A THERMIE PROGRAMME ACTION

THERMIE

Daylighting in Buildings

The European Commission
Directorate-General for Energy (DGXVII)

R.E.

The THERMIE Programme

This is an important European Community instrument. It is designed to promote greater use of European energy technologies. THERMIE is a major EC initiative, it will run for five years (1990-94) and it is estimated that the EC contribution during this period will amount to 700 million ECU.

The main aims of THERMIE are to:

- promote innovative energy technologies;
- disseminate information on these technologies;
- encourage greater use of new and renewable energy sources;
- improve energy efficiency;
- improve environmental protection.

THERMIE has been developed from previous EC programmes and provides enhanced provision for:

- co-ordination with complementary programmes in Member States;
- extensive dissemination of proven technologies;
- evaluation, follow-up, dissemination and co-operation;
- co-operation with non-member countries;
- consideration of environment and safety within eligibility criteria;
- liaison with key intermediary bodies within Member States to aid promotion of innovation.

The THERMIE programme covers a wide range of technologies for the production, transformation and use of energy. These are:

- rational use of energy in industry, buildings and transport;
- renewable energy sources including energy from biomass and waste, thermal and photovoltaic solar energy, wind, hydroelectric and geothermal energy;
- solid fuels, use of gaseous, liquid and solid wastes and gasification with a combined cycle;
- hydrocarbons; their exploration, production, transport and storage.

THERMIE Maxibrochures

A key element of the THERMIE programme is the enhanced dissemination of information relating to proven measures. This information is brought together for example in publications called Maxibrochures. These Maxibrochures will provide an in valuable source of information for those wishing to appreciate the current state-of-the-art within particular technologies.

Maxibrochures will draw together relevant information on specific subjects. This information will describe the current state-of-the-art within all member states and will therefore provide a pan-European assessment.

THERMIE Colour Coding

To enable readers to quickly identify those maxibrochures relating to specific parts of the THERMIE programme each Maxibrochure will be colour coded with a stripe in the lower right hand corner of each document, ie;

SOLID FUELS

RENEWABLE ENERGY

RATIONAL USE OF ENERGY

HYDROCARBONS

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Daylighting in Buildings

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Directorate-General for Energy (DGXVII)

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1 INTRODUCTION

It is difficult to overestimate the significance of daylight, and of sunlight, in the character of a building and in the lives of the people who use it. There are, of course, some building types, such as cinemas, theatres or nightclubs, where being cut off from the world outside is an essential part of the experience. In others, department stores or museums for example, daylight may be excluded from large areas of the building so as to give full play to carefully designed display lighting. But most interiors which are to be occupied by people, as opposed to goods or machinery, need plenty of light, and until the middle years of this century the limits of natural lighting were critical determinants in the plan of a building and in the design of its external envelope.

Dun Laoghaire Town Hall, Co. Dublin. John Loftus Robinson (1848 - 1894).

The arrival of fluorescent lighting and cheap energy made possible the multi-storey, deep-plan building where the ratio of usable floor area to external envelope was taken to its maximum. And with the deep plan came mechanical ventilation, followed by sealed windows and full air-conditioning. On expensive sites in dense, noisy and polluted urban areas the logic of this approach was particularly compelling. Daylight, in these circumstances, was no longer a critical design element - external walls might have some windows, no windows or, in the case of curtain walls, be all window. But this phase was to be short-lived. The energy crises of the 1970s together with recognition of the damage we are causing to the biosphere have been two of the factors encouraging a return to natural light and ventilation in buildings. Another, which is becoming increasingly significant, is the response of human beings to working in a wholly artificial environment.

There is concern about ‘Sick Building Syndrome’. Many factors - low humidity levels, bacteria and dust particles carried through poorly maintained air-handling systems, toxic emissions from building materials, flicker from fluorescent lamps, and daylight deprivation - have been implicated in a range of conditions from Legionnaires’ Disease through asthma, Seasonal Affective Disorder, chronic headaches and rhinitis, to non-specific malaise. Plainly these carry human and economic costs which one would wish to avoid, and they can indeed be minimised by the careful design, installation and maintenance of ‘artificial’ systems. But there is growing recognition that the more direct and rewarding solution may lie in a renewed emphasis on natural light and ventilation. Attempts to prove a direct relationship between productivity and the presence of daylight and views of the outdoors have been inconclusive, but research does show that people value the variety of daylight, enjoy the presence of sunlight in a building, and want at least a glimpse of the world outside. Daylight is the light to which we are naturally adapted; it is the light against which we measure all other kinds of light, in which we try to view things if we want to know what they ‘really’ look like. Historically, fine buildings have always exploited natural light and, after a brief interlude, the skillful use of daylight is once again being seen as a critical element in the design of buildings of high architectural quality.

The argument for daylighting in buildings therefore has three strands:

• it provides a healthier and more enjoyable indoor climate
• it conserves the earth’s resources
• because it saves energy, it saves money.

This publication is aimed at the professionals involved in the design of buildings and their clients. It is not a design manual, rather an introduction to the implications of daylighting strategy for the design of non-domestic buildings.

1.1 Visual Comfort

Visual comfort is the main determinant of lighting requirements. Good lighting will provide a suitable intensity and direction of illumination on the task area, appropriate colour rendering, the absence of discomfort and, in addition, a satisfying variety in lighting quality and intensity from place to place and over time.

People’s lighting preferences are subjective, relative and contextual and they vary with age, gender and the time of day or year (1). But the activity to be performed is critically important: the more intricate the task and the older the individual, the higher will be the level of light (**illuminance**) required. Poor lighting can cause eyestrain, fatigue, headaches and irritability, to say nothing of mistakes and accidents. Tables listing recommended illuminances for different activities, such as those appearing in the lighting guides published by the Chartered Institution of Building Services Engineers (CIBSE), London, are familiar to building professionals. Under the pressure of rising energy costs, and informed by research results on human visual performance, many countries have reduced their recommended lighting levels in recent years (1). It has been found, also, that where the source of light is natural, rather than artificial, people accept a wider range of illuminance values.

The colour appearance of objects around us depends on the spectral composition of the light in which we see them, and daylight is the norm by which we judge the colour rendering properties of other light sources. Even where very accurate colour rendering is not critical, the quality of light for most workplaces needs to be close to that of daylight, particularly during daylight hours. Lighting of good colour quality aids visual discrimination, and so reduces the quantity of light required for many tasks. While artificial light sources with a spectral composition very close to daylight are available, clearly, other things being equal, daylight itself is preferable.

Apart from providing daylight, windows have other advantages. It has been shown that where people are working for prolongued periods at one task visual fatigue is reduced by occasionally changing focal distance - by glancing from VDU screen to the landscape outdoors, for example. It has been found also that in schools, hospital wards and factories the absence of a view out produces psychological discomfort. In offices the psychological benefits of windows were found to be even greater than the physical benefits of which the occupants themselves were aware (2). One of the more subtle physiological benefits of windows is that they facilitate 'time orientation', so that our metabolic rythms are properly synchronised with the time of day or night.

Waterways Visitor Centre, Grand Canal Basin, Dublin. Office of Public Works.

The human eye is extremely adaptable and functions effectively over the range of illuminances from bright sunlight (100,000 lux) to moonlight (0.1 lux) - a ratio of one million to one. But this adaptability is constrained by the time required to adjust from one lighting level to another. In moving from bright exterior daylight to an artificially lit interior the eye can cope comfortably with a ratio of 200:1 between exterior and interior light levels, but it takes about 15 minutes to adjust to the first 100:1 of that drop. Seventy percent of the adjustment is made in the first 90 seconds. This time lag explains why extreme and sudden differences in light levels, such as moving between bright sunshine and a darkened room, cause a temporary 'blindness'. It also accounts for the discomfort caused when the eye has to cope, simultaneously, with great differences in light levels - a sunlit window in a shadowed wall, a direct view of the lamp in a light fitting, or bright reflections from a dark polished surface - the phenomenon we know as '**glare**'.

The position of the source of glare is important - generally the nearer it is, the larger it is, and the closer to a person's central field of vision, the more severe the impact. However, a study of glare from single windows concluded that discomfort was practically independent of size and distance from the observer but critically dependent on sky luminance. Other studies have shown that people have greater tolerance of glare from the sky, as seen through windows, than they have of glare from artificial sources.

1.2 Daylight as a Resource

The sun releases a power flux of 63 MW, equivalent to six thousand million lumens, for every square metre of its surface area. Of this around 134 kilolux reaches the earth's outer atmosphere. The atmosphere absorbs about 20% of this light and reflects another 25% back into outer space. A fraction of the remaining 55% reaches the ground directly, as sunlight, the rest is first diffused by the atmosphere (skylight) - these two together make up **daylight.**

The amount of daylight received on the ground varies with location. Latitude, coastal or inland situation, climate and air quality affect the intensity and duration of daylight. Current work on a European daylighting design guide suggests that thirty 'daylighting design zones' will be required to cover the variation in daylighting conditions across the European Union (3).

In addition, the quantity and quality of daylight in any one place varies with the hour of the day, time of year and meteorological conditions. Finally, the amount of daylight which a building receives also depends on its immediate surroundings - the orientation and tilt of its site, the presence or absence of obstructions and the reflectivity of adjacent surfaces. So an office building in a northern European industrial city, sited on a narrow street lined by tall buildings which are faced in dark stone, will have much less daylight available to it than a building located on an isolated, open, light-coloured sandy site on the Mediterranean coast.

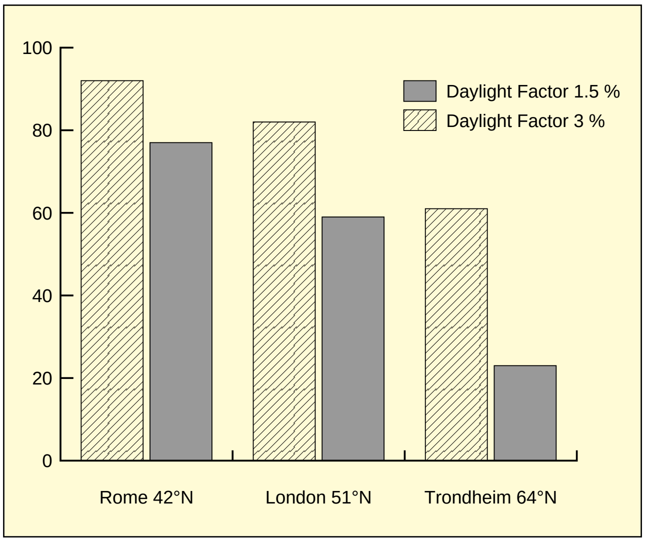


Figure 1: Percentage of working hours (9.00 to 17.00 hrs) throughout the year when an interior illuminance of 200 lux will be achieved in Rome, London and Trondheim.

Even in northern Europe, however, outdoor light levels greatly exceed the illuminances required for activities indoors for much of the day. The highest recommended indoor illuminance (approximately 1,500 lux for high-precision tasks) compares with average noon outdoor illuminances at Kew in England of 7,500 lux in December, 34,000 lux in July. And, except in the most northerly parts of Europe, working hours correspond with daylight hours during most of the year.

2 DAYLIGHT AND ENERGY

Artificial lighting is a substantial consumer of energy in non-domestic buildings. In offices it can account for as much as 50% of electricity consumption, and if the building has a deep plan it may use more energy than the heating does. During the summer months excess heat generated by artificial lighting may entail the consumption of further energy for mechanical cooling. Modelling studies of an identical, well designed and well controlled 54m^2 office room in Athens, London and Copenhagen indicated that in all three places artificial lighting accounted for about 35% of total lighting, heating and cooling costs over the year (4).

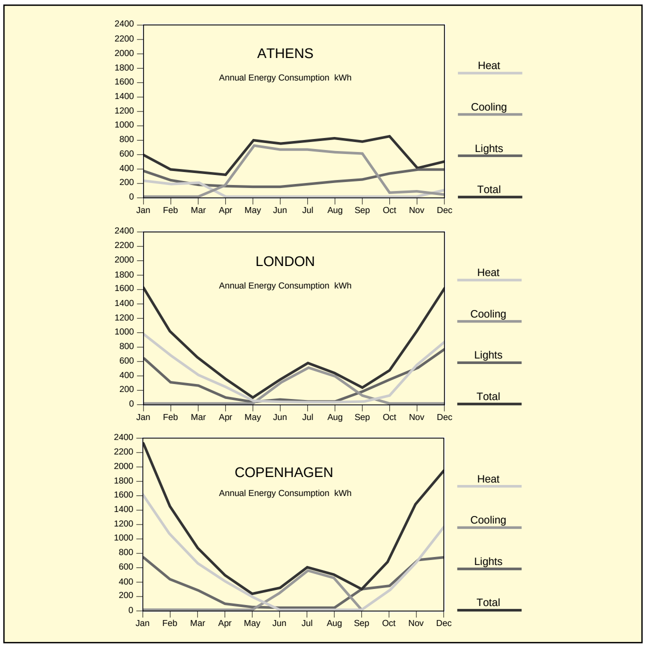


Figure 2: Energy costs in a model office room.

The substitution of daylight for artificial light can be expected to produce savings in the range 30 - 70%, provided that use of the artificial lighting installation is well controlled (5).

There are not many non-domestic buildings in which daylight can meet all lighting requirements, even during daylight hours; but equally there are few building types in which it cannot make a substantial contribution. In hospitals 20% - 30% of electricity use may be attributed to lighting; in factories typically 15%; in schools 10% - 15%. This does not mean that energy savings related to lighting are less worthwhile in these building types than in offices. A hospital or factory consumes very large amounts of energy in other activities (heating, sterilising or manufacturing, for example), so that the 15% or 30% attributable to lighting still represents a very substantial level of energy consumption and of financial expenditure.

The potential for savings through daylighting is affected by location, climate, building use and building form. We have seen that the amount and quality of daylight varies across Europe - so also does the need for heating and cooling. Heating, cooling and lighting are, of course, interdependent - unless carefully planned, the extra daylight may bring with it unwanted heat losses and/or gains. Particular site conditions too, such as orientation or site boundaries, may inhibit the optimisation of window size and position. The behaviour of the people who will use the building is another variable to be considered. Monitored data show that similar building types can vary in specific energy consumption by a factor of ten. The difference appears to be accounted for by building design, services design and occupant behaviour but, because of its long-term consequences, good building design is fundamental (6).

3 DAYLIGHTING DATA

The daylight that reaches a building is made up of light coming directly from the sun (sunlight), light diffused by the earth's atmosphere and light reflected from the ground or other surfaces. The problem in daylighting design is to assess the quantity and quality of light generated by all sources at a particular site.

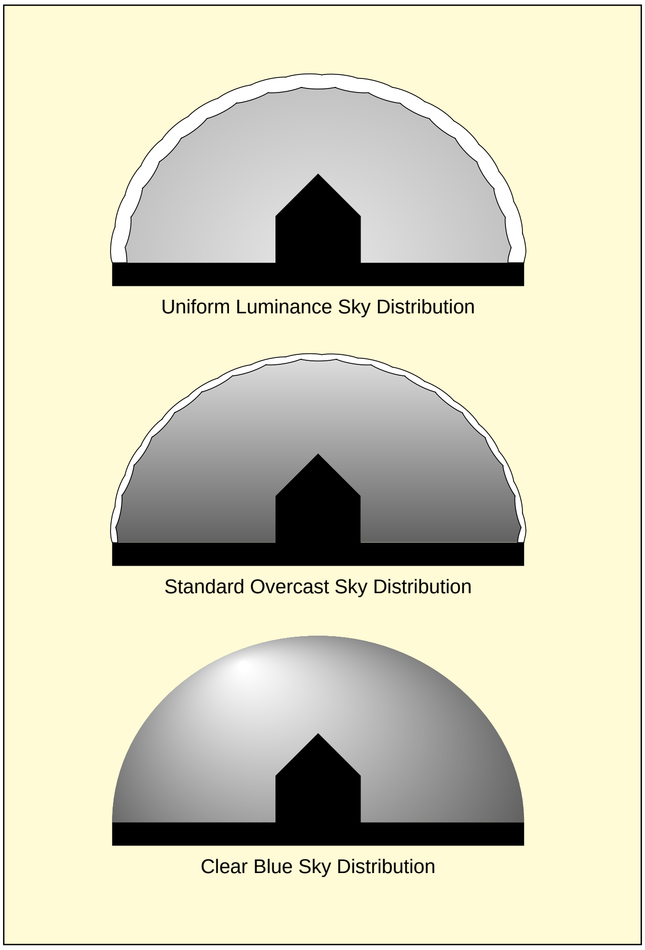


Figure 3: Standard skies.

The first factor to be considered is the **luminance** of the sky. The intensity of illumination from direct sunlight on a clear day varies with the thickness of the air mass it passes through- a function of the angle of the sun with respect to the surface of the earth. Light is less intense at sunrise and sunset than at noon, and less intense at higher latitudes than at lower ones. Sun angle also affects the luminance of overcast skies - at any one latitude an overcast sky may be more than twice as bright in Summer as it would be in Winter. Luminance varies across the sky vault - in a heavily overcast sky the luminance will vary by a factor of 3:1 between zenith and horizon, and in a clear blue sky the variation can be as much as 40:1 between the zone immediately around the sun and a point at right angles to the sun in the line of the solar azimuth.

The variations in sky luminance caused by the weather, season and time of day are difficult to codify. To meet this difficulty several ‘standard sky’ models have been developed. A standard sky provides approximate or notional luminance values for any part of the sky for use in daylight calculations or design. The simplest model is the **Uniform Luminance Sky Distribution**. It represents a sky of uniform and constant luminance, corresponding to a sky covered by thick white cloud, with the atmosphere full of dust, and the sun invisible. Another is the **CIE Standard Overcast Sky Distribution**, where the luminance varies from horizon to zenith and corresponds to a day when the sky is covered with cloud and the atmosphere is relatively clear. A third sky is the **Clear Blue Sky Distribution**, in which sky and atmosphere are clear, and luminance varies in relation to zenith, horizon and the position of the sun. Of these, the CIE Standard Overcast Sky model is the one most commonly used in simulation programmes and for the definition of standards and recommendations. Whereas this may be appropriate for northern European countries it will generate misleading results if applied in southern European conditions with clear blue skies. There are at present no standard models (though some formulae have been proposed) to represent the intermediate, partially cloudy or changing skies which are so often seen in reality.

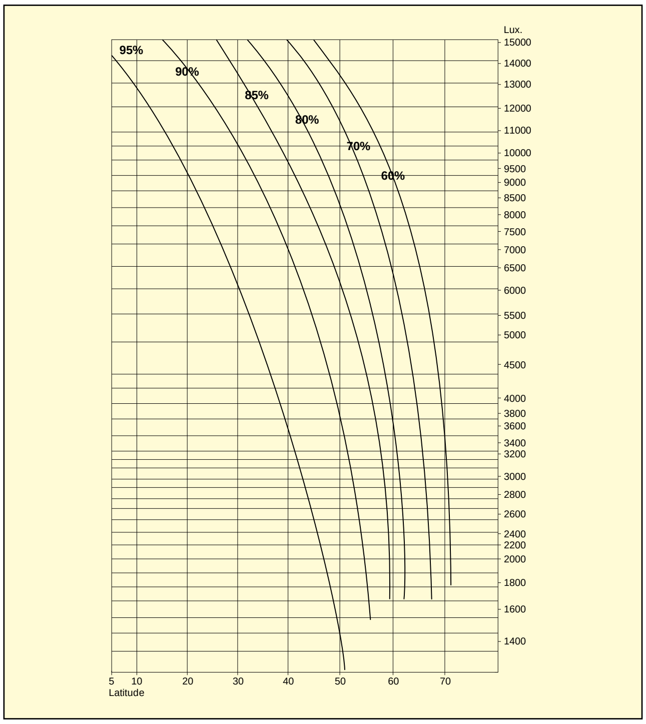


Figure 4 : Availability of outdoor light as a function of site latitude (7).

The period of time during which daylight is likely to meet the lighting requirements of a building can be calculated using a set of curves published by the Commission Internationale de l’Eclairage (CIE). These curves indicate for different latitudes the percentage of the working day (7.00hrs to 19.00hrs) during which a required exterior level of illumination on the horizontal plane will be reached, but they cannot, of course, take account of particular site conditions - overshadowing by hills, trees or buildings, for example, adjacent surfaces, or the design of the building itself (7).

For most buildings it is the exterior illuminance on *vertical* surfaces which is most critical for daylighting. Meteorological research carried out at 29 sites under the Test Reference Years (TRY) programme of the CEC has generated estimated figures for **global** and **diffuse illuminances** for the horizontal plane and for the four vertical planes facing North, East, South and West. The results are presented in the form of graphs showing daylight availibility at each test site during winter, mid-season, summer and for the year as a whole. The test sites were located in Belgium, Denmark, France, Ireland, Italy, The Netherlands and the UK. A separate project has produced similar data for four sites in Germany. Graphs showing illuminances at all 33 sites can be found in *Daylighting in Architecture* (8).

These models deal with light coming from the sky. The other source of daylight is light reflected from surrounding surfaces - ground, water, vegetation, other buildings. Reflected light is an important source of indoor daylight for apertures facing away from the sun, particularly in southern Europe where cloudless dark blue skies provide less diffuse light than do the cloudy skies of northern latitudes. The colour and the texture of surfaces around a building have critical consequences for both the quantity and the quality of reflected light - typical values are shown in the table below. Not only will the dark red glazed brick absorb 70% of the light falling upon it, but the 30% that it does reflect will be of a different, warmer, spectral composition.

Green grass	6%
Moist earth	7
Water	7
Asphalt	7
Gravel	13
Vegetation (average)	25
Dark red glazed brick	30
Concrete	40
White paint (old)	55
White paint (new)	75
Clean snow	74

Table 1 : Approximate reflectances of some outdoor surfaces.

4 COSTS

Daylight in buildings is not always free. Even a conventional window costs more than a blank wall, and buildings with a higher ratio of wall to floor area (necessary if most spaces are to be within reach of daylight) are more expensive to construct than those which are compact. Sophisticated daylighting devices are still relatively costly, although technological advances and larger scale production are making them increasingly viable. But many daylighting design decisions, if made early in the design process, involve no additional expenditure whatever.

Because daylighting is closely linked with artificial lighting, heating and cooling, ventilation, and general building costs, achieving cost-effectiveness will usually involve estimating the capital and running costs of several design alternatives. Payback periods will depend on local energy prices. In addition to direct savings due to lower capital and running costs for artificial lighting systems and the reduction or elimination of air-conditioning, other areas from which benefits can be expected include improved employee health and reduced absenteeism, increased building value and rentability, and a "green" corporate image.

5 DAYLIGHTING DESIGN

One of the attractions of using artificial light in factories, offices and other work-related buildings has always been its stability and its predictability. Daylight is always variable and frequently unpredictable. It is these very characteristics which account for people's liking for daylight and for the sparkle that daylight brings to the interior of a building, but which also make it challenging to work with. We want sunshine and daylight, but we don't like glare, downdrafts, loss of privacy, ultra-violet damage and severe temperature swings.

Kulturhalle, Remchingen. Professor Helmut Striffer.

The lighting, heating and ventilation of buildings, whether natural or artificial, are interdependent. Together they have profound consequences for the form a building will take. Too much glazing, the wrong kind of glazing, or glazing in the wrong place will produce heat losses or heat gains which may have to be countered by artificial heating or cooling. Too little glazing usually means too much artificial lighting - and sometimes artificial cooling as well. Daylight design should form part of a considered architectural strategy for the building as a whole.

We have seen that the daylight entering a building consists of light coming directly from the sun, light diffused through the atmosphere and light reflected from external surfaces. The distribution of light within the building depends on the size and geometry of the rooms, the size, position and detail design of windows and/or skylights, the characteristics of the glazing and the reflectance of interior surfaces. Good daylight design controls and exploits the available light, maximising its advantages and minimising its disadvantages. Most of the critical decisions are made during the early design stages.

Having drawn on daylighting data to establish the general character of local daylight availibility, it is necessary to analyse the particular site conditions. The slope and orientation of the site and overshadowing caused by mountains, vegetation or nearby buildings must be taken into account. *Energy in Architecture: the European Passive Solar Handbook* describes a graphic technique for analysing shading in mountainous areas. It also gives information on tools for assessing sunlight availability on site - among them a tripod-mounted Solar Site Selector, which gives instant readings of the skyline and solar obstructions for any time of the year for any point on the site, and the TNO Sunlight Meter, which displays the available periods of sunshine at any time of the year in the form of an image which can be photographed (9). Some simple techniques for assessing sunlight and daylight penetration in northern European buildings and the spaces between them are given in *Site Layout Planning for Daylight and Sunlight* (15).

The rooms in which daylighting is most important should be allocated the preferred positions and orientations, remembering that it is more difficult to screen the low-angle sun received on East and West facades and that this is where glare and overheating are most likely to occur. To arrive at a hierarchy of 'daylight need' the illuminance values and distribution required by the activities in each room must be established. In some spaces uniform lighting is required, in others some variety is desirable. In spaces where people occupy fixed positions, classrooms for example, design criteria will be more stringent than for rooms where people are free to move in and out of a patch of sunlight, towards or away from a window when the sky clouds over. Various agencies and textbooks list optimal illuminances for different activities. These are generally based on uniform and constant levels of artificial light falling on the working plane.

Corridors/Toilets	100-150 lux
Restaurant/Canteen	200
Library/Classroom	300
General office	500
Workbench	500
Drawing office	500-750
High-precision tasks	1500

Table 2 : Some typical recommended illuminances.

The starting point for daylighting design, however, is not a set of absolute values, but instead the **daylight factor**, a measure of indoor daylight illuminance at a given location as a percentage of illuminance outdoors. Recommended minimum daylight factors for the principal spaces in some non-domestic building types are given below. Lower daylight factors may be perfectly satisfactory for subsidiary spaces such as circulation areas.

Church	1%
Hospital ward	1%
Office	2%
Classroom	2%
Factory	5%

Table 3 : Recommended minimum daylight factors (4).

These figures refer to northern European conditions. In southern Europe, where outdoor illuminance is greater, daylight factors can be somewhat lower.

The daylight factor at any point on a working plane is calculated in terms of light coming directly from the sky (the Sky Component), light reflected from outside surfaces (the Externally Reflected Component), and light reflected from surfaces within the room (the Internally Reflected Component). Calculations are generally based on a model sky, such as the CIE Standard Overcast Sky. Daylight factor distribution can be plotted for any space or set of spaces at the design stage. With this information, and using the CIE curves shown in Figure 4, it is possible to estimate the percentage of the working year during which daylighting alone will meet the needs of the building's occupants. As Figure 1 demonstrated, the higher the daylight factors the greater will be this percentage.

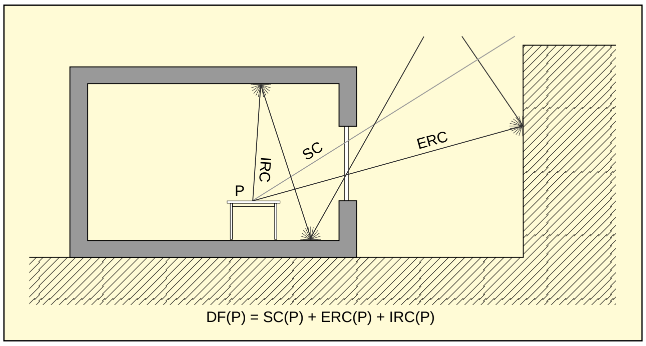


Figure 5: Daylight factor components.

In the early design stages the concept of the **average daylight factor** provides a useful technique for assessing the daylight potential of interior spaces under standard overcast conditions. The average daylight factor *df* is defined as:

$$df = (E_{in} / E_{out}) \times 100\%$$

where E_{in} is the average interior illuminance and E_{out} is the unobstructed horizontal outdoor illuminance. It can be calculated using the following formula:

$$df = TA_w \theta / [A (1-R^2)] \%$$

where

T is the diffuse visible transmittance of the glazing, including corrections for dirt on glass and any blinds and curtains. (For clean, clear single glass a value of 0.8 can be used).

A_w is the net glazed area of the window (m^2).

A is the total area of the room surfaces: ceiling, floor, walls and windows (m^2).

R is their average reflectance. (For fairly light coloured rooms a value of 0.5 can be taken.)

θ is the angle of visible sky in degrees, measured as shown in Figure 6.

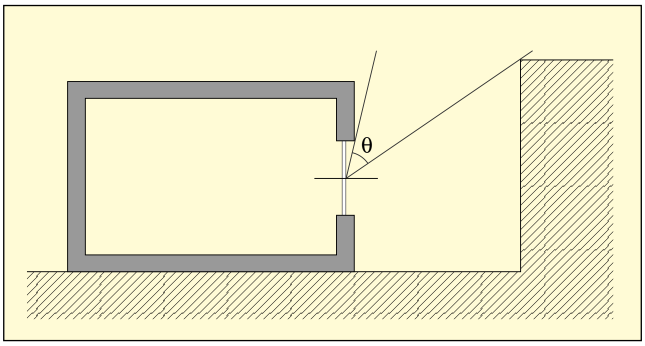


Figure 6 : θ is the angle subtended, in the vertical plane normal to the window, by sky visible from the centre of the window.

If a predominantly daylit appearance is required, then *df* should be 5% or more if there is to be no supplementary artificial lighting, or 2% if supplementary lighting is provided (15).

Daylight factors decrease as distance from windows increases, so that achieving good daylight levels away from the external walls is one of the principal challenges of daylight design. In conventional buildings one can expect to find that daylight penetrates significantly about 4 to 6m from the external walls. Generally a room will be adequately lit to a depth 2 to 2.5 times the height of the window from the floor, so taller rooms can be daylit to greater depth.

If a room is lit from one side only, the depth of the room, 'L', should generally not exceed the value given by the equation:

$$[(L / W) + (L / H)] \leq (2 / 1 - R_b)$$

where W is the room width
H is the window head height above floor level
R_b is the average reflectance of surfaces in the rear of the room.

If 'L' exceeds this value the back of the room may appear gloomy and supplementary daytime artificial lighting will be required (15). Our perception of room brightness appears to depend on the absence of dark areas, so that, for example, in a daylit classroom which is lit from both sides people tend to delay switching on the lights until illuminance falls below 150 lux.

Simply increasing overall window size may be counter-productive if it raises light levels close to the window more than it raises light levels deeper in the room. Peoples' perception of light is relative. Someone whose work station is in the inner area of a room may work happily in an illuminance of 200 lux while light levels beside the window are at 300 lux. But if the respective illuminances are 400 lux at the work station and 1000 lux by the window, the greater disparity may make 400 lux seem gloomy and lights may be switched on. This is a particular problem where an external obstruction prevents some work stations from having any view of the sky - these receive no direct sky light at all.

The reflectance values of room surfaces should be as high as possible. Daylight entering a room is reflected repeatedly off walls, floor, ceiling and fittings, some of its energy being absorbed each time. The amount of light lost depends on the colour and texture of the surface. A smooth, brilliant-white wall may reflect 85% of the light that falls upon it; a cream wall perhaps 75%; and a yellow only 65%. ‘Bright’ colours, such as orange or vermilion, absorb as much as 60% of the light that falls upon them but, on the other hand, may create an impression of warmth in places the sunlight cannot reach.

Where a window is intended to provide a view of the outdoors its design will depend on the nature of the exterior landscape, the size and proportions of the interior space and the positions and mobility of the people who occupy it. A window head that is too low, a sill that is too high, or a transome awkwardly placed may cut across the line of sight of people sitting or standing in the room. On the other hand, a high sill can be used to screen an unsightly forground from much of the room. With any window type, apart from a rooflight, people positioned in the depths of a room will see less of the landscape and skyscape than do people located by the window, and windows which are very restricted either in height or in breadth reduce the area of the room from which some view is obtainable. Minimum areas of glazing for rooms which are lit from one side only as shown in table 4. This total area should be distributed so as to provide some view from all occupied parts of the room.

Depth of room from outside wall (max.)	Percentage of window wall as seen from inside (min.)
< 8 m	20 %
8 - 11 m	25
11 - 14 m	30
> 14 m	35

Table 4 : Minimum glazed areas for view when windows are restricted to one wall (14).

To prevent glare from windows:

- the sun should be screened from direct view (by position and orientation of windows and the use of screening devices),
- brightness contrast in the window wall should be minimised (by splayed mullions and reveals in a pale coloured wall),
- brightness levels in the rest of the room should be raised (by light coloured finishes or additional light sources), and
- windows at focal points (beside blackboards or in line with VDUs, for example) should be avoided.

Maximum recommended values for the ratio between different parts of a visual field, the **luminance ratio**, are shown in Table 5.

Backround of visual task : environment	3 : 1
Background of task : peripheral field	10 : 1
Light source : adjoining field	20 : 1
Interior in general	40 : 1

Table 5 : Maximum recommended luminance ratios (4).

Most daylighting design calculations are based on diffuse daylight only and exclude the contribution of direct sunlight. But, provided that it does not cause visual or thermal discomfort, people welcome the presence of sunlight in building interiors and in the outdoor spaces associated with them. Most designers are familiar with **Sun Path Diagrams** and **Heliodons** which, used with drawings or physical models, permit the assessment of sunlight penetration during the design stage. In circulation spaces and in buildings where visual tolerances are wide - churches, shoppings malls, airport or railway station concourses, for example - sunlight and daylight can be used to dramatic effect.

Musée des Tumulus de Bougon. Studio Milou Architecte. (Photo: Fernando Urquijo).

In the following sections we look at new and traditional daylighting devices and products which can be used to control daylight and sunlight, and to moderate the conflict between good daylighting and a good thermal environment which glazing so often entails. Lightwells, roof monitors and clerestory windows are well established devices for getting light deep into buildings, as are blinds, shades and claustras or brise soleil for controlling it. The atrium can be seen as an elaborated and inhabited lightwell, lightshelves and coated or prismatic glasses as sophisticated shades and blinds, while lightpipes and transparent insulation are new concepts.

The design possbilities of the 'window' are, of course, extremely rich. Whether treated as a simple hole in the wall or as a complex three-dimensional element it makes a fundamental contribution to the quality of the interior spaces and the external appearance of a building. The way in which it frames a view, or captures light, or channels warmth and sound and air, helps determine the character of any room - whether it is intended to be merely a humane and comfortable working environment, a visually exciting and stimulating place of entertainment, or a solemn space with symbolic and spiritual impact.

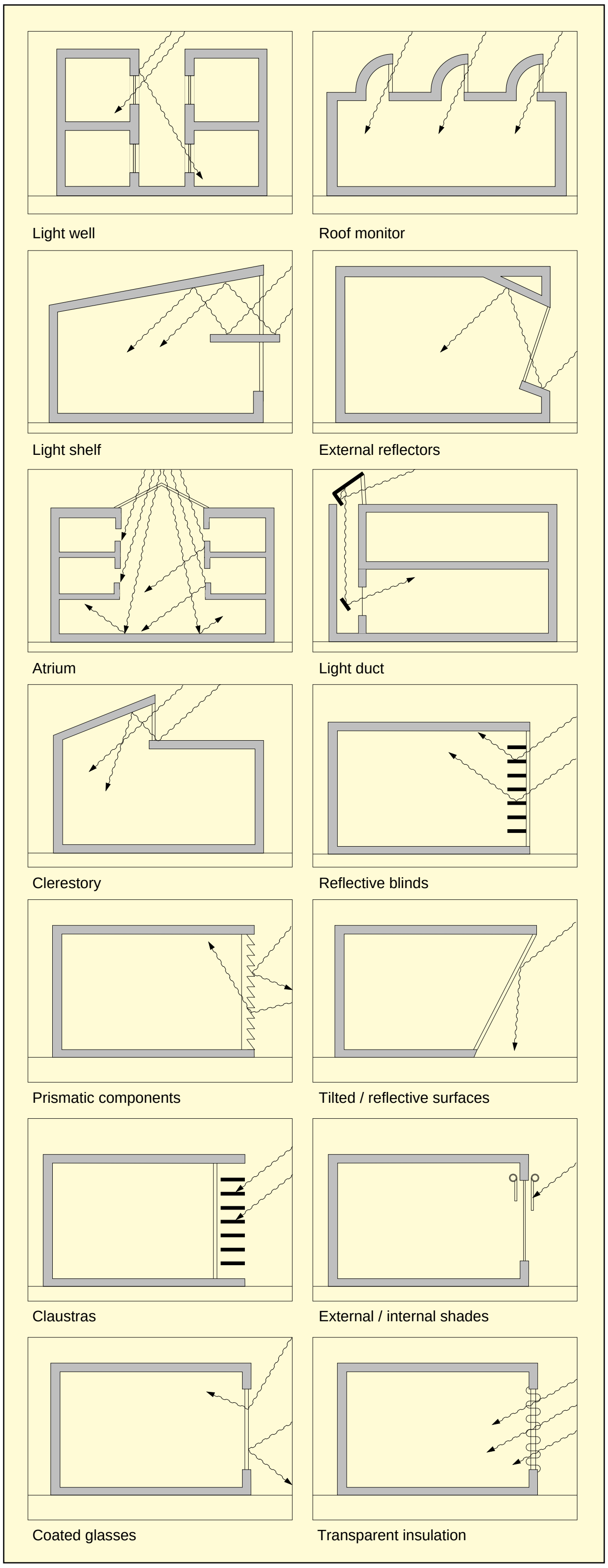


Figure 7: Daylighting devices.

5.1 Rooflights

Because the sky is generally brighter at its zenith than near the horizon, horizontal rooflights admit more daylight per square metre of glazed area than do vertical windows - a horizontal rooflight is proportionately three times more effective as a source of daylight than a vertical window. They cast their light over a space in a more uniform way, and they are less likely to be obstructed either internally or externally. Direct sunlight from horizontal openings can be diffused by translucent glazing, and glare controlled by baffle systems. Very beautiful effects can be created by fitting angled reflectors below horizontal rooflights or locating the rooflight beside a wall, so that ceilings or walls are washed with light.

Offices for Royal Life, Peterborough. Arup Associates Architects + Engineers + Quantity Surveyors. (Photo: Crispin Boyle).

A disadvantage of horizontal rooflights is that, compared to vertical windows, they collect more light and heat in summer than in winter - usually the opposite of what is desired. For this reason vertical or near-vertical rooflights - clerestories, sawtooth or roof monitors - are often preferred for lighting single-storey deep spaces. They can be oriented to North, South, East or West as circumstances demand, and screened with conventional devices. The duration and quality of daylight can be enhanced by placing light-catching scoops on the roof outside the glazing, and the distribution of reflected light into the space below controlled by rooflight geometry.

5.2 Atria

The daylight performance of an atrium is complex, and depends on its orientation and geometry, the character of its wall and floor surfaces, and the nature of its roof and glazing. The proportions of the atrium determine the amount of direct daylight reaching the floor - wide, shallow, square atria perform better in this respect than do deep, narrow, rectangular ones.

The design of the atrium walls significantly affects the distribution of light once it has entered the atrium. Dark finishes reduce internal reflectance, and the deeper the atrium the more important this becomes. Windows in the atrium wall, also, reduce the internally reflected component (IRC) of the daylight factor. Taking white walls as the reference condition, 50% glazing will halve the IRC and curtain-walling (100% glazing) reduce it by two thirds. The upper walls are the most critical in reflecting incoming light down into the atrium, so that it is best to limit windows in this area.

This arrangement corresponds with the requirements of spaces facing into the atrium - rooms at the upper levels tend to receive plenty of light but need protection from glare, while those at the base need to maximise the amount of light they receive. Other design strategies include making rooms near the base shallower, increasing their floor to ceiling heights, or stepping back the upper floors in successive steps so that all rooms have some view of the sky. (The same principles will apply to a building facade on a narrow street.) The closer the room is to the bottom of the atrium the greater its dependence on light reflected from atrium walls and floor. Reflectors may be fixed at the windows of lower rooms to redirect more of the zenithal light onto their ceilings, but this is generally cost-effective only when other considerations determine that the reflectances of atrium walls and floors must be low (8). And while rooms further from the atrium roof may have lower light levels, they may have better light quality in terms of uniform distribution and absence of glare.

Putting a glass roof over an open court will reduce daylight levels in the court by at least 20% and sometimes by 50% or more. The structure of an atrium roof, therefore, should minimise obstructions to the glazing area and its connections to the building should be such that light is allowed to wash the atrium walls.

Glare in an atrium is usually caused by the sky at upper levels, and by reflections from the atrium walls at lower levels. This can be controlled by baffles or shading, and careful design of wall surfaces. Fixed shading may reduce daylight to an unacceptable degree; movable shading which is responsive to changing conditions is preferable, but often costly to install and to maintain. Large areas can be shaded at relatively low cost by canvas sails, which are traditional in sunny climates and have considerable aesthetic potential.

5.3 Glazing

A conventional window, single-glazed with clear float glass will transmit approximately 85% of the light that falls upon it. Double or triple glazing will reduce light transmission to 70% and 60% respectively. Where lighting requirements demand larger areas of glass than would be thermally satisfactory, specially treated glass can be used to control heat losses or gains.

The early **tinted** glasses reduced solar heat gain to some degree but also cut down daylight transmission and distorted the colour of the landscape outside. **Heat absorbing** glasses do not reduce daylight transmission to quite the same degree, but reduce heat gain by only 10% because a large percentage of the heat absorbed is re-radiated into the interior. **Reflective** glass blocks solar radiation effectively (reflectances up to 50% are available) but, like tinted glass, it blocks light as well as heat, and it continues to do so in winter when heat gain and daylight may be beneficial. Selective **'low-e'** double glazing, with a heat loss equivalent to that of triple glazing, has a light transmission factor of approximately 80%.

Current developments include the responsive **chromogenic** glasses. **Electrochromic** glass changes its optical absorption properties and becomes dark or cloudy in response to an externally applied electric field. The opacity disappears when the field is reversed. It can be readily integrated into a responsive building climate control system, but the cost of the glass is very high and, at present, the life of a unit is too short for practical use in the building industry. **Thermochromic** glass switches between a heat-transmitting and a heat-reflecting state at selected temperature thresholds. **Photochromic** glass darkens and lightens in response to changes in light intensity. Material costs of both are high and durability at this time is uncertain.

The action of all of these coated glasses is selective blocking of radiation. Glass to which a **holographic film** has been applied does not block radiation but diffracts it. Windows with holographic film can be designed to direct incoming sunlight on to a reflective surface such as the ceiling, or deep into a room. A film can also be designed to reflect sunlight coming from well defined angles - high-angle sun on South facades or low-angle sun on East and West facades, for example. Up to four images containing different 'instructions' can be combined in one layer. A view out through the window is retained but from some viewing angles there is a rainbow effect. Its performance for diffused light is poor, but research is continuing. Costs are not high but at the moment holographic film is not available in the sizes needed for the building industry.

Prismatic glass (or plastic) controls transmitted light by refraction and can be used to redirect or to exclude sunlight. The direction of incoming daylight is changed as it passes through an array of triangular wedges whose geometry can be designed for particular conditions and orientations. Prismatic glass is translucent rather than transparent, so cannot be used where a view outdoors is required. In several recent applications it has been used to reduce glare. Normally a prismatic refracting panel consists of two sheets with their prismatic faces facing each other to protect them from dust accumulation. Prismatic sheets can also be used within double-glazed units. While the sheets themselves are inexpensive to manufacture, the overall construction cost is higher than for conventional glazing. Prismatic assemblies, including sophisticated systems incorporating silvered wedge-faces and several panel types, are increasingly available.

Glass block, because of the grid configuration of the mortar joints, will have some shading effect under high-angle sun. **Fritted** (screen printed) **glass** also has some shading effect. Some **translucent glasses** have good light diffusing properties, but their light transmission factors tend to be low, they can cause glare problems and, of course, they obscure the view outdoors.

Information on transmission factors, cost, durability, workability, fire performance and other qualities for a wide range of transparent and translucent materials is given in *Daylighting in Architecture* (8).

5.4 Transparent Insulation

Transparent Insulation Materials (TIM), which tend to be translucent rather than truly transparent, have been developed primarily as insulating materials for wall structures. Used as an outer leaf they reduce heat losses from the interior while permitting solar radiation to reach a heat-storing inner leaf. But, because they transmit light, they can also function as a glazing material. There are several categories of TIM, using different materials and a variety of forms - foamed, capillary, honeycomb, fibre and gel. Most need protection on one or both sides by glass or plastic sheets. Light transmission of TIM ranges from 45% to 80%, with a reduction of approximately 8% for each sheet of protective glass used. Insulation values are very much better than for glass. For example, 98mm hexagonal honeycomb polyamid TIM has a light transmission factor of 61% combined with an insulation value five times that of a double glazed window.

Transparent insulation material in the bottom section of a window assembly.

TIM can be incorporated into purpose-made window assemblies by most window manufacturers. Costs tend to be approximately three times those of conventional double-glazed windows. **Aerogel** windows, in which a transparent, fragile, low density solid of extremely low thermal conductivity is sandwiched between two sheets of glass, are extremely effective in preventing heat loss from the interior. Daylight transmission, however, is moderate, being in the region of 50% for 12mm glazing. An account of current TIM practice, with information on manufacters, can be found in *Transparent Insulation Technology (13).*

5.5 Lightshelves and Reflectors

The lightshelf**,** a flat or curved element placed at the window opening above eye level, redirects incoming light onto the ceiling and simultaneously provides shading for the area of the room close to the window. The underside of the shelf can also redirect light from a high-reflectance exterior ground surface onto the floor inside the room. A lightshelf is most efficient when it is external, causes minimal obstruction to the window area, has specular reflective surfaces, and is combined with a ceiling of high reflectance. Interior shelves have not been found to be as effective - they obstruct daylight entering the room while providing little compensating benefit. The sunshading and glare control functions of a fixed lightshelf are less effective for low-angle sun. In northern Europe lightshelves should generally be considered only if glare is a problem, or window size is restricted and internal surfaces (other than ceilings) must be of low reflectance (8).

Adjustable louvres with a specular finish on the upper surfaces of their blades can be angled to redirect sunlight or diffuse light in the same manner. They are more responsive than lightshelves and, if completely retractable, cause no obstruction to daylight on overcast days. Sophisticated fixed louvre systems, incorporating lenses and mirrored faces, are now available. These are custom-made for the particular latitude and facade orientations and will provide shading and redirect both direct and diffuse light deeper into the building.

5.6 Lightpipes and Lightducts

Lightducts and lightpipes are among the more mechanically complex daylighting devices. Sunlight is collected by heliostats (mirrors controlled by a tracking device), concentrated by means of mirrors or lenses, then directed to the core of the building through shafts or through acrylic rods or fibre-optic cables. Because they depend on direct sunlight, and are relatively expensive to install, they will be cost-effective only in regions where blue skies and clean air can be guaranteed for much of the year. Energy-efficient back-up lamps may be fixed at the head of the shaft to substitute for sunlight during infrequent overcast conditions. The recent development of thermo-hydraulic tracking systems powered by solar cells should improve the economic viability of these devices (10).

5.7 Shading

The type, size and positioning of any shading device will depend on climate, building use, and the source of the light to be excluded - high- or low-angle direct sunlight, diffuse sky light, or perhaps reflected light from paving on the street outside.

HQ for Legal & General Assurance, Kingswwod, Surrey. Arup Associates, Architects + Engineers + Quantity Surveyors. (Photo: Peter Mackinven).

Exterior shading devices are the most effective in reducing heat gains. Interior shades protect a room's occupants against the immediate effects of direct sunlight and against glare, but once infra-red radiation has penetrated the glazing most of it is trapped in the room and must be dissipated by ventilation or mechanical cooling. Reflective interior blinds, however, do reduce this 'greenhouse' effect. Interior shading - which may be inside the room or contained within glazing units - tends to be cheaper, more easily adjustable, and can be used for privacy, to control glare, and to avoid the black-hole effect of windows after dark. Exterior shades tend to be more expensive to install and to maintain, and to have greater impact on the aesthetic character of an elevation.

Fixed shading has disadvantages - it screens sunlight from some angles only and obstructs daylight that would be welcome on overcast days. Adjustable shades avoid these problems, but in non-domestic buildings movement must be planned. If the climate is such that adjustment is infrequent, simple manual adjustment or individual motorized controls may be adequate even for exterior shades. Control of interior shades is frequently left to the occupants, but this may not produce the best use of the system and some degree of automation may be cost-effective. Fully automated systems, which respond constantly to changes in sun angle, temperature and/or light levels, are not yet widely used.

High-angle direct sunlight, which most commonly falls on South-facing facades (but at lower latitudes on East- and West-facing facades also), can be readily excluded by fixed horizontal overhangs. Continuous overhangs are much more effective than those which extend across the width of the window only. A louvred overhang allows free air-movement across the facade - essential in hot climates - and can also shed snow. Fixed overhangs reduce daylight penetration, so retractable overhangs or awnings may be preferable at northern latitudes.

Low-angle direct sunlight, which is generally received on East- and West-facing facades, but in northern winters on the South as well, is more problematic. Overhangs are of little use, and fixed vertical fins, if they are to be really effective, exclude a great deal of daylight and obstruct the view. Rotating vertical fins can screen sunlight while preserving views from some positions within the room, but still reduce daylight penetration. Steel mesh sunscreens are almost ‘transparent’ but they too reduce the amount of daylight penetrating the windows. Interior blinds have the advantage that they can be left open for much of the time and drawn only when the sun-angle demands, but heat gain will remain a problem, particularly on West-facing facades. Retractable and adjustable external screens or louvres are effective but costly.

Excessive diffuse sky light generally presents as window glare and can be controlled by louvres, which redirect the light, or curtains and blinds which moderate the level of brightness without excluding all light. Louvred (‘venetian’) blinds are a well-tried and effective device which can be adjusted to shade the area near a window while reflecting light onto the ceiling and thence to the back of the room. The traditional exterior louvred or slatted blinds and shutters of southern Europe provide an excellent solution to the combined problems of direct sunlight, diffuse light, heat gain and ventilation in hot, sunny climates and, because they are openable, they provide no obstruction to light or views in cool or sunless weather.

Deciduous trees or vines can be used to screen the sun in summer and filter light in winter, and planting can sometimes solve the problem of reflected light from neighbouring structures or ground finishes. Otherwise, shading systems in or on the building must be employed.

Some shading devices may play double roles. Insulated blinds or louvres reduce heat loss when closed at night. The treated glasses and prismatic devices described in Section 5.3 can, like louvres with specular faces, provide selective shading and redirection of light.

Shading systems are often disliked by the people who occupy buildings - they are seen as an undesirable visual intrusion and a source of irritation (2). This tends to be less of a problem in southern European countries, where shade is associated with coolness and restful visual conditions, than in northern Europe, where it is associated with chilliness and gloom. Where possible, fixed shading devices should be fitted to the upper portion of windows only, leaving the lower part clear of obstructions.

Physical models or sun path diagrams can be used to predict the performance of shading devices, as can Horizontal Shading and Vertical Fin Analysis (9).

5.8 Artificial Lighting

No matter how good the daylighting design, virtually every building needs an artificial lighting system as well - for night time use, for windowless spaces, or to supplement daylight when it falls below acceptable levels.

Until recent years most workspaces were lit by tungsten or fluorescent lamps, with high-pressure discharge lamps sometimes being used for sports-related and industrial buildings. But newer compact metal halide and high-pressure sodium lamps with good colour rendering characteristics are now being used in offices and shops, particularly for decorative or display lighting.

The development of ‘energy-efficient’ lamps, coupled with the availability of a wider range of luminaire designs, has made possible very significant energy savings in general purpose lighting and has brought dramatic lighting effects within reach of relatively modest budgets (11). The **luminous efficacy** (lumens/watt) and the life expectancy of some typical lamp types is shown in the table below.

Lamp	Lumens/W	Hours
100W Tungsten	14	1000
20W 38mm Fluorescent	36	9000
18W 26mm Fluorescent	50	9000
20W Compact Fluorescent	60	8000
18W Low Pressure Sodium	66	7000
250W High Pressure Sodium	96	12000

Table 6 : Lamp efficacy and life.

Using high frequency (HF) control gear increases the luminous efficacy of fluorescent lamps and doubles their life span, so that energy costs, heat gain and maintenance costs are reduced. HF control gear also provides a better quality of light, which may be critical for some tasks, and eliminates the flicker effect in traditional fluorescent installations which some people find disturbing.

The design of the luminaire itself has a significant effect on the amount, direction and quality of light produced, and developments in reflector and louvre design have increased luminaire efficiency. Efficiencies of 75-80% used to be exceptional, but are now usual. Another improvement is the availability of 'suites' of luminaires accommodating a variety of lamp, reflector and louvre combinations, so that it is possible to specify appropriate fittings for different conditions while maintaining aesthetic consistency.

Concourse, School of Engineering, De Monfort University. Short Ford & Associates, Architects.

Where artificial lighting is used to supplement daylight it is important that the **colour appearance** and **colour rendering** qualities of the lamps corresponds fairly closely with those of the daylight in the space. Conventional cool white fluorescent lamps emit a blueish quality of light which might be appropriate in a room with north facing windows, but disturbing in a room of southerly aspect whose perimeter is bathed in sunlight. Many lamps of good colour quality are now available.

Glare control is as important under artificial lighting as it is in daylight, and the same principles apply. Concealing the light source from direct view and avoiding excessive brightness contrasts within a space, particularly in the task area, should be basic design objectives.

The savings achieved by changing from conventional to energy-efficient lighting systems are substantial - figures of 30% are readily achievable. Studies in Ireland have indicated that productivity need increase by only 0.3% to repay the cost of installing energy efficient lighting, while productivity increases of 7 to 30% have been recorded following the upgrading of artificial lighting systems in conventional buildings (12).

5.9 Integrated Controls

If a daylighting system is to produce energy savings it is important that artificial lighting is not switched on as long as daylight is providing adequate illumination. For example, it is common practice for large numbers of luminaires in a workspace to be controlled by one or two banks of wall-mounted switches located near the doorways. The first person arriving early on a dark winter morning will switch on all the lights. As the day brightens it is likely that no one will notice that the lights are still on or, if they do, bother to switch them off. One response to this problem is to provide light switches close to much smaller banks of luminaires. Accessibility is important - pull-cord switches can be used where there are no nearby partitions; hand-held remote control switches are useful in the same circumstances or where changes in partition layout are frequent. Simple local switching of this kind can produce 20% energy savings.

Another response is to provide lower levels of general lighting supplemented by individually controlled task lighting at each work station - this is particularly appropriate where work stations are intermittently occupied. Task lighting may also be designed to function as supplementary lighting within a daylighting system- a desk located deep in the room may need it while desks near the window have more than sufficient daylight. Task lighting in workplaces is generally liked. In addition to giving a good level of adjustable light it provides visual warmth and a sense of 'personal territory' - for which reason it may not be switched off even when daylight levels are adequate.

These are all **manual control** systems, dependent on human perception of light levels and on individual action. Simple **automatic control systems** can produce significant energy savings. Components of an automatic control system may include: **timers** to switch off lights at lunchtime, end of shift, end of day, etc. - workers returning will probably turn on lights again only if they are still necessary; **time delay switches** - a person switches on a light and the system switches it off after a predetermined interval. This is usually annoying and can be hazardous. An alternative is to use the time delay switch with a sensor - a person switches on the light and the system switches it off only after the sensor indicates that no one is present in the space; **movement sensors** or **sound detectors** signal when a space is occupied and are most often used in intermittently used spaces, such as some circulation areas, toilets and storerooms; **daylight sensors**, which may be mounted internally or on the exterior of the building, prompt switching or dimming of artificial lighting in reponse to daylight levels. Where these are used the control system should incorporate a time delay mechanism, so that lights are not switched rapidly on and off in response to fast moving clouds. **Voltage/current controls** can be used in large areas which are intermittently occupied - warehouses for example. Once the luminaires have reached full output, the voltage/current control will reduce the energy input by 10-20% but lighting levels by only 5-10%. A movement detector linked to the system can ensure that the optimum lighting level is restored while anyone is working in the space.

The sensors and timers, control panels, switches and luminaires in an automatic system can be linked in such a way that changes can be made in luminaire groupings and switch control patterns without changes to wiring or connections. Lighting control systems are available at different scales and in modular form; it is possible to start with a small system and add extra components or functions as circumstances demand or finances permit.

Any automatic control system should be designed so that it is possible to over-ride it when necessary. It is important also that the occupants feel that they have some control over lighting in their workspace - 'autocratic' control systems which 'arbitrarily' switch lights off and on may be disconnected.

In buildings of complex or sophisticated daylight design, particularly those with exterior adjustable daylighting devices, **integrated automatic control systems** are probably essential. Both daylighting and artificial lighting in the building will have been designed on the basis of annual weather statistics - fine-tuning its performance depends on being able to respond to actual conditions.

An integrated automatic control system will synchronise the performance of all the climate control systems in the building - daylighting and artificial lighting, heating, cooling and ventilation - as conditions change indoors and out. The system may consist of a hierarchy of computerised control units, connected to a central computer which optimises the operation of all equipment in terms of the comfort-to-operating cost ratio, and signals equipment failures so that repair or replacement can be arranged promptly.

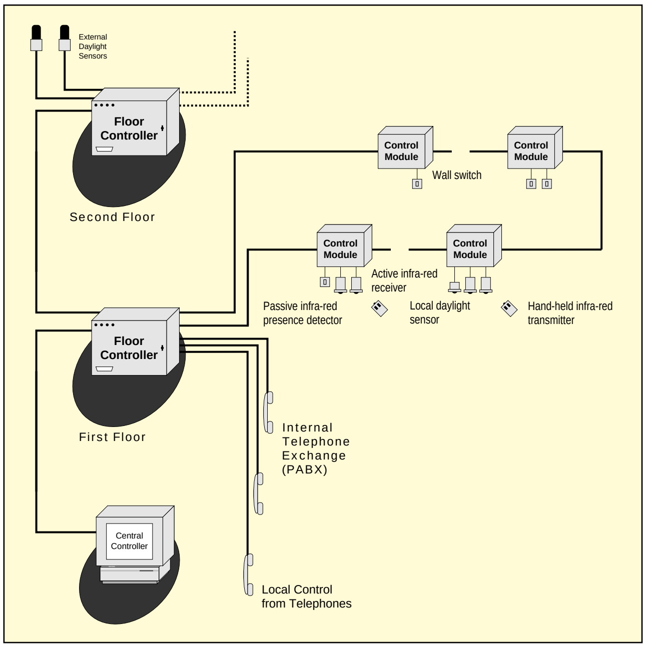


Figure 8: Diagrammatic layout of an integrated automatic control system.

Timers, together with temperature, humidity and movement sensors, are available in a wide range of qualities and at reasonable cost. Photometric sensors, for measuring visible light, are widely available but are not cheap.

Automatic control systems for blinds and louvres are readily available, as are control systems for artificial lighting. Hardware and software for centralised control systems which integrate all conventional building services - heating cooling and lighting, fire and security, call systems, lifts and escalators, for example - are also available on the European market. But software packages for centralised systems which incorporate the control of daylighting devices are at present generally custom-made, and so tend to be expensive - the area is not yet commercially mature.

6 RETROFIT

Upgrading the efficiency and quality of lighting in an existing building involves assessing a range of options in increasing order of cost and complexity. Daylighting and artificial lighting should be considered together, and individual circumstances will determine what measures are appropriate.

First, consider existing maintenance standards**.** In any system good maintenance is essential - dirty windows, dusty luminaires and grubby walls will reduce the effectiveness of both daylight and artificial light. Dirt on windows can reduce performance by 10% or more, on luminaires by 20-25%. Missing or dead lamps, defective wiring or broken blinds ensure sub-standard performance of the system.

Next, fit energy-efficient lamps and new reflectors in luminaires which can accept them. Simply replacing opal diffusers in luminaires with louvres will increase luminaire output by 30%. Paint dark coloured surfaces in paler shades. All of these can be done within the context of a normal maintenance schedule, so minimising capital outlay and disruption.

The Point Depot, Dublin. Shay Cleary Architects.

If luminaires have reached the end of their useful life (10 to 12 years) they can be replaced with more efficient ones. Simple control systems, such as localised or timed switching, can be introduced using the existing wiring and trunking systems. Interior blinds and louvres, which are relatively inexpensive, can improve conditions by controlling to some degree the light already entering the building.

If a complete interior fit-out is being carried out, the new room layouts, partitions and finishes, curtains and blinds, should be planned with daylight penetration in mind. A fully daylight-coordinated energy-efficient artificial lighting system with integrated controls should be installed. If heating, cooling and ventilation equipment is being replaced, it should be possible to reduce plant size. Linking these with the lighting in a full climate-control system is likely to be cost-effective.

Fitting special glass, prismatic systems or transparent insulation in existing openings will have a more radical effect on both the quantity and quality of daylight entering the building but is relatively costly, as are external shading or redirection devices. Either is likely to be economic only in the context of complete building refurbishment. Similarly, forming new window openings or rooflights, installing a lightduct, or glazing a courtyard to form an atrium will generally form part of a major refit. But, in some cases, simply installing a new window in the end wall of a side-lit room, or refinishing the interior walls and floor of an existing light-well, may be sufficient to lift a gloomy interior to a level that is not just adequate but positively enjoyable.

Any energy-saving programme requires the understanding and cooperation of the building's occupants. High comfort and satisfaction levels and good financial returns are more likely to be achieved if the people who use the building have been consulted, and are properly informed about how the systems work. In the case of retrofitting it is particularly important to set realistic targets and time scales, monitor performance, and provide good feedback to everyone involved.

7 TOOLS

The main difficulty in daylighting design lies in predicting lighting performance at the early design stages. Although solid experience in daylighting design is the best guarantee of success, there are good reasons for using design tools: it takes time to accumulate experience, and some architectural elements are so complex in their behaviour that detailed analysis is valuable. A range of design tools currently available is reviewed in *Daylighting in Architecture (8).*

The oldest, and often the best, technique is the use of a scale model. For complex conditions 1:1 mock-ups are useful. Scale models give accurate results because light behaves virtually independently of scale. Provided that the model is viewed under natural lighting conditions identical to those on the site, and its surfaces have the correct colours and reflectances, luminances and illuminances will reach the same values in the model as they will in reality. (Major items of furniture or fittings should be included in the model.) Used in pairs, models can be used for visual comparison of alternative design proposals. Scale models can also be used to make quantitative measurements, but for accurate results this requires the use of calibrated sensors and a well-defined 'outdoor' luminous environment, such as an artificial sky. Models can be fixed to a heliodon to assess the penetration of direct sunlight at different times of the day and the year.

Analytical techniques form another family of tools. The penetration of light through a building is a physical phenomenon which follows known laws. For instance, we know that illuminance on a surface due to a point source is equal to the product of the luminous intensity and the cosine of the angle of incidence, divided by the square of the distance to the source; or that diffusing surfaces tend to display the same brightness (luminance) when viewed from any direction. Light reflection inside a diffusing cavity is also a well understood phenomenon. Some of these functions have been pre-calculated to produce formulae, charts, nomograms and graphic tools which can be used to estimate Daylight Factors for straightforward situations, such as a rectangular room under well-defined sky conditions. Techniques for calculating the effect of fins, overhangs, lightshelves and blinds are being developed and tools for estimating glare are already available. The usefulness of any particular tool depends on the preferences of the user and the design stage at which it is to be used. All give approximate results.

There now exist a large number of computer tools for daylighting design. Modest micro-computer programmes for calculating Daylight Factors in simple spaces are common, but much daylighting software is still in the development stage and few programmes are properly documented or commercially distributed. Most are relatively unsophisticated and embody simplified assumptions about the design parameters involved. Only the most sophisticated - those using ray-tracing, radiosity or photon generation - can handle spaces of complex geometry. These give more accurate results and can provide very impressive photo-realistic impressions of lighted interiors, but at present require computers with very large memories. Designers need to be aware also that validation procedures for design software are in their infancy.

Many designers, while finding computer simulation useful as a learning technique, and for developing a feel for the sensitivity of daylighting performance to parameters such as room configuration, window size, and surface reflectances, are unwilling to rely on it when making final decisions on the visual effectiveness and aesthetic quality of a particular design proposal. This is a reasonable stance, since most computer tools cannot yet simulate the complex conditions found in real buildings. A single room may contain hundreds of individual surfaces of varying finishes (matt, specular or gloss) and reflectances and, ideally, the computer model would also need to simulate realistically, with all its variations, the climatic conditions on the site.

Simulating the performance of advanced daylighting components, or detailed assessment of fully integrated daylighting systems (including visual comfort, the luminous quality of interior spaces, thermal comfort and energy consumption) is at present outside the scope of the average professional practice and is more usually carried out by specialized design firms or laboratories.

A productive approach for any designer who wishes to develop good daylighting design skills is to make a practice of carefully observing and recording daylight performance in existing buildings, combining visual assessment with the use of a hand-held luxmeter. This will enhance the designer's ability to make a well-informed judgement on the significance of a set of figures generated by a design tool or the likely performance of a particular design proposal.

8 CASE STUDIES

8.1 College 'La Vanoise', Modane, France

This school for 600 second-level students was completed in 1989 for the Syndicat Intercommunal of Modane. Located in south-eastern France (latitude 45°3'N) at an altitude of 1000m above sea level, the building had to respond to severe weather conditions. Surrounding mountain ranges obstruct the sun, so that winter sunlight is available in the middle of the day only. Mean daily global radiation is 3600 Wh/m^2. Average daily sunshine duration is 5.75 hrs.

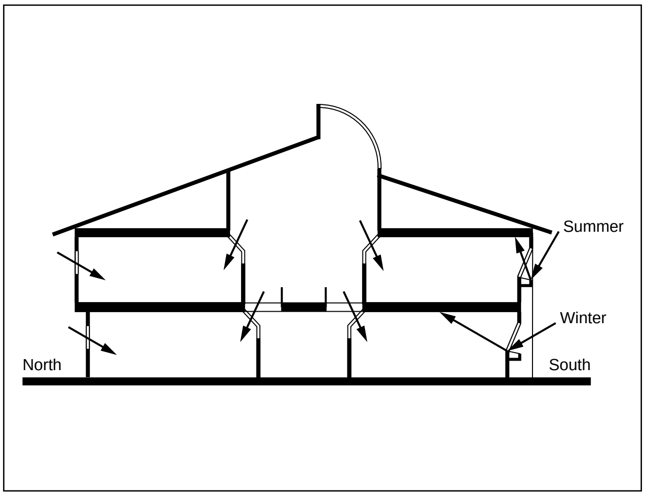
The 8000m^2 building is divided into three sections - restaurant and dormitories; teaching spaces (including thirty-three classrooms); and staff housing. Each classroom block has a central atrium which is lit by a rooflight, so that every classroom is lit from both sides and receives some winter sun, either directly or through the atrium. The rooflight is glazed with triple-layer transparent polycarbonate ribbed sheets. These require no glazing bars, so obstruction to daylight is minimal. Tilted glazing on the south facades reduces glare and heat gain in summer, while stainless steel external light-shelves reflect sunlight onto the classroom ceiling in winter. Combined with light from the atrium this provides a good daylight distribution across the 50m^2 rooms. Minimum daylight factors at the centre of each classroom exceed 1.5%, which is a satisfactory level in a double side-lit room.

Artificial lighting in the classrooms is linked to external daylight sensors and is also timed to switch off automatically at every class-break. However, the teacher can switch the lights on at any time.

The heating is electric and uses a 130m^3 water store to take advantage of off-peak electricity. The building is artificially ventilated, incorporating an air-to-air heat exchange system.

In use it has been found that the building needs no artificial lighting as long as outdoor horizontal illuminance exceeds 10,000 lux. Over 70% of the school's annual lighting needs between 9.00hrs and 17.00hrs is met by daylight.

The architect was Phillipe Barbeyer of Barbeyer - Dupuis - Atelier UA5; the daylighting consultants were Christine Badinier and Marc Fontoynont of the LASH/ENTPE research laboratory in Lyon.



8.2 School of Engineering, De Montfort University, UK

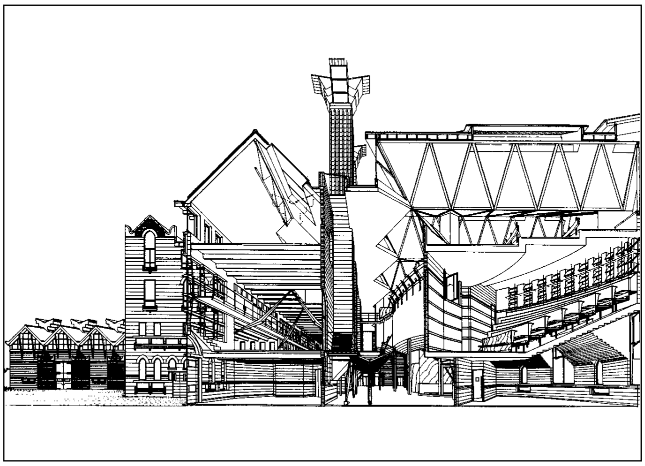
The School of Engineering and Manufacture at De Montfort University, completed in 1993, is located at Leicester in central England (latitude 52°40'N). The 10,000m^2 building, housing lecture theatres, classrooms, engineering laboratories, offices and a cafeteria, sits in a city-centre campus separated by street and courtyards from the surrounding two to four-storey buildings. (Mean daily global Irradiation 2424 Wh/m^2. Mean daily sunshine duration 3.7hrs. Shawbury.)

Because the building was to have 1,000 occupants and a large amount of heat-producing heavy machinery, a year-round cooling load could be predicted. In a conventional deep-plan solution for a building of this kind daytime artificial lighting would have added to this load. Instead, the school comprises a series of narrow buildings, wound round a full height internal concourse and creating a series of external courts. The entire building is naturally lit and ventilated.

The daylighting strategy varies with use and orientation, and proposals were tested with 1:50 models under an artificial sky. The electrical and electronics laboratories are daylit from both sides, with light-shelves to protect computer operators from direct sunlight and glare and reflect light onto high ceilings. Mechanical laboratories are lit by glazed gables and rooflights, with roof overhangs and deep reveals used to prevent direct sunlight reaching the laboratory floor. The drawing spaces are lit by rooflights and north-facing gable windows, but also look onto the fifty-metre-long day-lit concourse. The two lecture theatres also have windows both to concourse and exterior.

Except in individual offices, the artificial lighting is automated. All lighting is switched on at 6.00 hrs and off at 22.00 hrs. The building is reported to be constantly occupied during these hours, so no further timed switching is provided. During the day the lights switch off automatically when and if interior and exterior light sensors indicate that adequate illuminances have been reached. At night the lights switch on if movement sensors indicate that a space is occupied.

Massive brick construction evens out thermal fluctuations, while ventilation is achieved by opening windows, with cross-ventilation in narrow-section spaces, and stack ventilation through roof vents or solar chimneys in deeper parts of the plan. Most of the many small windows can be opened and closed in a variety of combinations by staff and students, and an automated building management system responds by adjusting dampers and heaters to keep environmental conditions within acceptable limits.



The capital cost of electrical and mechanical services was 24% of building costs, compared to 30% - 40% in a conventional building. It is estimated that energy savings of between 50% and 75% will be achieved. Environmental performance will be monitored by the Building Research Establishment and the Energy Technology Support Unit.

The architects were Alan Short and Brian Ford of Short Ford & Associates; the mechanical and electrical engineers were Max Fordham Associates.

8.3 Infante D. Juan Manuel Health Centre, Spain

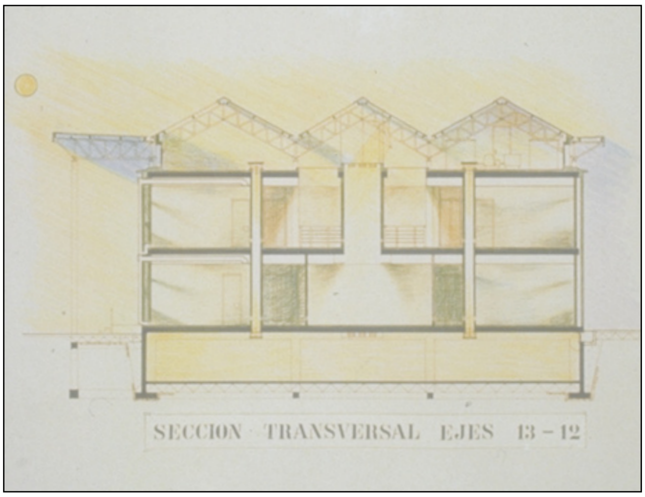
The Health Centre 'Infante D. Juan Manuel' is located in the town of Murcia in the south-east of Spain, latitude 37°59'N. (Mean daily global radiation 4850Wh/m^2. Mean daily sunlight duration 8hrs.) Daylight is not significantly obstructed by neighbouring 6-storey apartment buildings. The two-storey building has a floor area of 1,800m^2 and is planned for a maximum occupancy of 300 persons.

The health centre consists of three parallel bays with pitched roofs. Treatment, consulting and service rooms are distributed along the north and south faces, with the main stairway and the waiting spaces in a two-storey day-lit central bay on the east-west axis. The south elevation has large windows (set in a Trombe wall), the north has smaller ones, while east and west facades are almost windowless. The windows on the south facade are shaded from summer sun by a 3.5m loggia.

With the exception of one or two small bathrooms, all perimeter rooms are side-lit. There are small external light-shelves on these windows. Two of the three south-facing roof slopes are pierced by large rooflights which admit daylight and winter sunlight to the white-painted roofspace. This light is directed down into the upper atrium, and thence through lightwells and glass block flooring to the waiting areas, conference room and physiotherapy room on the ground floor. Awnings within the roof-space reduce sunlight penetration during the summer.

Brick construction and south-facing Trombe walls act as a heat store and even out temperature fluctuations. Summer cooling is provided by a ventilated sub-floor area, the deep ventilated roofspace, and the central atrium which acts as a thermo-syphonic chimney. In winter, warm air accumulating in the sunlit roofspace is drawn down into the building through fan-assisted internal shafts. None of the systems is automated.

It was predicted that the building would need no artificial heating in winter, but some assisted cooling on peak days during the summer. This is provided by a small gas-fired water heating/refrigeration plant. Construction costs were 5% higher than for a conventional building.



The combined effect of the natural heating, cooling and lighting strategies was expected to result in energy savings of 70% over those of a conventional building in the same area. However, no maintenance staff were appointed and the medical staff do not view adjustments to the climate control systems as their responsibility. Consequently, those elements which do not require intervention (ventilated roof, stack ventilation, daylit core and fixed shading) function as planned, while those which do (Trombe walls, night-time cooling, artificial light switching) are failing to perform as intended.

The client was the Instituto Nacional de la Salud. Construction was completed in mid-1993 and the architect was Tomas Menor Perez.

8.4 Conphoebus Office Building, Catania, Italy

This building is unusual, in that it was designed as a full-size test facility for energy-efficient building technologies. The client, Conphoebus, is a research institute for renewable energies, based in Catania on the east coast of Sicily at latitude 37°28'N. (Mean daily global radiation 4886 Wh/m^2. Mean daily sunshine duration 7.5hrs at Gela.) The building is located on a flat site in Catania's southern industrial zone.

The 1650m^2 of office and laboratory space is distributed over three floors in a 12m wide building whose long facades face north and south. The building is divided into four vertical segments, each with a different southern facade treatment and internal layout (on the upper two floors), and each fully insulated, with independent heat and air-exchange systems, and individually monitored. Ventilated transverse corridors separate the segments. One of the segments acts as a reference case - the other three are used to test differing passive solar strategies.

The concrete frame is penetrated by transverse air-channels in the floor and roof slabs and can be exposed to or isolated from the interior spaces by adjustable ceiling panels. The entire structure is enclosed in a dynamic double envelope whose configuration changes to meet winter/summer day/night conditions. Thus heat captured by the external skin can be stored, distributed or dispersed without interfering with natural ventilation or the activities of the occupants, and the building fabric can be cooled by natural or mechanical ventilation.

The east and west facades of the building are virtually windowless, windows on the north facade have lightshelves and internal adjustable screens, and the entire ground floor on the south facade has full-height windows with slatted, tilted, over-hanging shades. All windows are double glazed with clear glass.

On the upper levels of the southern facade there are currently four window configurations. In the reference case a 1.4 x 1.5m window is fixed to the inner face of a profiled reinforced-concrete cladding panel, which provides approximately 0.4m of overhang to window head and sides. These have internal blinds. In the 'Total Shading Grid' segment the same window-and-panel arrangement is shaded by a fixed, angled, reinforced-concrete brise-soleil. This is 0.7m deep, and the angle and pitch of its blades provide total shading during the summer.

The 'Air Collector Window' consists of several elements: an outer double-glazed pivot window, an insulated shutter with openings top and bottom, and between the shutters and the windows a pair of doors, each with one dark and one white face.

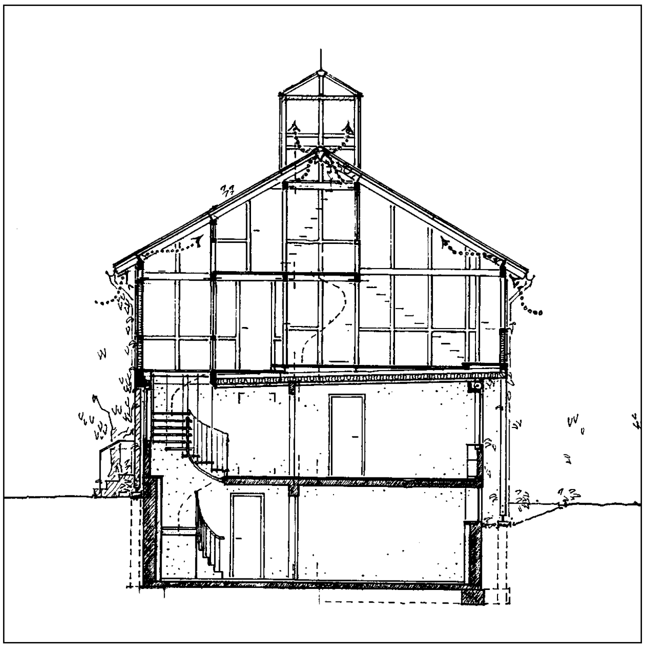
In the 'Smart Window" manually controlled pivoting windows recessed 0.5m from the outer face of the building are protected by automated external blinds with adjustable slats. The 0.5m recess together with the external blind box provide adequate summer shading under Catania's high-angle summer sun, while the external blinds prevent penetration by the winter sun.

One standard 2.9 x 3.9m office with 'Smart Windows' has been fitted with an integrated artificial and daylighting system. Computer software controls the blinds under sunlit and overcast conditions, while four 36 watt dimmer lamps are used to maintain a constant horizontal illuminance between 350 and 400 lux. Tests of this room have demonstrated energy savings of 1.8kWh per day.

The architects were Sergio Los and Natasha Pulitzer (SYNERGIA Progetti). Design began in 1979, the building was completed in 1989, and performance is being monitored by Conphoebus.

8.5 Architects' Office, Munich, Germany

In 1987/88 architects Florian, Franz and Wendelin Lichtblau added one-and-a-half floors of accommodation to their existing single-storey-over basement, flat-roofed, 1960s office building. The office is located among single family houses on a suburban site in Harlaching, Munich, latitude 48°08'N. (Mean daily global irradiation is 3198 Wh/m^2 and Mean daily sunlight duration 4.5 hours at Müldorf) The site is not overshadowed by neighbouring trees or buildings.



In this retrofit project 182m^2 of drawing office and gallery space were added to the building to make a total floor area of 414m^2. The new lightweight structure is of laminated timber with steel connectors. External walls are of plywood sandwich panels with mineral wool insulation, and windows are conventional double-glazed units in steel frames.

The roof construction is unusual - the entire 165m^2 of its 30° double pitch is treated as an insulated daylighting device. The laminated rafters support 72mm triple-glazed panels with a 40mm layer of transparent insulation in the inner cavity and fixed aluminium reflector louvres within the outer cavity. The angles of the louvre blades vary with orientation and have been designed, using seasonal sun-path patterns in the Munich area, so that direct sunlight is admitted in winter but excluded during the summer. Diffuse radiation is admitted at all times.

Windows on the north facade are few, and on the east and west facades are minimal. Windows on the south-facing facade are protected by overhangs and by external blinds.

The interior wall surfaces are painted white, and partitions glazed at high level allow light to flow from one space to another. This produces an even distribution of light, so that the building enjoys high illuminances, free of dark spots or glare, under all weather conditions.

The building is naturally ventilated through opening windows and controllable vents at the eaves and in the roof-lantern. Surplus heat from under the ridge could be ducted to the basement, but at present is simply directed to the ground floor by a thermostat-controlled fan. Back-up heating is provided by gas-fired boilers which were already present in the original building.

Construction costs for the roof were approximately one-third higher than for conventional construction. The building was monitored for one year after completion. Primary energy savings on heating and lighting were found to exceed 60% compared with a highly-insulated conventional building.

The louvre system within the roof construction was designed by Helmut Köster, Frankfurt.

8.6 Valongo do Vouga School, Agueda, Portugal

This school for 500 secondary level students was completed in early 1993 for the Ministry of Education and the Town Council of Agueda. It is located on a village site in the municipality of Agueda in western Portugal, latitude 40°35’N. (Mean daily global irradiation is 4731 Wh/m^2. Average daily sunshine duration is 7.1hrs.) The site slopes from North to South and is not overshadowed.

Classrooms, seminar rooms, laboratories, administration offices and the students’ room and bar are contained in the main building, which is laid out along an east-west axis, with classrooms on two floors facing South. The library, cafeteria and kitchen and the staff room are in a linked block to the North. Floor area is 2,000m^2 .

Multiple daylighting strategies have been used in this building. Some classrooms are 7.0m deep, others 10.6m. All are lit by windows in the south facade (40% of facade area). These are single-glazed with clear glass, and shading is provided by tilted horizontal overhangs incorporated in a 0.5m deep reinforced-concrete brise-soleil, and by internal light-shelves which have a highly reflective specular upper surface. These admit direct sunlight in winter, but in summer redirect it onto the classroom ceiling. In addition, the windows are fitted with two sets of curtains - one set above the light-shelf and one set below. This system provides adequate daylighting for the shallower rooms.

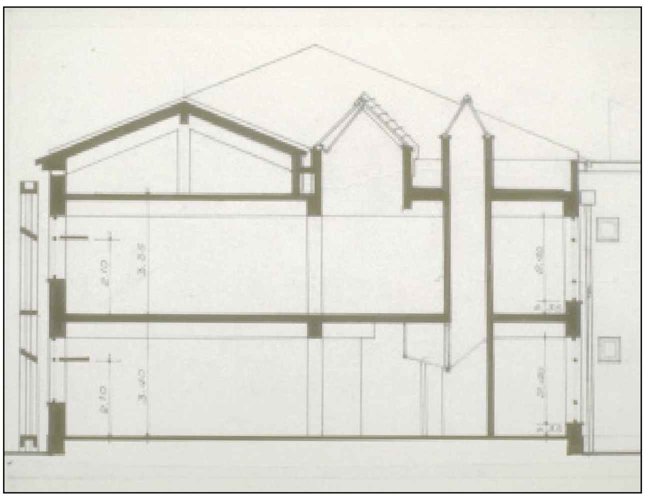
Deep classrooms on the first floor have ‘dual-mode’ skylights located over their inner zone. These are glazed with translucent polycarbonate on both pitches. External louvres shade the North facing pitch without excessive reduction of diffuse skylight penetration. Interior, adjustable, insulated panels shade the South pitch in summer and insulate the North pitch in winter. In either position they redirect sunlight into the room below. They are controlled by manual cranking devices on the roof.

The deep classrooms on the ground floor are equipped with light-ducts. These are 3.0m x 1.0m on plan, have clear glazed roolights, tilted reflective panels at the head and foot, and a specular surface lining. The ‘window’ at the foot of the duct is fitted with louvred blinds to reduce glare and overheating in the summer, and to provide black-out in the classroom when needed.

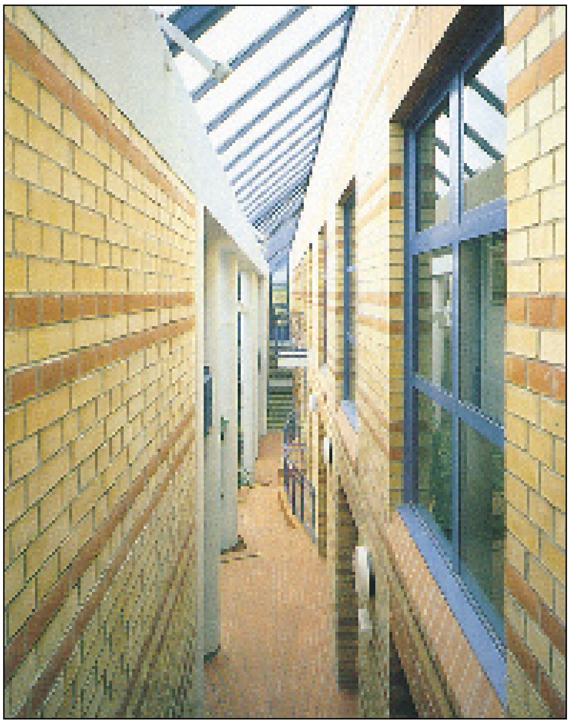
The artificial lighting is controlled (using daylight sensors and zoned switching) by an automated system which also handles the thermal controls, energy management, fire and security.

All classrooms are naturally ventilated, with high level opening lights in the window wall and vents in rooflights, light-ducts or corridor walls.

The architect was João do R. Mateus, and the daylighting consultant Licínio C. de Carvalho. Design proposals were evaluated using scale models under real skies and a computer model calculated daylight factors. It was estimated that 92% of the the school’s normal lighting requirements would be met by daylighting. The system is in the process of calibration and monitoring is being carried out by at team at the Department of Electrical Engineering at the University of Coimbra.

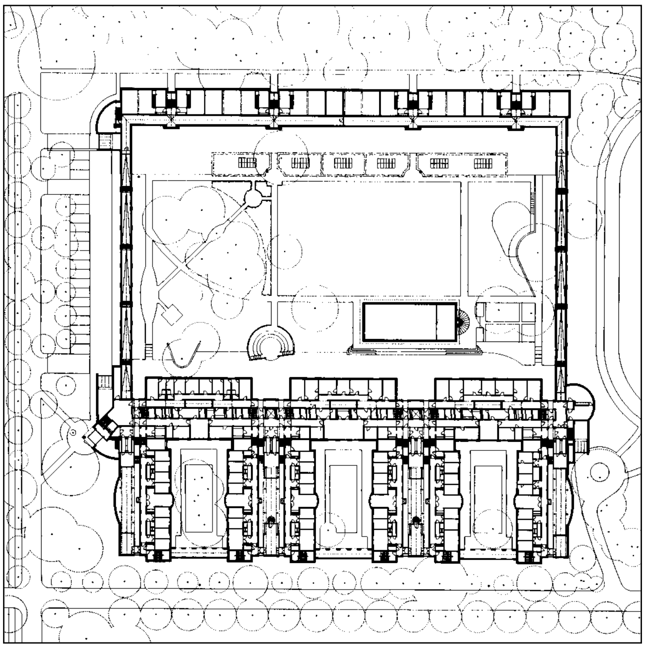


8.7 Psychiatric Prison, Berlin, Germany



This building, which was completed in 1988, is part of a very large complex of neurological facilities located on the outskirts of Berlin, latitude 52°23'N. The prison, which accommodates prisoners who are undergoing therapy in preparation for release into the community, is set in a parkland site within a dense suburban context. (Mean Daily global irradiation is 2805 Wh/m^2. Mean daily sunshine duration 3.6hrs.)

This is a high security unit, with the building itself forming the perimeter. Ward blocks, workshops, therapy units and staff accommodation (8150 m^2 in total) are used to enclose communal gardens and courtyards. Good orientation and good daylighting were among the principle generators of the plan. Visual contact with the landscape and the pervasive presence of daylight and sunlight in the building are intended to reduce the sensation of imprisonment. Many of the interior partitions are glazed, allowing deep penetration of natural light while also permitting continuing surveillance without the use of intrusive video technology.



In each residential wing the cells and communal spaces are organised around an atrium whose roof is entirely glazed. These and the corridors, whose roofs are largely glazed, capture heat and daylight. Openings in corridor floors mean that even interior ground floor corridors have natural light. Daylighting throughout the building is designed in response to the particular needs of each space, using direct light, light from atria or corridors, or both. The cells are shallow enough to be lit from one side only, but workshops and communal recreation spaces are lit from both sides.

Excessive heat gain in occupied spaces is largely avoided by locating staircases and corridors on the South face of each range of buildings. The workshops, which require relatively cool conditions, face North; the cells are oriented East-West. At the centre of each southern facade in the residential wings a free-standing recreation space is set within the atrium. This windowed space is of masonry construction, and has a roof which protects it from direct sunlight which penetrates the atrium glazing. The entire southern facade of the complex is shaded in summer by a double stand of mature deciduous trees.

The atrium serves as a thermal buffer - in winter or summer its thermal environment mediates between interior and exterior. Vents or windows in outer and inner walls of the rooms, and in the atrium and corridor roofs, promote cross-ventilation of all spaces. In summer the same system provides night-time cooling of the building fabric. The 0.5m thick brick-and-lightweight-block walls, concrete floors, and insulated concrete roof slab provide thermal inertia. There are no automated lighting systems, no special shading devices, and no cooling plant. Mechanical ventilation is installed only in the bathrooms, and in the enclosed surveillance posts which are located within the atria and have no direct contact with the exterior.

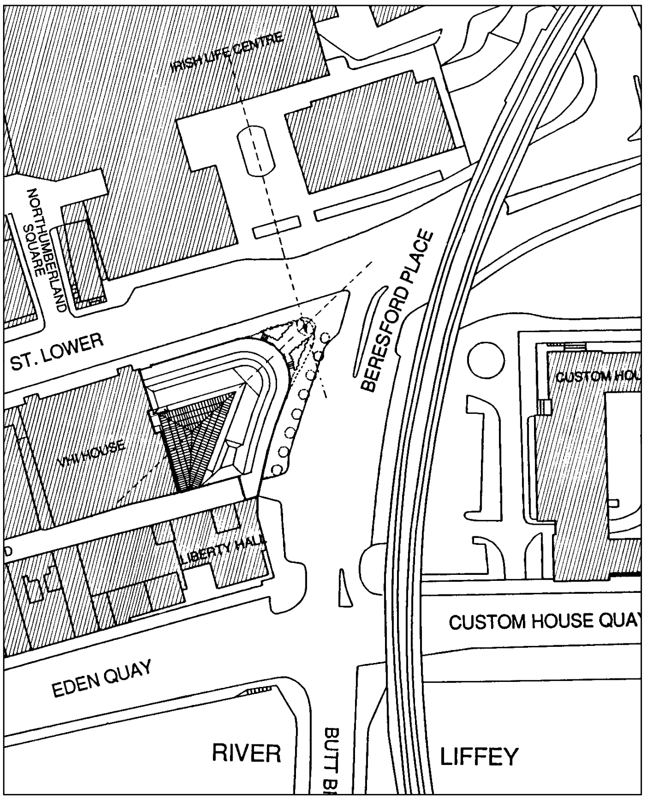
The architects were Joachim Ganz and Walter Rolfes.

8.8 Beresford Court, Dublin, Ireland

The investment managers of Irish Life Assurance plc occupy a small, almost triangular, corner site in the centre of Dublin, latitude 53°24’N. (Mean daily global irradiation 3062Wh.m^{2}. Mean daily sunshine duration 4.1hrs.) The organisation operates a flexi-time schedule, so the building is used well into the evenings by the 150 staff. Beresford Court was completed in 1991.

Most of the surrounding buildings are 5 to 6 storeys high, but a 17-storey tower building stands immediately to the South, overshadowing the site. An additional problem was that VHI House on the western site boundary had rights to light which could not be infringed. The solution was to wrap five floors of 13m deep office space around the North and South-East sides of the site, forming an atrium at first floor level, the West side of which is completed by the neighbouring building. This space is used as a coffee area by staff and visitors, as a waiting area, and for exhibitions and meetings.

All floors except the ground floor look into the atrium and have windows which open on to it, as do the old windows in the neighbouring building. All of the atrium structure, its walls and most of its floor are white. A 5.5m wide full-height window on the short southern boundary admits low-angle sunlight and provides a glimpse of the River Liffey from the upper office floors. These features, and a mirrored frieze located immediately below the roof, help to increase the apparent size of the relatively small space.



Windows facing the street are glazed with grey body tinted glass, but clear glass is used for those which look into the atrium. The atrium roof and tall South window are glazed with green anti-sun glass. Sails to shade the atrium were designed and there are recesses for blinds above all of the windows facing the atrium, but none of these have been installed because the shadow cast by the tower prevents overheating. Glare does not appear to be a problem in or around the atrium. Blinds have been installed in some of the windows which face East onto the street, where morning sun was producing reflections on VDUs.

Supplementary artificial lighting is provided by low-voltage luminaires. Lighting in all common areas of the building is switched on and off by passive and infra-red presence sensors. Task lighting is switched by hand-held remote control units. The average operating load for lighting is 10 to 11W/m^{2}.

The total floor area is 6165m^{2}. Except for the atrium, the building is fully air-conditioned and incorporates an ‘ice-bank’ which takes advantage of off-peak electricity for cooling. The atrium is heated and ventilated by ‘dumping’ the conditioned air which has already been circulated through the ground floor into the base of the atrium where it rises to filter out at roof level. As the atrium air-temperature rises, smoke-vents open to increase ventilation rates. In hot weather low-level vents in the South window admit fresh air. These are controlled by an automated building management system.

The architects were A & D Wejchert; the lighting consultants Homan O’Brien Associates. Performance is monitored by Irish Estates Management.

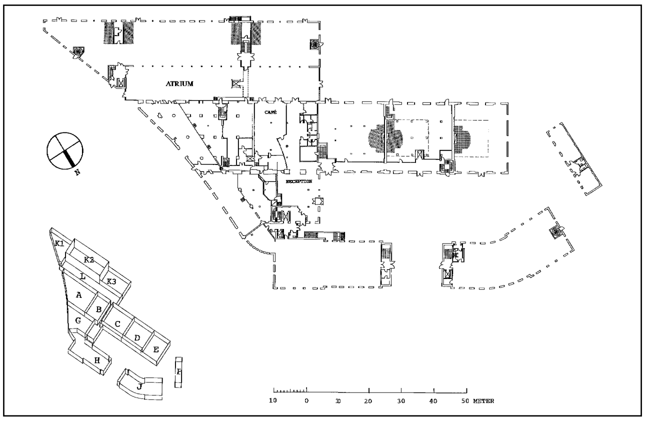
8.9 Sukkertoppen, Valby, Denmark

In this 1992 retrofit project an atrium was used to connect a new building to a pre-existing building in a disused sugar refinery. The location is Valby, an old industrial suburb of Copenhagen, latitude 55°41'N. (Mean daily global irradiation 2826 Wh/m^2. Mean daily sunshine duration 4hrs.) The 18,000m^2 complex, developed by Højgaard & Schultz for The Employees Capital Pension Fund, is now used as a multi-media centre.

The new 84m long, 13m deep office building is located to the South of the old 2-storey brick structure on an East-West axis. The new building and the atrium are 4-storeys high. The atrium, 10m wide by 60m long, was designed to reduce the space heating load while maintaining daylight penetration into both buildings. Site area was constricted and the presence of the atrium permitted the use of larger windows in both buildings, so that the distance between them could be reduced while still meeting building regulation requirements for daylight levels in ground floor rooms.

The atrium itself is double-glazed with 'low-E' glass and its minimum indoor air temperature is 15°C. This means that the atrium space can be inhabited and that windows facing into it can be single-glazed. The total heating load for the atrium and the parent buildings combined is 20% lower than it would have been for the parent buildings without the atrium.

The atrium structure and the facade of the new building are white, increasing daylight penetration. The floor is paved in pale grey brick, while the old building retains its dark brick facade. Window size in both buildings increases towards the base, so that those on the ground floor are full height. Computer modelling of this configuration showed that daylight factors are lower at the perimeter of ground floor rooms but higher 7m from the facade than would have been the case without the atrium, so daylight distribution is more even.



Shading to the atrium is provided by the bulk of the new offices to the South and by internal adjustable blinds on its South facing slope. It is naturally ventilated through openings in the roof and at 3m above floor level which are controlled automatically in response to climatic conditions. Overheating has not been a problem, even when the atrium has been densely occupied during warm sunny weather.

Artificial lighting in the atrium is by high level metal halide street lamps. Lighting and ventilation in the parent buildings varies with the requirements of the tenants.

The architects were Kristian Isager Tegnestue A/S and Ark. Hjembæk & Præstegård A/S. The daylighting consultant was Esbensen, Consulting Engineers FIDIC.

8.10 Byzantine Museum at Thessaloniki, Greece

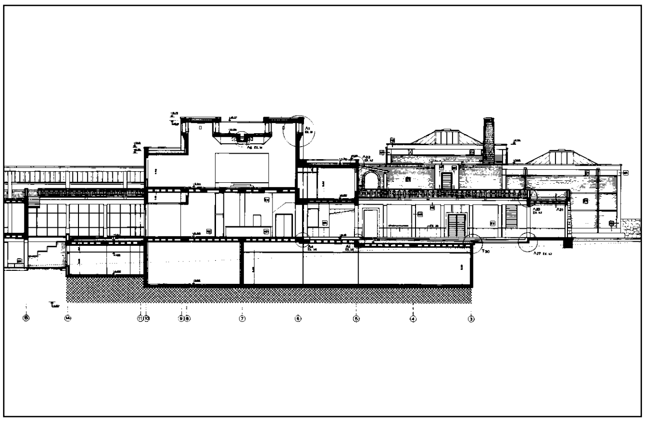
Completed in late 1993 for the Greek Ministry of Culture, the museum will house art objects of the Byzantine period. It is located on an urban site in Thessaloniki on the Aegean coast of northern Greece, latitude 40° 38'. Mean daily global radiation is 4649 Wh/m^2, and mean daily sunshine duration is 7.1 hours. The site is free on all sides so that there are no external obstructions to sunlight or daylight.

The daylighting strategy formed one of the principal generators for the form of the building. A series of courtyards bring light into the heart of the 12,000m^2 building, and loggias provide outdoor shade. Most low level windows are small and confined to the walls of circulation spaces. The galleries are lit by double sets of clerestory windows, screened by exterior vertical fins whose angle varies with orientation. Two square galleries are roofed by octagonal pitched structures with 50% glazing. These are fitted with horizontal sliding screens.

Floors throughout the interior are finished in pale grey marble, while walls and ceilings in the galleries are white painted plaster. In the courtyards and circulation areas the in-situ concrete frame and red-brick infil panels are exposed. Where rendered surfaces are used outside they are painted a deep terra-cotta, modifying glare in courtyeard spaces.

Artificial lighting to the galleries is contained in central bulkheads, which also carry the air-conditioning system. Natural ventilation is precluded by the nature of the objects being displayed, which include icons, frescoes and mosaics. All switching of the lighting system is manual.

The museum was designed by Kyriakos Krokos. It has not yet been opened, so no information on performance is available.



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