Climatic Design of Buildings using Passive Techniques

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Introduction

Problem

Buildings in developing countries are often designed without taking sufficient account of the climate. Factors such as the urban surroundings or site characteristics, orientation and architectural design of the building, choice of building materials, etc. are not given enough importance. Consequently buildings often have a poor indoor climate, which affects comfort, health and efficiency. The problem is found in dwellings as well as workplaces or public buildings, such as schools and hospitals.

As living standards rise people want to install heating and/or cooling equipment to improve thermal comfort. For buildings not adapted to the climate, the amount of energy to run the equipment, and its cost, will be excessively high, and it will have a negative impact on the environment. A good, or at least acceptable, indoor climate can often be achieved with little or no extra input of energy.

Apart from a general lack of norms and regulations, one reason why buildings are poorly adapted to the climate is lack of knowledge among architects, planners and engineers. Central concepts such as thermal capacity and thermal insulation are often misunderstood. The knowledge from traditional construction, which was fairly well adapted to the climate, is often lost or difficult to translate to modern techniques and society.

The objective of this study is to present information about the climatic design of buildings today, using passive techniques. It explains central concepts in climatic design and gives recommendations on how to carry out the design in different climates. The focus is on building design, but urban climate is also considered. Ways to gain more knowledge are presented and illustrated with a case study.

Method

This study is carried out as a desk study. The work is based on:

- compilation of the author's experience as a designer and researcher in North Africa, South-East Asia and Latin America,
- literature survey on experiences in other regions,
- synthesis of personal and collected information.

Organization of the Report

This report consists of two parts, Chapters 1–3 and Chapters 4–5. After this introduction to the problem and the method, Chapter 2 describes the concepts of climate, comfort and their relation to the human being and to buildings. Chapter 3 outlines some general recommendations. Part 2 is research oriented: Chapter 4 discusses ways to improve climatic design, and Chapter 5 presents a case study.

Some references for further reading are given at the end.

General considerations

Energy Consumption

Heating and cooling of buildings account today for high energy consumption. Higher living standards lead to active climatization of buildings such as offices and hotels, and also residences. Air-conditioning plants are installed without any adaptation of the buildings to these new appliances, which leads to excessive energy consumption and high cost, and may also damage the building (see Adamson and Åberg 1993). Alternatively, recent buildings without active climatization, both low-cost and luxury, give a poor indoor climate, leading to fatigue and health risks.

In many countries, especially in the industrialized world, buildings account directly for over 50% of total energy consumption, and even more when one includes what it costs to manufacture the materials required for construction.

For the building to be energy efficient it is necessary to control the input of energy through regulatory systems and/or through 'passive' techniques. The former requires sophisticated equipment and depends on their smooth functioning and energy supply. The latter, 'passive' techniques, normally requires more interaction, monitoring and knowledge by the user, and is therefore more sensitive to human factors, though technically simpler and more reliable.

Traditional buildings often mitigated the exterior climate, even if 'comfort' was not always achieved at all times of the day or in all seasons. Modern construction offers the technical possibilities to reach very good comfort though heating, cooling and other kinds of air conditioning. We therefore tend to forget the old knowledge about how to adapt our houses to the climate passively.

Norms and Regulations

As former colonies, most developing countries inherited European norms and regulation systems from the last century, before the energy issue was 'invented'. Some developing countries started to write regulations for energy savings during the international 'energy crisis' in the 1970s and the growing concern for the environment.

Norms, regulations and bylaws apply only to construction within the *formal* sector of the economy. Much of the housing stock in developing countries is built outside this legal framework. They may be indirectly influenced by legislation, especially in urban areas, but other means must be sought to complement these legal instruments to influence or control 'informal' construction activities.

Economy is a restricting factor that affects the perception of comfort limits, and also the ability or readiness to invest in the building structure. Here it is important to view the building in a life-cycle perspective. Payback periods are different for different components – the building envelope itself being the most durable.

Financial incentives, combined with educational programmes for consumers, builders, real estate agents and others can stimulate energy-efficient construction. Building codes for low-cost housing, manuals and training may also be important. Research is central to develop knowledge and methods, and to feed this data into the education systems and suitable knowledge-banks available to the market.

It is therefore important and urgent to increase our knowledge about present conditions concerning indoor climate, thermal performance and energy consumption in today's building stock, and to suggest improvements in the form of up-to-date norms and demonstration projects.

Climate and comfort

When designing an individual building the general outdoor climate is to be regarded as a given condition, though there might be climate change over a long time, and that it may be possible to affect the microclimate by urban and building design. This section discusses the climatic elements and their effect on thermal comfort.

Climatic elements

Temperature

The DBT, dry bulb temperature (°C, °F or K), is probably the most commonly used unit to describe climate. Air temperature is measured with a dry bulb thermometer protected from solar and heat radiation. This data is generally available in meteorological records as monthly means, maximum and minimum values (both normal and extreme). The wet bulb temperature (WBT) is the temperature at which vapour saturation occurs (see below).

Table 1 Relation between °C, °F and K

°C	°F	K	
– 273.15	– 457.67	0	Absolute zero
– 17.7778	0	255.3722	
0	32	273.15	Melting point of ice
100	212	373.15	Boiling point of water (at 1 atm)
1	1.8	1	Equivalents

Humidity

Air contains a certain amount of vapour, which is called air humidity. It can be specified as absolute humidity in grams per kg or m^3, or as partial vapour pressure (kPa). More common is however the expression *relative humidity* – RH (%) which describes the portion of vapour in relation to saturation. Hotter air can contain more vapour than colder, and when cooled to the limit – the dew point – the surplus condenses. Relative humidity can be measured with electronic hygrometers or with a simple sling hygrometer including a dry bulb and a wet bulb thermometer. Meteorological data on humidity is commonly available, often as maximum and minimum mean monthly values or at certain hours of the day.

Wind

At local level wind is the most irregular and varying component of the climate. It is affected by topography, vegetation and surrounding buildings; closeness to the sea may create on and offshore winds. Wind is described by its speed and direction and is measured with an anemometer. Frequency diagrams, wind roses, are often drawn for each month of the year or for the main seasons.

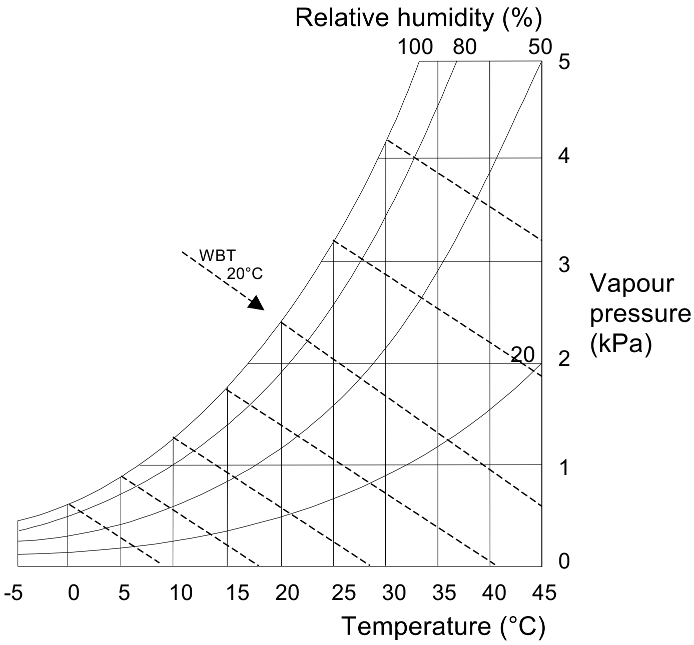

Fig. 1 The psychrometric chart plots the combination of temperature and humidity

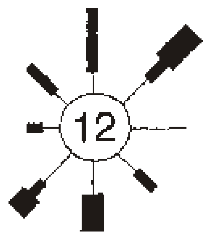

Fig. 2 A wind frequency diagram, a 'wind rose'. The length of the lines describes frequencies from different directions, and the thickness describes wind speed intervals, according to a scale and a legend. The figure in the middle is the percentage of calm.

Precipitation

Precipitation may vary considerably between seasons. Data on monthly means, extreme values and maximum precipitation during 24 hours are commonly found. Snow is most often measured in melted form, but data on snow depth may be available. Combinations with other elements could be interesting in relation to building design, e.g. at strong winds it rains 'horizontally' (driving rain).

Solar radiation and sky conditions

The sun may be described as the 'engine' of the climate since it supplies a large amount of energy to the earth. The sun's path is regular and depends on the latitude and the time of the year. The season also determines the total amount of irradiation through the length of the day. High altitudes give more intense solar radiation, because there is less absorption in the relatively thinner layer of atmosphere.

The position of the sun may be determined with the help of solar diagrams, available in most standard books on climatic design (see Figure 8). There is one diagram for each latitude, making it possible to read the altitude (vertical angle) and the azimuth (horizontal angle) of the sun at every hour of every day of the year.

Short-wave solar radiation is divided into direct (I_D) and diffuse (I_d) and the sum of these is global radiation (I_{GL}). These are often measured on a horizontal surface (W/m^2), but normal (I_N) radiation, facing the sun, is commonly used. Also values for vertical surfaces in various directions may be found. The relation between direct and diffuse radiation varies with the sky conditions. Humid air or overcast skies increase the diffuse part. Overlays to the solar diagram may give data on solar radiation on horizontal or other surfaces, but corrections for cloudiness and humidity must always be considered. Reflections from the ground and adjacent buildings, and shading from adjacent buildings and vegetation, affect the total solar radiation.

Energy is also dissipated *from* the earth *to* the sky by long-wave heat radiation. This is affected by air and sky conditions, such as cloudiness and pollution. The sky vault acts as a cold, black body: a heat sink, which may receive a considerable amount of heat during clear nights, but also during the day. An equivalent sky temperature can be defined for the sky vault, sometimes as low as 25 K below the air temperature.

Other phenomena

There are other phenomena related to the climate, such as hail, frost, thunder, fog, smog, rain, dust and sandstorms, hurricanes and earthquakes. These are more occasional, extreme conditions and are not addressed here, but where they might occur, they must be considered, since they may strongly affect the design of buildings.

Climate types

One of most commonly used classification system for describing the climate is Köppen's (described in Evans, 1980). The classification below mainly follows Köppen, with main groups given in parentheses if they deviate.

Cold climate (Cold Temperate, Sub-arctic and Arctic)

The average temperature of the coldest month is below 0°C; some subgroups have dry seasons. In arctic areas all months may have average temperatures below zero; elsewhere summer averages may reach 22°C.

A cold climate has average outdoor temperatures below comfort throughout the entire year. The potential for solar heating may be limited.

Temperate climate

Temperate climates have average temperatures ranging from 0–18°C for the coldest, and 10–22°C for the hottest month. Subgroups are defined by differences in rainfall distribution.

A temperate climate has average outdoor temperatures above the comfort zone part of the year and below during another part. Solar heating potential may be high, but overheating problems may be important during the hot season.

Hot-arid climate (Desert and Steppe)

Deserts have average temperatures above 0°C in winter and above 18°C in summer. Subgroups are defined by differences in rainfall distribution over the year. There are also cold dry areas, such as in central Russia and USA.

A hot-arid climate has a strong sunshine with a large portion of direct radiation. The clear night sky can cause great differences between day and night temperatures, and the potential for radiative cooling is high. Winter nights are cold in certain regions.

Warm-humid climate (Equatorial)

Minimum average monthly temperature is above 18°C and subclasses are defined by differences in seasonal rainfall distribution.

A warm-humid climate has a fairly constant temperature, both over the day and over the year. Humidity and cloudiness make diffuse solar radiation important, and the potential for radiative sky cooling is lower. Seasons are often determined by rainfall and winds.

Subgroups and seasonal variations

The division into main climate types above is rough. There is a range of subgroups, such as mountain and maritime desert climates. On the local scale the *microclimate* may differ much from the 'official' one. Topography, vegetation, lakes and surrounding constructions may alter temperatures, solar characteristics, wind patterns and humidity. In

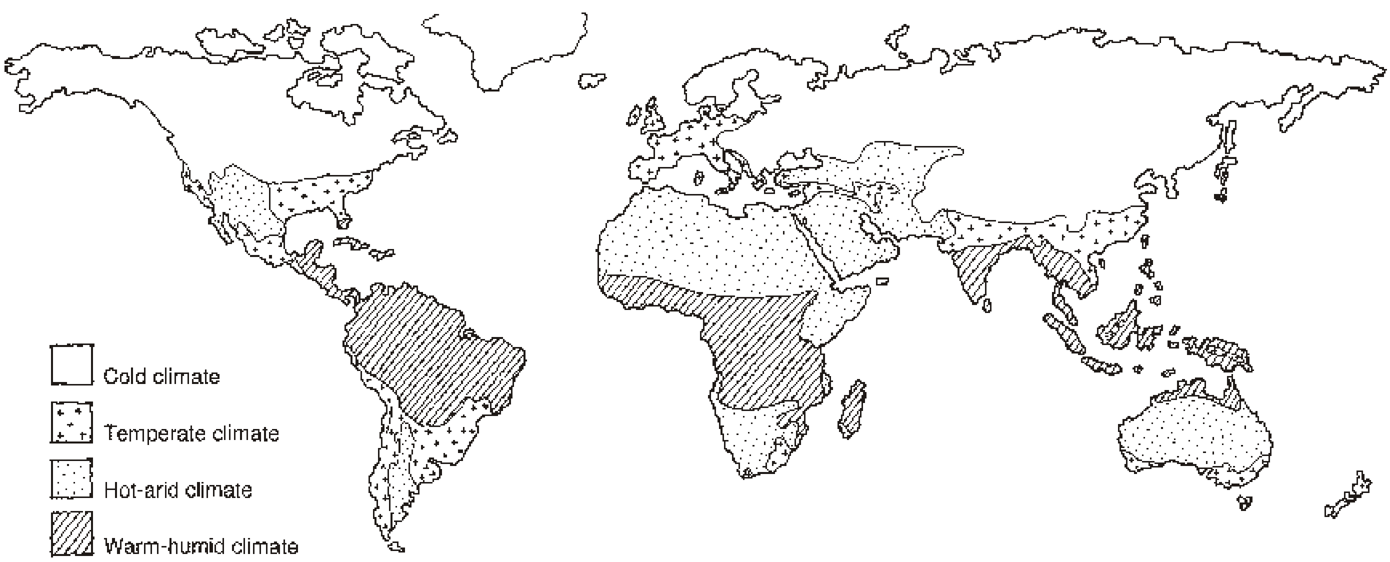

Fig. 3 Main climatic zones (after Köppen).

cities the *urban climate*, affected by heat production but also by changed surface properties, shading, wind protection, pollution, etc, is often different from that of the hinterland.

Most climates also include seasonal variations as indicated above. Hot/cold or dry/humid seasons have to be considered in all climatic design. However, it is also important to take account of intermediate seasons, when both heating and cooling may be required, or when the solar path requires special arrangements for shading or solar access.

Comfort

The human being, like other bodies, exchanges heat with its environment through conduction (by direct contact), convection (transported by air), radiation (mainly short-wave visual light and long-wave heat) and evaporation/condensation (heat released through change of state of water, also called latent heat). Factors influencing the heat balance are *environmental*, such as air and mean radiant temperatures, vapour pressure and air motion, but also *individual*, such as metabolic rate (Table 2) and clothing (Table 3). The thermal equilibrium must be maintained within narrow limits for survival, and the range of comfort is even narrower.

Table 2
Metabolic rate of different activities (average for adults). The unit met *is equal to 58.2 W/m^2.*

Activity	met	Metabolic rate (W)
Sleeping	0.7	75
Reclining	0.8	85
Sitting	1.0	105
Standing, relaxed	1.2	125
Typing	1.2–1.4	125–145
Cooking	1.6–2.0	170–210
Housecleaning	2.0–3.4	210–350
Walking (level, 3–6 km/h)	2.0–3.8	210–400
Dancing, gymnastics	2.4–4.4	250–460
Heavy machine work	3.5–4.5	370–470
Pick and shovel work	4.0–4.8	420–500

Table 3
Approximate values of clo for various clothing. The unit clo is equal to 0.155 m^{2}K/W.

Clothing	clo
Nude	0
Shorts	0.1
Walking shorts + short-sleeve shirt	0.4
Knee-length skirt + short-sleeve shirt + pantyhose	0.5
Trousers + shirt	0.6
Sweat pants + sweat shirt	0.7
Trousers + shirt + jacket	1.0
Knee-length skirt + long-sleeve shirt + half slip + pantyhose + long-sleeve sweater or jacket	1.0–1.1
Men's heavy three-piece business suit	1.5
Men's heavy suit + woollen overcoat	2.0–2.5

Comfort is a subjective experience, and not all people agree about optimal comfort. To handle comfort, it was necessary to define some kind of index, or a 'comfort zone'

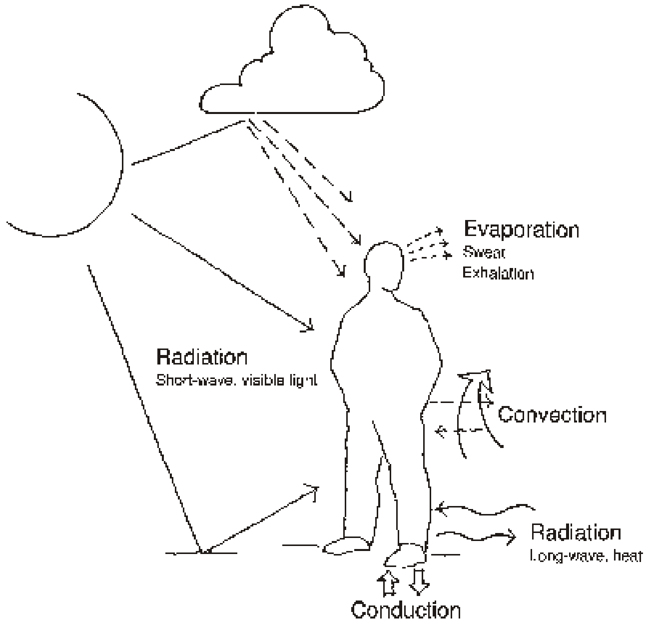

Fig. 4 The four modes of heat exchange: conduction, convection, radiation and evaporation.

where the majority of people experience well-being. This is normally done by the votes of a population in an experimental situation. A number of scales were developed, and some are shown in Table 4.

Gagge's DISC index expresses degrees of *discomfort* rather than comfort. The most common definition of the 'comfort zone' is DISC ±0,5, which means that 80% of the population is satisfied, though extending limits to DISC ±1, where 70% are satisfied, could be proposed when resources are limited.

Table 4 Thermal sensation scales. (based in part on Markus and Morris 1980)

	ASHRAE	Fanger (PMV)	Rohles & Nevins	Gagge's DISC	SET (°C)
Painful			+5	+5	
Very hot			+4	+4	37,5–
Hot	7	+3	+3	+3	34,5–37,5
Warm	6	+2	+2	+2	30,0–34,5
Slightly warm	5	+1	+1	+1	25,6–30,0
Neutral	4	0	0	±0.5	22,2–25,6
Slightly cool	3	–1	–1	–1	17,5–22,2
Cool	2	–2	–2	–2	14,5–17,5
Cold	1	–3	–3	–3	10,0–14,5
Very cold			–4	–4	

The *Standard Effective Temperature (SET)* developed by Gagge et al. (Markus and Morris 1980) describes a uniform environment with:

- 50% relative humidity,
- air speed of 0.125 m/s,
- activity level of 1 met (sitting) and
- clothing of 0.6 clo ('indoor clothes').

An air temperature of 20°C in these conditions results in a SET of 20°C. A change in *any* of the parameters will result in a change of the SET.

For indoor conditions the *Operative Temperature* mainly defining an average temperature between air and surrounding surfaces could be used for comfort assessments.

The Comfort Diagram

Plotting the SET index in comfort diagrams, based on the psychrometric chart, gives a modern index that is easy to understand and applicable for hot climates.

One can construct an individual comfort diagram according to activity types, local clothing habits, etc. The diagram in comprises a comfort zone of:

- DISC ±0.5, where 80% of the population is satisfied, accepting the normal standard for comfort. (70% satisfaction would extend the temperature limits to 16–17°C and 31–38°C.)
- light summer clothing (0.6 clo) as an upper limit, and 'normal' clothing (1.0 clo) setting the lower level. A certain adaptation in clothing to the indoor climate is thus assumed.
- sedentary activity (1 met) that includes sleeping, reclining and sitting, where the body dissipates about 100 W. More demanding tasks, such as house cleaning (2–4 met), are not included, since they would probably not occur at the hottest time of the day.
- low air movements: 0.1 m/s is considered still indoor air, but the possibility of using a fan to increase air speed up to 0.5 m/s is included and shown as an additional comfort zone to the right of the dashed line in the diagram.

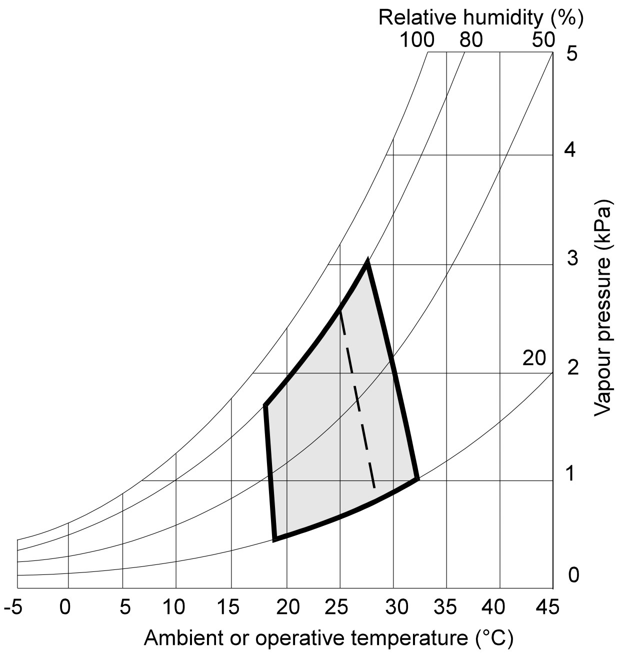

Fig. 5 The comfort diagram for: DISC ±0,5; 0,6–1,0 clo (upper and lower limits respectively); 1 met; v=0,1–0,5 m/s (the higher value to the right of the dashed line). After Markus and Morris 1980, where 55 combinations of parameters can be found.

Relation to other factors

Other factors than those of climate mentioned above may also influence the feeling of comfort. Age, sex, and adaptation have little or no influence according to most researchers. Psychosocial conditions, health, air quality and acoustical and optical influences may also be mentioned, but are difficult to quantify.

Thermal conditions for good *performance* may not coincide completely with the comfort zone, but are more related to the level of *arousal*, see Figure 6.

Large temperature swings may increase rates of working, though they cause thermal discomfort. The conditions for optimal performance in physical and mental work are normally different. In cold conditions the brain has a high priority, and mental performance is therefore less affected than in a hot environment. Thermal imbalance in the surrounding environment can also affect mental performance. A hot ceiling or a large, cold window may cause discomfort, though the mean radiant and operative temperatures are within the comfort zone.

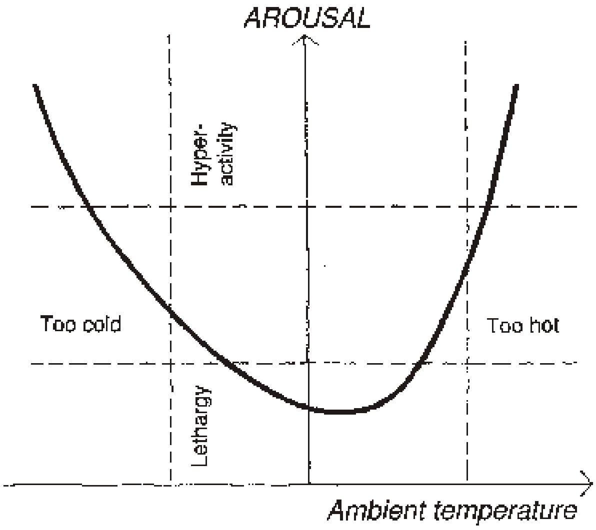

Fig. 6 Temperature and arousal. An adequate arousal level does not always coincide with the comfort zone. It may occur when it is too cold or too hot, and it may not occur within the thermal comfort zone, as shown in the figure. (After Markus & Morris 1980).

Finally economic status also influences the expectations of comfort, and this could be considered a psychological factor. What is out of reach may be regarded as optimal or perfect, but instead of going for comfort one has to settle for the endurable.

Design

A main purpose of buildings is to give shelter – for privacy and for thermal comfort. Privacy includes elements of social, psychological and religious character, but is physically created by enclosing a space by an envelope, sizing and positioning the openings towards the surroundings, and providing acoustic insulation. For thermal comfort, the building must act as a barrier, transforming the outdoor climate to conditions suitable for indoor activities. However the border between outside and inside is not always clear: interaction takes place through many kinds of semi-closed spaces, such as urban spaces, streets and courtyards, which make the climatic transition successive rather than abrupt.

The typical design process is a weighing of conflicting demands, such as between passive and active climatization, between privacy and solar access, between cross-ventilation and noise reduction, etc., to reach a satisfactory compromise. Applying a *systems approach* means to optimize the whole system (a building with its surroundings and components) not sub-optimizing its parts. In a process of modernization there are a lot of contradictions, most clearly seen in the 'grey zone' of buildings between active and passive climatization, between traditional and modern forms, and between formal and informal sectors of the economy.

The designer's role becomes that of a creative *enabler* of latent solutions. As such the designer needs powerful tools and techniques for simulation, prediction and visualisation.

Climatic design

The climatic design process requires special attention. Already in 1974 the Building Research Establishment in the UK applied a systems approach by stating:

> *It is not practicable to plan a building exclusively on economic, functional or formal grounds and expect a few minor adjustments to give a good indoor climate. Unless the design is fundamentally correct in all aspects, no specialist can make it function satisfactorily. Climate must be taken into account when deciding on the overall concept of a project, on the layout and orientation of buildings, on the shape and character of structures, on the spaces to be enclosed and, last but by no means least, the spaces between buildings. In other words climate must be considered at the early design stage.*

Koenigsberger et al. (1974) distinguished between three stages in climatic design:

1 *Forward analysis*, which includes data collection and ends with a sketch design.

2 *Plan development*, which includes the design of solar controls, overall insulation properties, ventilation principles and activity adaptation.

3 *Element design* comprises closer examination and optimization of all individual building elements within the frames of the agreed overall design concept.

This consecutive approach is typical for the time before the introduction of powerful computers in the building design process. Rather simple tools used in the forward analysis gave some overall principles. In the last stage it was practically impossible to go back and correct systematic errors; only minor changes in thermal performance could be obtained by a different element design.

To remedy this it is necessary to give the architect a set of methods and powerful tools to use for a better integration of climate adaptation into the design process of buildings. Integrated data and knowledge bases, and case-sensitive defaults, can help the designer. Developing appropriate and powerful tools, and inclusion of evaluation and feedback in the system is therefore crucial to better integrate climatic issues in a 'normal' design process.

Tomorrow's design?

A newly awakened interest for passive climatization should have a great deal to learn from the past, but purely traditional solutions assuming continuity of lifestyles and kinds of work seem rather unlikely. Combining traditional knowledge and advanced technology is therefore necessary.

The case study presented in this report focuses on *grey zones.* In one grey zone, between formal and informal sectors of the economy, the first can influence the second through demonstration objects. In another grey zone, between passive and active climatization, there are a great number of small public buildings, such as private and local authorities offices, schools and health clinics. In these buildings air-conditioning is increasingly used. Improved climatic design of these *formal, public* buildings would affect the *informal*, mainly *housing* sector, by providing good examples and ideas, since they often have about the same size, and use similar building materials and techniques.

Today's passive buildings should last for at least 20–50 years. They must therefore meet the demands for future active climatization as far as possible. Additional heating and cooling should represent only a marginal energy use, while the building itself must account for the main part of the climatization through its materials, structure and design. In any case, better climate-adapted buildings raise the limit at which the non-consumer, even if economically capable, gets fed-up with a bad indoor climate and becomes an energy consumer.

Surroundings

The surroundings of a building have great influence on its indoor climate, whether it is in a city or in the countryside. Providing for or protecting from certain winds, creating solar access or shading, etc, must be considered in each individual case. Topography, surrounding buildings, vegetation and water are elements that transform the regional climate into a specific microclimate, which is the input for the indoor climate of the individual building. The limits between regional, micro- and indoor climate are not abrupt, but describe a continuous change.

Urban climate has been studied in recent years. The structure of the city creates an urban 'air dome' above and around the city. Inside the city, up to roof level, the 'urban canopy' filters the outside climate gradually down to the street level, like the canopy of a tree.

Fig. 7 Transformation of the climate by the surroundings of a building.

The phenomenon of the 'urban heat island' increases urban air temperatures, creating differences of 1–2 K during daytime and normally 3–5 K at night, but there can be extremes of up to 10 K, according to Givoni (1998). The main factors generating the heat island are:

· Lower heat radiation loss during the night, due to the geometry of the city.
· Heat storage in the building mass.
· Heat generating activities (transportation, industry, etc).

- Lower evaporation due to less vegetation and different surface structures.
- Heating and cooling of buildings both of which generate heat to the urban environment.

The microclimate will not be further discussed in this publication. For more information, see the references.

Passive techniques

Historically, passive techniques were the only way to cool buildings, while heating could be obtained by burning wood or coal. There are now technical means that would allow building design to ignore the climate; but while this is technically possible, there are still good reasons to adopt passive techniques, not only economic, but also to promote environmental sustainability at both local and global levels.

'Passive' has changed its meaning to include what are called hybrid techniques, i e the limited use of low-energy equipment such as pumps and ceiling or table fans if their COP (coefficient of performance: the relation between energy output and input) is high. Simple mechanical devices and locally available parts and skills characterize passive systems. Usually the passive system is an integral part of the structure and has multiple uses. One example is an ordinary window, which can provide view, light, ventilation and solar gain.

Passive and low energy design helps the building take advantage of the climate when it is advantageous, and protects the building from the climate when it is not. This requires good knowledge of local climate and a greater sophistication on the part of the designer. The designer must therefore have adequate tools for this sophisticated task of passive design.

Heating and cooling

While *passive heating*, mainly based on solar energy, has resulted in a wide range of technical solutions such as solar heaters and photovoltaic cells, the evolution of *passive cooling* has been much slower. The problem is more difficult to analyse, and there are many devices, such as roof ponds and earth cooling tunnels that seem to work best in theory.

Passive cooling sources are the sky, the atmosphere, and the earth – all natural heat sinks. The sky acts exclusively by radiation, the earth and the atmosphere by convection and latent energy processes (evaporation).

Principles of passive cooling are: shading, reflection, insulation, reduction of internal gains, ventilation, fans, and tightness of buildings. Heat reduction is best achieved by excluding unwanted heat rather than removing it later, often by air conditioning.

Form

The form of the building includes its main proportions, scale/volume, attachment etc.

Table 5 shows differences in energy consumption for a number of modifications to an air-conditioned, 3-apartment house in a given climate. It should also be indicative for indoor climate in non-conditioned buildings. Dividing the building into single houses increases the energy consumption as much as a 5-fold change of roof insulation. Air infiltration and efficiency of the equipment also play a large role for air-conditioned buildings.

Table 5

Change in energy consumption as a function of change in air-conditioned, 3-apartment house in a given climate. (after Ekwall 1991)

Action	Change %
Division into single-family buildings	+22
U-value of roof increased from 0,18 to 1,0 W/m²K	+22
U-value of walls increased from 0,23 to 2,2 W/m²K	+175
Absorptivity decreased from 0,7 to 0,3 for roof,	–3
for walls	±0
SCOP[1] increased from 3,5 to 4,4	–20
to 7,0	–50
Air changes from 0,6 to 1,0	+27
to 0,4	–13

1 The Seasonal Coefficient Of Performance (SCOP) depends on the load and is typically 5–10% less than the Coefficient Of Performance (COP).

Roof form is often discussed. Where wood was scarce, vaults and domes were normal in traditional architecture. Cylindrical and dome roofs have a higher heat transfer coefficient and larger area than flat roofs of the same base. The solar energy absorbing area is nearly the same, whereas the convection heat transfer area is higher for the curved types. There are thus no big differences between the constructions as such.

The ceiling height is another issue related to roof form. Traditional buildings in hot climates often have high rooms, especially those with domes or vaults which add to the room height, and thus also to the volume.

Givoni (1976) found that in a hot climate, a reduction of the height from 3.6 to 2.4 m only corresponds to about 2% increase in the overall cooling requirements of the body. If insulation is included in the roof construction, the ceiling temperatures are also reduced, and the reduction in height thus has little, if any, significance in terms of radiation.

The stratification of air requires a certain room height to create a cooler, lower occupation zone. Hot air pockets above the level of door and window lintels can however transfer heat by convection to the occupation zone.

Lower ceiling heights also reduce construction costs, and in combination with insulation, give better indoor climate in colder seasons. Attention should be given to the quality of the air if room volumes and ventilation rates are reduced. (See the section on Ventilation below.)

Orientation

In areas where comfort is acquired mainly by air movement, it is important to orient the building according to prevailing winds.

In regions where ambient temperature has greater influence on comfort than ventilation, orientation with respect to the sun is important. A north-south orientation of the main facades is preferable, since the summer sun penetrates facades and openings only marginally in these directions, while in winter when the path of the sun is lower, there is possibility of solar access.

Solar radiation on facades and through openings can easily be calculated by solar diagrams, see Figure 8. Dimensioning of shading devices and the effect of surrounding buildings and vegetation can also be studied. Sets of diagrams and instructions are found in many reference

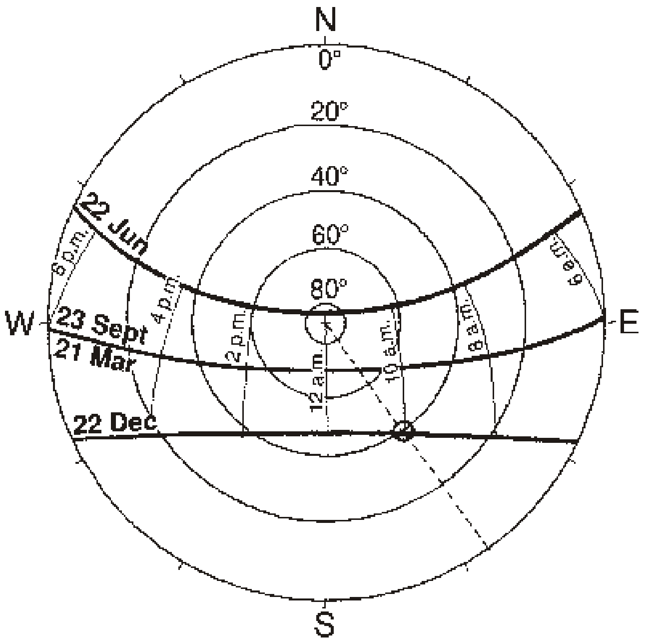

Fig. 8 Solar diagram for latitude 20°N.

books, such as Markus and Morris (1980) or Koenigsberger et al. (1974). Lippsmeier (1980) offers good instructions on how to use solar diagrams.

Ventilation

There are many purposes of ventilation: thermal comfort and structural heating/cooling, but also health, and moisture removal.

Thermal comfort can be created by increasing air speed through cross ventilation, which promotes evaporative cooling of moist skin. Placement of openings for inlet and outlet of air is essential for directing the air current to the occupation zone. Ventilated attic spaces, preferably with some ceiling insulation, reduce radiative heat transfer from the roof sheeting. Also external conditions, such as surrounding buildings and vegetation may affect the ventilation flow, see Figure 9.

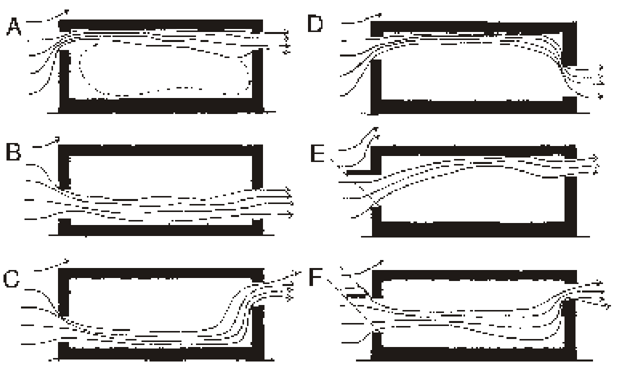

Fig. 9 Cross ventilation airflow in relation to wall openings and surrounding vegetation (after Evans 1980).
A High inlet and outlet do not produce good air movement at body level.
B Low inlet and outlet produce a good pattern of air movement, when it is required for cooling.
C Low inlet and high outlet also produce a low level wind pattern.
D The airflow at ceiling heigh produced by a high inlet is hardly affected by an outlet at low level.
E Projection shading devices produce an upward airflow in the room.
F A slot between wall and shade results in a more direct flow of air.

Wind angles up to 45° to the openings are acceptable and may even give better ventilation rates than in a perpendicular direction. Insect meshes may have a largely negative effect on ventilation, but this can be improved if they are not placed in line with the facade, or provided with wind-catching devices.

Calculation of ventilation rates is difficult. Wind tunnels and advanced computer simulation programs (CFD – Computational Fluid Dynamics) may give fairly accurate results, but are complicated to use. Simple simulations of fluid flow may give some general ideas, and so could this ASHRAE formula:

$$Q = E \times A \times v$$

Where:
Q = Air flow (m^3/s)
E = Effectiveness of the opening,
0.25–0.35 for diagonal winds
0.50–0.60 for perpendicular winds
A = Area of the opening (m^2)
v = Wind speed (m/s)

Structural cooling by night ventilation has long been common in hot and arid regions. During the daytime, a sufficient amount of internal building mass can serve as a heat sink to absorb, by radiation and natural convection, the heat penetrating into and generated inside the building. To enhance this effect, the building should in most cases be unventilated during the daytime to prevent heating the interior by the hotter outdoor air. Not ventilating could conflict with thermal comfort, but comfort can be improved by increasing the indoor air speed with a fan, while minimizing ventilation with outdoor air.

As a rule of thumb, night ventilation can create an indoor maximum temperature of 7–8 K below the outdoor maximum. During daytime, when the building is closed, the thermal mass is cooler than the indoor air, making the operative temperature lower, further enhancing the comfort. See Figure 10.

The effect of fans is controllable by force and direction. Ceiling fans cover wide areas, but require high ceilings, about 3 m.

Extra ceiling height or solar chimneys create air movement by stack effect. Wind towers are particularly effective; they create a breeze and promote cooling by evaporation. Wind towers are frequent in the Middle East in regions with suitable prevailing winds during the hot season.

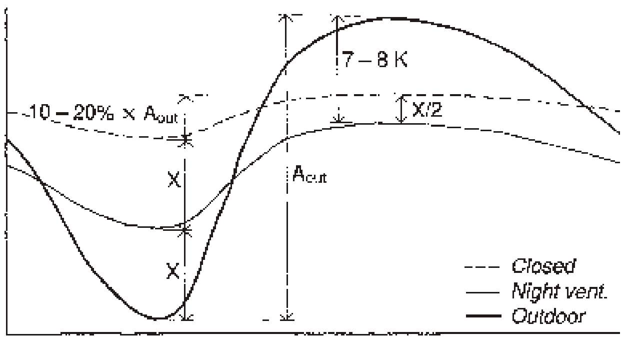

Fig. 10 Effect of night ventilation in high-mass, well-insulated and shaded buildings. Schematic, according to Givoni (1991).

The choice of ventilation system thus strongly affects the form of the building.

Minimum health ventilation must be secured. Only 0.14 l/s per person (resting) is needed to supply oxygen, but 2 l/s is needed to balance the vapour added by breathing. A good indicator for air quality is CO_2 concentration. To keep odours and emissions away, CO_2 should not exceed 1,000 ppm, which corresponds to an air supply of about 7–10 l/s and person, or about 0,35 l/s and m^3, or 0,5 air changes per hour, which could be recommended for housing.

Moisture removal from wet areas such as kitchens and bathrooms, requires higher rates of ventilation. Double rates are recommended. For more details, refer to ASHRAE 1997.

Evaporative systems

Evaporative systems can be used successfully where there is a great difference between dry-bulb (DBT) and wet bulb (WBT) temperatures. Mechanical systems (regarded as *active*), e.g. outdoor air sucked through wet pads by a fan, can reduce the air temperature by 70–80% of the DBT–WBT difference.

Passive direct evaporative systems involve very high rates of outdoor airflow. Pads in wind-facing large windows 50–100 mm thick can provide temperature reductions of 40–50% of the DBT–WBT difference. A downdraft cooling tower combined with a solar chimney at the opposite side of the building can give 88% DBT–WBT reduction.

Indirect evaporative cooling is by roof or ground ponds. These systems are generally less suitable for regions with limited water supply. They are also far too complicated for low-cost buildings, and roof ponds may cause leakage.

Radiative cooling

Low equivalent sky temperatures in arid regions have been used for radiative cooling of heavy roofs in traditional architecture. The gain of insulating the roofs for solar protection during the day, or for reduced heat losses in cold seasons, is however often greater. There are prototypes for ‘sky coolers’, but they are far too complicated or expensive for practical and low-cost use.

Heat capacity systems

Earth cooling has high investment costs and passages could be difficult to keep free of harmful bacteria. Efficiency is often low. An intermediate between structural mass storage and earth cooling is the rock bed. There are passive, active and hybrid systems. Rock beds are suitable for housing and other small buildings. However, the investment costs are high. Usable basement rooms could give this effect to some extent.

The Trombe wall, a well-known system among architects and researchers, is a mass wall behind a glass pane. It has some effect in theory, but is too complicated to manage for normal users. The use is therefore not widespread. Glazed spaces are more useable.

Materials

Too much attention is often given only to the choice of one main building material for the construction. Seen in a systems approach the building materials may be different for different building elements. They also interact with the *design* of the building, which may play a greater role for the overall thermal performance.

A standard recommendation is that ‘local’ materials should be used as far as possible. However, the choice of materials should take into account, not only the production, transportation and construction costs and energy, but the life-cycle cost of the building, including the operation and the demolition and possible recycling of the material. A more ‘intermediate’ or ‘expensive’ material may in that perspective save resources compared to a ‘local’ or ‘cheap’ material.

Thermal properties

Thermal resistance and thermal capacity are more or less antonyms, but all building materials possess both of them in different proportions. There are three factors influencing these properties:

The *density* (ρ, *kg/m*^{3}) plays a great role for the thermal properties: the lighter the material the more insulating and the heavier the more heat storing.

The *conductivity* (λ, *W/mK*) describes the ability to conduct heat. Insulating materials have low conductivity.

The *specific heat* (c_p, *Wh/kgK*) indicates how much energy can be stored in the material. High specific heat means good thermal, that is heat storing, capacity.

Density, conductivity and specific heat for some common building materials are shown in Table 6. Local variations may occur, especially in relation to moisture content.

Table 6 Thermal properties for some common building materials (based on various sources).

Material	*Density kg/m³*	*Conductivity W/mK*	*Specific Heat Wh/kgK*
Adobe blocks	1 000–1 700	0.3–0.8	0.28–0.30
Aluminium	2 700–2 800	160–200	0.25
Bricks	1 200–2 000	0.42–0.96	0.25–0.30
Clay	1 600–2 000	0.45–0.9	0.22–0.24
Concrete	2 200–2 400	1.2–2.0	0.23–0.30
Cork, expanded	115–200	0.043–0.052	0.47–0.58
Lightweight concrete	200–1 600	0.08–0.80	0.27–0.31
Mineral wool	20–300	0.034–0.049	0.18–0.21
Sand	1 500–1 700	0.40–0.50	0.23
Steel	7 800	50–60	0.13
Stone	2 000–2 800	1.3–3.5	0.20–0.25
Wood	500–900	0.14–0.16	0.66–0.76

The combination of thermal properties has influence on the *time lag* and the *attenuation* of building elements. The time lag is the time from outside to inside maximum surface temperature, and the attenuation is the proportion of inside to outside temperature amplitude (swing). These properties strongly affect the indoor climate.

Surface properties of building materials are *absorptance*, which is the ability to absorb short-wave, visible light, and *emittance*, correspondingly to long-wave, heat radiation. Absorptance, relates to colour, and values between 20% for white paint and 95% for black surfaces are normal. Emittance relates more to surface structure, and is normally about 85–95% for building materials, except shiny metal surfaces, which may have 10–30% emittance.

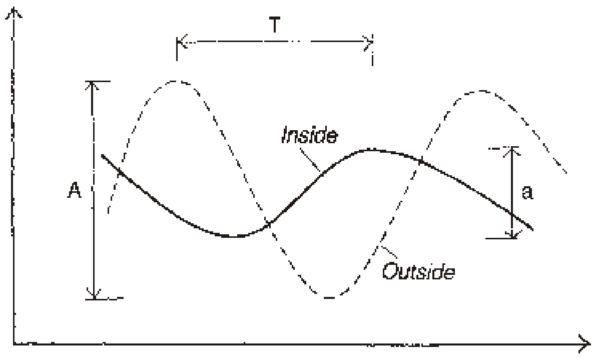

Fig. 11 The concepts of time lag and attenuation. The chart could describe the outside and inside temperatures of a construction element. Time lag (T) is the duration between outside and inside maximum. Attenuation is the relation between inside and outside amplitude, a/A. The concept can also be applied to a whole building, relating outdoor and indoor temperatures.

Consequently, a white-painted rendering reflects most of the solar radiation but may emit a great deal of heat, e.g. to a clear night sky.

Table 7 Absorptance and emittance of some building materials (based on various sources).

Material		Absorp-tance (a)%	Emit-tance (e)%
Aluminium sheet	New	20–40	10
	Oxidized	30–50	20–30
Burnt clay bricks	Cream	30–50	85–95
	Yellow	55	90
	Red	65–80	85–95
Concrete	Light	45–70	85–95
	Dark	90	90
Earth		80	90
Grass, leaves		75–80	85–95
Paint	White	20–30	85–95
	Light grey	30	90
	Light green	50–60	90
	Medium grey, yellow, orange	55	90
	Light brown, grey, red	65–70	90
	Dark brown/ red/green	80–90	90
	Black	85–95	85–95
Steel sheet	Galvanized, new	30–65	15–30
	Galvanized, oxidized	80	20–40
	Rusty	60–85	60–90
Stone	White marble	50	85–95
	Limestone	60	85–95
	Yellow	50–70	85–95
	Red	65–80	85–95
Thatch		60–70	85–95
Whitewash	New	10–15	20–30
	Weathered	20–30	20–40
Wood	Pine	60	90–95

The *thermal resistance (R-value)* of a material layer is calculated, for steady-state conditions, as the thickness divided by the conductivity (d/λ). The overall thermal resistance of a building element is the sum of the R-values of each layer of the element, including the so-called film resistance of the air layers close to the element's outer (0.03–0.04 m^2K/W depending on wind) and inner (0.11–0.16 m^2K/W for non-reflective materials, depending on position and heat flow direction) surfaces. The *thermal transmittance (U-value)* is the reciprocal of the thermal resistance. For complex elements, such as stud walls, the average U-value may be calculated as the proportional average of the U-values for each part (Example: 20% studs with U=0.6 and 80% insulation with U=0.3 gives $U = 0.2 \times 0.6 + 0.8 \times 0.3 = 0.36$ W/ m^2/ K).

Structure

Traditional building materials were heavy in many regions, and therefore old buildings were confined to the same technique. Today there are lightweight, insulating materials, and technically we can choose to arrange the structure of a building with separate functions for thermal accumulation and insulation.

In climates that require high thermal mass, this is most efficient if put inside the building. However, insulation outside the heavy structural layer reduces the amount of heat penetrating during the day. High temperature fluctuations, when nocturnal radiation may cool the outer surfaces far below air temperature, cause rapid expansion and contraction, especially on a roof, making it important to find durable cladding and waterproofing materials that can endure these temperature changes. Even external rendering of insulated walls needs special attention.

Problems with mould can be avoided by rain protection on the external side and adequate ventilation indoors. Some materials need to be protected against ultraviolet radiation from the sun.

User influence

Measurements and computer simulations with the aim of developing new designs are often carried out in laboratory-like environments. The thermal performance of the *building* can be evaluated, but these experiments do not take the *user* into account. The user might be calculated in as an internal heat load, but it is difficult to foresee how he/she will react to a new passive climatization device or design concept. The behaviour of occupants influences the effectiveness of the design in use. Users' demands must therefore be taken into account.

User patterns and the time of occupation may also affect the design of individual rooms. In a bedroom that is not occupied during the day the indoor climate during daytime is of no interest, and the design should be optimized for night comfort. An office should normally be optimized for comfort during working hours.

One passive approach is migration. In the past daily and seasonal migrations were responses to climate changes. They occurred, for example, in traditional Arabic courtyard houses, but smaller modern dwellings do not accommodate this kind of climate adaptation

Recommendations

Each building site offers its own conditions for a good climatic design, and it is the task of the designer to exploit the positive and avoid the negative. Even if it is difficult to give any general rules, some recommendations are summarized below for each main climate type. The recommendations are in the form of a checklist referring back to the sections of the previous chapter.

General

Generally, building design should be passive as far as possible to minimize the need for energy input. If this solution is not fully satisfactory, complementary hybrid or active systems may be used. However, these systems should be simple and cheap to build, operate and maintain, integrated as far as possible in the building structure, and they should meet any user requirements.

Climate types

The definitions below comply with those in the chapter on page 6.

Cold climate

Surroundings
The urban fabric, site layout and building orientation should protect from cold winds. Solar access is important during the long, cold season when the sun is low. Glazed-over or covered urban spaces may be adequate, but risks of occasional overheating must be considered. Drifting snow may cause problems in some areas.

Heating and cooling
Indoor heating of buildings is often required all year around. Internal heat loads from lighting and equipment in offices or workshops may call for occasional cooling.

Form
A minimized and well-insulated building envelope that reduces heat losses is most adequate. Pitched roofs are suitable for rain protection. Snow loads may have to be considered.

Orientation
Orientation for solar access is important, especially in the winter. Double or triple glazing is required. Large glazed areas may require shading in some directions if the summer is hot. Windows in direction opposite from the equator should be minimized.

Ventilation
The ventilation rate should be kept at a minimum to reduce heat losses, but not so low that it causes health or moisture problems.

Other techniques
The potential for solar heating may be limited, at least when most needed. Long-term storage may be difficult or too expensive. Hybrid solutions, such as heat pumps, may be appropriate.

Materials
Thermal insulation of buildings is important to raise the temperature of inner surfaces for better comfort, and to reduce the amount of energy used for heating. High insulation makes outer colour less important.

Design tools
With low variations in temperatures, steady-state calculations from U-values and outdoor and indoor design temperatures may give good estimates of energy consumption. The effect of thermal storage is less important. Many computer simulation programs for thermal performance give detailed results with good precision.

Solar diagrams may be used to assure solar access to windows and outdoor areas.

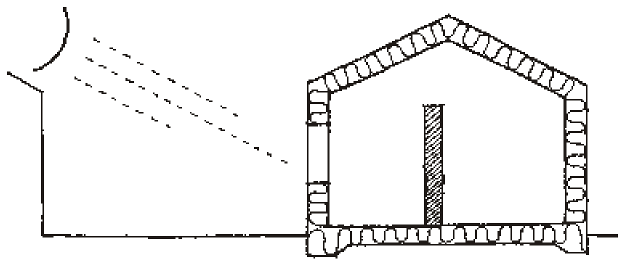

Fig. 12 Design principles for cold climates.

Temperate climate

Surroundings
On the urban scale both protection from cold winter winds and from summer heat must be considered. Vegetation may create comfortable shading during summer and, if they drop their leaves, allow for solar access in the winter. Also arcades may shade public space in the summer, while letting the lower winter sun in.

Heating and cooling
A temperate climate, often having both cold and warm seasons, normally requires both heating and cooling of buildings. Solar heating should be adequate for a great part of the year.

Form
Different seasons require different building forms. One solution could be to design an insulated and heated central winter unit, with open, shaded or glazed spaces around this core for seasonal use.

Orientation
Correctly placed windows and sun spaces can take advantage of the sun for winter heating but must be protected during hot seasons.

Ventilation
Different seasons may also require widely different ventilation solutions. Compare with the recommendations for cold, arid and humid climates.

Other techniques
Sun spaces offer flexible and inexpensive solutions for different seasons, while heat capacity systems may be advantageous during transition periods with a wide temperature difference between day and night.

Materials
There is a need for both thermal insulation and thermal storage capacity (heavy mass).

Design tools
Dynamic calculation models, taking heat capacity into account, are necessary to assess the thermal performance of buildings. Solar diagrams could be useful for finding combined solutions for all seasons. Simpler models for ventilation may be sufficient.

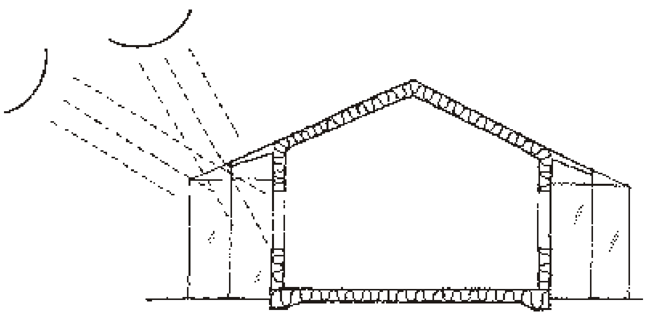

Fig. 13 Design principles for temperate climates.

Hot-arid climate

Surroundings
A compact urban plan is preferable for obtaining an acceptable microclimate in the hot season. Narrow streets, that might also be covered or lined by arcades, create shade and may act as cool ponds where buildings get their ventilation air. Protection from airborne sand and dust could be important. Though highly reflective surfaces are thermally preferable they may create glare. Solar access during colder seasons may improve urban climate.

Heating and cooling
Cooling is most important for the greater part of the year, but there may be cooler seasons requiring heating.

Form
A compact layout of buildings minimizes solar exposure in the summer and heat losses in the winter, if any. Courtyard houses create intermediate zones that can differ greatly from the outer climate.

Orientation
Orientation according to the sun is most important, and north-south orientation of the main facades is preferable. If there is a cooler season, correctly placed and oriented windows may improve indoor comfort during winter. Solar protection is important, especially towards the west where afternoon sun coincides with high air temperatures.

If there are prevailing winds suitable for cooling they can be caught by correctly placed openings or by special devices.

Ventilation
Increased ventilation during the night cools the structure, and if kept well closed during daytime the building may keep a lower indoor temperature. Ceiling or table fans may improve indoor comfort while the building is closed.

High vents prevent the creation of hot air pockets under the ceiling. For a dome or vault, an air vent at the apex, which is a low-pressure zone, is effective.

Wind towers/catchers may increase ventilation if there are prevailing winds. Ventilation chimneys, creating stack effects, may work where there are low or no winds.

Other techniques
Evaporative systems have great potential. However, clean water is needed. Mechanical systems have the highest efficiency, but also passive techniques give reasonable results. Fountains and vegetation in courtyards are useful and often found in such climates.

Radiative cooling towards the clear sky can give considerable dissipation of heat, especially from surfaces with a high sky view factor, such as a roof.

Materials
The great changes in day and night temperatures can be utilized by incorporating heavy materials to help moderate the indoor climate.

Some thermal insulation is advantageous, particularly of the roof, which receives the most solar radiation during hot periods. A lightweight and insulating envelope reduces overall heat transfer, especially during winter, but requires heavy internal elements for heat storage.

Spaces for night occupation only may be constructed in lightweight materials, permitting quick structural cooling in the evening.

Design tools
Calculation of thermal performance of buildings must include heat storage. There is a range of computer programs on the market, but normally do not include evaporative cooling calculations. Solar diagrams should be used for designing shading devices, etc.

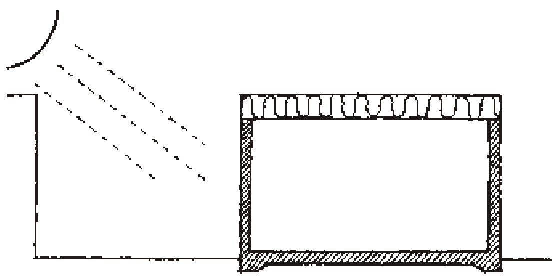

Fig. 14 Design principles for cold climates.

Warm-humid climate

Surroundings
Shading and ventilation are the most important factors for comfort. Solar radiation is mainly diffuse. The main issue is that buildings should have the right placement and spacing to allow wind flow, in contrast to arid climates where the sun position is most important. Surrounding vegetation may offer sky shading and wind deflection.

Protection from strong winds could be essential, especially in areas that experience hurricanes, typhoons or tornadoes.

Heating and cooling
Most warm-humid climates have no cold season. If air conditioning is partly required, it must be possible to close the building well.

Form
Buildings should be of open structure with large openings providing cross ventilation. Pitched roofs with wide overhangs or verandas create shade and rain protection. There should be storm water drainage leading away from the building.

Orientation
Since there is less direct sunshine, it is important to orient the building according to prevailing winds. There should be special care to admit desired winds and to protect from cold winds if there is a cooler season.

Ventilation
Adequately placed and designed openings can direct airflow into the spaces normally occupied. High vents prevent the creation of hot air pockets under the ceiling. It is important to provide for good ventilation in attic spaces, but be sure to protect against insects and other harmful animals.

Simple ceiling or table fans help improve indoor comfort if wind speed is not sufficient.

Good ventilation, together with protection from rain penetration into the building, prevents the growth of mould.

Other techniques
Evaporative systems do not work well where there is high humidity, and radiative cooling is less effective since skies are seldom clear.

An open building structure may create problems with noise and privacy, and special care must be taken if this is important.

Materials
Lightweight materials are suitable in most cases, since there are only small differences between day and night temperatures.

Ceilings, moderately insulated if possible, in combination with ventilated attic spaces help protect from solar heating through the roof. The roofing sheets should be light coloured, and the inside should be shiny to decrease heat emission downwards. However, oxidation often rapidly decreases this effect.

Design tools
Modelling ventilation is most essential in a hot-humid climate. Wind or water tunnel tests, or advanced computer models (CFD) may give useful results. Thermal calculations work well for closed, air-conditioned buildings. The high humidity level must be considered for comfort assessment. Solar diagrams are useful to dimension shading devices.

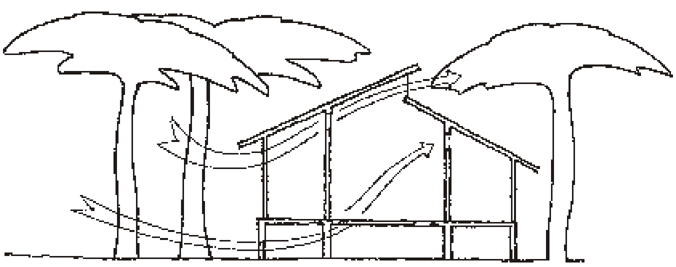

Fig. 15 Design principles for warm-humid climates.

Guidelines for Good Climatic Design

This chapter deals with collecting the data to improve climatic design in a specific situation. It is directed mainly to researchers, but it might also be useful to practising architects and engineers.

The method proposed to develop a detailed knowledge-base about the thermal performance of buildings is based on Rosenlund 1995, and contains three main parts, the ‘three cornerstones’. The interconnections among these ‘cornerstones’ and the step by step learning process are shown in Figure 16.

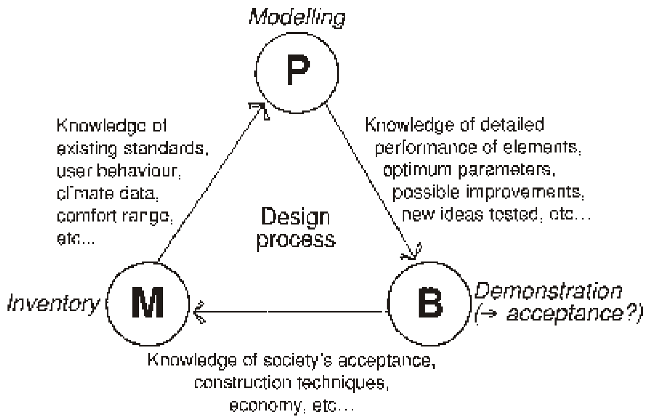

*Fig. 16 The ‘Triangle’. Relation between the ‘three cornerstones’ of the study: Field **M**easurements, **P**arametric studies, and experimental **B**uilding.*

Field measurements

The process normally starts with ‘M’ – *field measurements.* These are carried out in *existing* buildings. In this phase information is collected about the outdoor climate at the micro level, and the indoor climate normally experienced by the population. The measurements can take place in a number of objects, such as both traditional and modern buildings, and differences between such types can thus be revealed. The behaviour of the users or occupants is also studied, e.g. activity and occupation patterns, opening and closing of windows or the management of other passive or active appliances. A basic comfort range, and possible discrepancies to normal standards, may be established through interviews.

The purpose of this step is to establish a reference standard for the ‘normal’ indoor climate experienced by the population, and also to reveal possible differences between building types, such as traditional and contemporary buildings.

Methods

The measurement studies normally cover a long period to include different seasons and to get variations in the climate. User influence on the indoor climate can also be identified if periods with and without occupation are measured, or if parallel observations of the occupants’ behaviour are made (number of people, activities, opening and closing windows and shutters, etc).

It is especially important to compare findings with official climate data from the nearest meteorological station to see if the measured climate at the time is 'normal' or 'extreme' for the season, and if the time of measurement is within a stable period, if an evaluation of normal conditions is required.

Measurements over long periods can give large amounts of data. When evaluating these results it is important to decide what to study and then pick out the corresponding data. Regression analyses may be done, and these require continuous data over a longer period to be reliable.

Tools

Long-term studies require programmable loggers for data collection. Although they are becoming more and more reliable, loggers need periodic surveillance and control. Battery power or backup is essential, especially in remote areas, where there might be frequent power cuts, and infrequent site visits.

The data loggers and their probes must be regularly calibrated. The accuracy may also be checked occasionally with simple hand instruments or against available data, such as those from meteorological stations. Lastly the researcher must judge if the results are reasonable, according to his/her own experience.

Parametric modelling

A set of relevant parameters may be identified when evaluating the results of the field measurements. The second 'cornerstone', the *parametric modelling* study, is a process where the influence of each parameter (such as orientation, window size, building materials, or ventilation) on the indoor climate or energy consumption is assessed. After a first stage with systematic studies of each individual parameter a more intuitive process normally follows, where combinations of parameters are studied. The objective is *system* optimization or 'best possible solution' – not optimization of individual elements.

New design concepts, materials and techniques, or innovative applications of available materials and techniques may also be tested in this phase.

Methods

One or several typified baseline cases for computer modelling are created (such as one 'traditional' type and one 'modern'). Occupation patterns may also add variations to the baseline cases (e.g. one 'living house' and one 'office'). The baseline cases should be simplified as far as possible to be more generally representative for each of the building types, and to be easier to handle in computer modelling and calculations.

The baseline cases should be representative in terms of:

- general building concept: functional layout, orientation, detachment, courtyards, etc,
- unit size, roof spans, ceiling heights, etc,
- sizes, orientation and shading of openings,
- construction materials.

From one or more baseline cases the influence of changing one parameter at a time, such as window size or ventilation rate, is studied. This can give information on positive/negative or strong/weak influences, optimum dimensions, etc. Finally the results from these type-buildings must be translated into real construction and into recommendations, often as rules of thumb, sometimes also quantified into norms and regulations.

Tools

Instead of massive experimental buildings, today's techniques offer computer simulations as a relatively cheap method of pre-testing new building concepts or materials. Programs to be used in *research* require a great deal of knowledge to enter the input data and interpret the results correctly. They need to be validated through measurements of real buildings. This is especially important when working with non-conventional building design. Links to some programs can be found on HDM's homepage, see References.

Some ordinary *design* tool simulation programs are simpler but offer limited possibilities for modelling and calculation. Sometimes the algorithms assume a steady state and do not calculate dynamic processes, while others do not account for the effects of thermal storage. These simpler programs are often considered valid for their limited use, as an aid in the design of ordinary buildings, and they may even be certified for official use, such as for energy balance estimates in building permit applications.

Integration with other programs, and further development of computers could make the 'design-oriented' simulation programs more reliable, and usable early in the design process. Expandable databases, based on simulations, rules of thumb, expert systems, and heuristic models, integration with CAD and other modules would make both building design and production less expensive and more precise in the future.

Experimental buildings

In the third step the results of the parametric modelling are used in the design of an *experimental building*. The experimental building should be a 'real' building – to be occupied and evaluated by users.

This is when the research results are disseminated. There must be reasonable investment and operation costs for acceptance by clients, and simple construction techniques and materials are essential for the contractor and the building industry. Authorities may have jurisdiction over environmental impacts, energy consumption limits, health and safety, etc. General acceptance of the design, functionality and operation by the users can mean that the new building is conceived as 'modern'.

The experimental building is also used as a basis for further improvements of the design through measurements and computer simulations. The building now exists (a 'new reality' or standard is obtained), and we enter a second cycle (Figure 16), leading to the next experimental building, etc. – a process of increased knowledge and improved climatic design.

Methods

Design principles resulting from the previous phases of field measurements and parametric modelling are used as a basis for the conceptual design of an experimental building. Architects and engineers in a 'normal' design process may also use them as rules of thumb. Computer simulations may also be used as a complementary design tool for experimental buildings.

The experimental building should not only be an optimal result of the research, but also a 'real' building, serving a purpose and functioning together with its occupants and their activities. Interviews and discussions with the users lead to a deeper knowledge of the reactions to new concepts, indicating a degree of acceptability, and leading to further improvements of passive systems.

Experimental buildings also serve as demonstration objects. Good examples play an important role in introducing new design concepts and technical solutions, especially within the informal sector. The advantage of making *official* experimental buildings is that they are generally accessible to the public, and that there is often some person responsible for the operation of equipment, for opening and closing windows, etc. Small-scale buildings may also have many building materials and techniques in common with housing construction.

Fig. 17 An experimental building – a Children's Centre – built in Tozeur, Tunisia.

Experimental buildings should not be too extreme, if user acceptance and replication are intended. Yet they have to be perceived as 'modern' since, apart from a small number of romantics, a 'moderate modernity' is what most people want – or dare to identify themselves with.

Tools

A central process in the construction of experimental buildings is cooperation between research teams, possibly in several countries. In addition to researchers, practising architects and engineers should be involved. The importance of acceptance from these groups must be underlined. Without their understanding, cooperation and support, the dissemination of the ideas through professional channels cannot succeed.

The building industry and contractors play an important role. Integration into current and modern construction techniques, locally available materials, and a sound economy are essential for the viability of new ideas. The construction of an experimental building is a good opportunity to evaluate these factors, even if costs often are higher than normal.

Experimental buildings are often erected outside the framework of accepted norms and regulations. Finally, authorities must accept the new design concepts to integrate them into construction within the formal sector of the economy. A dialogue with concerned ministries, energy institutes and local authorities is important through the entire process.

Case study

As presented in the previous chapter, the research method consists of three main parts: field measurements, parametric computer modelling and the construction of experimental buildings. In this chapter a case study is analysed according to these three 'cornerstones'. The study was carried out as research cooperation between Lund University and ARRU – Agence de Réhabilitation et de Rénovation Urbaine, an authority for urban upgrading in Tunisia. The objective of the study was to increase knowledge about passive climatization of buildings in the hot and arid climate of southern Tunisia, and to demonstrate the findings in a real building – a children's centre to be built in the city of Tozeur.

The region and the climate

The city of Tozeur has a large oasis, and was founded by the Romans as the last outpost before the desert. Today it is the county capital with its main income from agriculture and tourism.

The traditional town centre, the Medina, is compact and the microclimate profits from the oasis. The buildings are of courtyard type and made of thick sandwich walls of local, low-fired bricks with mud between. New living areas have wide streets, and the houses are of both inward and outward looking types. The common building materials are concrete hollow blocks and lightweight bricks.

Tozeur is situated at 33°N at an altitude of only 37 m above sea level. There is a big salt lake south of the town forming the border to the Sahara desert. Normal temperatures are 6–16°C in January and 25–40°C in July. Extreme temperatures were between 0°C and 48°C in 1979–88. Relative humidity is normally 40–78% in January and 18–60% in July. Solar radiation is mainly direct and strong with 3,200 sunshine hours per year. Total annual rainfall is only 84 mm. Average wind speed is 2.6 m/s, from east or northeast in the spring/summer and from west in the autumn/winter.

Field measurements

To get a basic idea about indoor climate in the region, measurements were collected in two buildings in Tozeur (see Figure 18):

- One 'traditional' house in the historical centre (the medina), where the master bedroom was studied.
- One primary school on the outskirts of Tozeur, where the headmaster's office was measured. This construction can be characterized as 'modern'.

Room air and surface temperatures were measured in both places, and in the traditional room the relative humidity was recorded. At the school the outdoor climate was measured: air temperature, wind speed and direction, and global solar radiation on horizontal surface.

User behaviour

Due to the different functions of the buildings, the user influence was also different. Table 8 shows the principal usage of the two rooms.

The room in the traditional house was mainly occupied at night and closed during daytime, while the modern office was the opposite, except during the summer, when the school was closed. Irregularities in the usage of the spaces can also be seen in the results of the measurements.

Table 8 User behaviour. Measured traditional and modern buildings.

Traditional bedroom		
Summer	06	Rise. Shutters and door are closed (the glass windows are closed only if there is a lot of dust or a sandstorm).
	19	Windows and door are opened. Sometimes the courtyard is wetted.
	23-24	Go to bed.
Winter	The room is closed all the time. There is no heating.	
	06	Rise.
	21-22	Go to bed.
Modern office		
Summer	The semester starts September 15.	
	07.15	Arrival. Door, windows and shutters are opened.
	13	Departure. Door and shutters are closed.
	15	Return. Doors and shutters are opened.
	18	Departure. Door, windows and shutters are closed.
Winter	07.15	Arrival. Shutters are opened, but the windows are kept closed. The heater (600W) is turned on.
	13	Departure. Heater turned off.
	15	Return. Heater turned on.
	18	Departure. Heater turned off, shutters closed.

Measurements

Six days, the 23–28/8 1991, being a rather stable period, are chosen as an example of detailed studies.

The two roof constructions (a and b) show great differences in behaviour. The heavy traditional roof, more insulating than concrete, gets very high maximum external surface temperatures due to the solar radiation. The night minimum is much lower than the minimum air temperature, due to the long-wave radiation towards the night sky. The decrement factor, that is the remaining temperature swing on the inside in proportion to the outside, is about 15%. The modern concrete roof shows a lower outside swing, because the heat passes quickly into the structure, but the decrement is 35%, giving 4 degrees higher maximum ceiling temperatures than the traditional roof.

Comparative simulations

Simulations were carried out with two objectives:

- To validate the simulation models by comparing their results to the measured data.
- To equalize the different user influence through additional heat, ventilation and heating, and the possible difference in microclimate, recognized in the measurements.

A direct comparison of the measurements and the simulations shows that the simulated temperatures were generally higher than the measured. The correlation was higher be-

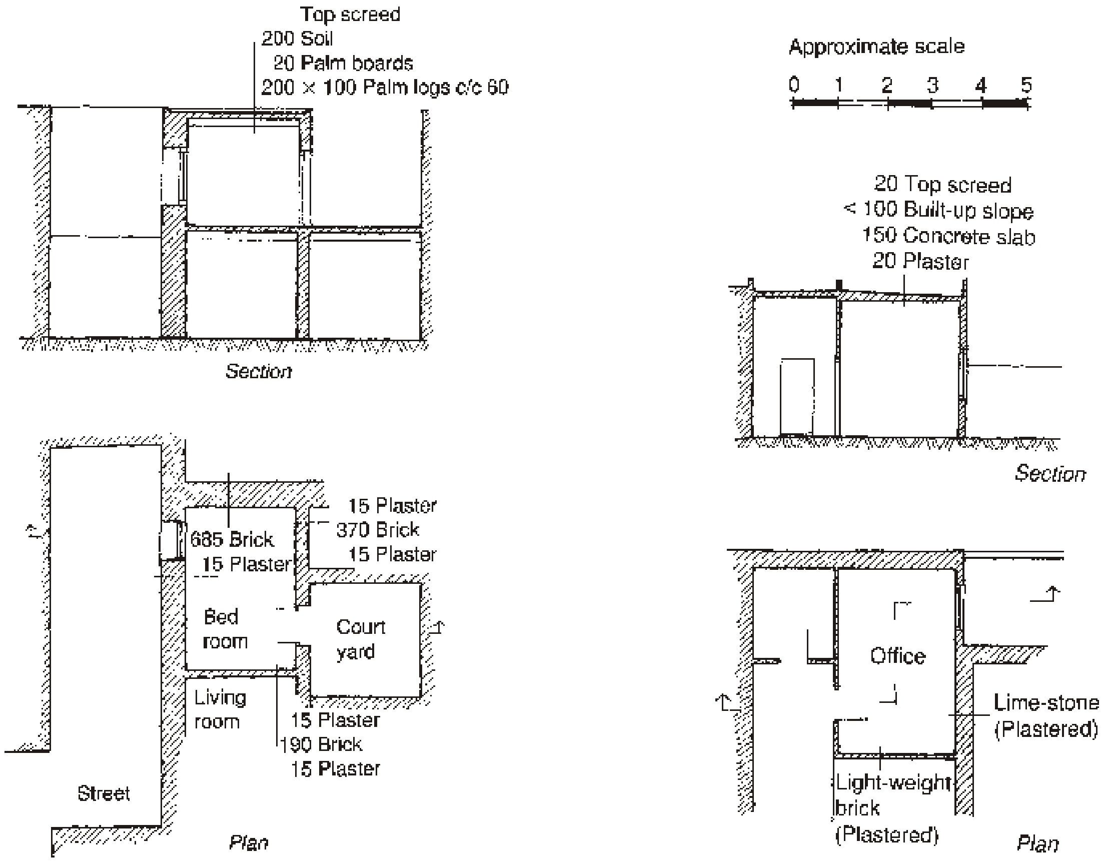

Fig. 18 Measured buildings in Tozeur, Tunisia.
Left: Traditional house, old town. Right: Office, primary school.

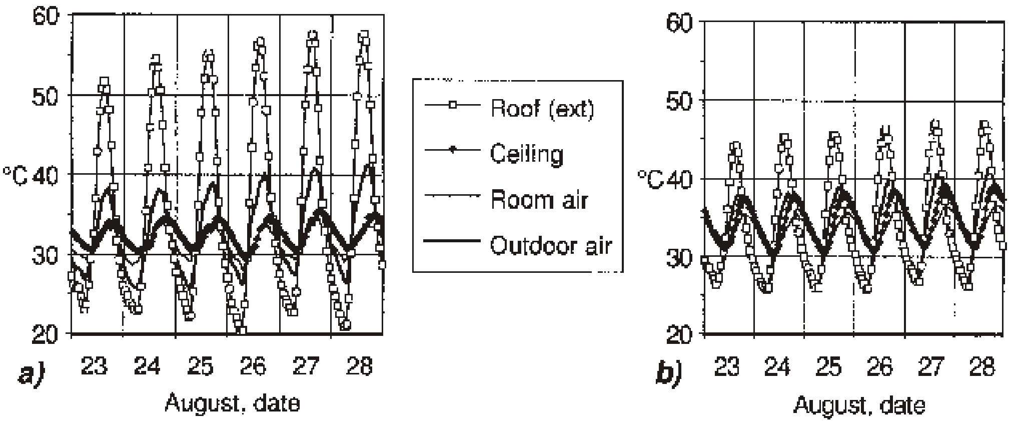

Fig. 19
Thermal behaviour of the roof.
Measured in the:
a traditional room,
b modern office.

tween midday and midnight, while during the rest of the night the real temperatures, especially that of the modern concrete roof, decreased more due to the night radiation. The reason for the difference was that the version of the simulation program used did not take into account long-wave sky radiation.

It was also found that the outdoor temperature in the old centre was lower than at the site of the primary school on the outskirts of the town.

In order to compare the two buildings under equal conditions, they were subjected to simulations with the same climate and ventilation (1 air change per hour 07–19 and 40 ach at night), and the shutters were closed during the day.

The results of the simulations showed that in the heavy traditional building temperatures are stable, only the ceiling temperature is slightly elevated. The modern office has high evening temperatures in the ceiling and the light-weight west and south walls (Figure 20 a–b).

Conclusions

The two buildings include different types of elements, based on thermal storage capacity and on insulation properties. The indoor climate of the rooms, described by the operative temperature (Figure 21), being in principle the same, shows that the individual building components are not primarily interesting as such, but the *combination* of them, the 'design', shapes the total climate of the building. See Figure 21.

The roof is the most sensitive element, and adding insulation would seem positive. If thermal insulation replaces heavier materials, it could also diminish the weight of the

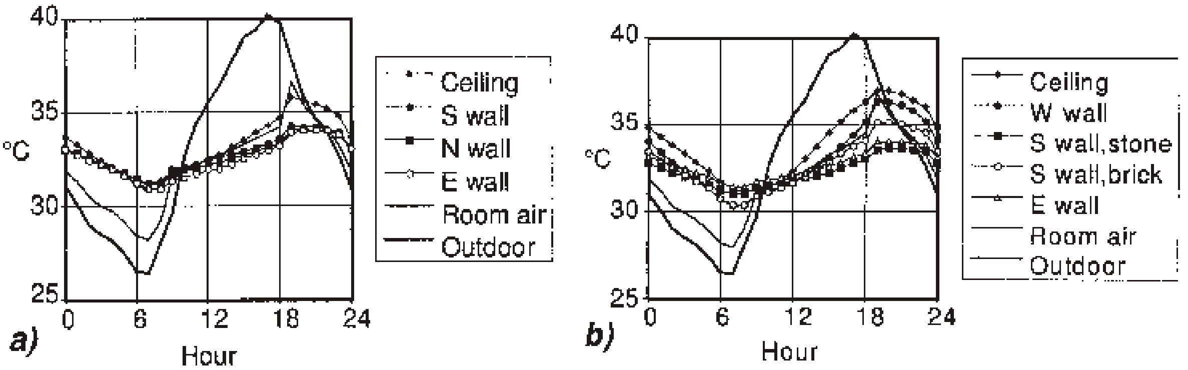

Fig. 20 Equalisation. Simulation with both buildings under the same conditions of microclimate, user behaviour and ventilation.
a Traditional room.
b Modern office.

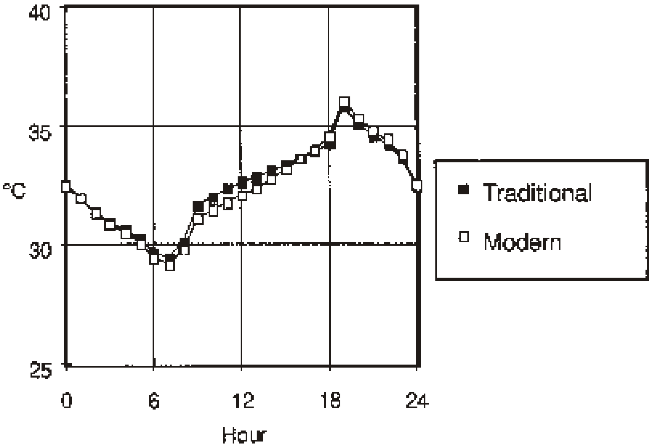

Fig. 21 Operative temperatures in the 'traditional' and the 'modern' buildings in Tozeur, Tunisia. Simulation where the two objects are submitted to the same conditions.

roof and thus the total cost of the construction. However, a problem with insulated roofs is the high and varying temperature of the outer surface, and cracking must be prevented.

The internal walls seem to be the most suitable for heat storage, since they are not exposed to the outdoor climate. They should therefore be heavy, while the outer walls should be insulated.

Intermittent active climatization, such as an electric heater under a desk as used in the modern building for 'local' comfort, has little influence on the heavy and semi-heavy building elements. However, permanent heating or cooling is too costly because of high heat losses through the poorly insulated envelope. Therefore, a conscious passive architecture, that is: provision of adequate ventilation, shading in the summer and utilization of solar energy in the winter, is more efficient.

It should also be noted that not only the design of the *building* influences indoor comfort; the immediate surroundings, through the *microclimate,* also play an important role.

Parametric modelling

Program

Simulations were carried out with *DEROB-LTH* developed by the Department of Building Science at Lund Institute of Technology, Lund University, Sweden (1999). The program runs under Windows and can handle up to eight volumes, each with 27 facing surfaces, and up to 100 building elements in total of 25 different types. It uses an RC network for thermal model design, calculating the indoor climate and possible energy consumption for heating and cooling.

The simulation result is given as hourly values of volume, surface and operative temperatures, solar radiation, heating and cooling requirements, comfort level, energy flows, etc, and as statistics for each month and for the whole simulation period. *DEROB-LTH* also includes a graphic module for checking the geometry of the building model from different angles. It is possible to view the building from the sun's position, where insolation on surfaces and through openings can be visualized for any day and hour of the year. Integration with CAD and databases will improve – probably not too far in the future.

Model

The building model was adapted to local practice in terms of size, form, materials and glazed areas. The model consists of a very long building where two rooms were studied: one room (A) at the western end, with a large area of outer walls, and a room (B) adjacent to the first. The outline is presented in Figure 22.

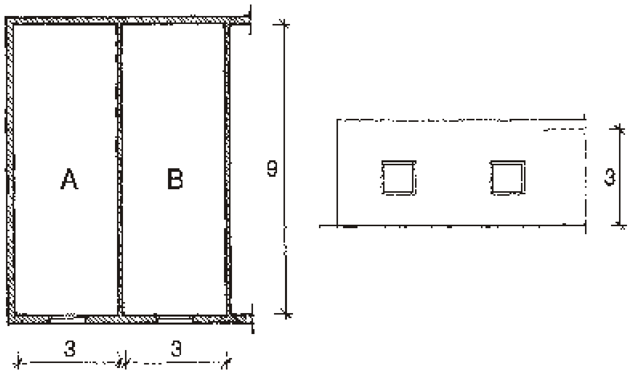

Fig. 22 The simulation model. Two rooms in the end of a long building are studied.

After checking each individual parameter, two different building types, denoted 'traditional' and 'modern', were modelled and compared in a series of simulations. These building types represent common building techniques and are outlined in Figure 23. Some fixed parameters for both these baseline cases are:

- The outer absorptivity is set to 0.3 (white to light cream), which is assumed to be the lowest practically obtainable value.
- The night ventilation in the summer is 20 air changes per hour (ach), and the same rate is used for winter day ventilation in some cases. This rate is deemed to be possible

to attain without special arrangements. At all other hours the minimum infiltration of 0.5 ach is assumed.

- The windows are towards the south and have shutters, closed during summer days and winter nights.

Climate data for Ghardaïa, Algeria, similar to that of Tozeur, was used throughout the study. Some of the results are presented below.

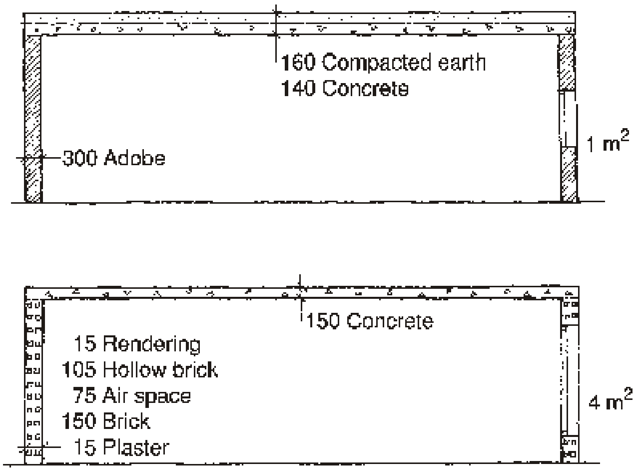

Fig. 23 'Traditional' and 'modern' models. Final baseline cases of the 'adapted' building. Top: 'Traditional'. Bottom: 'Modern'.

Roof insulation

An insulated roof, a 150 mm woodwool slab with a 50 mm concrete cover, only marginally improves the indoor climate in the traditional building, see Figure 24a.

In the modern building (Figure 24b), the temperature increase during summer days, mainly through solar heating of the roof, is reduced by 3 K when the roof is thermally insulated. In the winter heat losses are heavily reduced, especially at night. The temperature rises so much that day ventilation gives negative effects. When the building is kept closed, the maximum temperature almost reaches 20°C.

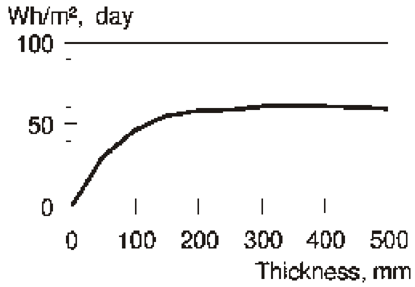

Fig. 25 Diurnal conductive heat storage in a concrete inner wall (per side) in July. Thickness over 150 mm has very little effect on the heat storage.

Window sizes

To obtain reasonably comfortable indoor winter temperatures through passive techniques in the traditional building, the whole south wall has to be glazed, i e 9 m^2 glass area, corresponding to 33% of the floor area. This implies radical changes in architecture or extensive reconstruction of existing buildings to adapt them to the climate.

In the modern type of building, the proposed 4 m^2 window (15%) is adequate, otherwise there is a risk of overheating, even in winter.

Occupation

The building model has been subjected to two different user profiles, both adding a total energy of 6.25 kWh per room and day. One 'office' model adds heat from 8 am to 6 pm, and one 'residential house' profile spread out over all hours has peak levels in the morning and evening.

For both building types with insulated roofs the indoor climate during the summer is about equal, with maximum operative temperatures about 32°C. In the winter, however, the difference is considerable: while the traditional building remains at temperatures about 13–15°C, the modern building rises up to 19–22°C.

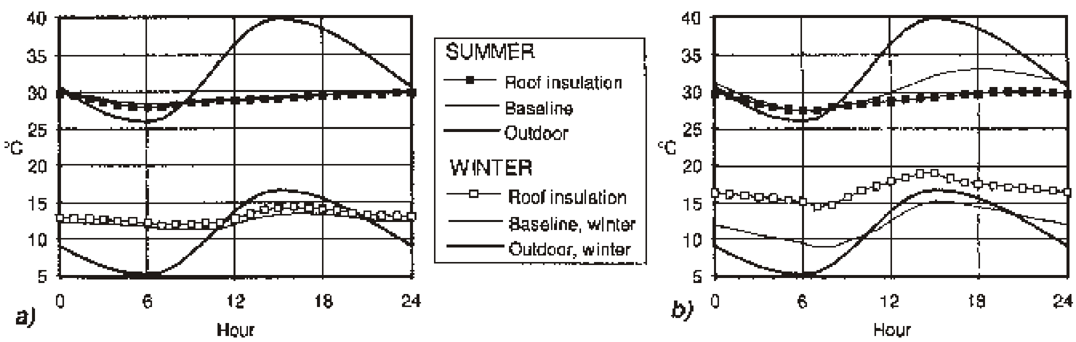

Fig. 24 Roof insulation. Effect on operative temperatures in room A of unoccupied buildings: a 'Traditional', b 'Modern'. (No increased day ventilation assumed in the modern winter case).

Thermal storage

Making the inner walls in the modern building of 150 mm concrete instead of 100 mm hollow brick can decrease the maximum summer temperature by 1 K due to the increased efficiency of the night ventilation. Thicker inner walls have a very marginal effect on diurnal heat storage and are a waste of building materials if not structurally justified, see Figure 25.

Active climatization

The possibility of future active climatization is essential to consider when making passive design. Figure 26 shows that roof insulation heavily reduces energy demands for active climatization. At the same time maximum power requirements decrease, leading to cheaper equipment.

Experimental building

The experimental building, the children's centre, which was built within the research cooperation with ARRU, is

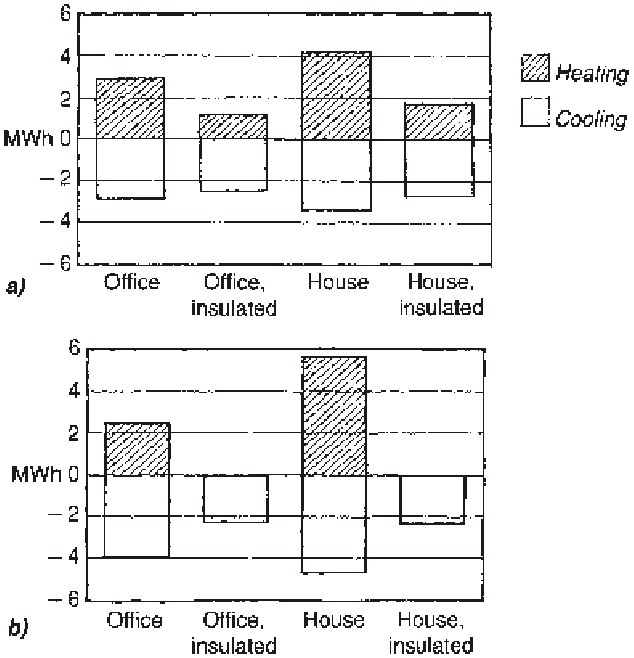

Fig. 26 Yearly energy demand for the baseline cases, without and with roof insulation;
a) ‘traditional’ b) ‘modern’,
Thermostat settings: 18–27°C, at 08–18 in the office, and at all hours in the residential house.
Floor area: 54 m^2. Climate: Ghardaïa, Algeria.

intended as a prototype for a small public building adapted to the climate of southern Tunisia.

Table 9 Simulation cases, Children's Centre. Seven combinations of wall and roof materials simulated in the design process.

Case	Outer walls [a]	Roofs [a]
1	500 stone	25 rendering 50 concrete 50 hourdis[b]
2	15 rendering 105 hollow brick 75 air space 150 hollow brick 15 plastering	
3		25 rendering 150 foam concrete 50 concrete
4		25 rendering 50 concrete 150 woodwool slabs
5	15 rendering 105 hollow brick 75 cork 150 hollow brick 15 plastering	
6	15 rendering 105 hollow brick 75 air space 150 cement stabilised soil 15 plastering	
7	500 stone	

a Ordered from outer to inner layers. Inner walls of stone and concrete.

b Hourdi = concrete hollow element.

Computer Aided Sketch Design
Computer simulations were now used as a *design tool*, and were run on the basis of a first sketch, mainly to study the effect of different building materials (Table 9) and window sizes (Table 10). Ventilation rates were assumed at 1 ach permanently in November–March and during the day in the summer, when the building is night ventilated with 40 ach 21–09. Occupation 09–18 is rated at 1,000 W in the activity hall, 500 W each in the workshop and the library, and 200 W each in the laboratory and the offices.

Table 10 Children's Centre. Three window sizes simulated (m^2).

Case	Activity hall	Laboratory	Workshop	Library
Small	3,4	1,7	1,7	1,2
Medium	6,7	3,4	3,4	2,4
Large	10,1	5,0	6,7	4,8

South facing window area, single glazed

Most of the building materials tested in these simulations are available on the market in southern Tunisia. However, some innovative solutions were sought.

The simulation results show that case 4, with double brick walls and an insulated roof, gives the highest indoor operative temperatures in the winter and also the lowest summer temperatures. The normal building practice, stonewalls and ‘hourdi’ roof, gives the worst indoor climate in both seasons (Figure 27a–b).

Given the materials of case 4, Figure 27c–d show the influence of window size on the temperatures. The large windows give higher indoor temperatures in January than the medium and small windows. The equal performance of the latter two is a result of *DEROB-LTH's* inability (in that version) to treat insolation correctly. In reality there should be a difference. In the summer all cases perform equally, since the shutters are closed during daytime.

Final design
The choice of wall materials was evident: case 4 performed best in both seasons. The roof was built of prestressed concrete beams at a c/c of as much as 1 m, thus saving many expensive beams and reducing the thermal bridges found in normal construction. See Figure 29.

The size of the windows followed practical and esthetical restrictions, and the windows roughly correspond to the ‘medium’ alternative in Table 10.

Construction
The construction of the children's centre was started by a small, local contractor in late 1993. The building was finished, except for external works, in spring 1995.

Measurements
Measurements in the youth club during operation are not yet evaluated. Figure 30 shows results from a similar building, where the difference between ‘optimal’ and ‘actual’ user behaviour can be seen. The users must learn how to manage the building, or the design must be revised.

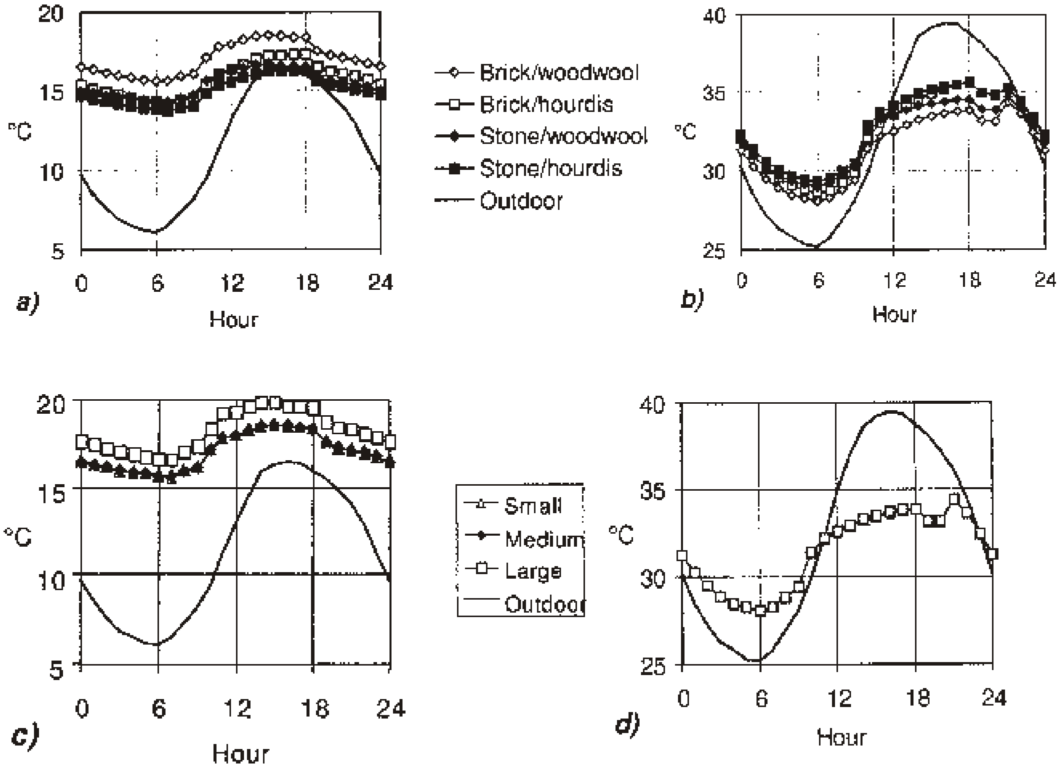

Fig. 27
Simulation results, Children's Centre, Tozeur. Operative temperatures in an occupied building. Influence of envelope materials (walls/roof) for medium-size windows:
a January, b July.
Influence of window sizes for the brick/ woodwool alternative (case 4):
c January, d July.

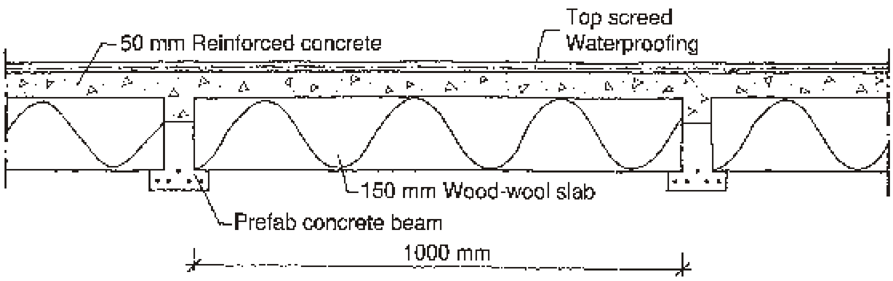

Fig. 29 The insulated roof of the Children's centre.

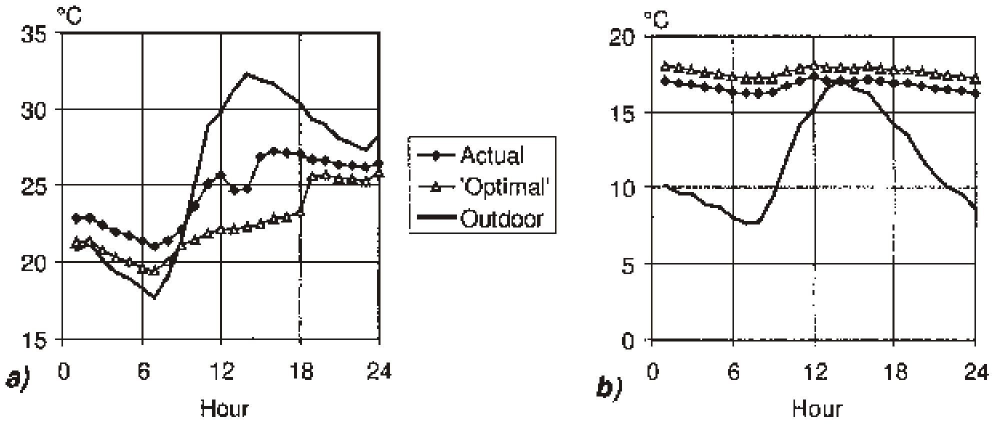

Fig. 30
User influence. Operative temperatures in the activity hall of the youth club in Tamerza, Tunisia. Actual measured data compared to simulations under 'optimal' conditions.
a) October (night ventilation, solar shading,)
b) November (minimum ventilation, solar access).

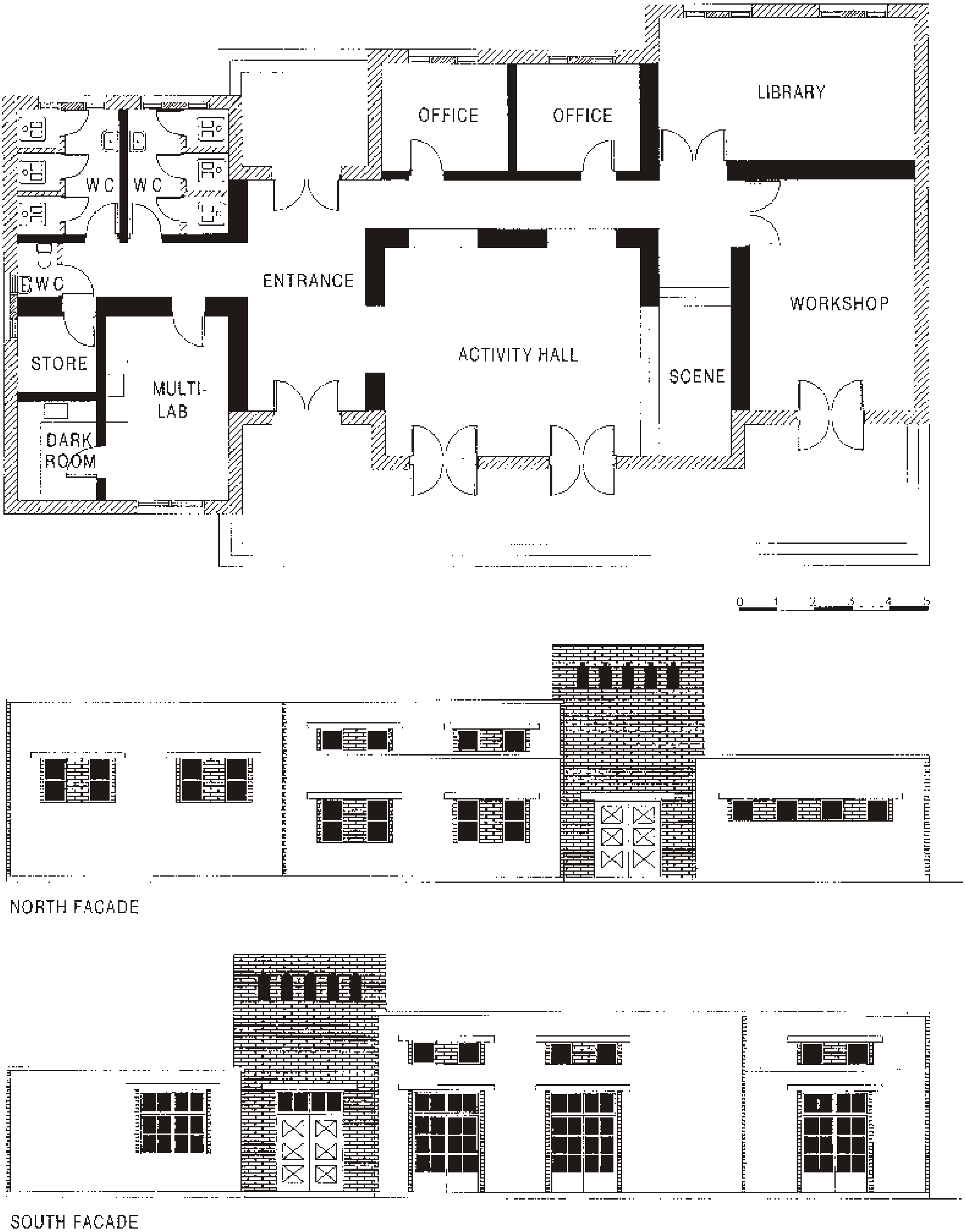

*Fig. 28 Children's centre. Tozeur, Tunisia
Plan and facades.*

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http://www.hdm.lth.se
The homepage of HDM – Department of Housing Development & Management at Lund University, Sweden, contains some simple tools and links to other relevant sites, including computer simulation programs, international energy organizations, courses and conferences.