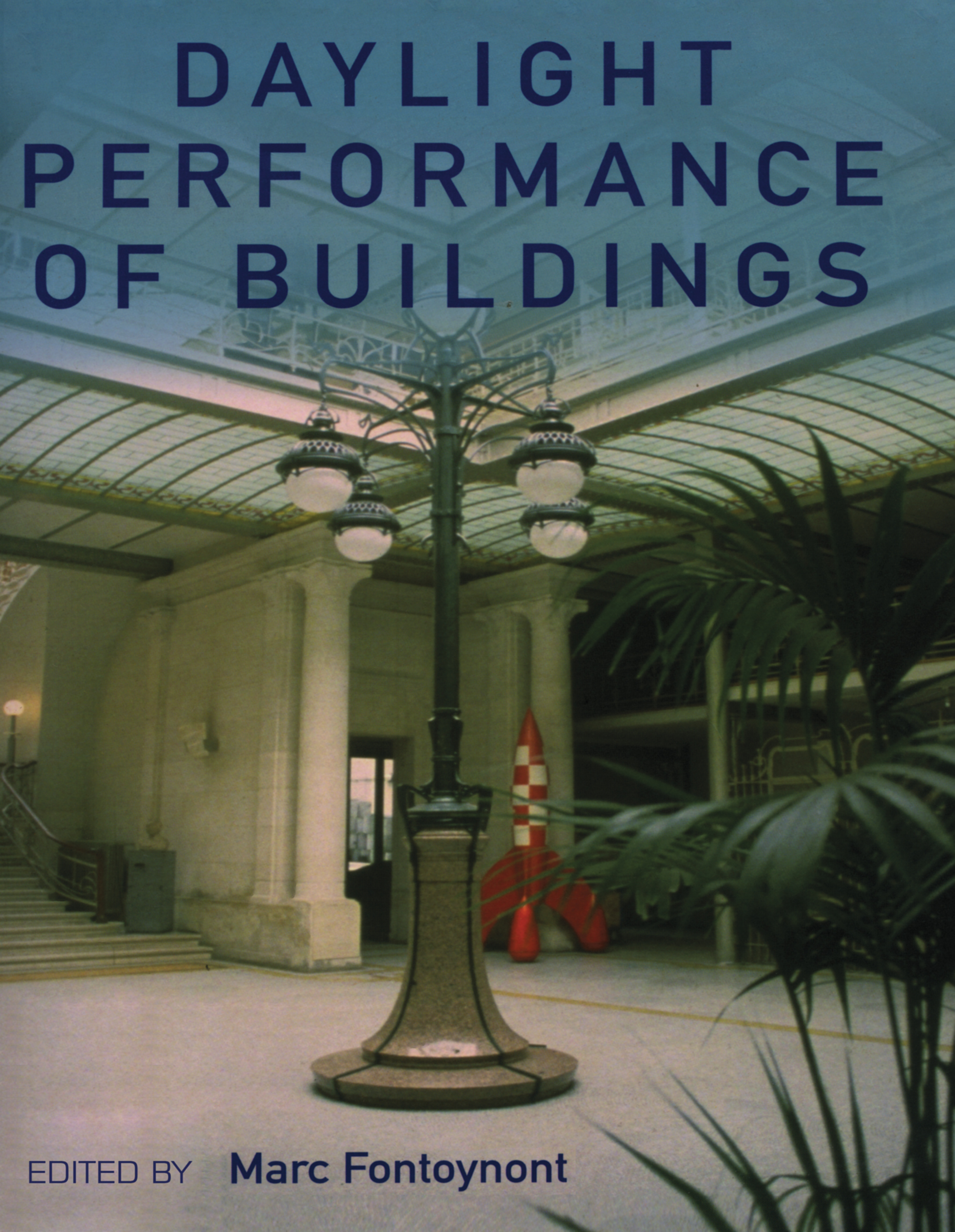
DAYLIGHT PERFORMANCE OF BUILDINGS



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Daylight Performance of Buildings

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Daylight performance of buildings

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The results presented in this book are mainly hand-on measurements and visual analysis for specific daylight conditions.

Variations of climatic conditions may modify the characteristics of light distribution.

Results are presented in good faith for the improvment of building design and daylighting conditions in buildings throughout Europe.

In undertaking daylight monitoring and measurement activities, those involved should take all reasonable precautions to ensure that the work is carried out in a manner which does not endanger the health and safety of those undertaking the work, other building occupants or the public, or cause damage to the building. They should also ensure that any relevant Health and Safety Regulations and guidelines are adhered to fully.

Preface

For more than two decades the European Commission has strongly supported a wide range of Research and Development and dissemination activities to improve the energy efficiency and environmental performance of our buildings, which account for almost half of Europe's total energy use and consequent impact.

Daylighting has become a major topic in energy conscious design. By optimizing the potential of daylight the energy for lighting our buildings can be drastically reduced, especially in buildings used mainly during the day, and the use of air conditioning can be reduced or eliminated.

In *'Daylight Performance of Buildings'* the daylighting behaviour of sixty buildings throughout Europe, new and old, large and small, with a wide variety of functions has been monitored and objectively assessed. The resulting case studies provide a valuable resource for building designers and incorporate quantitative and qualitative assessment of a range of daylighting solutions.

This collection of case studies of buildings with notable daylighting features illustrates the complexity and range of issues which need to be taken into account in good daylighting design. In addition to its potential for significant savings in energy use and consequent environmental impact, good daylighting design can dramatic-ally improve our living and working conditions.

Dr Georges Deschamps
European Commission,
Directorate General XII
for Science, Research and Development

Until the beginning of this century, daylight was the most important light source for daytime use for factories, offices, domestic and public buildings. The availability of affordable artificial lighting led to a building designs primarily dependent on electric lighting in deep-plan buildings with smaller windows.

Daylight is now reassuming its importance and desirability in design criteria for buildings used mainly during the day. People prefer daylight, and daylight use can offset the need for artificial lighting, saving running costs and reducing the environmental impact of energy use in buildings. Daylight design of buildings is becoming an integral part of the concept of sustainable buildings, along with improved indoor comfort and working conditions.

Daylight use in buildings requires daylight admission and distribution in the building to be considered. Shallow buildings are preferable, window design and size are important and solar control and shading systems are essential. An integrated design approach has to be adopted.

Throughout the predominance of artificial lighting, the daylight design tradition among architects and engineers was lost. The EU Daylight Europe project was begun to disseminate techniques of good daylight design to architects and engineers. Good examples of daylit buildings need to be documented, as do appropriate designs. The two main deliverables of the Daylight Europe project: Daylight Design of Buildings, and the present book, seeks to fulfill this need.

Much can be learned by studying older examples of buildings that were built with daylight as their primary light source. This book of case studies contains several historic examples of buildings, such as the two thousand years old Pantheon in Rome, and the beautiful seventeenth-century Trinity College library in Cambridge, United Kingdom. Most examples are from this century, and many newly completed buildings are included, such as the United Kingdom's Stansted Airport, and Alex Tombazis' office in Athens, Greece.

The 60 buildings documented in this book represent a unique source of information, since this is the first time that so many daylit buildings have been monitored and documented. We hope that the book will find use as a source of inspiration in architects' offices, and thereby contribute to the design of buildings that are more comfortable and inspiring to be in, and have a smaller environmental impact.

Poul E Kristensen
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Contents

60 case studies

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Introduction

by Marc Fontoynont

This book attempts to provide an original view of the built environment, whether it concerns modern architectural landmarks or architecture representative of the end of the 20th century. The objective is to offer some understanding of the way daylight penetrates and propagates in a building, and to determine the causes of the effects which can be observed: the reasons for bright spaces, shadows, contrast, glare, and, more generally, the way occupants, lighting requirements are fullfilled by daylight.

In this respect, the built environment around us can be considered as a large laboratory in which lighting phenomena can be observed and understood.

The 60 case studies which are presented have been proposed by participants of the "Daylight Europe" programme, which has been supported by the European Commission, DG XII for Science Research and Development, consists of within the JOULE Programme. The range of buildings selected for study comprises those which were accessible to the participants and is thus more supply-led than demand-led. The sample is therefore rather heterogeneous - but such is reality! We have presented them according to themes to allow more interesting, topic-related, discussions.

The spirit of our work has been to offer as objective as possible an analysis of the daylighting qualities of the buildings studied. The measuring campaign which has been undertaken will provide valuable data in the future for building designers and daylighting scientists.

The measuring campaign required the development of a precise procedure which is described in this document. The level of experience in undertaking lighting measurements was rather heterogeneous among members, and various difficulties may have lead to some errors in the measurements, although, in most cases, inconsistent results have been re-evaluated. The major potential source of error has been in the simultaneous measurement of indoor and oudoor illuminance under very precise overcast sky conditions. This task becomes difficult if the studied building is far from the location of the monitoring team, or if access to the building was limited. Sometimes sky conditions, which were required to be continuously overcast, were unsuitable for measurements.

As coordinator, I tried my best to collect the most useful data concerning the monitored building. Sometimes this led to difficulties since the measuring teams had to visit the building again and perform measurements in locations difficult to access.

The work which is presented here is the result of a three-year long international task, with all the difficulties that entails in the management of the measuring campaign and collection of the data.

A significant level of expertise has developed among the participants, with improved confidence in their measuring capabilities and processing of the data. It is anticipated that this work will be continued in the future by participants or by other teams, once the book is published.

We hope that our document will find a place on your bookshelves and that you will use it regularly, and that it will inform and encourage you in future daylight design and monitoring activities.

I woud like to thank the participants of the Daylight Europe Programme for all their efforts to produce information of high quality in sometimes difficult circumstances. I would like to thank John Goulding from University College Dublin for his advice and his assistance in the detailed reviewing of the text before publishing; Vincent Berrutto from ENTPE, France, for his coordination of the monitoring campaign and his involvement in the definition of measuring procedures; Pascale Avouac-Bastie, from ENTPE, for collecting the data from all participants, adapting them to our requirements and producing the DTP version of the results.

∇ Marc Fontoynont, editor and coordinator of the monitoring subtask of 'Daylight Europe'.

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Daylight performance of buildings: 60 European case studies

The results of a three-year monitoring campaign of buildings throughout Europe are presented in this book. We present here a summary of them, obtained through the observation of the daylighting behaviour of 60 buildings. Various types of buildings were involved, from offices to museums, libraries to churches and more specific buildings such as airports or factories. Classical buildings (such as the Pantheon in Rome built in 128 AD) are included, some of which are historical landmarks (such as Ronchamp church by Le Corbusier), others are more recent (such as the Stansted Air Terminal by Foster & Associates). The sizes range from one single room of 11 metres (Anatomical Theatre, Gothenburg, Sweden) to a large-scale office building (100,000m² floor area of the Tractebel building, Brussels). The study shows the extraordinary potential of daylighting techniques, to improve amenity and energy performances for the benefit of building occupants and managers. However, opportunities are often missed, with performance of daylighting solutions sometimes overestimated by designers, or with significant problems of overheating and insufficient attenuation of glare. Above all, this monitoring campaign shows the broad scope of daylighting design, and the importance of careful assessment of side effects which need to be analysed with the benefit of experience and knowledge of the physical principles; and appropriately managed.

A three-year monitoring programme throughout Europe

For a period of three years between September 1994 and August 1997, a large scale monitoring programme was conducted at European level, dealing with the daylighting performance of 60 buildings throughout Europe. More than 10 organizations were involved in the task which required about 30 people to carry out measurements, process the data and supply the results to the coordinator. The task included observations, indoor luminous measurements for specific climatic conditions and calculation of performance indicies. For some buildings, a specific Post Occupancy Evaluation study (POE)

The understanding of the behaviour of a ▷ building with respect to daylight requires the measurement of specific parameters sometimes in locations with difficult access.

to assess the effects of daylighting strategies on the occupants. In parallel, a simulation group conducted detailed energy calculations for six monitored buildings aimed at comparing the energy saving potential of the proposed daylighting techniques with a reference case or other options.

Using reality as a source of information

In recent years, there has been a growing concern about the development of tools to provide assistance in daylighting design. The oldest and most used tool is still the scale model (light propagation follows the same rules in a scale model and in full scale reality). Now, various computer programs have been proposed either to simulate the daylighting behaviour of a building with well characterized daylighting sources, or to assist designers in their strategic decisions. For any tool used, there is always some doubt about its validity, and concern about its limited field of investigation.

It is clear that the performance of daylighting systems can be judged objectively and subjectively, and that energy aspects are partly visible and partly invisible. However, only on-site observations and measurements can detect some aspects of daylighting which are difficult to predict with tools: exact final optical performance of systems, rendering of the indoor space, quality of views, dynamics of daylight, and above all, the global impression given to the visitor as well as the occupants. Finally, it has been found that a database of buildings, some of them well known and most of them accessible to the public, would be of great interest to building designers.

Selection of 60 buildings

The 60 buildings were selected for their interesting daylighting features, either generally or at least regarding a specific feature. Ease of access also played a part in their selection. All participants made proposals regarding the buildings they intended to monitor and it was decided that 60 buildings appeared to be the maximum achievable number with respect to the allocated budget. A decision was made to include standard building configurations and not to focus only on cases where the solution was elaborate or unusual. It was decided to offer a large range of buildings and applications, with solutions offering a large variety of ways to bring daylight into building interiors.

A standard procedure for collecting information

In order to extract useful information from the 60 buildings, a monitoring procedure was established. It dealt with a series of measurements and observations, and with their analysis. The following is a summary of the tasks conducted:

Tasks

1 Geometric assessment (glazing area/ dimensions)

2 Daylight factor assessment, through the simultaneous measurement of indoor and outdoor illumination under overcast sky conditions.

3 Material characterization: measurement of reflections and transmissions of opaque surfaces, glazing materials and awnings.

4 Visual comfort assessment, through the determination of luminances in the field of view of the occupants.

5 Homogeneity of daylight penetration, through the comparison of vertical illuminance measured in the centres of rooms.

6 Assessment of luminous flux penetration through various apertures, under standard overcast conditions (external horizontal illuminance equal to 10,000 lux)

7 Photography, with wide angle lenses and fish-eye lenses to display the patterns of daylight penetration in the space, for diffuse light and sunlight.

8 Recording of occupants' comments

9 Energy calculations for various daylighting options

The procedure developed for this task required some training seminars to help teams master the various aspects of daylighting measurement. The sensors used by the teams were calibrated together. However, errors can still occur, particularly if measurements are taken in non-standard climatic conditions. The recording of material properties on site also required some specific conditions of incident light on the surfaces. It is clear that some errors may have still occurred in the monitoring campaign, although a great effort was made to minimize these.

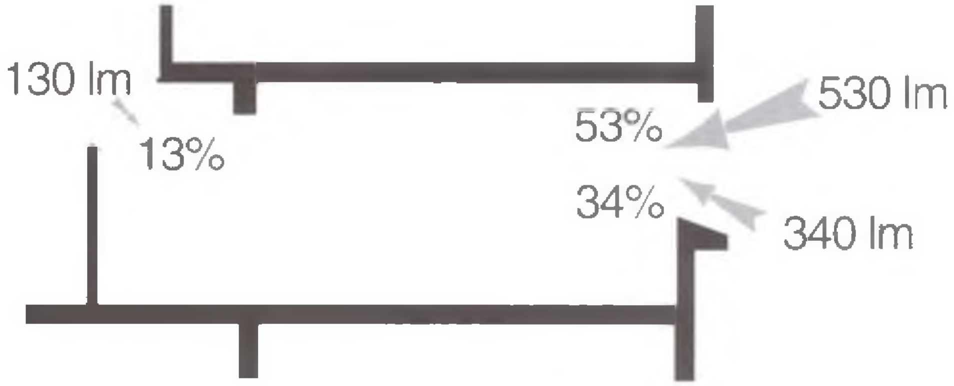
The importance of objective assessment

Any example of architecture can be considered as an optical element allowing some daylight to penetrate it and then reflected it by the indoor surfaces. In order to compare two buildings, a reference light source needs to be defined, regardless of its significance with regard to the local climate. The best reference sky condition is a totally overcast sky, the luminance of which is larger near the zenith than near the horizon (typically two to three times). Since we are mainly interested in relative values, such as ratios of indoor to outdoor values (daylight factors), or ratios of indoor to indoor values (luminance contrasts, homogeneity, etc.), the global brightness of such skies has no importance, and measurements can be conducted any time during the year: a sky twice as bright as the reference one leads to indoor spaces two times brighter. This also means that measurements under overcast sky conditions apply for Mediterranean buildings, even if such skies are rare in these climates.

Objective assessment helps us to discover the difference between the perceived brightness of a space and the exact amount of daylight used to light it. This started useful discussions about the comparison of the performance of daylighting systems and about the role played by material finishes.

Finally, it was decided that objective assessment was probably the best method for a large-scale monitoring programme, to reduce the differences in assessment between participants, and to provide useful data to the largest possible audience.

A typical exercise which was conducted for many case studies was the assessment of *the luminous flux* provided by daylighting systems under standard overcast conditions (representing an outdoor horizontal illuminance of 10,000 lux). This allowed a quick comparison of the amount of light admitted by facade windows and secondary lighting windows. The value could also be compared with the amount of light provided by luminaires to give an idea of the potential of daylighting to replace artificial lighting.



△ **Example of assessment of the origins of natural light fluxes entering a room per 1,000 lux of total incoming light flux. This technique clearly displays the amount of light provided by the secondary daylighting window by comparison with the facade window.**

Simple systems often perform better.

The amount of natural light entering a building is related to three major factors:

1) the luminance of the section of the sky as seen from behind the window,
2) the associated solid angle of this section,
3) the capacity of the window to bring daylight inside (area and transparency).

The final amount of light available inside is related to the area of the absorbing surfaces (by comparison with the window area) as well as their reflectances, and particularly those of the surfaces directly hit by the incident daylight.

For this reason, most systems with additional surfaces, even if reflective, tend to globally decrease daylight penetration through the reduction of the solid angle of light collection (2), and adding additional light absorptions in process (3). This means that greater control of daylight often leads to a reduced overall luminous performance. In this way, the best performance remains that of the horizontal roof aperture collecting daylight from a large section of the sky with very little obstruction. But we all know that protection against sunlight and the provision of a view to the external environment are needed in most buildings.

For this reason, it was found that a combination of simple systems (roof and facade apertures for instance) performed better than advanced facade systems attempting to deviate diffuse daylight deep into the building

▷ **A combination of simple systems and bright indoor finishes was found to perform rather well.**

▷ **Corridors of the Reiterstrasse Office building in Bern are lit with natural light, partly hidden from the field of vision, filtering between obstructions, leading to a low luminance level, glare-free, but pleasant space.**

∆ In the bright Baroque church of the Neresheim Monastery, daylight factors range between 1 to 1.5%, values higher than usually found in cathedrals where values around 0.5% or below are common.

∆ The Architects Office in Athens is a good example of a building where facade window area has been reduced to a minimum size because of the climate, still achieving a bright work space near each window. The rest of the room benefits from ambient light admitted by a central roof monitor equipped with shading devices.

through the addition of reflective surfaces.

Furthermore, complex systems involving highly reflective surfaces have performances which are very dependent on maintenance and durability of the components. Dust, condensation or surface deterioration quickly reduce optical efficiency, sometimes by more than 50%.

Some spaces perform well with rather low levels of light

If we take away the cases for which high illuminances are required (such as about 500 lux on the work plane for instance, or more for some factory work), many spaces can appear bright at modest levels of illuminances. The reason can be that the general brightness of the space is higher than that expected due to its function. This is the case in the church of the Neresheim Monastery, where indoor finishes are particularly bright, and stained glass has been replaced with clear windows.

Circulation spaces frequently do not need a high level of illuminance. Values of 10 to 50 lux may be acceptable as long as the eye of the occupant is adapted to the luminance of the indoor surfaces, and not to the outdoor luminance, which is usually much higher. This suggests that apertures should be partly hidden from the field of vision, with natural light pouring in behind architectural elements.

Adding small apertures gives better performance than increasing window sizes

Increasing window sizes leads to more daylight being admitted, but can also cause more glare and more constraints regarding the shading systems. Beyond a certain level of daylight penetration, increasing window area may in fact generate far more problems than the benefits of letting some additional natural light in.

For instance, increasing daylight factors from 3 to 4% (through an increase in window area of 33%) will only lead to

∆ These secondary daylighting windows are clearly undersized with regard to their potential to add extra daylight to the corridors from the daylit offices.

∆ In Collège La Vanoise, Modane, France, the most attractive daylighting feature is the tilted secondary lighting system allowing daylight to penetrate from the atrium roof to the interior. The tilt angle of the windows leads to a transmitted light equal to 3 times that transmitted by vertical windows. Daylight distribution in classrooms becomes balanced and the general impression is of a very bright space.

▷ The translucent floors and ceilings of the Waucquez Department Store in Brussels allow daylight to penetrate deep into the building, because their area (comparable to the area of the glazed roof) compensates for the optical losses associated with the triple absorption of light coming from the outside. At ground level, daylight factors reach values above 1%.

an increase of the daylighting period during the year of less than 5%. The challenge therefore is in bringing more daylight into areas where daylight factors are low, and lighting requirements high. Examples can be found among the case studies, where roof apertures, secondary daylighting windows or double side lighting solutions are used instead of single side facade solutions.

◁ In Stansted Air Terminal, the rooflight elements associated with the supporting columns are the major aesthetic feature of the large square hall (120m x 120m).

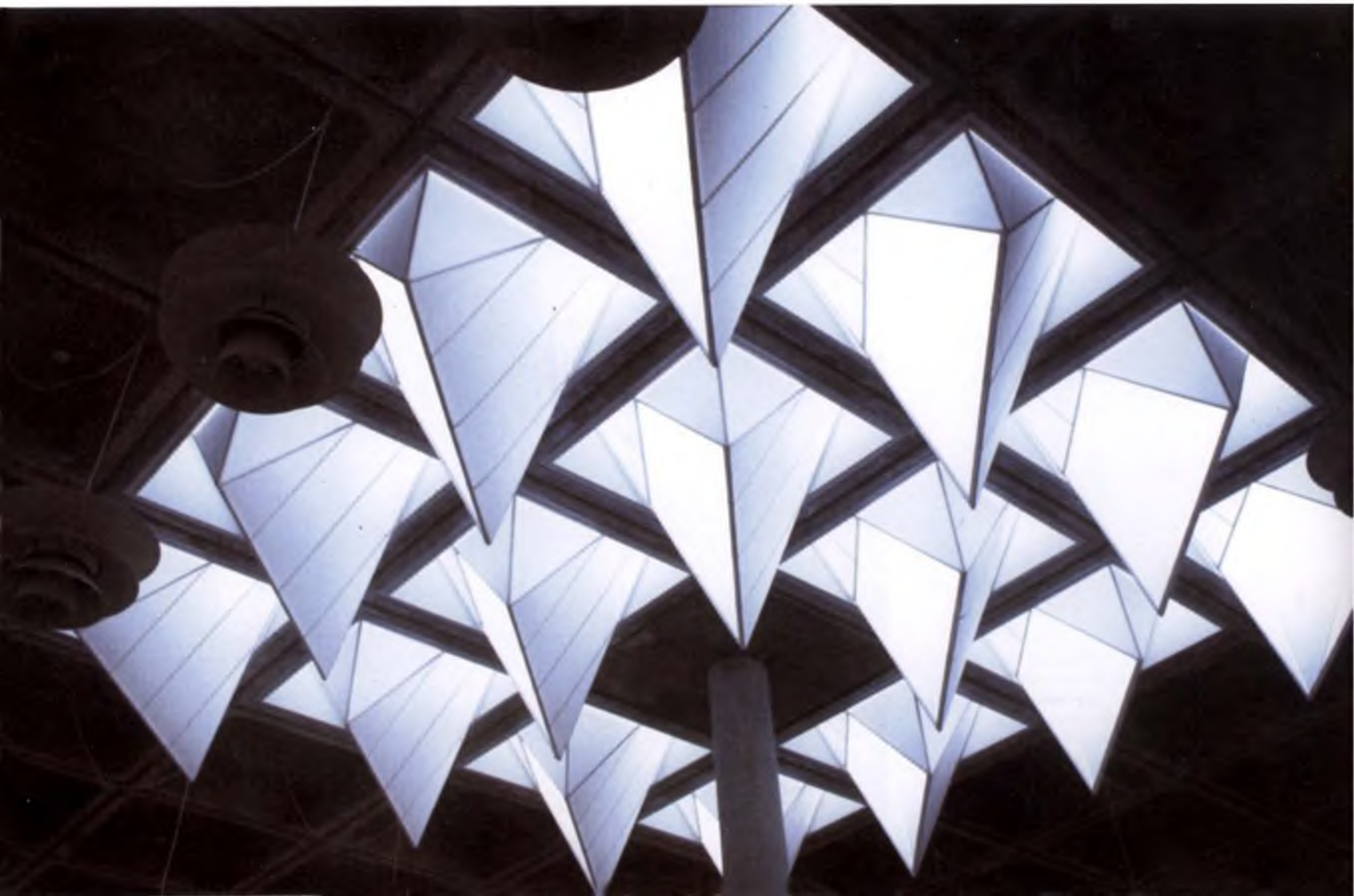
Translucent floors

Secondary daylighting is of great interest, as an accepted way to bring daylight deep into a building. Internal walls or ceilings can be transparent or translucent. However, the light falling on these surfaces can be 10 to 100 times lower than the illuminance on a vertical window on the facade. This suggests that secondary daylighting can be applied only if the daylight factor on the surface concerned is sufficient (typically more than 1%) and the glazing area should be as large or larger than the original window area on the roof or the facade. Ideally, a secondary lighting window should occupy the entire surface of the indoor wall or partition.

Daylight, a large contributor to the amenity of the space

The daylighting system can also be considered as a piece of sculpture, in the same way as a chandelier behaves with artificial lighting. It becomes an aesthetic object on its own. However, it needs to be assessed in terms of its ability to fulfill visual criteria such as glare control (moderate luminances) and

▽ In the Trapholt Art Museum, Denmark, daylight is brought from the ceiling through hanging canvas 3D forms, a unique and remarkable design.



overall performance (production of a luminous flux and distribution in the space). Among the 60 buildings which have been studied, some of them have integrated aesthetic elements, such as the rooflights of Stansted Air Terminal, UK, the hanging pyramids of Trapholt Museum, Denmark, the occuli of Bibliothèque Nationale in Paris, etc. Sometimes they integrate artificial lighting so that artificial and natural lighting are associated in the final rendering.

Sizing of daylighting systems needs to be based on visual specifications for the users

The larger the window area in the facade, the higher the risk that occupants will be exposed to glare and overheating in summer. Hence, shading devices, which must operate in glare situations and provide the desired attenuation, have a crucial role. If their luminous transmittance is too high (above 10% in general), the risk of glare is significant, with luminance reaching more than 1,000 cd/m^2 for an illuminance on the awning of 40,000 lux.

Increasing use of computer screens make luminance control more critical

Vision on computer screens with typical maximum luminance values in the range of 80 to 120 cd/m^2 is sensitive to veiling reflections due to luminous elements around them

A daylight source generates high luminance. First, through direct vision of the sky (2,000 to 10,000 cd/m^2) or the outdoor environment (similar values if lit by sunlight). Second, because it causes high levels of illuminance on surfaces near the aperture (1,000 to 5,000 lux typically, and more if there is a sun patch). If the receiving surface is bright (reflectance above 60%), its corresponding luminance can reach values in the range of 200 to 1,000 cd/m^2. Even if the typical reflectance of a computer screen is low (less than 5% usually), the luminance of the reflection on the screen may be 50 cd/m^2 for a 1,000 cd/m^2 light source, and 100 cd/m^2 for a 2,000 cd/m^2 light source. This is significant by comparison with the maximum brightness (about 100 cd/m^2) of the screen. The resulting situation is a veiling luminance or reflection which makes reading the screen difficult.

Atria: buffer spaces which may also work as light boxes

Various monitored buildings included atria, designed mainly for thermal reasons, acting as buffer spaces with temperatures warmer than outdoor temperatures in winter. While heat losses can be reduced, overheating needs to be avoided through high ventilation rates and proper shading.

∇ Overglazed facades and poor shading may lead to indoor spaces with extreme glare or overheating. Occupants may have no other option but to install their own protective measures.

◁ Multiple apertures tend to be preferable to create bright interiors. However, this may lead to more veiling reflections on computer screens if the apertures are not hidden or if the surfaces receiving most of the light are too bright.

The addition of an atrium as a refurbishment of a courtyard may lead to a reduction of daylight to the adjacent windows by more than 50%.

The main difficulty is that illuminance levels on atria walls are much lower than on external facades (often a third to a fifth). Daylight falls on the windows surrounding the atria at a high incident angle, leading to poor penetration in the interior (daylight penetrates two metres typically). Also, shading on the atrium roof will affect the amount of light available. Secondary daylighting windows facing into the atrium need to be large, at least 50% of the wall surface, to offer any significant contribution of daylight to lighting needs.

The role of surface finishes was assessed. It was found that the reflectance of the floor of the atrium was a significant factor in the daylighting of the two lower floors surrounding the atrium.

Specific problems at high latitudes

At high latitudes, the sun's trajectory is closer to the horizon. If one wants to collect sunlight during the heating season, which is predominant across the year, south-facing clerestories are more appropriate than horizontal roof glazings.

On the contrary, sunlight is a serious source of glare, and fixed overhangs on south facades would need to be large and would reduce significantly the penetration of diffuse light from the sky.

However, the fact that the sun is closer to the horizon leads to shading from obstructions, which can be significant throughout the year.

Thermal trade-off often affects perception of global performance by occupants

Although no specific monitoring was performed regarding the energy performance of the 60 buildings, the thermal trade-offs have been part of our concern: when it was possible, occupants and users were interviewed, and for six selected buildings detailed thermal analyses were performed to assess the energy impacts of the daylighting features.

The energy performance of the buildings as they are today was computed using the energy simulation programme ESP-r (ESRU, 1997) and comparisons were made for configurations without the daylighting features. The RADIANCE programme (Ward, 1993) was used both for the generation of optical parameters for ESP-r and for specific assessment of glare issues.

△ In the atrium of the Beresford Court office building, daylight reflections on the bright floor contribute substantially of the light penetrating the lower floor.

▽ In Göteborg, Sweden, the south-facing clerestory above the atrium of a law court building collects low-level sunlight and reflects it downward.

For most cases, it was found that the savings in annual lighting consumption tended to be large, but that the thermal impact is slightly positive in the case of atria, but negative with light redirecting facade systems. When an increase in thermal loads was reported, they tended to be smaller than the benefits of savings in lighting electricity. However, glare and reduction of diffuse light penetration was found to be critical. For instance, glare was found to be significant when atrium walls would receive direct sunlight.

Conclusion

Working together within a group of about 30 people for three years has led to the establishment of a common know-how in daylighting monitoring which will benefit all participants, their colleagues and institutes, while a significant and valuable resource has been created for building designers and daylighting specialists. No doubt these references will also facilitate the advancement of knowledge when experts and teachers will refer to them when explaining daylighting principles. It is expected that other daylighting monitoring campaigns will be launched in the future, and be more ambitious in terms of their assessment of performance.

Acknowledgements

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Δ In Trondheim, Norway, the sun's elevation above the horizon is low. This leads to frequent shadowing effects by neighbouring buildings, and severe risks of glare when the sun is visible.

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Daylight performance of buildings: monitoring procedure

This section presents a procedure which was developed to allow the assessment of the behaviour of buildings and building components with respect to daylight. The goal was the characterization of windows as 'daylighting luminaires', in relation to the space lit and the materials used. Reasons for the success or failure of daylighting options can be deduced from site measurements. An objective analysis of the resulting visual environments is proposed, a means of investigating how they are adapted to the visual needs of occupants. This information should be seen as complementary to subjective assessment, where aesthetics and amenity are of concern. The proposed procedure has been developed within a European monitoring campaign which studied 60 European buildings, and ran from 1996 to 1997 [1]. It focuses on various buildings, old and new, including offices, museums, schools, houses, glazed streets, churches, factories, etc.

Introduction

There is a gap between the large amount of discussion associated with daylight in architectural magazines and the often small amount of useful, scientific information which can be gleaned by readers from these articles. Photographs can give an instant impression of the quality of daylight in a space, but the image depends so much on the skill of the photographer and the selected climatic conditions at the time that it is sometimes difficult for the reader to really understand the dynamics of daylight: is the building bright or dark? In the building are the levels of illuminance well adapted to the activities of the occupants? Are shading devices efficient? This introduces the concept of the 'performance' of a building, or a component with respect to daylighting. This suggests that there is a way to go beyond the image to report the quality of lighting.

On the other hand, light propagation is a well-known phenomenon today, and there are measurement tools to characterize it. A building can be seen as an optical system in which light propagates. Window sizes, surface shapes and finishes affect this propagation, and it should be possible to identify, on site, the exact role of each element in the

∇ The aim of the monitoring procedure has been to understand the optical phenomena involved and how they have created the luminous environment we see in the building.

process. By determining the influence of each element in the final success or failure of architectural options, we can provide useful information to the design community.

∇ Windows are the sources of daylight. Their size needs to be compared with the floor area of the zone they illuminate. The ratio of the glazed area to the floor area is the aperture ratio.

Geometric description

The first consideration in daylighting is the dimension of the window with respect to the space to be lit. But the most useful parameter is the exact glazing area, which needs to be adjusted by the transmittance of the glazing. When performing on-site monitoring, it is useful to have access to architectural drawings when they are available. Measurements can then be easily written onto the drawings.

Of great interest is the ratio of the glazed area to the floor area; this is called the 'glazing ratio'. Typically in the range from 5% to 30%, this ratio gives a rapid idea of the general brightness of the space over the year, and also the sensitivity of the space to outdoor climatic conditions.

However, some tinted or diffusing glazing used today may have a transmittance of less than 50%. This means than the glazing ratio needs to be corrected to take account of the transmittance of the glazing. On the other hand, brightness of finishes may multiply amount of light in areas of rooms situated away from apertures by two or three times.

Characterization of opaque and translucent materials

The most important aspect of the optical properties of materials is the difference in behaviour with a point light source (such as the sun for instance) and a diffuse light source (such as an overcast sky or, in general, the luminous conditions inside a building). During a monitoring campaign, it is easy to determine the transmittance of non diffusing glazing perpendicularly to the glazing plane (normal-normal transmittance). It is also useful to assess the transmittance of any glazing (clear, tinted or diffusing) for a diffuse light source such as an overcast sky: this is the hemispherical-hemispherical transmittance. Indoor finishes can be characterized by their reflectance under diffuse light, such as the indoor lighting when the sources of light are not in one direction (for instance when point-light sources such as lamps are well distributed over the space, or when daylight comes from two opposite directions). When mirrors are used, it is possible to measure their specular reflectance for given angles.

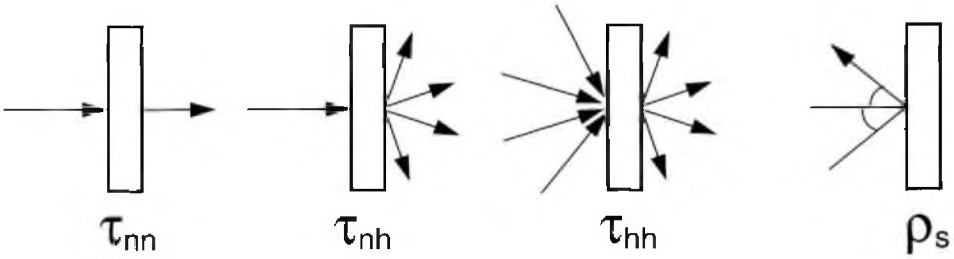
Measurements require luxmeters, measuring illuminance (lux) incident on the sensor, and luminance meters, measuring the luminance (cd/m^2) of surfaces as they appear from specific points of observation.

Overcast sky as a reference light source to characterize architecture

Although often more appealing, the indoor luminance environment under sunny conditions cannot be easily recorded. Overcast sky conditions are the most standardized conditions in which to perform monitoring. This is the only way to draw comparisons between different daylighting features installed under different climates. Such skies are typically brighter near the zenith than near the horizon. For this reason, a luminance range check should be performed prior to the measurements. This means ensuring that the average horizon luminance is no more than half the zenith luminance.

Daylight factors for assessment of daylight penetration

Indoor light distribution can be characterized through the measurement of illuminance on all useful surfaces: workplane, walls, paintings, copy-machines, computer screens, etc. However, since the intensity of natural light varies, it is necessary to consider the ratio of the local illuminance to the



Δ Various definitions of transmittance of glazing: normal-normal transmittance, normal-hemispherical transmittance (for diffusing glazing only); hemispherical-hemispherical transmittance; and reflectance.

Δ On-site determination of normal-normal transmittance (τ_{nn}) of clear glazing, which the ratio of the luminance of an object seen behind the glazing (L_{in}), in a direction perpendicular to the glazing plane, to the luminance of the same object, in the same direction, without the glazing (L_{out}). $\tau_{nn} = L_{in}/L_{out}$. Practically, the measurements are taken once with the window closed, and once with the window open.

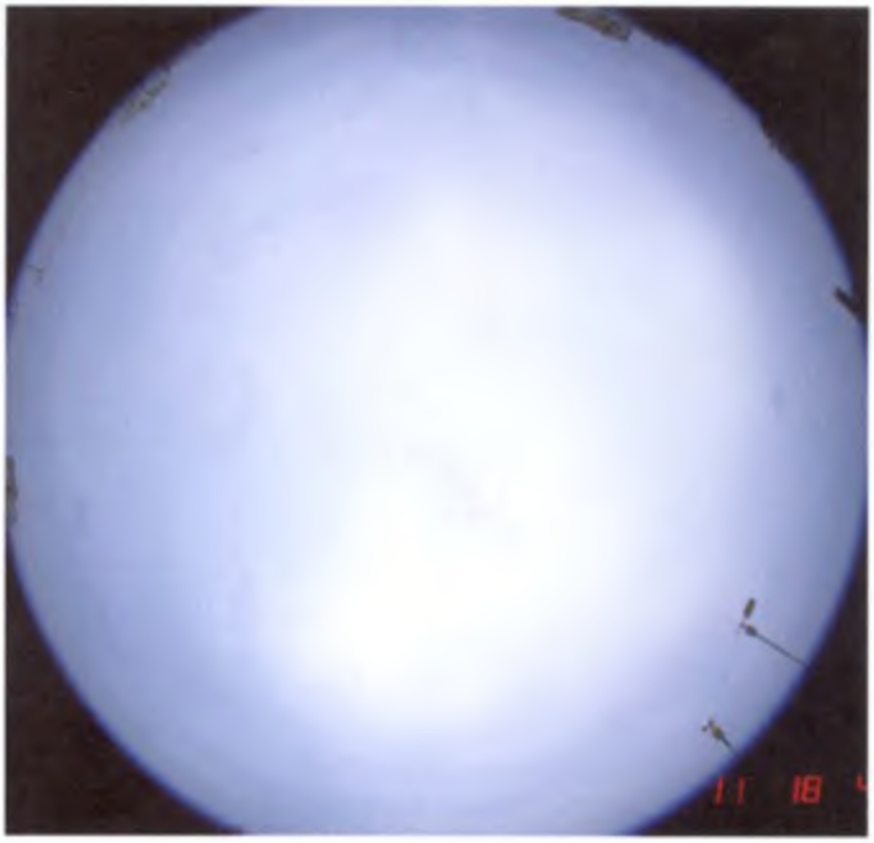
Δ On-site determination of the hemispherical-hemispherical transmittance (τ_{hh}) of clear or translucent glazing, which the ratio of illuminance behind the glazing (I_{in}) and in front of the glazing (I_{out}), with the luxmeter being located outside. $\tau_{hh} = I_{in}/I_{out}$. This measurement needs to be performed under overcast sky conditions.

Δ On-site determination of the hemispherical-hemispherical reflectance (ρ_{hh}) of materials: the luminance of a given wall surface (L_{wall}) is compared with the luminance of reference samples (one white- L_{white}, one grey L_{grey}). The luminous conditions should be as diffuse as possible: no artificial lighting, no daylight at low/high incidence, etc.

$$\rho_1 = \rho_{white} \cdot \frac{L_{surface}}{L_{white}} \qquad \rho_2 = \rho_{grey} \cdot \frac{L_{surface}}{L_{grey}} \qquad \boxed{\rho_{hh} = \frac{\rho_1 + \rho_2}{2}}$$

Δ On site determination of the specular reflectance (ρ_s) at a given angle: the luminance of the reflection (L_r) is compared to the luminance of the source of light (L_s), seen from the sample. $\rho_s = L_r / L_s$

simultaneous outdoor horizontal illuminance due to an unobstructed sky, and this ratio is called the 'daylight factor DF(%) [2]'. For this reason, two luxmeters are needed, as well as a way to guarantee that the two readings are performed simultaneously. Typically two people are needed, one inside, one outside. They can communicate by radio or the person outside can record the illuminances at regular steps, every 15 or 30 seconds for instance. Such a measurement procedure was proposed by the Building Research Establishment [3]. During illuminance measurements, sky conditions are continuously checked to make sure that the sky is close to a CIE standard overcast sky, so that measurements are reproducible.



▷ Picture taken with a fish-eye lens. An overcast sky is a practical reference light source allowing comparison of performance between various daylighting systems.

◁ In order to be considered as suitable for monitoring, an overcast sky should have a luminance near the horizon not exceeding half that of the zenith luminance.

Δ Daylight factors are obtained by performing indoor illuminance measurements and simultaneous outdoor measurements and expressing the result as a ratio. The outdoor sensor is positioned horizontally, in an unobstructed location, such as the roof of the building for instance. Indoor illuminance (I_{in}) measurements are performed at all locations where they can be compared with specifications of lighting requirements: work places, paintings, computer screens, floors, etc. Simultaneously, the outdoor horizontal illuminance (I_{out}) is recorded, to eliminate errors due to fluctuations of daylight.

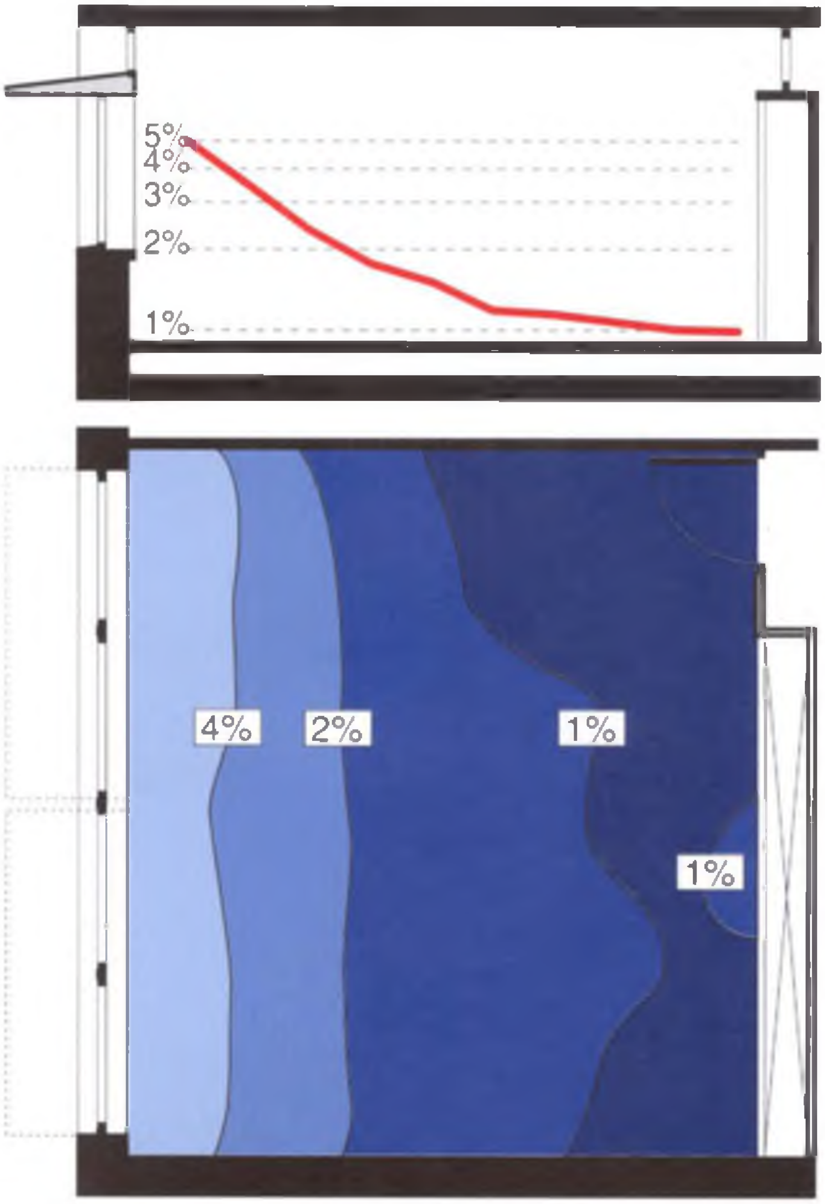
On the reference plane, the grid of measurement points needs to be equally spaced in both directions across the room. Across the width of the room, a bigger spacing is reasonable, compared to the spacing in the direction perpendicular to the windows. The distance between points must be adapted to the size of the space, however a minimum of 15 points is recommended to draw contours of equal daylight factor to produce a plot of the distribution of daylight throughout the room. Daylight factor contours are plotted using logarithmic interpolation between points as well as a logarithmic scale.

Light flux provided by daylighting systems

The comparison of the light fluxe (lm) provided by various apertures is of great interest. Incoming light flux is the product of the average illuminance behind a glazing facing outside (I_{in}) and the area of this glazing ($A_{glazing}$). With this technique, it is possible, for instance, to assess the benefits of secondary daylighting windows by comparison with facade windows. For simplicity, the reference climatic conditions used for this assessment are those of an overcast sky providing an outdoor horizontal illuminance of 10,000 lx.

Characterization of the luminous environment

One further stage in the assessment of daylighting performances deals with the attempt to characterize the indoor luminous environment as the occupants



Δ Daylight factors are then plotted along a cross-section or with isolux contours on a plane (such as the typical workplane height of 0.8 metres above floor level) to describe daylight penetration. The display of daylight factor (DF) contours provides a clear interpretation of daylight penetration in the monitored room. DF (%) = $I_{in} \times 100 / I_{out}$

Δ **Determination of the contribution of light reflections on the external ground. The luxmeter is oriented upward and downward to compare light coming from the upper and lower hemispheres.**

see it. The measurements are vertical illuminance, and luminance in specific directions.

As far as visual performance is concerned, luminance distribution can cause disability glare and transient adaptation problems [4]. Formulae are proposed in the literature to quantify these two physiological phenomena [4] [5]. However, they require knowledge of some characteristics of the glare source which cannot be easily measured with our spot luminance meters.

As far as visual comfort is concerned, poor luminance distribution can cause discomfort glare which is a different physiological phenomenon than disability glare. However, no index has actually been recommended for assessing discomfort glare due to windows. The Daylight Glare Index (DGI) was proposed for evaluating the discomfort glare produced by the direct view of an unobstructed sky (but not by sunlight) [6]. However, there are four elements which suggest avoiding using this index:

1) it is based on very few experimental data
2) some studies carried out in realistic situations failed to replicate the results which had led to the definition of DGI [7]
3) DGI formula cannot integrate the unmeasurable psychological influence of the prospect viewed through the window;
4) it is not feasible to measure, with standard spot luminancemeters, the parameters required for the calculation of DGI. Several other glare evaluation systems have been used worldwide [8]. However all of them, even the most such as the Unified Glare Rating, are designed for artificial lighting and are not recommended for use with daylighting.

Δ **Under standard sky conditions adjusted for a horizontal external illuminance of 10,000 lux, the luminous fluxe entering the space can be computed by multiplying the illuminance behind the windows by the area of the glazing. This leads to comparison of the performance of various daylighting systems in terms of lumens brought to the space.**

For our procedure, it was decided to conduct a few luminance measurements in relevant directions, particularly in buildings with work places. At chosen reference locations, luminance was measured in 5-6 typical sight directions simultaneously with the horizontal illuminance outside, as for daylight factor measurements. Then the luminance would be readjusted for a reference overcast sky providing 10,000 lux on the horizontal plane outdoor. The measurement points should be located on the visual task, the surrounding area of the field of view and the remote surfaces. Luminance values are divided by external illuminance values, where upon they are multiplied by 10 klx and reported in wide-angle pictures taken at the chosen reference locations. While this procedure allows us draw general comparisons between different daylighting design systems, it also enables an assessment of whether the ratio of the task background luminance to the adjacent surrounding luminance lies between 0.3 and 3, and whether the ratio of the task background luminance to the remote surface luminance lies between 0.1 and 10, as is often recommended to prevent disability glare and transient adaptation problems especially at work stations [5]. There are, however, three major drawbacks to this procedure:

1) it may be difficult to locate the surfaces which have the highest (or lowest) luminance in the field of view
2) assuming that these surfaces have been located, it may be impossible to correctly measure them with the luminance metre
3) it may also be difficult, especially for remote surfaces, to determine exactly whether the selected surface causes problems or whether it is necessary for visual interest and distant eye focus. It is indeed recommended to provide in a luminous environment small visual areas which exceed the luminance-ratio recommendations [5].

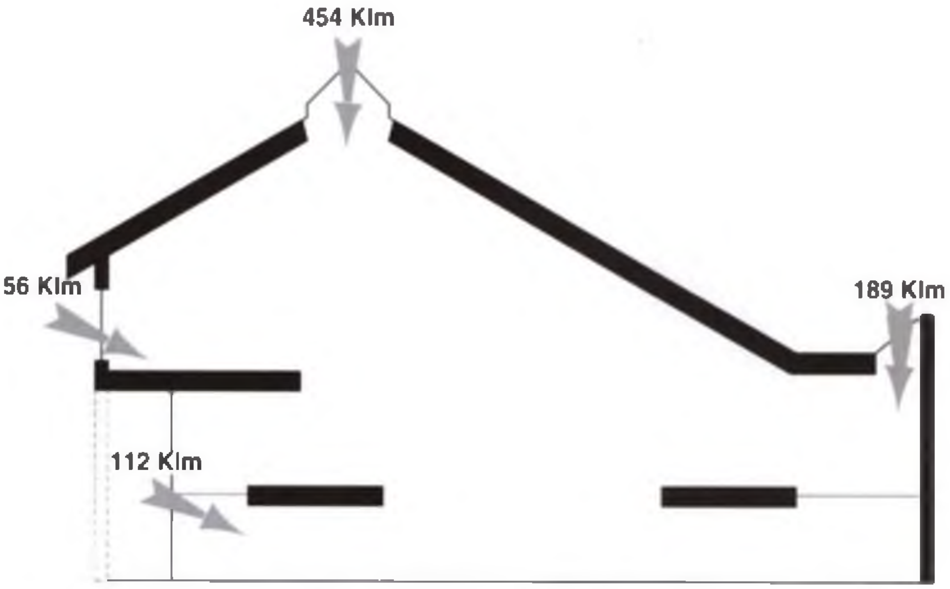
Vertical illuminance measurements are performed to assess the homogeneity or non-homogeneity of the luminances distribution in the field of view of an observer. They lead to the rating of the ability of a daylighting system to attenuate glare. The measurements are conducted under standard overcast conditions, and adjusted for a reference outdoor illuminance of 10,000 lux.

Veiling reflections are disturbing light reflections on a screen, a table, a painting due to the specular nature of its surface. The origin of the veiling reflection is identified in installing a mirror on the medium displaying the light source.

Sunlight penetration

There are some measurements or visual assessments which can be performed objectively under sunny conditions.

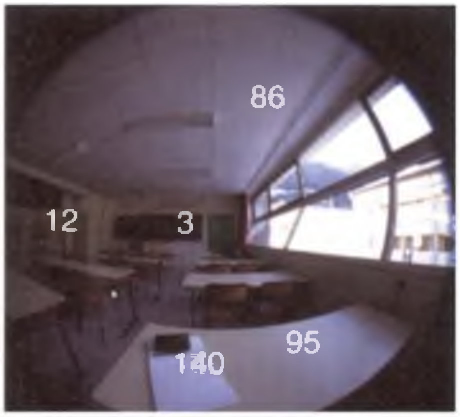
Pictures and measurements conducted under sunny conditions with and without shading show the attenuation of light due to the sunshading system: sun patches may still exist even if attenuated, or awnings may become a



∆ Values of fluxe in lumens allow a quick comparison with the theoretical number of lamps or luminaires providing an equivalent light flux. The typical performance index used for this comparison is 60lm/W corresponding to modern fluorescent or metal halide sources in efficient luminaires (values shown for an overcast sky leading to a horizontal illuminance of 10,000 lux).

▷ Luminance measurement from an observer's point of view allows the determination of excessive contrasts. For instance, luminance values larger than 10 times the luminance of the task will appear as sources of disability glare and would lead to transient adaptation problems. If the luminance surrounding the task is below 10% of the task luminance, eye strain may also be caused, since the task itself will become a source of glare.

▷ A fish-eye lens is best suited to display all elements in the field of vision.



Δ Assessment of hemispherical - hemispherical transmittance of diffusing awnings. No direct sun beams should hit the window pane - overcast sky conditions prefered.

Δ Sequences of pictures of sunlight penetration at referenced dates such as solstices and equinoxes showing the response of the architecture or the daylighting system to incoming sunlight.

glare source if they are both brightly coloured and diffusing. It is suggest that recording and observation should be done for equinoxes and solstices.

Sequences of pictures may show the varying patterns associated with the movement of sun patches in the interior.

▷ Veiling reflections on glossy surfaces are identified using a mirror surface. It shows the image of the disturbing light source. If no light source is visible in the mirror, it shows that it is located in such a position that no veiling reflections are generated.

Conclusion

This procedure has been tested and used for 60 buildings throughout Europe. It has required cross-checking of the calibration of the instruments, and training sessions. Regular discussions at meetings between particpants occured during the three years of the programme. Further details regarding the procedure, the results, and the equipment will be found in [9].

Using simple measuring equipment was a real challenge undertaken by the participants of 'Daylight Europe'. The procedure described in this section was successfully tested in a pilot study and is currently being applied all over Europe. A companion volume to this book dealing with daylighting design guidelines has also been prepared within the Daylight Europe project [10].

Acknowledgements

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[10]Nick Baker, Editor Daylighting Design Guidelines, James and James Science Publishers Ltd, London, 1999.

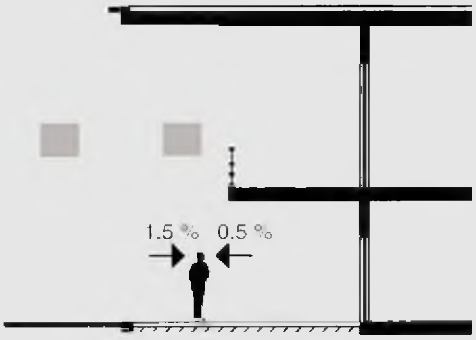
Daylighting systems used

		Country	Page	Glazed roof	Roof monitors	Translucent ceiling / floor	Atrium / courtyard	Glazed street	Glazed wall facade	Windows	Clerestories	Light-shelves	Prismatic devices / optical	Secondary daylighting	Passive sunlight control	Active sunlight control	View versus glare	Video Display Units (VDU's)	Bright Indoor finishes	Colouring effects
Glazed Streets	SAS Headquarters	SWE	29	•				•	•					•					•	
	St Hubert Galleries	BEL	33	•				•						•						
	Galleria V. Emmanuele II	ITA	37	•				•						•						
Transportation buildings	Stansted Airport	GBR	41		•				•						•			•	•	
	Waterloo International Terminal	GBR	45	•				•	•									•		
Churches	Saint Jean Cathedral	FRA	51							•	•									•
	Chapel Notre Dame du Haut	FRA	55							•	•				•				•	•
	Baroque Church	DEU	59							•	•								•	
	Sainte-Marie de la Tourette Convent	FRA	63		•						•				•					•
	Pantheon Dome	ITA	67		•										•					
Museums	Neue Staatsgalerie	DEU	73	•		•								•	•	•			•	
	Wallraf-Richartz-Museum	DEU	77		•										•	•			•	
	Byzantine Museum	GRC	81		•						•				•				•	
	Musée de Grenoble	FRA	85		•										•				•	•
	Trapholt Art Museum	DNK	89		•								•		•				•	
	Waucquez Department Store	BEL	93	•		•	•							•	•					
	Modern Art Centre	PRT	99						•		•				•		•		•	
	Sir John Soane's Museum	GBR	103		•						•									
	Louvre Museum	FRA	107		•										•				•	•
Offices	Tractebel Building	BEL	113						•							•	•	•	•	
	Sukkertoppen	DNK	117	•				•	•					•			•	•		
	Trundholm Town Hall	DNK	121				•		•					•	•		•	•		
	Domino Haus	DEU	125	•			•		•					•		•	•	•		
	Architects Office	GRC	129							•	•							•	•	
	Beresford Court	IRL	133	•			•		•					•				•		•
	EOS Building	CHE	137								•	•		•	•		•	•		
	Reiterstrasse Building	CHE	141		•		•			•								•		
	UAP Insurance Building	CHE	145								•					•		•		
	Victoria Quay	GBR	147				•			•	•			•	•		•	•		
	National Observatory of Athens	GRC	151								•						•	•		
	Statoil Research Centre	NOR	153								•				•			•		
	Kristallen office building	SWE	157	•			•			•				•			•	•	•	
	CNA-SUVA Building	CHE	161								•		•		•			•		
	Gothenburg Law Courts Annex	SWE	165		•		•			•				•				•		
	LNEC Main Building	PRT	169							•	•				•	•	•	•		
	Irish Energy Centre	IRL	173				•			•	•					•		•		
Educational buildings	Dragvoll University Centre	NOR	179	•				•		•				•	•	•				
	Pharmacy Faculty	PRT	183		•		•			•				•	•	•				
	Queen's Building	GBR	191								•	•			•	•	•	•		
	Anatomy Lecture Theatre	SWE	197								•									
	Collège de la Terre Sainte	CHE	201		•		•							•		•				
	Collège La Vanoise	FRA	205		•		•					•		•	•	•			•	•
	Berthold Brecht School	DEU	211		•		•							•		•			•	
	Training Centre-Agricultural Bank	GRC	215		•						•	•		•	•	•				
	Teachers Training College	PRT	219		•						•			•		•			•	
Libraries	Stockholm Public Library	SWE	225								•				•					
	Darwin College Library	GBR	229							•	•					•	•	•		
	Bibliothèque Nationale de France	FRA	233		•					•	•				•					
	Trinity College Library	GBR	237								•							•		
	APU Learning Resource Centre	GBR	241	•			•				•	•			•			•		
Houses	La Roche House	FRA	247							•	•								•	
	Architect's House	GRC	251		•		•			•	•			•						•
	Casa Serra	ESP	255		•					•	•			•						
	Hawkes' House	GBR	259							•	•			•						
Demonstration projects	German Pavilion	ESP	265						•						•				•	
	Conphoebus Office Building	ITA	269								•	•			•	•				
	Brundtland Centre	DNK	275		•		•		•			•		•		•		•		
Others	The Palm House	GBR	281	•			•		•											
	Fagus-Werk	DEU	285		•		•		•							•				
	Paustian House	DNK	289		•		•			•	•			•					•	

What will you get in this book ?

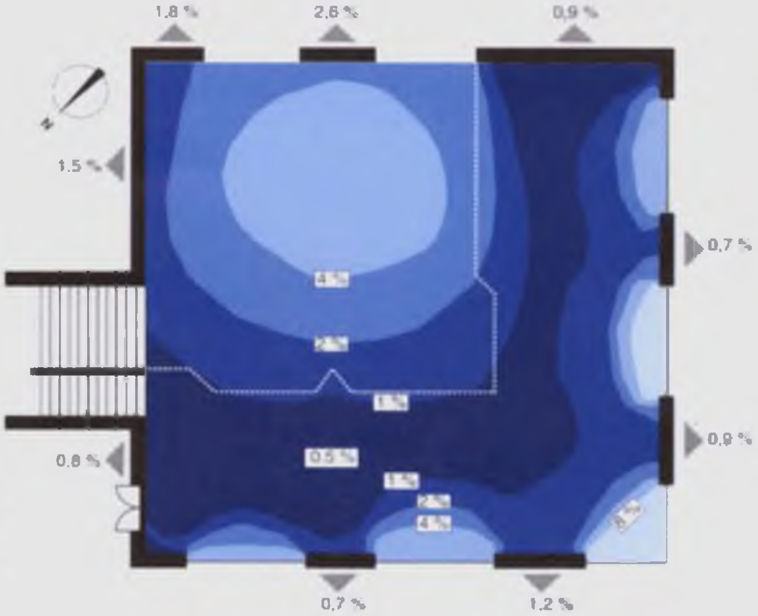
Daylight factor variations.

Expressed in % of the outdoor horizontal illuminance simultaneously measured for an unobstructed sky. They have been measured for specific overcast conditions (see section on the monitoring procedure for more details). Under overcast conditions the indoor illuminances are proportional to the out-door horizontal illuminance: when the outdoor illuminance is doubled, all indoor illuminances are also doubled. The daylight factor is a quantity which describes best the ability of a building to let natural light in. It can be used to assess the fraction of the operating time during which given illuminance thresholds are exceeded.

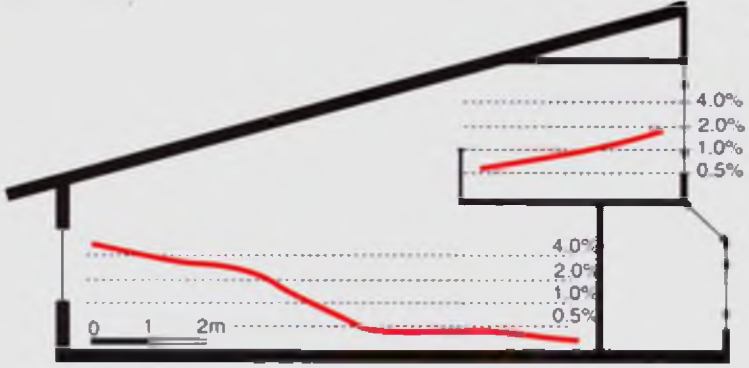


◁ Vertical daylight factors are measured either to assess the corresponding average luminance in the field of view (L = E/p), or to assess the amount of light penetrating vertical windows.

▽ Daylight factors variations displayed in plan, using iso-DF lines. This presentation gives an indication of the areas concerned by daylight penetration, or its absence.

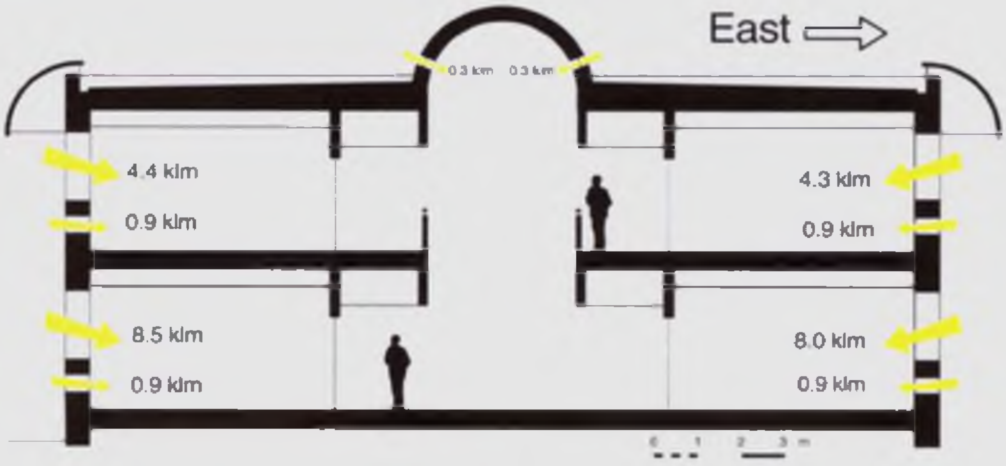


▽ Daylight factors variations displayed along a cross-section. Note that the vertical scale is logarithmic, since such is the perception by the human eye.

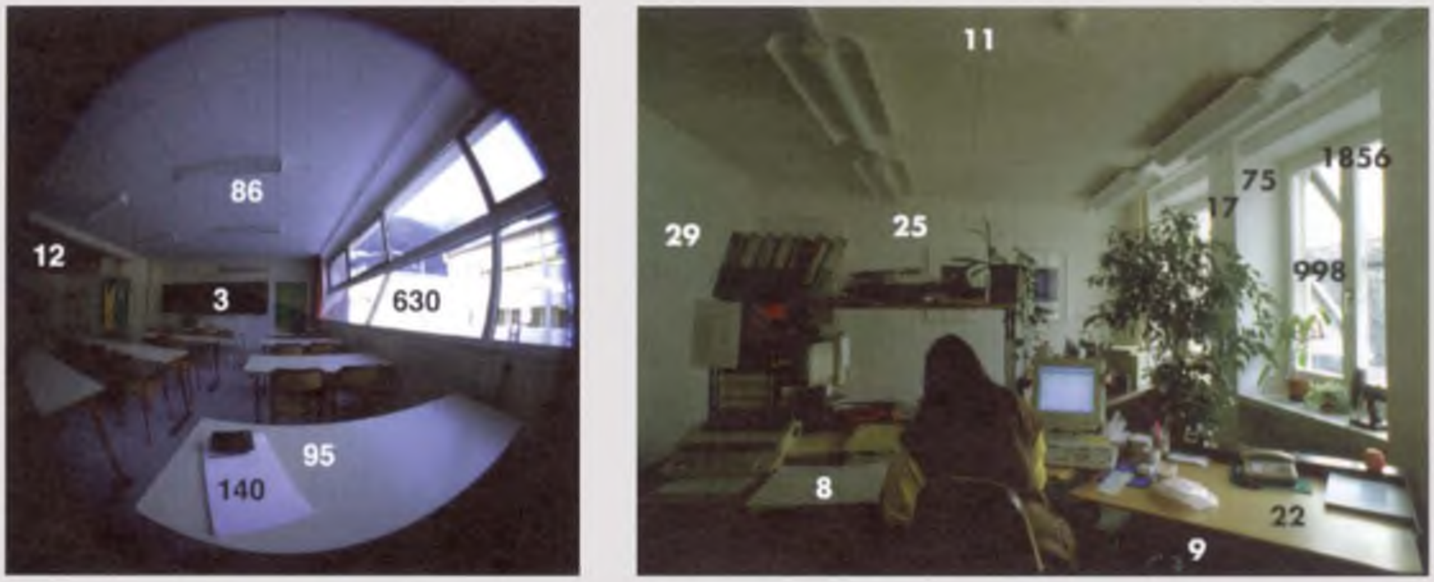


Assessment of luminous fluxes

A luminous flux is expressed in lumen (lm). For instance, a 60 W incandescent light bulb produces around 900 lm, a 36 W T8 fluorescent tube around 3,000 lm. We present sometimes the luminous fluxes penetrating windows for one standard overcast sky condition, the one which would lead to an outdoor horizontal illuminance in the absence of obstructions of 10,000 lux. The value of the luminous flux (lm) crossing a surface S is the product of the value of its area (m^2) by the illuminance (lux) measured in its plan.



△ Comparison of luminous fluxes penetrating a room through various openings under a standard overcast sky condition providing an outdoor illuminance of 10,000 lux. It could be compared with fluxes supplied by luminaires equipped with fluorescent tubes. A luminaire equipped with a 36W T8 tube produces around 1.5 Klm.



Δ Comparison of luminances of windows and indoor surfaces for assessment of glare. Left: with fish-eye lens, right with 20mm lens.

Luminance distribution (cd/m^2)

The luminance is a quantity which can be measured (with a luminance meter) to describe the 'brightness' of a surface, such as a wall, a desk surface or a transluscent window. It is sometimes useful to measure the luminances of surfaces in various directions in the field of view of an observer, to characterize the homogeneity or non-homogeneity of the luminances. It should be remembered that the sensitivity of the eye to light is logarithmic. Typical luminances of surfaces in a building are in the range of 1 to 100 cd/m^2, 100 to 1,000 cd/m^2 for surfaces of bright appearances: clear walls under daylight, lampshades when lamps are turned on or dark skies seen from the interior of a building. In the range of 1,000 to 10,000 cd/m^2 are most light sources (sky, reflections of sunbeams on construction elements or clear indoor finishes and luminaires (unless 'low luminance luminaires'). In this range of luminances, the sources are often glary if they are in the field of vision. The filament of an incandescent light bulb, or the sun, reach much higher luminances, above 100,000 cd/m^2.

Materials properties assessed on site

	Colour	Hemispherical-hemispherical reflectance
Floor	light grey/white	51%
Ceiling (concrete)	dark grey	19%
Wall	white	84%
	Normal-normal transmittance	Hemispherical-hemispherical transmittance
Double glazing	71%	78%

▷ Bright finishes lead to substantial increase of illuminances particularly in areas far away from apertures.

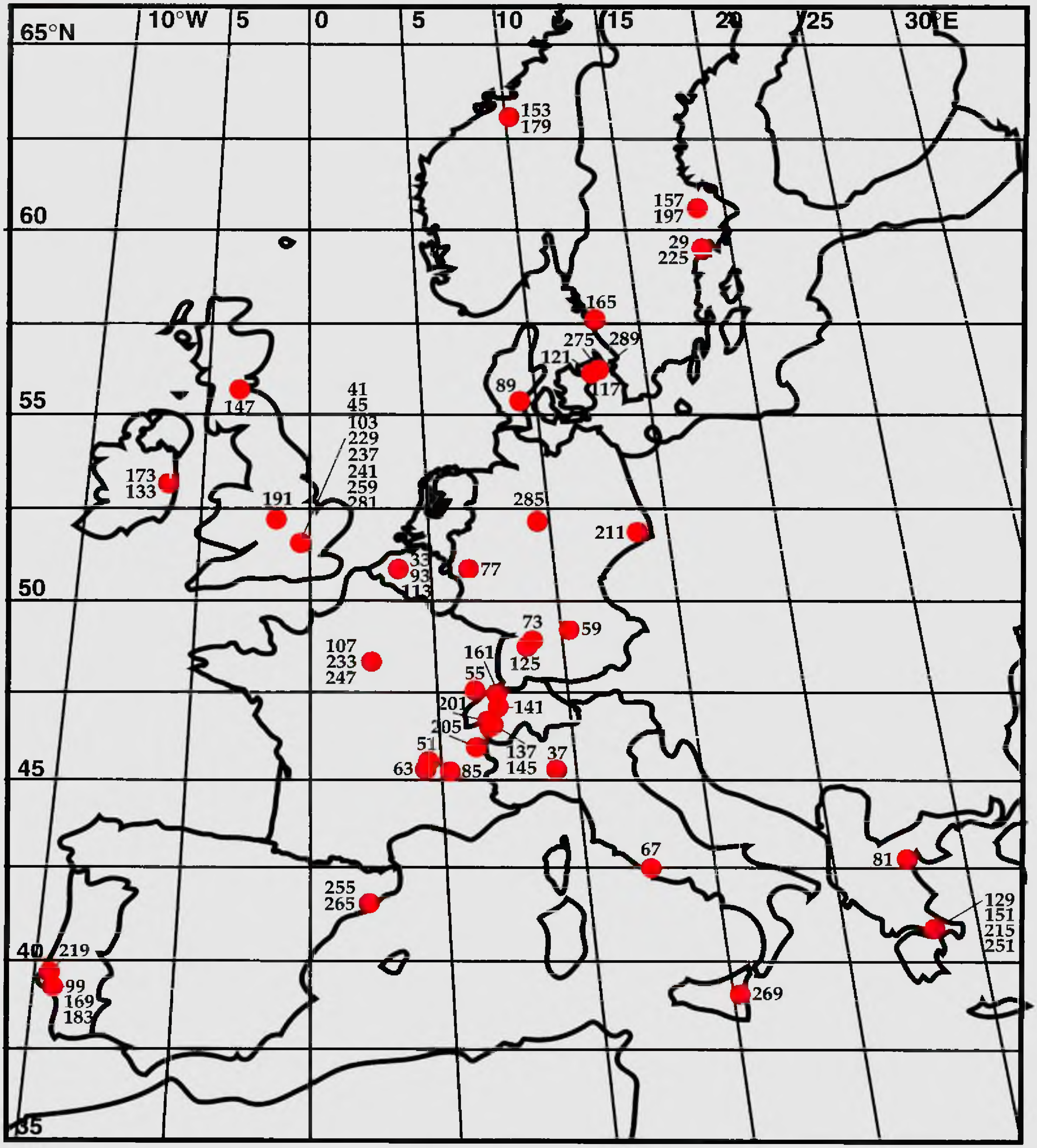
▽ Bookshelves and walls made of wood absorb daylight penetration.

Material properties

Indoor finishes and glazing materials contribute to final illuminance levels in a building. In areas far away from the apertures, indoor finishes may be the major contributors to the amount of light available. The transmittance of glazing or shading has a direct effect on the amount of light penetrating a building. On-site characterization of material's optical properties has been conducted for each case study. The detail of the procedure is described in the section 'Monitoring procedure'.

Map of Europe

● 147 *Number indicates page of case study*



Buildings monitored by each organization

Team	Case study building
BBRI	Tractebel Building, Brussels
	Waucquez Department Store, Brussels
	St Hubert Galleries, Brussels
BRE	Queen's Building, De Montfort Univ., Leicester
	Waterloo International Terminal, London
Camb	Stansted Airport, Stansted, Essex
	The Palm House, Royal Botanic Gardens, Kew
	Darwin College Library, Cambridge
	Trinity College Library, Cambridge
	APU Learning Resource Centre, Chelmsford
	Hawkes' House, Cambridge
	Sir John Soane's Museum, London
CONPH	Conphoebus Office Building, Catania
	Pantheon Dome, Rome
	Galleria V. Emanuele II, Milan
CUT	Anatomy Lecture Theatre, Uppsala
	Stockholm Public Library, Stockholm
	SAS Head Quarters, Stockholm
	Kristallen office building, Uppsala
	Göteborg Law Courts Annex, Göteborg
EFI	Dragvoll University Centre, Trondheim
	Statoil Research Centre, Trondheim
ENTPE	Bibliothèque Nationale de France, Paris
	Musèe of Grenoble, Grenoble
	German Pavilion, Barcelona
	Saint-Jean Cathedral, Lyons
	Chapel Notre Dame du Haut, Ronchamp
	Sainte Marie de la Tourette Convent, Eveux
	La Roche House, Paris
	Collège La Vanoise, Modane
	Louvre Museum, Paris
EPFL/LESO	EOS Building, Lausanne
	Reiterstrasse Building, Berne
	UAP Insurance Building, Lausanne
	CNA - SUVA Building, Basle
	Collège de la Terre Sainte, Coppet
ESB/SBI	Brundtland Centre, Toftlund, Denmark
ESRU/EDAS	Victoria Quay, The Scottish Office, Edinburgh

Team	Case study building
FIB	Fagus-Werk, Alfeld an der Leine
	Neue Staatsgalerie, Stuttgart
	Wallraf-Richartz Museum, Cologne
	Domino Haus, Reutlinger
	Baroque Church, Neresheim Monastery
	Berthold Brecht School, Dresden
LNEC	Pharmacy Faculty, Lisbon
	Modern Art Centre, Lisbon
	Teacher's Training College, Setbal
	LNEC Main Building, Lisbon
SBI	Trapholt Art Museum, Kolding
	Sukkertoppen, Valby
	Trundholm Town Hall, Trundholm
	Paustian House, Copenhagen
U. of Athens	Byzantine Museum,Thessaloniki
	Architects Office, Polydroso, Athens
	National Observatory of Athens, Athens
	Architect's House, Kifissia, Athens
	Agricultural Bank of Greece, Athens
UCD	Beresford Court, Dublin
	Irish Energy Centre, Dublin
UPC	Casa Serra, Barcelona

BBRI = Belgian Building Research Institute
BRE = Building Research Establishment
Camb = University of Cambridge
CONPH = Conphoebus
CUT = Chalmers University of Technology
EFI = Norwegian Electrical Institute

ENTPE = Ecole Nationale des Travaux Publics de l'Etat
EPFL = Ecole Polytechnique Fédérale de Lausanne
LESO = Laboratoire d'Energie Solaire et de physique du bâtiment
ESB = Esbensen, Consulting Engineers
ESRU = Energy Systems Research Unit

EDAS = Energy Design Advisory Service
SBI = Danish Building Research Institute
FIB = Fraunhofer-Institute für Bauphysik
LNEC = Laboratório Nacional de Engenharia Civil
UCD = University College Dublin
UPC = Universitat Politècnica de Catalunya