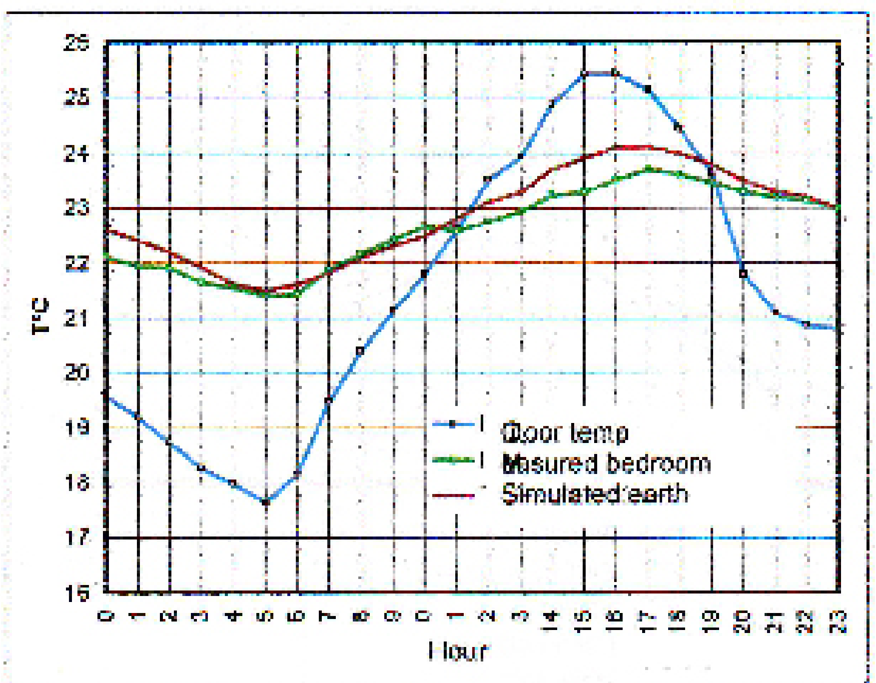

Figure 12.19. Comparison between the indoor temperatures registered in the bedroom with the HOBO and the indoor temperature obtained with the numerical simulation.

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 KW/ m²K
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.

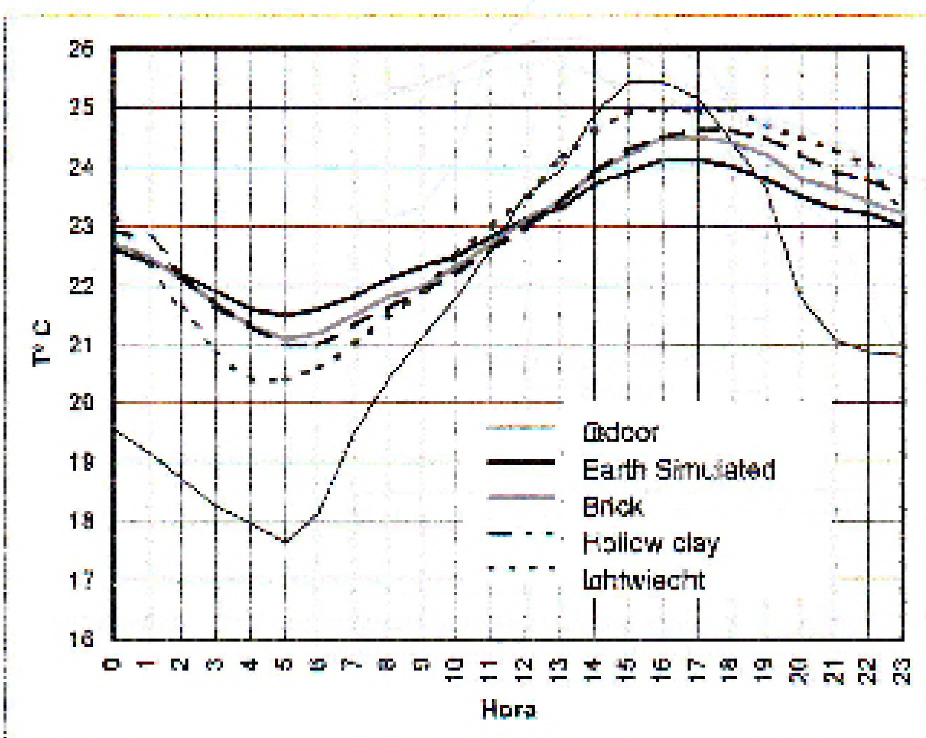

Figure 12:20. Simulated indoor temperatures with different constructions in summer. .

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

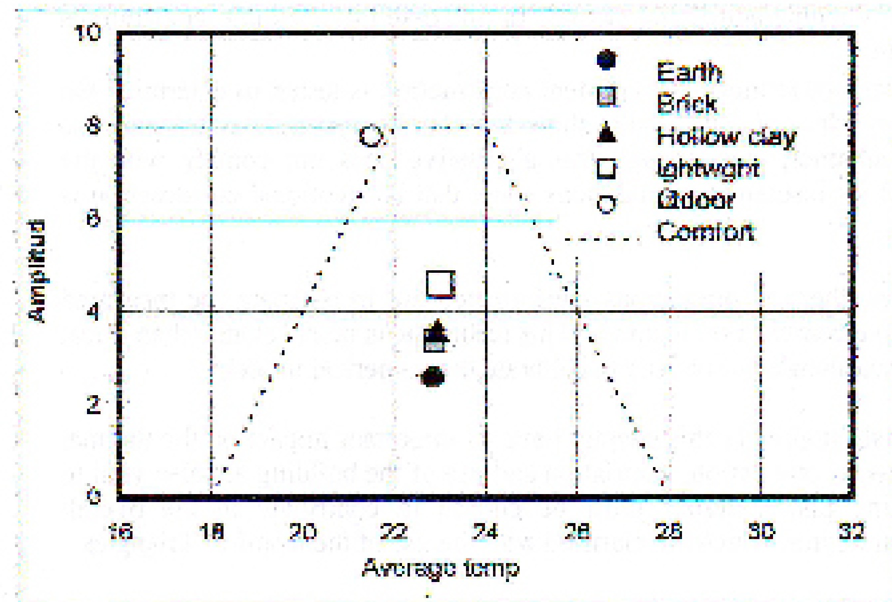

Figure 12.21. Simulated indoor average temperatures and temperature swings in the module compared with outdoor temperature conditions..

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, Sate 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 6, 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.

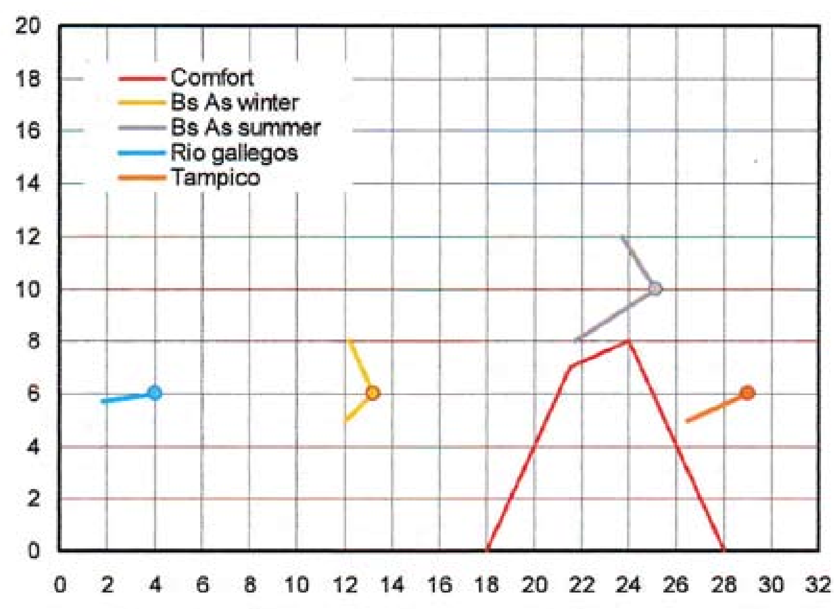

Figure 13.1. Variation between rural and urban conditions, shown by the circular dot.

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	

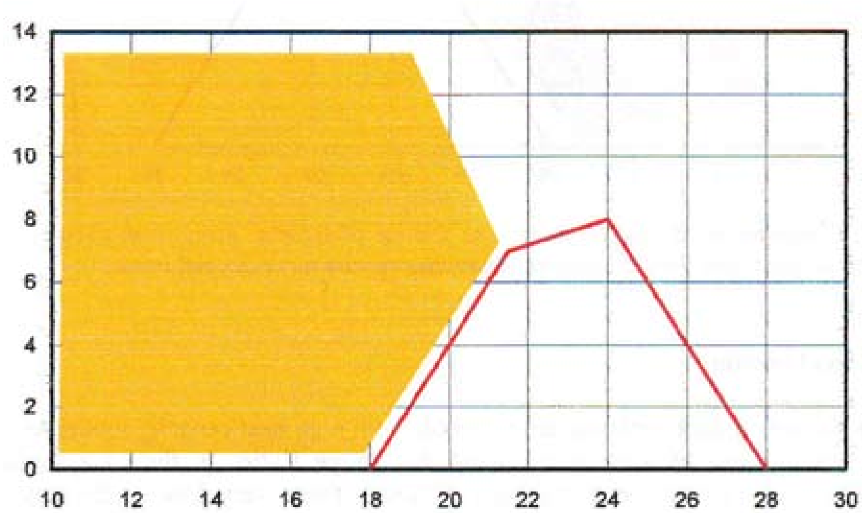

Figure 13.2. Combination of outdoor conditions for effective solar gains, combined with thermal mass in all cases.

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, electrodomestic 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 an 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.

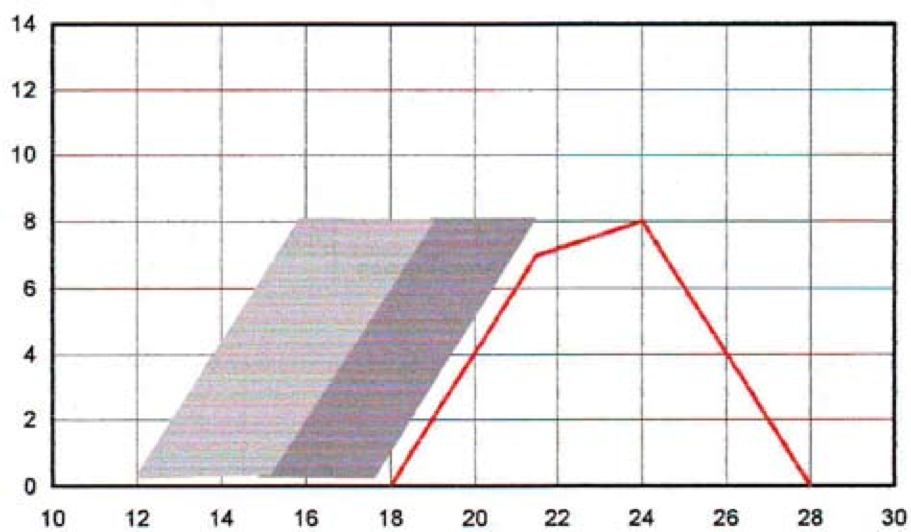

Figure 13.3. Combination of outdoor conditions for use of internal gains, with average and excellent thermal insulation. Higher temperature swings require more thermal mass.

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 withnight 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

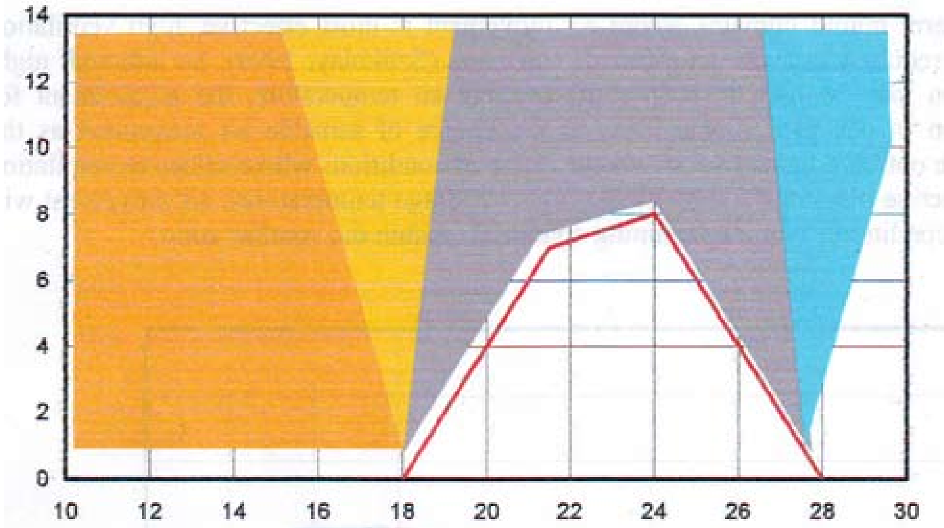

Figure 13.4. Conditions for the use of thermal inertia can be used to achieve comfort (grey), and with additional night ventilation (blue), day ventilation (yellow) or solar gains (orange).

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.

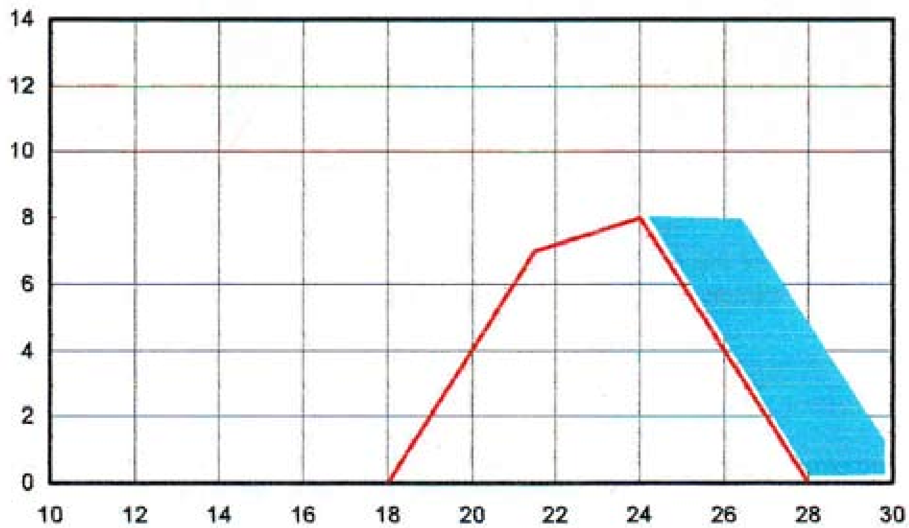

Figure 13.5. Conditions where air movement provides effective apparent cooling

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.

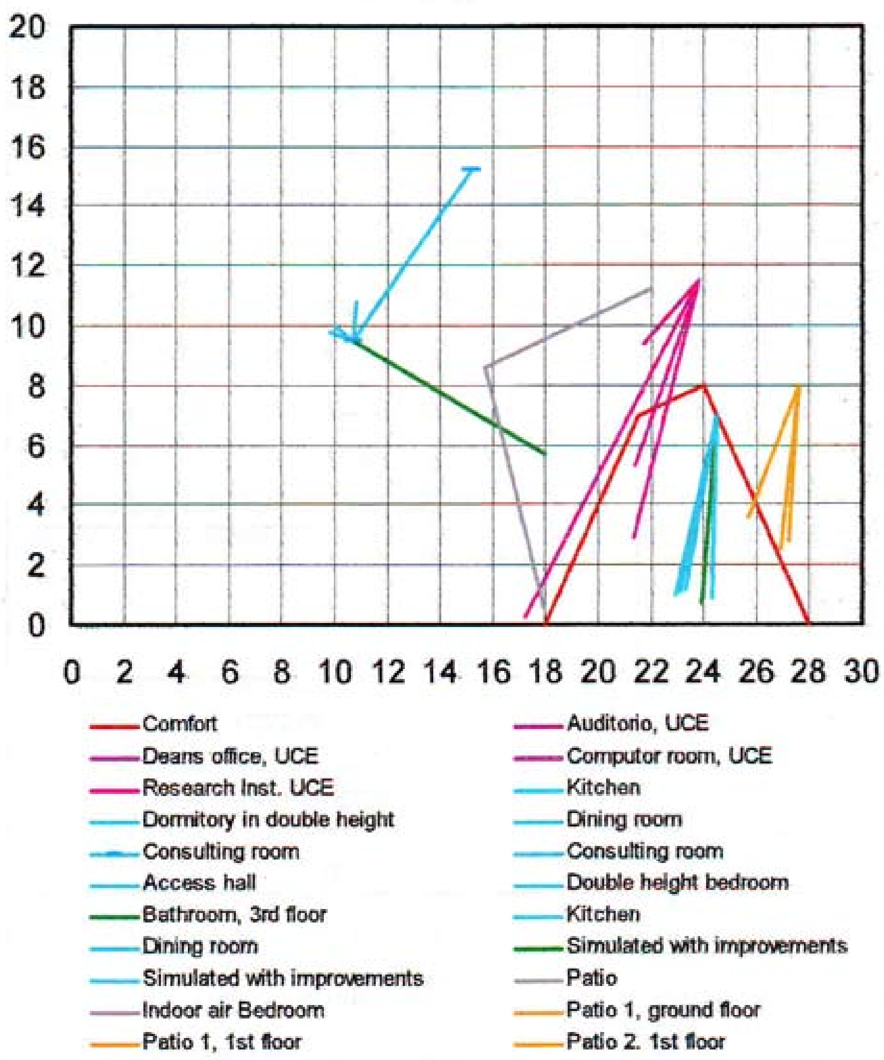

Figure 13.6. Bioclimatic modification achieved in the case studies

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.

Heating/cooling

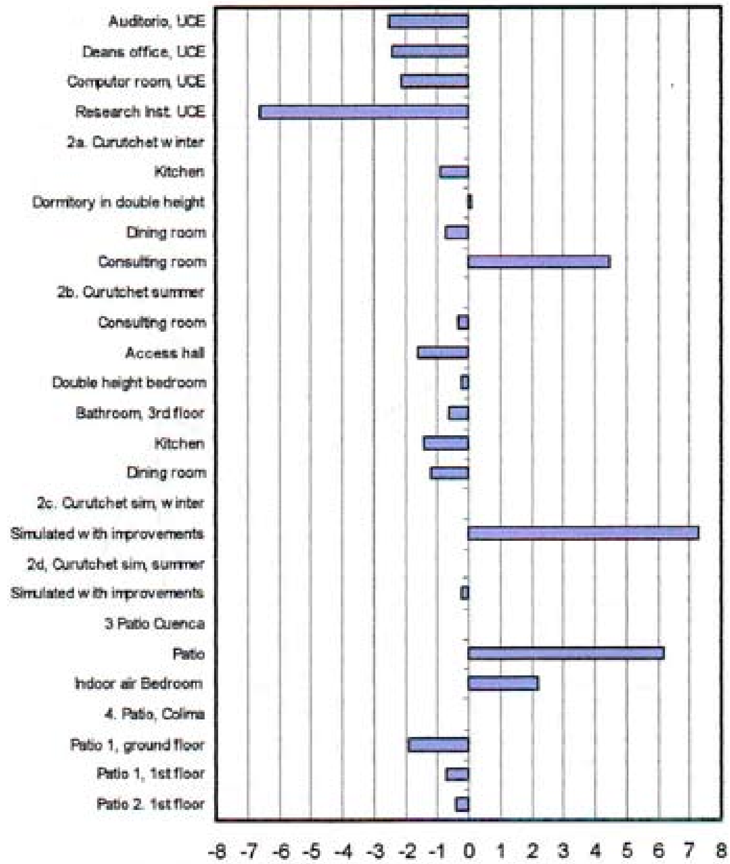

Figure 13.7. Heating and cooling measured or simulated in the case studies

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.

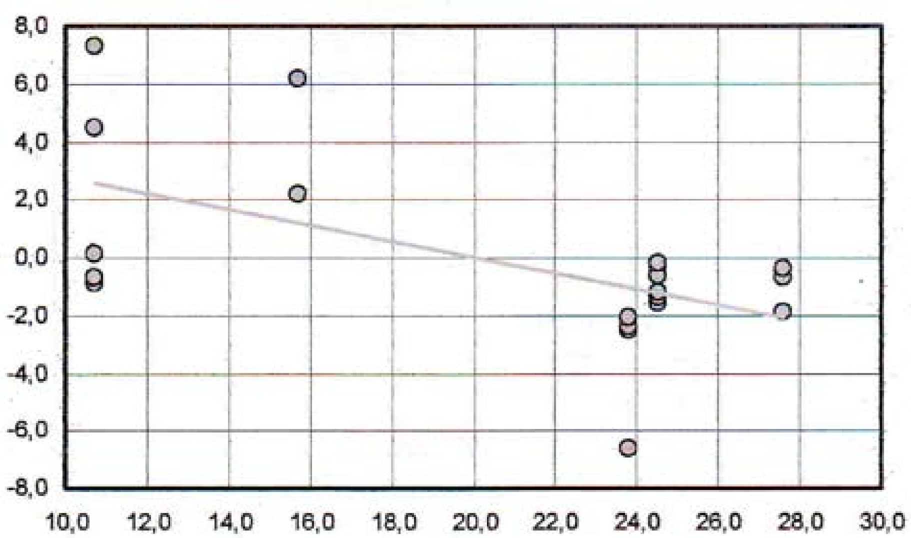

Figure 13.8. Relation between average outdoor temperature and average indoor-outdoor temperature change: negative values correspond to cooling and positive to heating.

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.

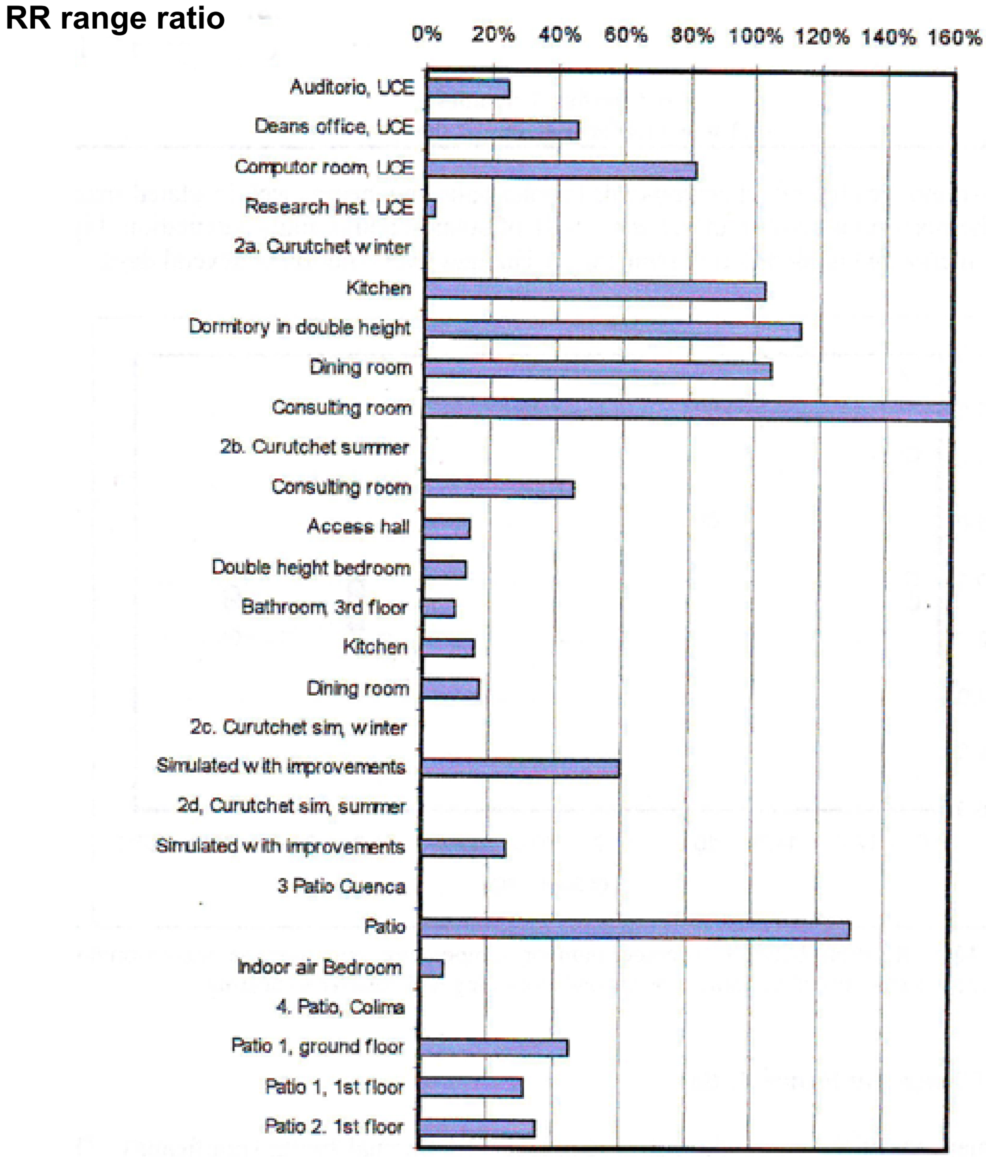

Figure 13.9. Values of RR the range ratio registered in the case studies.

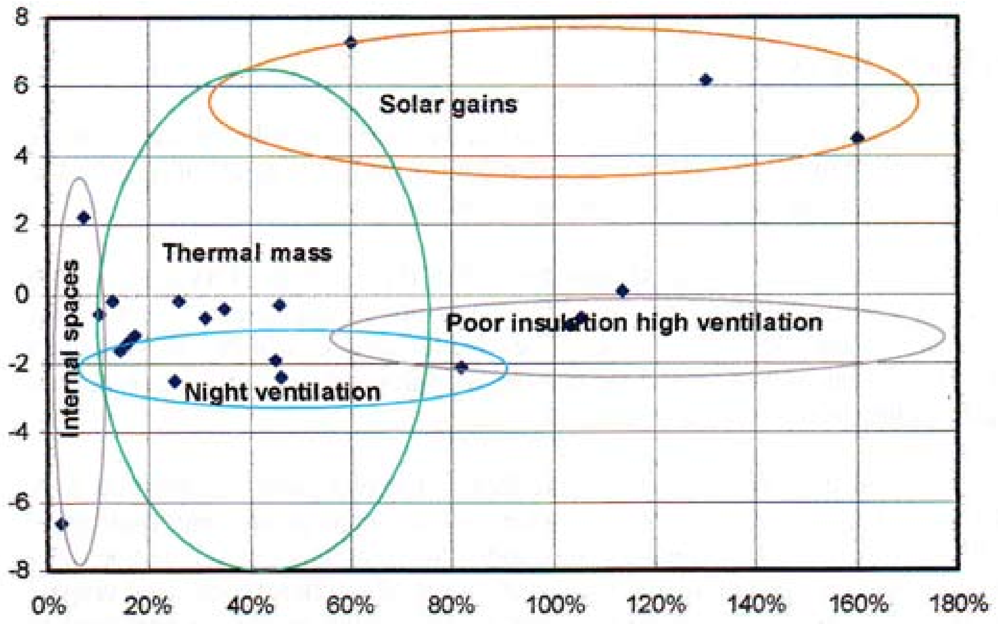

Figure 13.10. Relationship between RR, the Range Ratio (horizontal scale) and the heating or cooling effect (vertical scale), with corresponding strategies.

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.