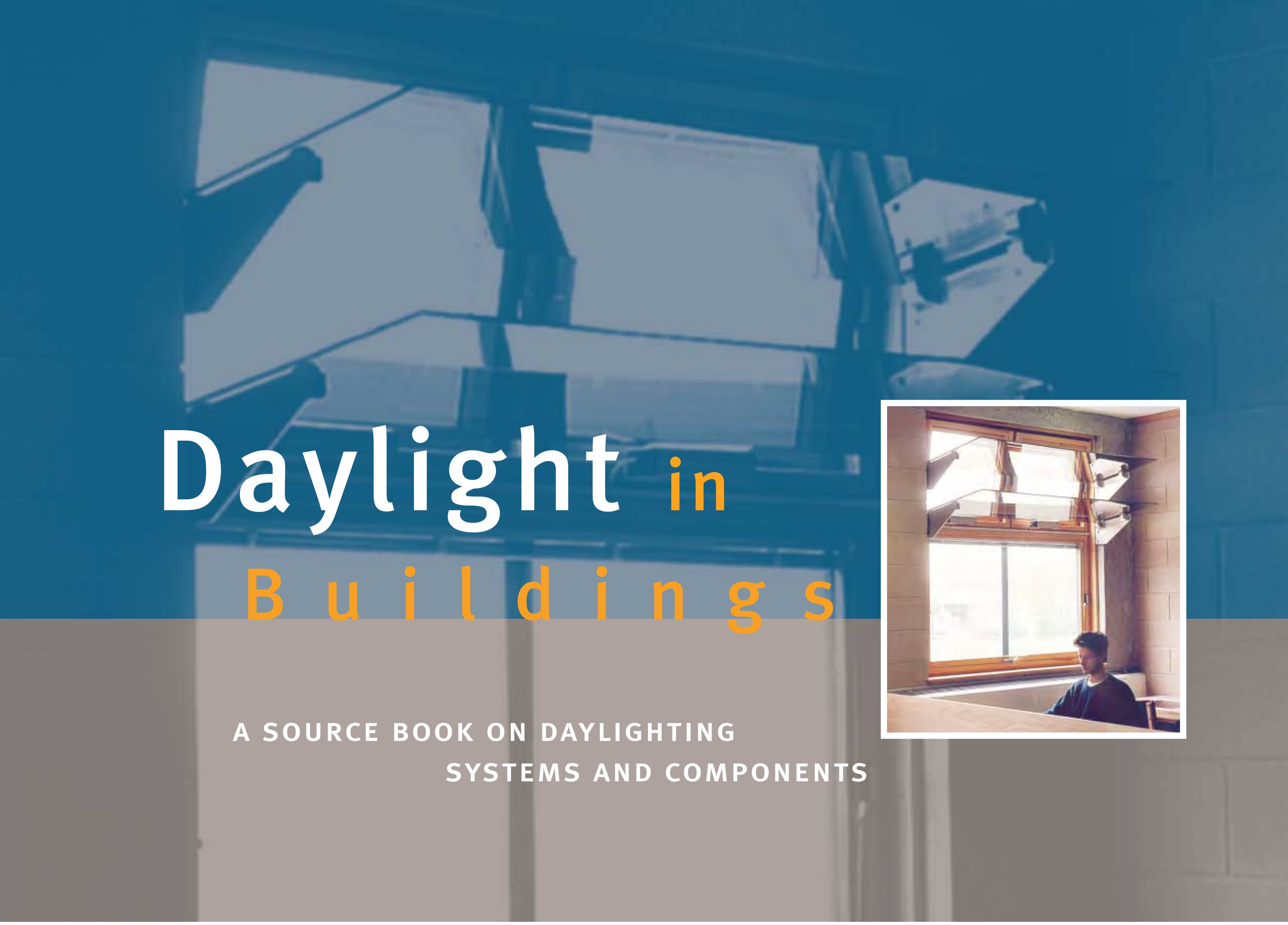

Daylight in Buildings

A SOURCE BOOK ON DAYLIGHTING SYSTEMS AND COMPONENTS

International Energy Agency
Energy Conservation in Buildings and Community Systems Programme

International Energy Agency
Solar Heating & Cooling Programme

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A report of IEA SHC Task 21/ ECBCS Annex 29, July 2000

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By Nancy Ruck with Øyvind Aschehoug, Sirri Aydinli, Jens Christoffersen, Gilles Courret, Ian Edmonds, Roman Jakobiak, Martin Kischkoweit-Lopin, Martin Klinger, Eleanor Lee, Laurent Michel, Jean-Louis Scartezzini, and Stephen Selkowitz

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Information on how to obtain additional copies of this book and other products referred to in this book can be obtained from the Internet site at http://www.iea-shc.org or contact the IEA SHC Executive Secretary, Pamela Murphy Kunz, Morse Associates Inc., 1808 Corcoran Street, NW, Washington, DC 20009, USA, Telephone: +1/202/483-2393, Fax: +1/202/265-2248, E-mail: pmurphy@MorseAssociatesInc.com.

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Preface

For some time the building industry has been in need of a comprehensive reference that describes new and innovative technologies for utilizing daylight in buildings and assesses the performance of these systems. This information is of particular benefit to building design practitioners, lighting engineers, product manufacturers, building owners, and property managers. This book is the result of a coordinated international effort to gather the most up-to-date information available about the application and evaluation of advanced daylighting systems to enhance daylighting in non-residential buildings. Although the text emphasizes the performance of daylighting systems, it also includes a survey of architectural solutions, which addresses both conventional and innovative systems as well as their integration in building design. Innovative daylighting systems are assessed according to their energy savings potential, visual characteristics, and control of solar radiation.

This book is based on work carried out by the Solar Heating and Cooling (SHC) Programme of the International Energy Agency (IEA) under IEA's Task 21, Energy Conservation in Buildings & Community Systems, Programme Annex 29, Subtask A: Performance Evaluation of Daylighting Systems. Subtask A's work programme was coordinated with research carried out by the other IEA SHC Task 21 Subtasks. These included Subtask B: Daylight Responsive Controls, Subtask C: Daylighting Design Tools, and Subtask D: Case Studies.

The IEA was established in 1974 as an autonomous agency within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an international energy programme. A fundamental aim of the IEA is to foster cooperation among 25 of the OECD's 29 member countries and the Commission of the European Community in order to increase energy security and reduce greenhouse emissions. The IEA sponsors research and development in a number of areas related to energy. Within the program of Energy Conservation in Buildings and Community Systems (ECBS), the IEA is carrying out various activities to predict more accurately the energy use of buildings. These activities include comparison of existing computer programmes, monitoring of buildings, comparison of calculation methods, and studies of air quality and occupancy.

The IEA Solar Heating and Cooling Programme (IEA SHC) was initiated in 1977 as one of the first collaborative R&D agreements established by the IEA. The participating countries carry out a variety of projects intended to advance active solar, passive solar, and solar photovoltaic technologies for building applications. The main objectives of the IEA SHC Programme Task 21 and ECBS Annex 29: Daylight in Buildings are to advance daylighting technologies and to promote daylight-conscious building design.

Denmark is the Operating Agent for IEA SHC Task 21. The participating countries are:

Australia	France	Norway
Austria	Germany	Sweden
Belgium	Italy	Switzerland
Canada	The Netherlands	United Kingdom
Denmark	New Zealand	United States
Finland		

Executive Summary

This source book gives a comprehensive overview of innovative daylighting systems, the performance parameters by which they are judged, and an evaluation of their energy savings potential and user acceptance. The book has been written to overcome a lack of evidence of the advantages of daylighting in buildings and a lack of knowledge regarding the performance of innovative daylighting systems in buildings in various climatic zones around the world. The information presented here is intended to be used in the earliest stages of the building design process.

Innovative daylighting systems are designed to redirect sunlight or skylight to areas where it is required, without glare. These systems use optical devices that initiate reflection, refraction, and/or use the total internal reflection of sunlight and skylight. Advanced daylighting systems can be designed to actively track the sun or passively control the direction of sunlight and skylight. The systems included in this book have been generally limited to passive devices.

This book describes in detail the wide range of innovative daylighting systems available worldwide today, including information on their components, principles on which they are based, applications for which they are appropriate, production, control, costs and energy savings, maintenance, examples of use, and performance assessments.

The performance assessment results were obtained by monitoring the system using physical models under sky simulators, or full-scale test rooms or actual buildings under real sky conditions. The types of innovative systems selected for testing are currently available in the marketplace or have been recently developed in laboratories. The results summarized here demonstrate that, if selected according to daylight climate and integrated appropriately with electric lighting and shading controls, the majority of these systems can enhance daylight in building interiors and thereby promote energy savings. It should be noted, however, that performance in actual buildings will differ from test room results.

Daylighting strategies are seldom considered in the earliest stages of a building design. This is, in part, a result of the absence of simple tools that can predict the performance of advanced daylighting strategies. This source book provides information on simple design tools that can predict performance and can be used by non-experts. The book also includes an introduction to the appropriate use of shading and electric lighting controls in order to promote energy savings.

Barriers to the use of advanced daylighting systems still exist, particularly in the transition from research to building practice. There is much to do in research and development as well as in practical application. Two key areas that need further research are the human dimension of the daylighting equation and the integration of daylighting systems in buildings to arrive at low energy solutions that meet human needs. New research in these two areas will be carried out under the auspices of Task 31 (see http://www.iea-shc.org). Nonetheless, the information presented in this book demonstrates that the use of advanced daylighting technologies can close the gap between potential benefits and actual achievements in building practice.

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Introduction 1.

In a world newly concerned about carbon emissions, global warming, and sustainable design, the planned use of natural light in non-residential buildings has become an important strategy to improve energy efficiency by minimizing lighting, heating, and cooling loads. The introduction of innovative, advanced daylighting strategies and systems can considerably reduce a building's electricity consumption and also significantly improve the quality of light in an indoor environment.

Importance of Daylight 1.1.

Evidence that daylight is desirable can be found in research as well as in observations of human behaviour and the arrangement of office space. Windows that admit daylight in buildings are important for the view and connection they provide with the outdoors. Daylight is also important for its quality, spectral composition, and variability. A review of peoples' reactions to indoor environments suggests that daylight is desired because it fulfils two very basic human requirements: to be able to see both a task and the space well, and to experience some environmental stimulation [Boyce 1998]. Working long-term in electric lighting is believed to be deleterious to health; working by daylight is believed to result in less stress and discomfort.

Daylight provides high illuminance and permits excellent colour discrimination and colour rendering. These two properties mean that daylight provides the condition for good vision. However, daylight can also produce uncomfortable solar glare and very high-luminance reflections on display screens, both of which interfere with good vision. Thus, the effect of daylight on the performance of tasks depends on how the daylight is delivered. All of these factors need to be considered in daylighting design for buildings.

Introduction 1.

In a world newly concerned about carbon emissions, global warming, and sustainable design, the planned use of natural light in non-residential buildings has become an important strategy to improve energy efficiency by minimizing lighting, heating, and cooling loads. The introduction of innovative, advanced daylighting strategies and systems can considerably reduce a building's electricity consumption and also significantly improve the quality of light in an indoor environment.

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Daylight strategies and systems have not always lived up to their promise as energy-efficiency strategies that enhance occupant comfort and performance. One reason is the lack of appropriate, low-cost, high-performance daylighting systems, simple tools to predict the performance of these advanced daylight strategies, and techniques to integrate daylight planning into the building design process.

Common barriers that have hindered the integration of daylight in buildings in the past are:

- Lack of knowledge regarding the performance of advanced daylighting systems and lighting control strategies,
- Lack of appropriate, user-friendly daylighting design tools, and
- Lack of evidence of the advantages of daylighting in buildings.

The barriers, identified at the beginning of the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Task 21: Daylighting of Buildings, were resolved by coordinated tasks that covered three broad areas: 1) assessment of the performance of systems and lighting control strategies, 2) development of integrated design tools, and 3) case studies to provide evidence of daylight performance in actual buildings.

To remedy the lack of information about the performance of advanced daylighting systems, specified systems were assessed using standard monitoring procedures in test rooms in actual buildings, and using scale models under artificial skies. Parameters to measure both quantity (e.g., illuminance and luminance) and quality (e.g., visual comfort and acceptability) of daylight were determined prior to testing. This source book describes the systems tested, the results of the assessments, and the appropriate application of the results. On the whole, the study's results indicate that, when appropriately located, the majority of systems tested improved daylighting performance in perimeter building zones relative to the performance of conventional windows.

The daylighting of buildings is essentially a systems integration challenge for a multidisciplinary design team, involving building siting and orientation and the design optimization of fenestration, lighting and control systems. A survey of existing architectural solutions is included in this source book as a CD-ROM, which shows the integration of systems in building design and includes conventional as well as advanced systems with some indication of the problems that may result from wrong design decisions.

This source book is aimed at building design practitioners, lighting engineers, and product manufacturers. It should be used in the earliest stages of the design process because the initial conception of the building envelope, the location of openings and their size and shape, and the systems for solar and daylighting control are all crucial to daylighting design.

Objective and Scope of This Source Book 1.2.

The objective of this source book is to promote daylighting-conscious building design. Selected advanced daylighting systems are described in detail, as well as ways in which these daylighting systems can be integrated in the overall building design process. The reader is also introduced to shading and electric lighting control systems and design tools.

Daylighting planning needs to be considered from a building's conceptual design phase through the selection of systems and their application. **Chapter 2** outlines initial-stage planning parameters, such as basic decisions on shape and window size, as well as specific functional objectives of the daylighting strategies. Application of daylight strategies for windows and rooms is also discussed, along with advice on how to choose systems for specific sky types.

Innovative daylighting systems work by redirecting incoming sunlight and/or skylight to areas where it is required, and, at the same time, controlling glare. These systems are particularly appropriate where an interior space is too deep for conventional windows to provide adequately uniform lighting or where there are external obstructions. Systems that control glare as well as the quantity of daylight entering a space may also be a good solution for shallow rooms; thus these systems also merit consideration as innovative.

A daylighting strategy can be characterized by its performance parameters. These parameters include quantity of light, distribution of light and glare, cost, and energy use. **Chapter 3** defines these parameters and discusses each in a worldwide context. Because daylight offsets the need for electric lighting energy, issues that influence energy savings, such as design and commissioning of lighting control systems, are also addressed.

Chapter 4 focuses on selected innovative daylighting systems that can be applied in new and existing buildings that have a high aggregate electricity savings potential (such as offices, schools, and other commercial and institutional buildings). The systems are classified according to whether they have been designed as shading or non-shading systems. An overview is given in Chapter 4.2 of all the described systems using a matrix format. The detailed systems descriptions include light shelves, louvers and blinds, prismatic panels and films, laser-cut panels, light-guiding materials, holographic optical elements, and anidolic systems, which are systems with reflectors based on non-imaging optics. Detailed information on each system follows the matrix. This information includes, for each system, a technical description, factors related to its application, methods of control, cost and potential energy savings, examples of use, and, in most cases, measured results. Potential energy savings are expressed in terms of daylight enhancement. Chapter 4 does not include glazing systems that selectively attenuate light without redirecting it, e.g., electrochromic or angular selective glazings.

Proper integration of daylight with electric light ensures that energy is efficiently used and that glare is controlled. This integration can only be achieved through a carefully coordinated design of the daylighting and electric lighting systems. An introduction and adjunct to IEA SHC Task 21's Application Guide on lighting controls is provided in **Chapter 5**. This chapter includes general information on the nature of daylight and electric light and their integration, the application of shading and electric lighting control systems with daylighting systems, and the benefits from controlling daylight and electric light input.

Chapter 6 summarises state-of-the-art of daylighting design tools with emphasis on tools that address the advanced daylighting systems that are the focus of this source book. Daylighting design is a creative process. Because it aims to generate appropriate architectural and/or technical solutions while reducing energy consumption of buildings, it is both an art and a science. Qualitative information and visual feedback on a given daylighting concept are as important for a building designer as quantitative figures. Because there are so many parameters to consider in daylighting design, design tools play a significant role in the decision-making process and must therefore fit the most significant phases of architectural projects. These tools provide support for designers as they make a sequence of decisions that leads from the formulation of daylighting concepts to the final implementation of daylighting strategies in real buildings.

Chapter 7 summarises the results of this work and indicates future work required to ensure that daylighting becomes the preferred option for building design in the 21st century. **Appendices** to this book include a glossary, chapter references, an overview of the monitoring procedures used in our daylighting system evaluations, the measurement methods used to determine each system's physical characteristics for formulating computer software algorithms, a description of the test room facilities used, and a list of product manufacturers.

This is the only book currently available that provides this essential information about advanced daylighting systems. Much still remains to be done in the areas of human response and acceptance of daylighting systems, which is a critical element in any daylighting design, and in the integration of these new advanced daylighting systems with the hardware and software elements in a design. More research on these issues is currently being proposed within the IEA SHC framework.

Other IEA SHC Task 21 Publications 1.3.

In addition to this source book, other publications resulting from IEA SHC Task 21's work include:

- **The Application Guide for Daylight Responsive Lighting Control Systems** is in two parts. The first part addresses general design considerations involving electric lighting and shading controls, installation procedures, and the prediction of energy savings and costs. The second part consists of the monitoring procedures used and the results of performance evaluations of lighting controls installed in test rooms.
- **Survey: Simple Design Tools** lists various types of design tools, including simple computer tools, with different fields of application.
- **ADELINE 3.0** is a software package that brings together several programme modules required for an integrated lighting design.
- **LESO-DIAL**, a programme that gives architects relevant information regarding the use of daylight during the very first stage of the design process. (This software includes about 100 terms in a daylighting and lighting vocabulary.)
- **Daylight in Buildings: 15 Case Studies from Around the World**, contains 15 case studies representing a range of building types worldwide. All were constructed or refurbished after 1990. The case studies were monitored according to standard procedures and give evidence that daylighting strategies save energy. Post-occupancy evaluations were performed for a small set of selected buildings in this group to determine occupant reactions.

How to Use This Source Book 1.4.

This book is not intended to be read page by page from beginning to end. Readers are invited to go directly to the sections that address their interests. For example, readers seeking general knowledge about the daylighting of buildings should go to Chapter 2. Specific knowledge about advanced daylighting systems can be found in Chapter 4.

Daylight in Building Design 2.

For centuries, daylight was the only efficient source of light available. Architecture was dominated by the goal of spanning wide spaces and creating openings large enough to distribute daylight to building interiors. Efficient artificial light sources and fully glazed facades have liberated designers from these constraints of the past. Advanced daylighting systems and control strategies are another step forward in providing daylit, user-friendly, energy-efficient building environments. These systems need to be integrated into a building's overall architectural strategy and incorporated into the design process from its earliest stages. This chapter outlines the design considerations associated with enhancing a building's daylight utilization while achieving maximum energy efficiency and user acceptance.

Planning for Daylight at the Conceptual Design Phase 2.1.

building	room	window	daylighting systems
daylight availability	relation to adjacent spaces	design of facades and windows	function of system(s)
latitude	autonomous	single design	multiple functions
sun shine probability	borrowing light	multiple design	glare, shading, redirection
temperature	giving light	division within windows	glare, solar shading
...	interchanging light	division between windows	glare, redirection
obstruction	fenestration		shading, redirection
building design scheme	unilateral, sidelight		single function
beam shaped	unilateral, top-light		protection from glare
courtyard/atria	multilateral, sidelight		solar shading
block	multilateral, sidelight and top-light		redirection
nucleus	proportion		other function
...	height to depth, ratio		

Table 2-1:

The process of designing for daylight in buildings

Daylighting strategies and architectural design strategies are inseparable. Daylight not only replaces artificial lighting, reducing lighting energy use, but also influences both heating and cooling loads. Planning for daylight therefore involves integrating the perspectives and requirements of various specialities and professionals. Daylighting design starts with the selection of a building site and continues as long as the building is occupied.

Daylighting planning has different objectives at each stage of building design:

- **Conceptual Design:** As the building scheme is being created, daylighting design influences and/or is influenced by basic decisions about the building's shape, proportions, and apertures, as well as about the integration and the role of building systems.
- **Design Phase:** As the building design evolves, daylighting strategies must be developed for different parts of the building. The design of facades and interior finishing, and the selection and integration of systems and services (including artificial lighting), are all related to the building's daylighting plan.
- **Final/Construction Planning:** The selection of materials and products is affected by the building's daylighting strategy; final details of the daylighting scheme must be worked out when construction plans are created.
- **Commissioning and Post-Occupancy:** Once the building is constructed, lighting controls must be calibrated, and ongoing operation and maintenance of the system begins.

2.1.1. Daylight Availability

All daylighting strategies make use of the luminance distribution from the sun, sky, buildings, and ground. Daylight strategies depend on the availability of natural light, which is determined by the latitude of the building site and the conditions immediately surrounding the building, e.g., the presence of obstructions. Daylighting strategies are also affected by climate; thus, the identification of seasonal, prevailing climate conditions, particularly ambient temperatures and sunshine probability, is a basic step in daylight design. Studying both climate and daylight availability at a construction site is key to understanding the operating conditions of the building's facade. The daylighting design solution for the building should address all of these operating conditions.

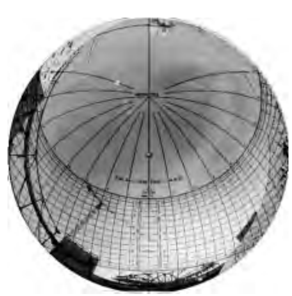


Figure 2-1: Sunpath diagram projected on a fisheye photograph of the site

There are several sources of information on daylight availability [Dumortier 1995]. For example, daylight availability data has been monitored every minute at more than 50 stations worldwide since 1991 (http://idmp.entpe.fr) and has also been monitored in the Meteosat satellite every half hour from 1996–1997 (under beta testing).

High latitudes have distinct summer and winter conditions; the seasonal variation of daylight levels is less apparent at low latitudes. At high latitudes where winter daylight levels are low, designers usually aim to maximize daylight penetration in a building; redirection of daylight into buildings from the brightest regions of the sky is an appropriate strategy at these latitudes. By contrast, in the tropics where daylight levels are high throughout the year, the design emphasis is usually on preventing overheating by restricting the amount of daylight entering the building. The obstruction of large parts of the sky, especially of areas near the zenith, and the admission of daylight only from lower parts of the sky or of indirect light reflected from the ground are useful strategies in tropical regions.

Daylight availability strongly depends not only on the latitude but also on a building's orientation; each orientation will require a different design emphasis. Study of vernacular architecture and past successful daylighting designs is a good way to understand the relationship between climate and building design.

2.1.2. The Building Site and Obstructions

At a construction site, the sky is usually obstructed to some extent by surrounding buildings and vegetation.

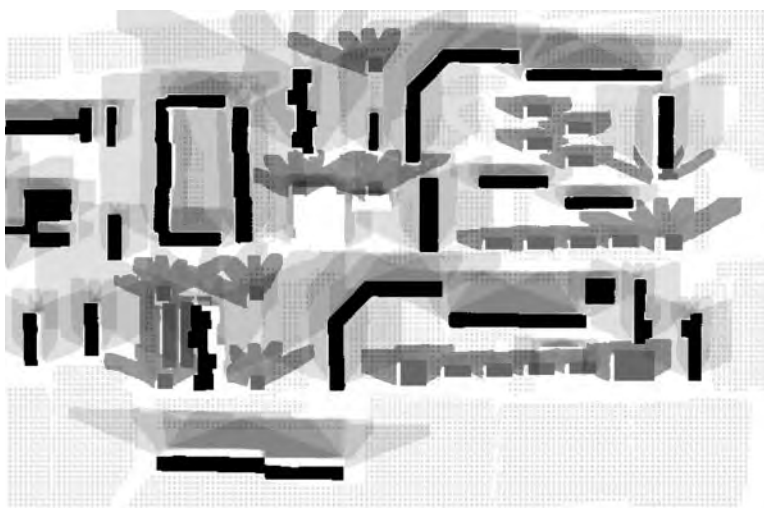


Figure 2-2: Shading study in a large-scale urban housing area in Berlin. Existing building blocks are shown in black, proposed new buildings in grey. The study was carried out with a physical model in an artificial sky. The picture shows the superposition of shadows for 08:00, 10:00, 12:00, 14:00, and 16:00 on March/September 21.

Studying the obstructions at a construction site tells a designer about the daylight potential of the building's facades and allows him or her to shape the building and to allocate floor areas with respect to daylight availability. In many cases, buildings are self-obstructing, so building design and obstruction studies become interconnected.

Local zoning regulations limit a building's design (e.g., building size, height, etc.) and the impact a new building can have on surrounding, existing buildings. The latter restrictions have their origins in fire protection, imposing minimum distances between neighbouring buildings to prevent fire from spreading. These regulations evolved into legislation to protect the right to daylight, originally drafted (as early as 1792) when powerful sources of artificial light were unknown or unavailable to the majority of the population, and the availability of daylight was essential in building interiors. In selecting daylighting strategies, a designer must take into account the degree to which the new building will create an obstruction for existing buildings, reducing their access to daylight, and/or will reflect sunlight that might cause glare at the street level or increase thermal loads in neighbouring buildings.

Zoning regulations and floor area indexes that regulate the extent of urban density also affect daylighting design. The aim of maximizing floor area in order to get the best economic return from a new building may conflict with the design goal of providing interior daylight.

Several methods and tools are available to analyse obstructions. The basic approaches are:

- plotting the "no-sky line" on the work plane of a selected space; the no-sky line divides points on the work plane that can and cannot "see" the sky [Littlefair 1991];
- examining obstructions from one specific view point by projecting the sun's course or a daylight availability chart on a representation of the building site (Figure 2-1);
- computing the amount of incident daylight and radiation for specific locations and orientations on the site; or
- projecting shadows that will fall on the facade or ground when the sun is in specific positions; this approach gives an overview of the availability of sunlight at the site (see Figure 2-2).

For heavily obstructed facades, daylight-redirecting systems can improve the distribution of light to interior spaces. Glass prisms have been used for this purpose for more than a hundred years; today a range of systems can be used, including holographic elements, laser-cut panels, and anidolic elements.

2.1.3. Building Schemes and Building Types

Commonly encountered constraints on different building types over the years have resulted in typical building shapes and design schemes for standard types of building uses. These schemes generally incorporate daylighting strategies from which designers can learn.

Daylight design and building design can merge to different degrees. In some buildings, such as churches (see Figure 2-3), the daylighting strategy and the building design scheme are almost identical; in buildings where the organization of floor areas is complex, daylight is treated as one design issue among a host of others. The more that daylight is the generating factor for a design, the more the daylighting strategy is an architectural strategy.

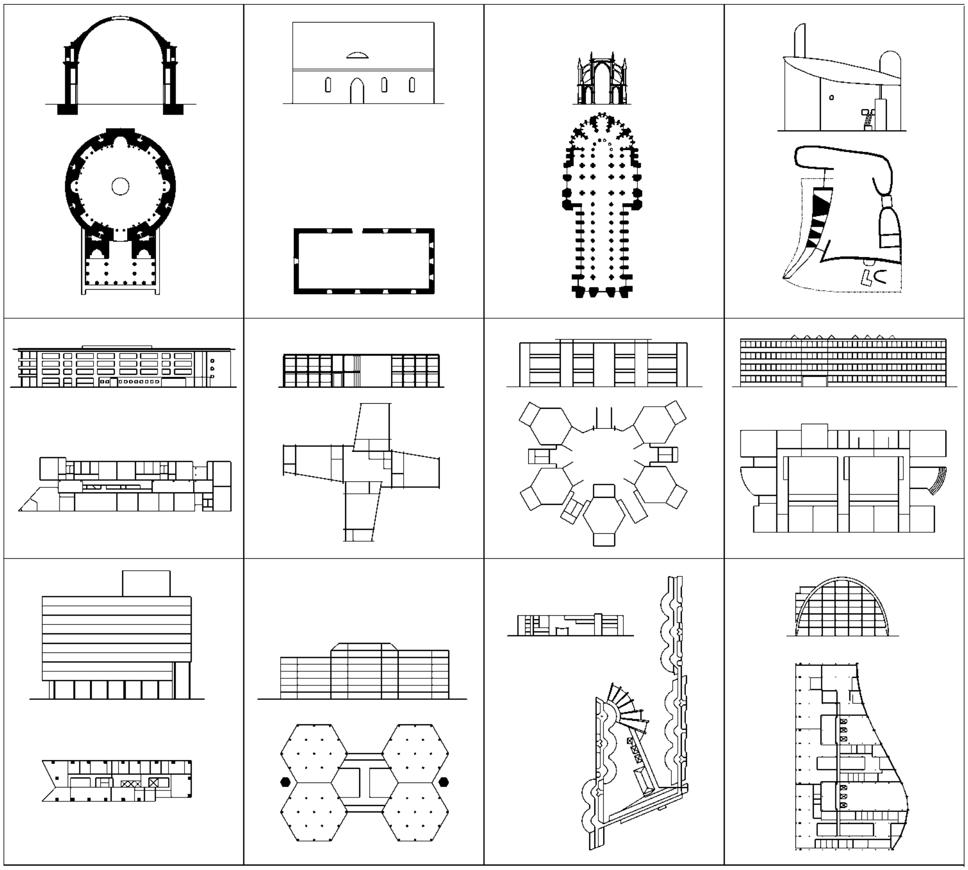


Figure 2-3: Daylighting design strategies for different building types. Churches (top row): Pantheon, Roman hall church, gothic basilica, modern. Schools (middle row): linear atrium, cross of Hamburg, nucleus, courtyards. Office buildings (bottom row): cellular, open plan, group offices, combination offices

Different organisations of building floor space develop in response to different needs. The bottom row of Figure 2-3 shows various ways of organizing space in office buildings. It is easy to see that a cellular design and an open plan design, for example, will demand different daylighting strategies. A conventional window may be adequate to distribute daylight to a shallow office room, but bringing daylight into deep spaces requires more complex design strategies.

Figure 2-4: Light and shadow in the Ronchamp chapel designed by Le Corbusier

One of the first steps in planning for daylight is to list all of a project's floor spaces and determine the lighting requirements of these areas. The required daylight level and degree of control over the visual environment are among the most important criteria (see Chapter 3).

Performance parameters are usually objective design criteria; however, the attractiveness of spaces cannot be expressed in purely quantitative terms. The work of architects such as Alvar Aalto, Le Corbusier, and Louis Kahn show how to use architectural design features to create impressive spaces with daylight (Figure 2-4).

The building's overall design scheme determines daylighting strategies and daylight potential in all building zones; therefore, performance parameters should be checked during the initial design phase. Incorrect assumptions about the distribution of daylight within the space will result in poor daylighting performance.

During the initial design phase, the daylighting designer's goal is to make sure that the specified performance can be achieved within the framework of the design. The proportion of spaces in relation to apertures should be checked. If the performance of the daylight strategy depends on the performance of particular daylighting systems, these systems have to be included in the prediction method. Rules of thumb, graphical methods, and simulation of daylight with physical or computer models are applicable at this stage of the design process (see Chapter 6). Most of these methods do not adequately account for a design's thermal behaviour even though the thermal strategy and the daylighting strategy are inseparably linked; a daylighting design should therefore include thermal calculations.

Figure 2-5: Typical building of the late 20th century that does not comply to today's daylighting standards

2.1.4. Retrofitting/Refurbishment

In most industrialised countries, the proportion of retrofit activities in the construction sector has increased steadily during the past two decades. Today, a large number of buildings are refurbished because of:

- a poor indoor environment (air quality, visual environment, etc.),
- high energy consumption,
- a poor state of repair, or
- the need for a new floor layout.

Figure 2-6: Power Gen, UK. The daylight strategy and the building design strategy are inseparably linked to each other.

Daylight design is an important component of a retrofit when building components that affect the building's daylighting performance are replaced. Common retrofit measures include replacement of windows or of the whole facade; old windows are often leaky and thus a source of heat loss. Refurbishment is a chance not only to replace old building components with new ones, but also to redefine the functional concept of a building in order to meet today's requirements.

Selection of the right glazing is of major importance for a building's daylighting strategy. The combined application of new glass and new daylighting systems, particularly those that provide solar shading, glare control, and the redirection of light, can increase daylight and decrease cooling loads. Daylighting measures are only efficient when the performance of artificial lighting systems is also addressed, i.e., new efficient lamps and luminaries and an advanced control system are installed. Combining daylighting and artificial lighting systems through, for example, a combined control strategy or the integration of lamps in an interior light shelf, is a design option in retrofits as well as new construction.

The increasing tendency to replace heating, ventilation, and air conditioning (HVAC) plants with hybrid HVAC-thermal-lighting systems and hybrid or natural ventilation strategies will affect the building envelope design. HVAC plant sizing and redesign should be integrated with envelope design because significant load reductions can occur as a result of new window and daylighting technologies.

Daylighting Strategies for Rooms 2.2.

The aims of room daylighting are to adequately illuminate visual tasks, to create an attractive visual environment, and to save electrical energy. Both the building design scheme and the application of systems play roles in meeting these goals.

The performance of a daylighting strategy for rooms depends on:

- daylight availability on the building envelope which determines the potential to daylight a space;
- physical and geometrical properties of window(s), and how windows are used to exploit and respond to available daylight;
- physical and geometrical properties of the space.

Figure 2-7: Window, clear view

Figure 2-8: Window with exterior louver blinds, where the view is partially obstructed

Figure 2-9: Window with interior vertical lamellas, where the view is completely obstructed

2.2.1. Function of Windows

The old definition of a window as an aperture in an opaque envelope is no longer strictly applicable. Innovations such as fully glazed skeleton structures and double-skin facades defy the scope of this definition. Nevertheless, we will use the term “window” to analyse daylighting strategies. Windows have several functions, which vary depending on the individual design case.

One key function of a window is to provide a view to the outside. View plays an important role in an occupant’s appraisal of the interior environment even if the exterior environment is not especially attractive. The size and position of windows, window frames, and other elements of the facade need to be considered carefully in relation to the eye level of building occupants. Daylighting systems can affect the view to the outside. If an outdoor view is a priority in a daylighting design, visual contact with the exterior has to be maintained under all facade operating conditions. Advanced daylight strategies therefore often allocate different functions to different areas of the facade or to different facades. View windows then can be preserved without being compromised by other functions.

Daylighting is one of the main functions of windows. The window design determines the distribution of daylight to a space. Windows chosen solely for their architectural design features may perform satisfactorily in many cases. For dwellings and other buildings that have relatively minimal visual requirements, application of advanced daylighting systems is not usually appropriate.

Advanced daylighting systems can be useful in cases where:

- difficult tasks are performed, and a high degree of control over the visual environment is required;
- the building’s geometry is complex, e.g., there are heavily obstructed facades or deep rooms;
- control of thermal loads is required (adjustable solar shading can be an effective strategy in this case).

Daylighting is inseparably linked to solar gain. In some design cases, added solar gains from daylighting may be welcome; in other cases, heat gain must be controlled. If solar gains are desirable, windows are a good way to provide them. In general, the goal of building design is to reduce cooling loads. There are a number of ways to control solar gains from windows and facades; the simplest method is the direct gain approach, where a shading system simultaneously controls the visual and thermal environments. More advanced techniques, such as collector windows and double-skin facades, allow some degree of separate control over the thermal and visual environments. In passive solar architectural concepts, solar gains are controlled by the orientation and the application of shading systems as a function of the sun’s position.

The operability of windows needs to be considered when daylighting systems are selected. Shading systems located in the window pane do not work properly when the window is open; if daylight-redirecting systems are attached to the window, the window's operation will have an impact on the systems' performance. Operable windows also often serve as fire escapes. The impact of fire balconies on daylight performance needs to be considered.

Glazed areas are an interface between exterior and interior; therefore, windows involve a number of design considerations. Aside from the above-mentioned primary functions, the following issues are especially important for glazed areas:

- glare,
- privacy/screening of view,
- protection from burglary.

2.2.2. Design Strategies for Windows

A window system must address the range of a building's exterior conditions to fulfil the range of interior requirements. The placement and sizing of windows are among the most powerful features of architectural design for daylight. Because the design of windows has a decisive effect on the potential daylight and thermal performance of adjacent spaces, it needs to be checked very carefully [O'Connor et al. 1997]. The LT (Light-Thermal) method, which was developed for typical climates in the European Union, allows the estimation of energy consumption for heating, lighting, and cooling as a function of glazing ratio [Baker and Steemers 2000]. Simple design tools (see Chapter 6) allow a quick evaluation of window design and room geometry.

Figure 2-10: Large rooflights without shading system in cloudy England

Windows are almost always exposed to the sky; daylighting systems can adapt windows to changing sky conditions and transmit or reflect daylight as a function of incident angle. Daylighting systems are primarily used for solar shading, protection from glare, and redirection of daylight. Whether or not daylighting systems are required to support the performance of window systems, and which system or systems is appropriate, are key decisions in the design process. See Chapter 4 for a detailed description and evaluation of innovative daylighting systems.

The adjustment of daylighting strategies to specific sources of skylight is an important characteristic of daylighting strategies.

Strategies for Skylight

Strategies for diffuse skylight can be designed for either clear or cloudy skies; however, the most significant characteristic of these strategies is how they deal with direct sunlight.

Solar shading always is an issue for daylighting except on north-oriented facades (in the northern hemisphere). If solar shading is only of minor importance as a result of orientation and obstructions, a system to protect from glare can be used for solar shading as well.

Solar shading and glare protection are different functions that require individual design consideration. Solar shading is a thermal function that primarily protects from direct sunlight, and glare protection is a visual function that moderates high luminances in the visual field. Systems to protect from glare address not only direct sunlight but skylight and reflected sunlight as well.

Strategies for Cloudy Skies

Daylighting strategies designed for diffuse skylight in predominantly cloudy conditions aim to distribute skylight to interior spaces when the direct sun is not present. In this case, windows and roof lights are designed to bring daylight into rooms under cloudy sky conditions, so windows will be relatively large and located high on the walls. Under sunny conditions, these large openings are a weak point, causing overheating and glare. Therefore, systems that provide sun shading and glare protection are an indispensable part of this strategy. Depending on the design strategy, various shading systems that transmit either diffuse skylight or direct sunlight may be applicable in this case. To avoid decreasing daylight levels under overcast sky conditions, moveable systems are usually applied.

Some innovative daylighting systems are designed to enhance daylight penetration under cloudy sky conditions (see the classification of systems in Chapter 4). Some of these systems, such as anidolic systems or light shelves, can control sunlight to some extent. The application of simple architectural measures, such as reflective sills, is another opportunity to enhance daylight penetration, but the design of the window itself is the main influence on the performance of this type of strategy under cloudy conditions.

Strategies for Clear Skies

In contrast to daylighting strategies for cloudy skies, strategies that diffuse skylight in climates where clear skies predominate must address direct sunlight at all times. Shading of direct sunlight is therefore part of the continuous operating mode of this strategy. Openings for clear sky strategies do not need to be sized for the low daylight levels of overcast skies. Shading systems that allow the window to depend primarily on diffuse skylight are applicable in this case (see Chapter 4).

Direct Sunlight

Strategies for sunlight and diffuse skylight are quite different. Direct sunlight is so bright that the amount of incident sunlight falling on a small aperture is sufficient to provide adequate daylight levels in large interior spaces. Beam daylighting strategies are applicable if sunshine probability is high. Since sunlight is a parallel source, direct sunlight can be easily guided and piped. Optical systems for direct light guiding and systems for light transport are applicable in this case (see Chapter 4). Apertures designed for beam daylighting do not usually provide a view to the outside and should therefore be combined with other view openings (→ Palm Springs Chamber of Commerce[1]). Because beam daylighting requires only small apertures, it can be applied as an added strategy in an approach that otherwise focuses on cloudy skies.

Figure 2-11: Homogeneous window design

2.2.3. Functional Division of a Window

If a designer can allocate one predominant function to a window, he or she can design it for optimum performance that will not be compromised by contradictory requirements. The designer must then make sure that all windows together fulfil the full range of requirements in a room.

Figure 2-12: Heterogeneous window design

When a window has to satisfy several functions in any operation mode, the range of applicable daylighting systems is constrained because the system selected must take account of all of the window's functions. The design approach for this type of opening therefore usually consists of applying moveable systems that can be recessed when not needed. The designer should consider controlling systems using a building energy management system because they might not otherwise be operated appropriately.

The heterogeneous design of a window allots specific functions to specific areas of a window. Different daylighting systems can be applied to different parts of the window, or similar systems may be operated separately for different areas of the window. The interaction of daylighting systems in this case needs detailed design consideration.

2.2.4. Strategies for Fenestration

Whether to use sidelighting or toplighting, unilateral or multilateral daylighting strategies should be decided during a building's conceptual design stage.

Although unilateral sidelighting is the standard daylighting case, its implementation requires care. It aims to distribute daylight into the depth of a space, to provide enough light to perform a task in the room while avoiding glare and allowing a view to the outside. Because these ambitions may conflict, the division of a facade into openings with specific functions is a promising way to apply sidelighting (→ Willy Brandt Building).

[1]→This notation is given for case study buildings documented in the Survey of Architectural Solutions, which is included on the CD-ROM.

Facades generally have a limited ability to distribute daylight into the depth of a space. Several rules of thumb apply to potential daylighting zones for diffuse skylight and appropriate window design. During the conceptual design phase, the daylighting zone may be considered to be a depth of about two times the window head height [Robbins 1986].

Unilateral toplighting can only be used on the top floor of a building. Spaces on lower floors can only be connected to rooflights by core daylighting systems or atria. Rooflights receive light from the brightest regions of the sky, so they are powerful sources of daylight. They do not, however, provide users with a view to the outside, so daylighting strategies that depend exclusively on rooflights are limited to spaces where a view is not necessary.

Because toplighting is exposed to high incident sunlight, solar shading is usually essential to prevent overheating. The size of rooflights needs to be carefully balanced to meet lighting, thermal performance, and shading requirements. Various rooflighting shading strategies and systems exist. Rooflights are often glazed with light-diffusing glass to protect the interior from direct sun rays. Light-diffusing glass does not provide solar shading, however, and becomes very bright when hit by direct sunlight, which may cause glare. The use of light shafts to baffle and disperse sunlight is a classical architectural rooflight concept (→ Gentofte Public Library). The use of awnings is another traditional technique to shade large rooflights (→ Trapholt Art Museum).

Traditionally, toplighting concepts have been used at high latitudes with predominantly cloudy skies, but advanced daylight-redirecting shading systems, such as laser-cut panels, holographic optical elements, and optically treated light shelves, can "cool" rooflights in sunny, hot climates (→ Center for Desert Architecture, Palm Springs Chamber of Commerce, Park Ridge Primary School).

Because the ability of facades to distribute daylight to deep spaces is limited, especially under cloudy skies, bilateral and multilateral lighting is an option for rooms that cannot be lit adequately by only one facade. The design of the building's fabric determines the availability of daylight on room facades. Atria and courtyards are often used to provide bilateral daylighting (→ Bertolt Brecht School).

Bilateral daylighting with a functional division between facades is a powerful daylighting strategy that can be applied in different ways. One way is to allocate the function of view to the outside to one facade using daylighting systems such as overhangs that shade sunlight but do not obstruct the view. The other facade can be used to distribute daylight to the space (→ Protestant School). The most common design solution for bilateral daylighting is to combine a window that fulfils the full scope of functions for a large portion of floor space with a clerestory to increase the illuminance level in the depth of the space (→ OSZ Wirtschaft).

Bilateral sidelighting can provide occupants with a view to the surrounding landscape. This strategy allows effective solar shading by moveable systems on a sunny facade while the second facade, which is not hit by direct sunlight, distributes daylight to the space (→ Gropius School).

Figure 2-13: Unilateral sidelighting in a laboratory

A bilateral combination of sidelighting and toplighting can distribute daylight to deep interior spaces (→ Gentofte Library). The primary function of the rooflights is usually to distribute daylight while windows provide occupants with a view to the outside (→ Park Ridge Primary School). Another application of this strategy is to create areas with their own specific apertures that provide individual lighting environments.

Figure 2-14: Unilateral rooflighting in an art gallery

Figure 2-15: Bilateral lighting, sidelight and rooflight

Core daylighting systems are optical systems in which the daylight-receiving aperture and the light-emitting opening are far apart. These systems can distribute daylight to windowless spaces. Occupants may not notice the difference between piped daylight and light generated by artificial light sources. A strategy to make these systems more cost-effective is to use them as distribution systems for artificial light as well. Core daylighting systems are usually designed to pipe direct sunlight. There are various types of core daylighting systems — sun-tracking as well as fixed systems that use optical fibres or light ducts.

Figure 2-16: Sun tracking daylighting system with fresnell collector and liquid light pipe

2.2.5. Relation to Adjacent Spaces

Clerestories in corridor walls of offices can distribute daylight to these otherwise windowless spaces; for shallow offices, this is a suitable strategy (→ DIN-Building). Daylight-redirecting systems can contribute to the distribution of daylight to these spaces in the core of a building; daylight-redirecting systems should be applied simultaneously to control glare. Windows facing an atrium have less daylight potential than windows facing an open courtyard because the glazed roof reduces the luminous flux. High reflectances within an atrium space can increase the depth of light penetration (→ Dragvoll University Center).

Even if borrowed light from interior windows does not significantly increase daylight levels to an interior space, the presence of these windows may improve light distribution and make a visual link between a space located in the core of a building and other zones of the building. The view to a daylit environment or even to an interior building landscape can increase the attractiveness of otherwise windowless spaces.

2.2.6. Finishing, Furnishing, and Using a Space

Interior finishing has to be part of the daylighting strategy. Daylight-redirecting strategies usually direct daylight to the ceiling of a room. The reflectance characteristics of the ceiling therefore influence the way daylight will be distributed. Specular in-plane ceiling surfaces reflect redirected light deep into the space but may be a source of glare. Specular out-of-plane ceiling surfaces can be shaped to deflect redirected daylight to specific areas in the room (→ Geyssel Office Building). These surfaces can act as reflectors for artificial light as well. A diffuse ceiling of high reflectance can also distribute light from daylight-redirecting systems, which may be more comfortable for occupants than a highly reflecting environment. The reflectance of walls, floor, and furniture also have a large influence on the impression created by a space. The floor reflectance should not be too low (>0.3).

Designers often assume that lighting requirements are homogeneous throughout a space and thus aim to provide uniform lighting levels, but surveys in occupied rooms show that there are patterns in how spaces are used. For example, in a cellular office occupied by one person, the desk is usually placed in the window area.

The furnishing of a space represents a frozen image of activities in the space. It affects where occupants do certain tasks. Thus, furnishing acts as a specification of lighting requirements. If the real use of a space can be determined, designs should be based on this information rather than on the assumption that a uniform luminous environment is required.

2.3. Design Strategies for Daylighting Systems

As outlined above, the application of daylighting systems is only one constituent of a daylighting strategy. Although a poor selection of systems can spoil the performance of a building with good daylight potential, a sound selection cannot compensate for errors and omissions in previous design stages.

To select a system, the designer must understand:

- the function of the window or other opening(s),
- the function of the system, and
- the interplay of the system with other systems.

A reasonable selection of systems should reduce the negative effects of windows and enhance daylight performance without interfering with other desirable effects of windows for all design cases (all seasons and sky conditions).

Daylighting systems can be categorised by many characteristics. When selecting a system, the designer must be aware of all of its properties. Function and performance parameters have the most pronounced effect on performance, but costs and details related to the skin of the building are also important. As for many decision within the design process there exists no definite procedure how to select a daylighting system. The ultimate criterion is the performance of the overall design solution.

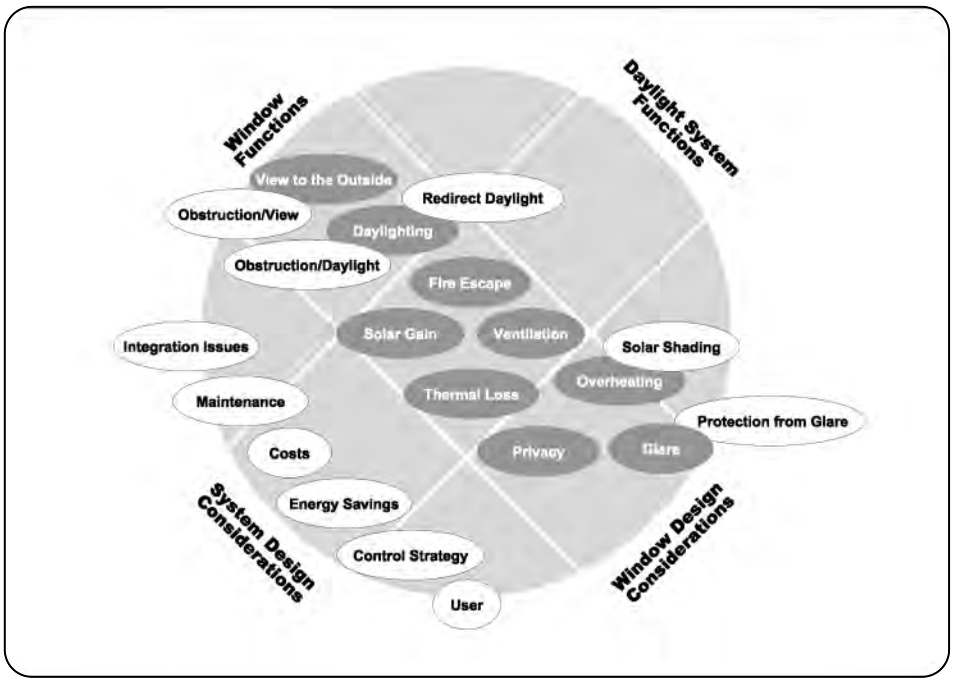


Figure 2-17: Functions and design considerations of windows and daylighting systems

Windows and rooflights have different roles in a daylighting strategy. The ambience of spaces receiving skylight is completely different from that of spaces receiving sidelight. For example, the design of Le Corbusier's "Le couvent de la Tourette" emphasises the different nature of skylight and sidelight. In this design, skylight is used only in spaces that play a significant role in religious life; all secular spaces receive sidelight.

Rooflights are usually not designed for a view to the outside; therefore, obstructing elements such as deep light shafts or non-transparent daylight systems can be applied in rooflight design. The control of glare with such systems is much easier than with sidelighting designs, which must provide occupants with a view to the outside. Solar shading is a crucial issue with rooflighting. One design strategy for rooflighting in sunny hot climates is to use a very small aperture and to apply innovative daylighting systems to distribute the light homogeneously in the space (→ Waterford School, International Centre for Desert Architecture). In classrooms of the Park Ridge Primary School in the sunny but temperate climate of Melbourne in southern Australia, tunnel lights are used to exclude direct sunlight and to distribute skylight to the space (→ Park Ridge Primary School).

Shading systems for rooflights, such as sun-protecting mirror elements, prismatic panels (Chapter 4.5), and directional selective shading systems using holographic optical elements (Chapter 4.11) can be applied to large glazed roof areas in higher latitudes. When situated in the window pane, these systems are protected from dust and require little maintenance. These systems need to be adjusted to the individual application.

2.3.1. Function of Systems

multiple functions

protection from glare, solar shading, redirection
- exterior slatted blinds, awning

protection from glare, solar shading
- trees, fins, directional selective shading systems

protection from glare, redirection
- deep window reveal, mirrored prismatic panels

solar shading, redirection
- lightshelf, anidolic ceiling, lightguide

single function

protection from glare
- screen, blinds, curtain...

solar shading
- overhang, sunshade, fixed lamellas, reflective glass...

redirection
- reflectors, laser cut panels, scattering glass...

light transport
- heliostat, light-pipe, solar-tube, fibres, solux...

enhancement of daylight level
- high lintel, glass with high light transmission

aesthetic function
- glass block brick, coloured glass, printed glass

thermal
- double skin, pivoting window

The system matrix for the division and description of daylighting systems that is included in Chapter 4.2 of this book makes a distinction between two major categories of daylighting systems: those with and those without shading. This division is useful for building designers. Daylight-redirecting systems that do not shade usually need to be complemented by other window systems; shading systems might be applied as stand-alone systems for windows or window areas.

Daylighting systems have three major functions:

- solar shading,
- protection from glare,
- redirection of daylight.

Windows need protection from glare and solar shading in order to create acceptable interior conditions. The redirection of daylight can save energy but is not an indispensable function. The view to the outside is not a function of a daylighting system but a primary function of the window itself; the impact of daylighting systems on the view to the outside needs to be considered carefully.

Some systems, such as exterior louvered blinds (Chapter 4.4), are designed to satisfy all functions of a standard window as a stand-alone system. But, as outlined above, such a "one size fits all" system, which usually covers the whole window area, will, in most cases, have a poor performance. A good selection of systems means a good mixture of systems.

Figure 2-18: Exterior glazed lamellas for solar shading

Reflecting profiles in the cavity of the glass are designed for solar shading, redirection of daylight, and glare control, but create considerable obstructions to view. When this technology is applied to a facade, low incident daylight is redirected to the ceiling, and high incident daylight is rejected. This strategy performs well under sunny skies in high latitudes when oriented to the south (in the northern hemisphere), but it has poor daylighting performance under overcast conditions. It is primarily a selective shading strategy that can be applied to control the thermal performance of large areas of glazing.

Figure 2-19: Light guiding shade for solar shading and redirection of day-light

Architectural design features often to some extent fulfil or support the functions of daylighting systems, but they cannot address the full range of exterior conditions, so additional daylighting systems are generally needed. An overhang, for example, acts as a solar shading system but only for high sun positions. It does not protect from glare or redirect light into the space. Fins act to some extent as solar shading devices, attenuating and redirecting sunlight and partially controlling glare, but they are not a stand-alone daylighting system. These architectural design features selectively attenuate daylight so that simple daylighting systems can be added to supply missing functions. Other examples of architectural features that shape daylight are arcades, atria, balconies, and deep window reveals. The performance of these elements can only be evaluated within the context of a specific design solution, so surveys and case studies are useful assessment resources. In addition to the survey of architectural solutions included in

Figure 2-20: Interior fabric to protect from glare

this source book, some very useful compilations of case studies have been published in recent years [Fontoynont 1999, LUMEN 1995, *IEA SHC Task 21 Daylight in buildings: 15 Case Studies from Around the World*].

In high latitudes with predominantly cloudy skies where the exterior illuminance on winter days at noon is often even less than 5,000 lux, measures to increase daylight during winter are appropriate. A high window with a sloping lintel has proven to be more efficient in this case than most daylight-redirecting systems. The application of glass with high light transmission is also very useful. Because a large window designed for low levels of daylight on overcast days is vulnerable to overheating and glare on bright days, effective shading systems are needed to make this daylighting strategy work.

A light shelf (Chapter 4.3) combines solar shading and sunlight redirection, improving the distribution of daylight and allowing a view through the lower part of the window. Light shelves are applicable in sunny climates in mid-latitudes for south orientations (in the northern hemisphere). Light shelves are a classical device in the daylighting toolbox.

Other systems are designed for only one function; zenithal light-guiding glass (Chapter 4.10), for example, redirects sunlight but does not provide solar shading or glare protection. Interior roller blinds primarily protect against glare, but they only have a limited effect on solar shading and usually do not redirect daylight. A pivoting window adapts to summer and winter light availability conditions but has no effect on daylight distribution.

2.3.2. Location

location

1. exterior
   - deciduous trees, overhang, balcony, arcade, sun-shade, fins, louvers
2. window pane
   - holographic elements, laser cut panels, glazing with reflecting/redirecting elements, switchable glazing, light guiding glass...
3. interior
   - curtain, blinds, interior lamellas, reflective sill, prisms and venetian blinds
4. combined systems
   - light guiding shade, anidolic ceiling, light transport systems

The location of a daylighting system can be described in relation to the window pane as exterior, interior, or within the pane. Some complex systems such as the anidolic ceiling (Chapter 4.12) combine exterior and interior elements. The location of a daylighting system can affect the thermal performance of the building.

Exterior systems are most suitable for solar shading; interior systems allow for solar gains. Systems located in the cavity of the glass or within a double facade can be applied as part of an advanced ventilation strategy to serve as exhausts in summer and solar collectors in winter.

Exterior devices are costly because they have to be constructed to resist all weather conditions. Moveable exterior systems require a lot of maintenance and often collect dust. Interior systems are much less expensive, but they have only a limited solar shading effect.

The designer should therefore aim to find the right size and position of windows and use fixed elements in the window design if applicable, so the need for moveable exterior systems can be reduced. Innovative systems are often located in the window pane. They control daylight as a function of incidence angle but affect the view to the outside.

2.3.3. Ability to Change

ability to change

1. fixed, no change
   - overhang, lightshelf, anidolic ceiling, angular selective skylight, solar tube, sun protecting mirror elements
2. fixed, with change
   - switchable glass, photo-chromatic glass, thermo-chromatic glass, deciduous tree
3. adjustable, can not be recessed
   - turnable lamellas
4. adjustable can be recessed
   - venetian blinds, roller blinds, awnings
5. sun tracking
   - heliostat, solux, fibres

Because one of the main functions of daylighting systems is to adapt the building to changing sky conditions, the ability to change is an important characteristic of these systems. A system itself does not necessarily need to change. A design using fixed systems that reflect the trajectory of the sun can be sensitive to sky conditions, for example. Orientations to the south (in the northern hemisphere) are especially appropriate for such a design. Although fixed systems, such as overhangs, sun shades, horizontal lamellas, and fins, are useful for solar shading, they do not control glare; therefore, another system that controls glare needs to be added to make these design solutions work. Because the glare protection device is not used for solar shading in this case, an interior system can be applied (→ OSZ Wirtschaft).

Many buildings in hot climates have in recent years been designed for solar shading rather than for daylighting. Reducing cooling loads was the driving force in these designs. Sun-shading glass has been used to exclude solar radiation, and window function has been limited to providing occupants with a view to the outside. Today, advanced daylighting systems in combination with advanced controls can bring daylight deep into a space and reduce cooling loads relative to those experienced with artificial lighting. If thermal loads are a major concern, tracking systems can be used to regulate daylight levels.

2.3.4. Transparency

Because a primary function of windows is to provide occupants with a view to the outside, the transparency of daylighting systems is a major issue. The construction material of a daylighting system need not necessarily be transparent itself in order to provide a view out; the subjective impression of visual contact to the outside is most important. The function of a system to protect from glare inevitably affects the view to the outside. Sun shading and the redirection of daylight affect the view as well.

Some advanced systems, such as holographic optical elements, laser-cut panels, and light shelves, aim to shade or redirect daylight from some incidence angles while not interfering to any great extent with the view to the outside (see Chapter 4). These systems do not control glare. Fixed daylighting systems that do control glare, such as sun-protecting mirror elements in the cavity of the glass, anidolic ceilings, and light-guiding shades, do not provide occupants with a view to the outside.

Louvers and blinds and other moveable systems that can be recessed are designed to shade and protect from glare when needed, but they do not interfere with view when they are recessed. The transparency of these systems depends on the operating conditions.

Electrochromic glass can adjust the transmission of radiation over a wide range without changing the distribution of daylight. Glass with light transmission that varies depending on the amount of incident daylight or the temperature is a promising technology that has been developed in laboratories.

Performance Parameters 3.

Introduction 3.1.

Performance parameters characterise a daylighting system within the context of a specific building application and can be used to determine whether a system should be used to achieve the design objectives. Parameters include visual performance and comfort, building energy use, economy, and systems integration. The primary energy-related design objectives of a daylighting system are to provide usable daylight for a particular climate or building type for a significant part of the year, which allows electric lighting to be offset by natural daylight and cooling and heating loads to be reduced. Conventional window and skylight solutions meet some of these needs; this guide focuses on new technologies and solutions that extend performance beyond that of conventional solutions. The functions of these new design solutions can be summarised as follows:

- provide usable daylight at greater depths from the window wall than is possible with conventional designs,
- increase usable daylight for climates with predominantly overcast skies,
- increase usable daylight for very sunny climates where control of direct sun is required,
- increase usable daylight for windows that are blocked by exterior obstructions and therefore have a restricted view of the sky, and
- transport usable daylight to windowless spaces.

The term “usable daylight” encompasses objective and subjective measures for visibility and comfort:

- higher illuminance levels, often at greater depths from the daylight opening, than provided by conventional solutions under both cloudy and clear sky conditions,
- greater uniformity of light distribution,

- reduction of glare and cooling loads by controlling direct sun without compromising daylight admission.

An objective evaluation of an innovative system requires definition of performance parameters. In addition, the evaluation depends on defining baseline conditions against which the performance should be compared. The performance parameters are summarised in the table below. In the following sections, these terms are defined within the context of the general field of lighting and their respective ranges of acceptable or target values are given, if available. A discussion follows concerning how these terms apply to the unique, light-redirecting daylighting systems covered in this book. Many existing performance parameters are not directly translatable to advanced daylighting either because the parameters were developed for static electric lighting sources, or because research has been insufficient to develop adequate, robust performance models. These issues are also briefly discussed.

Table 3-1: Performance parameters

Parameters	Independent Variables	Baseline

Visual Comfort and Performance
    Illuminance
    Distribution
    Glare
    Direction
Visual Amenity
    Outside view
    Appearance
    Apparent brightness
    Colour
    Privacy
    Social behaviour
Thermal Comfort
Device Characteristics
Building Energy Use
Lighting Energy
    Space conditioning energy
    Shading system
    Peak demand
Economy
Codes and Standards
Construction & Systems Integration
    Product data
    Systems integration
    User considerations
	Climate
	    Daylight availability
	    Temperature
	Site
	    Latitude
	    Local daylight availability
	    Atmospheric conditions
	    Exterior obstructions
	    Ground reflectance
	Room
	    Geometry
	    Surface reflectances
	Window
	    Size
	    Placement
	    Orientation
	    Daylighting system
	    Shading system
	Lighting System
	    Ambient and task system
	    Control system
	Task
	    Reading, writing
	    Computer or self-illuminating equipment
	    Occupancy schedule
		Clear, unobstructed glass
		Glazing with shading system

Systematic evaluations of daylighting systems involve performance assessments for several critical independent variables such as weather, site building conditions as well as room and task condition. Useful formats for data presentation and analysis will depend on the decision-making criteria. For example, visibility performance data can be summarised by various statistical measures: instantaneous data (time of day), average data (yearly, seasonal), or binned data (distribution or percentage of time above a given constant).

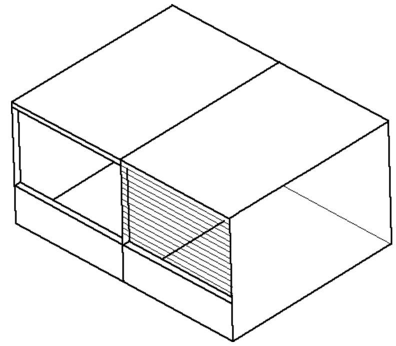


Figure 3-1: Unobstructed window versus conventional window with shading device

Definition of the base case condition will affect the results of the evaluation. Two base case categories are used by IEA SHC Task 21 laboratory and field test facilities: 1) a conventional window with glazing and shading systems, and 2) clear, unobstructed glass. The first conventional base case includes clear, tinted, or coated glass and an interior or exterior shading device, such as venetian blinds or roller shades, to control direct sun and glare, as found in typical commercial buildings. Clear glass is used for many European climates (e.g., in Scandinavia), and tinted or coated glass is often used for sunnier, warmer climates. The unobstructed, clear glass base case (2) can easily be characterized by thermal and daylighting simulation tools and duplicated among test facilities. This case was used by most of the field tests documented in Chapter 4. and as defined by the monitoring protocol (Appendix 8.5).

It is important to note how the choice of base case category will lead to certain expected results. For example, the unobstructed, clear glass base case will almost always result in higher illuminance and intolerable glare levels during the year than a daylighting system occupying the same aperture, simply because it admits direct sun and poses fewer obstructions to incoming daylight. On the other hand, more realistic window base cases may obstruct too much daylight, so the test case will yield consistently higher illuminance levels and show more favourable and perhaps misleading results.

The importance given to one performance metric over others differs with climate and building type. A method to rate the overall performance of a daylighting strategy is not provided here because of the complexity of the decision-making process. For example, for an office building located in a mild climate, designers may place more value on illuminance levels and lighting energy use; for the same building in a hot location, designers may be very concerned with thermal performance. It is important to note that a strategy should be evaluated on the basis of all its attributes, not a single parameter. Total performance ratings will differ among applications, so the reader is advised to be aware of the concepts that underlie each performance parameter, and to prioritise parameters based on the building application. Finally, as with all performance evaluations, computation analysis can often obscure the complexity of underlying concepts (e.g., physiological processes of the eye, human adaptation, etc.), so strict adherence to numerical rating systems for decision making is ill-advised. To obtain data applicable to a particular building design, see Chapter 6, Design Tools. Researchers developing and evaluating new innovative systems should see the monitoring protocol in Appendix 8.5.

3.2. Visual Comfort and Performance

Visual function parameters are used to determine whether a given lighting condition permits sight or visibility and are directly related to the physiology of the eye [IES 1993a]. Generally, good visibility is defined by an adequate quantity of light for the expected visual task, uniform distribution of illuminance and luminance, sufficient directionality to model three-dimensional objects and surfaces (direction of incident light from the side or from above), the absence of glare, and sufficient spectral content to render colours accurately when required.

3.2.1. Illuminance

Guidelines for electric lighting have defined ranges of “design” illuminance levels based on task, viewer’s age, speed and accuracy requirements, and task background reflectance [IES 1993a, CIE-29.2 1986]. For daylighting, the total energy balance between lighting and thermal loads (i.e., from solar heat gains) is an added consideration. For paper-based tasks such as reading and writing, satisfactory task illuminance levels can exceed recommended electric lighting levels by factors of two or more if there is no glare and if the associated heat gains have a minimal mechanical system energy impact (especially in cooling-dominated climates). For computer-based or other self-illuminating tasks characterized by low luminance values (<85 cd/m^2), however, these guidelines may represent the maximum range of illumination, because exceeding these guidelines can often result in reduced visibility.

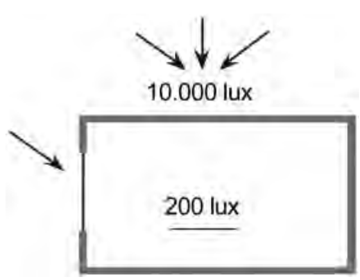


Figure 3-2: If the indoor illuminance is 200 lux when the outdoor global illuminance is 10,000 lux, the daylight factor is 2%

For some countries, an absolute illuminance level is used in a systematic evaluation. For other countries, particularly those that are dominated by cloudy sky conditions, the *daylight factor*, or the ratio between the illuminance measured indoors at a reference point (e.g. work plane) and the outdoor global illuminance on an unobstructed, horizontal surface, is used as a measure of light quantity (Figure 3-2). Because of the variability of daylight available from the sun and sky, daylighting systems are evaluated based on the quantity of illumination provided at a task *over time*. For office work that involves both paper-based and computer-based tasks, the larger the number of hours per year that a system is able to meet but not grossly exceed the design illuminance level, the more successful the design. This concept is also connected to the electric lighting energy savings potential, as discussed in Section 3.6.1 below.

For systems designed to redirect light to greater depths than is possible with conventional technologies, "good" systems are those that can meet the design illuminance level at greater depths and for a greater percentage of the year than conventional window systems. As a rule of thumb, conventional windows can daylight a room to a depth of 1.5 to two times the height of the window above the floor. Some daylighting systems are designed to achieve light redirection to depths of two or more times the window height for a greater percentage of the year than is possible with conventional designs. Task locations are often ambiguous or change frequently, so an evaluation is usually conducted at representative locations within a space.

3.2.2. Distribution

The distribution of illuminance and luminance is a measure of how lighting varies from point to point across a plane or surface. For good visibility, some degree of uniformity across the task plane is desirable. Poor visibility and visual discomfort may result if the eye is forced to adapt too quickly to a wide range of light levels. Illuminance and luminance ratios such as maximum-to-average or average-to-minimum are used to quantify lighting uniformity and are typically measured across a horizontal work plane at a height of 0.8 m above the floor for paper or reading tasks. For office lighting, for example, the ANSI/IESNA RP-1 guidelines set maximum contrast ratios among all task, background, and remote surfaces within the occupant's field of view [IES 1993b]:

- variation in luminance across the immediate task (within one's central or ergorama vision) should be kept to a maximum of 2.5:1 to 3:1;
- variation in luminance between the task and background (central or ergorama vision; e.g., black letters on a white background) is permitted, typically 3:1;
- greater variation is permitted between the task and remote surfaces (panorama view; e.g., walls, ceiling, and floor), typically 10:1, but the design must meet additional guidelines for glare (e.g., 20:1 to 40:1).

A systematic evaluation of daylighting systems is complicated by a number of factors, however:

- the sun is a variable-position light source, so the sheer number of conditions one must evaluate is large;
- the task location is often ambiguous, requiring one to either consider all views within the space or to select several representative task locations;
- if direct sun is not excluded or is redirected, continuous surface luminance maps may be the only method to determine the location, size, and intensity of bright areas of sunlight;

- the luminance of exterior obstructions (e.g., opposing semi-reflective buildings) or the ground (e.g., snow) varies with task location and solar conditions;
- occupants may accept much greater luminance variations when spaces are lit by daylight than when they are artificially lit, which further complicates comparisons.

At minimum, the illuminance profile throughout the space can be measured or simulated, and contrast ratios can be computed. This profile typically illustrates how daylighting systems achieve more uniformity throughout the space than conventional windows.

3.2.3. Glare

Disability Glare

Disability glare is caused when intraocular light scatter occurs within the eye, the contrast in the retinal image is reduced (typically at low light levels), and vision is partly or totally impeded (e.g., when the eye is confronted by headlights from oncoming automobiles). With windows and daylighting systems, which are large-area light sources, disability glare can at times be significant. Experts agree that this apparent reduction in contrast is affected by the total intensity of the glare source — not just by the brightness or area alone [Hopkinson 1972, Hopkinson 1963]. However, there are no known satisfactory models to predict and evaluate this condition.

Figure 3-3: Glare in a typical office

A daylighting design should be evaluated to determine whether there are strategies or features that enable occupants to control situations where the eye is forced to adapt to different brightness regions within the field of view.

Discomfort Glare

Discomfort glare is a sensation of annoyance caused by high or non-uniform distributions of brightness in the field of view (Figure 3-3). The physiological mechanisms of discomfort glare are not well understood; an assessment of discomfort glare is based on size, luminance, and number of glare sources, source-task-eye geometry (or glare source locations within the field of view), and background luminance. The Daylighting Glare Index (DGI) is used to indicate the subjective response to a large-area glare source and can be calculated for a person facing the window or the side wall at various distances from the window wall [Hopkinson 1972 and Appendix 8.5]. However, the DGI can only be used for large areas with a nearly homogeneous luminance distribution, e.g., a view to a uniform sky luminance through a window. When the luminance distribution from daylighting systems varies substantially, the DGI cannot be used.

To simplify analysis, several rules of thumb can be applied to evaluate daylighting systems. The values given below come from the ANSI/IES RP-1 guidelines [IES 1993b] for office tasks using computer visual display terminals (VDTs). Other applicable standards include CIE-117 [1995] for discomfort glare (which introduces the Unified Glare Rating, UGR).

Luminance. For tasks involving a computer screen with an average luminance of 85 cd/m^2, the maximum luminance level of surfaces within the field of view is 300 cd/m^2 for tasks within the immediate background and 850 cd/m^2 for tasks within the general background.

Size. The average luminance of any 0.6 by 0.6 m area within the field of view should be kept below 850 cd/m^2.

Luminance Ratios. See Section 3.2.2.

Geometry. Glare sources must be kept out of the line of sight. For a horizontal view angle, sources within 50-90° above the horizontal can cause high-angle or overhead glare.

Veiling Reflections

Visual discomfort or glare results from bright reflections off shiny surfaces. These veiling reflections reduce contrast and impair visibility. Daylighting systems can reduce or eliminate veiling reflections by controlling direct sun and luminance levels within the offending zone or the area viewed by the task surface.

3.2.4. Direction

For some tasks, sufficient directionality is required to model and evaluate three-dimensional objects and surfaces. The greater the amount of diffuse light, the less shadowing occurs, reducing an occupant's ability to evaluate the depth, shape, and texture of a surface. A balance between diffuse and directional light enables an occupant to evaluate the smoothness, nap, grain, iridescence, specularity, and other properties of a surface. For horizontal tasks, sidelighting from daylighting systems can enable better visibility than lighting from an overhead electric lighting installation.

There are no standard performance parameters to evaluate the direction and diffusion of light. Direct sunlight is typically directional with sufficient diffuse light from the sky to balance out the contrast of a three-dimensional object. Daylighting systems that rely on sky light will typically produce diffuse omni-directional light. Some daylighting systems using non-imaging optics (e.g., anidolic systems) can redirect diffuse daylight in the same way a light projector does, so some directional effects appear even in diffuse daylight.

3.3. Visual Amenity

Visual amenity encompasses the human responses to a lit environment that go beyond pure visibility criteria, including psychological elements. Light affects people's behaviour and their impressions of an environment. Little research has been conducted to enable quantification of the visual amenity provided by advanced daylighting systems. Cognitive factors such as attention, expectation, and habituation will affect an occupant's ability to recognize objects and discern details.

3.3.1. Outside View

Windows are highly valued for their views of the natural environment and for their connection to the outdoors (Figure 3-4). Movement and changes in light levels throughout the day can be mentally restful or stimulating. Views of landmarks or scenes can give a sense of place. Time of day, weather conditions, and personal safety conditions can be determined by a glance out the window. Interiors without sufficiently large side windows and without clear or lightly tinted glass can cause claustrophobia. Tolerance for moderate levels of glare may increase in proportion to the quality of view.

If view is desired, daylighting strategies and systems can be ranked from best to worst by: a) complete unmitigated, undistorted view, b) partial view (e.g., upper daylighting aperture with lower view window), c) occasional view (user can operate the system to obtain an unobstructed clear view), and d) no view. View will depend on the location of the occupant. In open plan offices, for example, direct view is often obscured within less than ~2 m from the window wall by partitions, particularly if occupants near the window deploy full-height shades to control direct sun and glare.

Figure 3-4: View of the outdoors with prismatic blinds

3.3.2. Appearance

Patterns of daylight can affect an occupant's aesthetic judgement of the environment's coherence, legibility, mystery, and spatial complexity. Architects have used direct sun to great artistic effect — to punctuate space or create spiritual effects. Daylighting rarely creates random patterns, which can often be found in electric lighting solutions. However, patterns of light and shadow can cause confusion and contrast in the visual field. Daylighting systems that create areas of excessively striated or noticeable patterns must be used judiciously.

3.3.3. Apparent Brightness

The brightness impression of an interior is an important psychological aspect of daylighting; i.e., whether the interior *appears* to be dark or bright can be independent of the physical value of illuminance or luminance. Consider two rooms with identical task illumination. If the view from a window in one room is obstructed by a building, that room may give a lower brightness impression. The other room, with no obstructions to the view, will seem brighter. The same effect occurs with different window sizes. Two rooms with the same illumination levels but different size windows will give different brightness impressions. The room with larger windows will give an impression of greater brightness.

Gradients of luminance may affect perception of brightness. For example, a non-uniformly artificially lit room appears brighter than a uniformly lit room, perhaps because the non-uniformly lit room has greater luminance contrast [Tiller and Veitch 1995]. Most office workers in Tiller and Veitch's study preferred high-brightness surfaces with some uniformity; dimly lit spaces were perceived as gloomy.

Conventional sidelighting concepts typically result in a cave-like luminance distribution (dark ceiling, bright lower side walls and floor). Light-redirecting daylighting systems that illuminate the ceiling may improve the apparent brightness of a room while providing the same task illuminance as a conventional system.

3.3.4. Colour

True colour rendition is important for tasks that involve colour matching, quality control, and accurate colour perception. Generally, the less a daylighting system changes colours from their true state, the better the system or strategy. For museums, retail, health care and other similar uses, accurate colour rendition can affect judgement and perception. The spectral distribution of the light source after it enters the building determines colour rendering. Outdoor "natural" daylight defines full-spectrum lighting, i.e., true colour rendition.

Some daylighting systems can be combined with tinted or coated window glazing that can cause shifts in both interior and exterior view colour perception. Low-transmission glazing can give a gloomy or muddy appearance to exterior views. Some holographic diffractive glazings and prisms can cause chromatic dispersion, resulting in a rainbow lighting effect and, possibly, reduced interior colour rendition.

3.3.5. Privacy

The degree of privacy afforded by a daylighting system may be difficult to quantify. Privacy depends on the relative brightness of the interior compared to the exterior and the perception of privacy by the occupant. Reflective glass, for example, will yield complete privacy during the daytime with completely unobscured views. At night, when the relative brightness is reversed, the glazing from the interior is completely reflective yet affords no privacy.

Designers should consider the level of privacy desired for the building application and provide opaque, operable shades where privacy is critical.

3.3.6. Social Behaviour

Social psychologists have conducted studies to determine the effects of illumination levels, spectral distribution, window size, window location, and other lighting factors on mood, intellectual task performance, and styles of conflict resolution (e.g., [Baron et al. 1992]). The essential argument is that a daylit environment can evoke an emotional response that affects the mood and social behaviour of an occupant. Direct sun can be stimulating through its non-uniform luminance distributions, directionality, movement, and luminous variability.

These perceptions can be altered if essential properties of the light source are modified. For example, real daylight from a skylighting tube with an opal diffuser may appear to be an artificial lighting system, and some colour-corrected, hidden electric lighting systems may appear to be sources of daylight.

3.3.7. Health

Daylight can have health effects on skin, eyes, hormone secretions, and mood. Its temporal variation may be used to combat jet lag and sick building syndrome. In some climates, daylighting systems that provide more illuminance during the winter and less during the summer (in inverse proportion to daylight availability) are considered more desirable, to counter the effects of seasonal affective disorder.

3.4. Thermal Comfort

Daylighting systems can affect thermal comfort in a variety of ways. A cold window surface can increase thermal discomfort caused by longwave radiative exchange between the window and occupant in the winter, and a hot window surface can do the same during the summer. Convective downdrafts caused by cold window surfaces and infiltration can also contribute to discomfort. In some cases, direct sun can contribute to greater thermal comfort during the winter.

Generally, the thermal comfort of daylighting systems can be evaluated using simple measures. Options to control direct sun should be available. An insulated window will increase inside window surface temperatures and improve comfort. Local standards and guidelines that govern acceptable surface temperature, direct sun control, etc. should be followed.

Device Characteristics 3.5.

Many of the fundamental properties that define the optical and thermal characteristics of advanced daylighting systems are difficult to measure and thus to compare, principally because the properties are angle- or system-dependent.

For daylighting applications, optical properties typically quantify how solar radiation and visible light are modified by a material or system by means of transmission, reflectance, absorption, scattering or diffusion, diffraction or refraction (Figure 3-5). Total solar transmittance and reflectance can be measured for planar, transparent glazings using laboratory equipment for analysis and simulation of optical performance. However, measurement protocols are still under development for typical non-homogeneous, complex, and movable systems and materials (see Appendix 8-3). Most daylighting devices fall into this category.

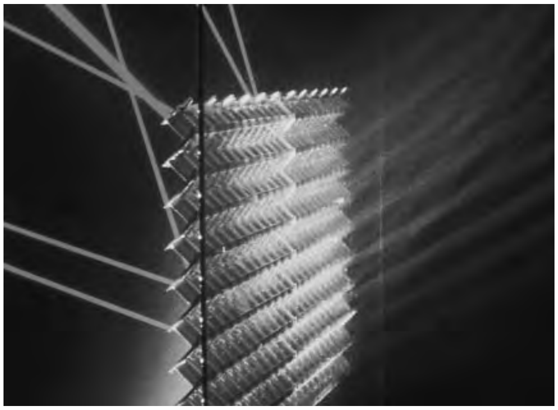


Figure 3-5:
Laser visualization of light redirection, transmittance, and reflectance properties of complex Siemens louver system

Radiant and thermal properties need to be identified in order to determine window heat gains. When a daylighting system is irradiated by sunshine, the glazing materials become hotter than the air at its indoor and outdoor surfaces. Heat then flows by radiation and convection from the outer surface to the atmosphere and surrounding environment, and from the inner surface to room air and interior surfaces. Quantities defining the absorption and re-radiation or emittance of solar radiation as a function of wind speed and indoor and outdoor air temperature (known internationally as the g-coefficient, or in the U.S. as the solar heat gain coefficient (SHGC)) have not been measured for many daylighting systems and strategies.

Similarly, properties related to ultraviolet protection, durability, sound transmission, colour rendition, structural strength, flammability, weight, and resistance to condensation are not systematically available for daylighting devices. Refer to Chapter 4 for detailed information on specific systems.

3.6. Building Energy Use

3.6.1. Lighting Energy

From the energy-efficiency perspective, daylight offsets the need for electric lighting by providing adequate levels of task or ambient illuminance. At the simplest level of evaluation, task locations, solar conditions and illuminance data at given depths from the window wall can be compared to evaluate the energy-efficiency performance of daylighting systems. These data can be presented as 1) the percentage of time when the building is occupied that interior daylight illuminance levels equal or exceed the desired design illuminance level or, 2) binned absolute illuminance data over the course of a year. Use of these data will depend on the electric lighting control strategy.

For manual or automatic on/off switching, the first method of presenting data yields what is known as “daylight autonomy” or the yearly relative “time of utilization.” These are terms that essentially denote the percentage of work hours when interior daylight illuminance levels meet or exceed the required illuminance levels so that the electric lighting system can be turned off. For dimming systems, the second method of presenting the data can allow a user to roughly estimate the number of hours, for each set of bin data, during which the lights can be dimmed to a particular power and light output level. “Usable light exposure,” a term used in Europe, denotes the yearly percentage of added electric lighting needed to increase the daylight levels to the design illuminance setpoint [Aydinli and Seidl 1986]. If yearly data are not available, data can be given for a subset of days and hours representing typical solar conditions (e.g., equinox and solstice clear sunny days, and overcast day). Summarised weather data can then be used to obtain a rough estimate of annual lighting energy use.

For greater accuracy, hour-by-hour building energy simulation tools can be used to evaluate the energy effects of simple daylighting systems given monitored weather data, a detailed description of the interior space, and the characteristics of the electric lighting system and its controls. For more complex systems such as those described in this book, however, such simulation tools require functional modifications to adequately predict daylighting impacts. Simulation tools for homogeneous (e.g., conventional transparent glazing) and optically complex daylighting systems are described in Chapter 6.

The above methods use horizontal work plane illuminance data to estimate potential lighting energy use reductions. For more complex evaluations involving dimming systems, one may conduct field tests or build mathematical models to accommodate the response characteristics of automatic electric lighting dimming control systems.

The performance of both the daylighting system and the electric lighting system can be expected to degrade with time, as a result of accumulated dirt, oxidation of high-reflectance films, or occupant intervention. Manually deployed shading devices will decrease interior daylight levels. Poor design, faulty installation, and lack of system commissioning will degrade the performance of automated lighting control systems, as well as contribute to user dissatisfaction. User switching behaviour for manually controlled systems is known to be motivated by non-energy-efficiency considerations (e.g., transient adaptation, apparent brightness, a desire to signal that the occupant is “in”).

3.6.2. Space-Conditioning Energy

If the interior space is mechanically conditioned, daylighting systems will typically affect the thermal load on the HVAC system by increasing window heat gains but decreasing electric lighting heat gains (if the lights are controlled in response to daylight).

Generally, window and lighting heat gains are beneficial for heating-load-dominated buildings and are detrimental for cooling-load-dominated buildings. In some European countries dominated by cloudy sky conditions and heating loads, building codes prohibit the use of air-conditioning systems in commercial buildings unless the need for the system can be demonstrated (e.g., for protecting the hardware in a computer centre). In this case, the cooling load criteria can drive the design and selection of the window system to ensure thermal comfort during occasional sunny periods.

Evaluation of daylighting systems’ energy use typically involves an hour-by-hour calculation of the thermal loads produced by the daylighting system, followed by calculations to determine the mechanical energy used to meet these loads. Some building energy simulation programmes cannot perform calculations for optically complex daylighting systems without simplifying assumptions or modifications to the algorithms within the programme. Energy performance modeling has been done by some researchers. Available references are given for each system in Chapter 4.

3.6.3. Peak Demand

Peak demand is the maximum power used by a building during the entire year. For commercial buildings, this peak occurs typically during the hottest period in the summer when the cooling system is running at maximum capacity, and the building is fully occupied. Because the peak cooling load is used to size the mechanical cooling system, its reduction can lead to reduced first cost as a result of system downsizing.

Reduced peak demand also has environmental consequences, because the local utility company must often use expensive, non-environmental energy sources to accommodate this non-recurring load. Utility companies will often penalize building owners for exceeding a maximum load by charging significantly higher rates during peak periods.

Daylighting systems are an effective option to reduce peak demand simply because there is good daylight availability during summer peak periods. Lighting energy use can be significantly reduced if automated control systems are installed in a building. However, in some climates, solar heat gains from uncontrolled daylighting can increase the cooling load. Building energy simulations are required to determine the optimum balance between electric lighting use and cooling energy.

3.7. Economy

Daylighting system material costs are typically greater than the costs of conventional systems, principally because of low volume in an immature market. Rebates and incentives for these early market technologies are offered in some countries. Utility deregulation has contributed to a decline of these economic measures, however. Concerns regarding "free ridership" have resulted in creative methods to reduce the first cost to the consumer of new technologies (e.g., procurement programmes).

Daylighting systems can contribute to lower first costs for a building's mechanical system by lowering peak cooling load relative to that of the same building with conventional lighting design. Mechanical system downsizing is dependent on the mechanical engineer's confidence in the estimated load and the reliability of the daylighting system to reduce loads during peak periods. Since mechanical systems are offered in standard sizes, however, incremental differences in calculated capacity may not always result in a change in equipment size.

Operating costs for energy can be calculated using the local utility rate. It is important to model utility rates accurately (as opposed to using an average flat rate), particularly for daylighting technologies, because savings are often realised during summer peak periods when electricity costs are the highest.

Some daylighting systems should be maintained on a regular basis. Light-admitting apertures that are inclined or horizontal should be cleaned on a scheduled basis to maintain optical efficiency. Systems with operating parts or those that rely on sensors for proper operation must be tuned or recommissioned when the interior space is reconfigured or its use is redefined. If the system is static and enclosed, then maintenance costs will probably be equal to those for conventional systems. Systems that permit natural ventilation may require more maintenance because of increased exposure to weather and dirt.

Environmental costs in all phases of the building life cycle (construction, operation, refurbishment, and dismantling) should also be considered. Some daylighting reflectors require the use of high-grade aluminium coatings to maintain optical efficiency. Anodized aluminium foil represents a large amount of embodied energy (100 MJ/m^2 in the case of recycled aluminium and 360 MJ/m^2 in the case of primary aluminium) whereas aluminium deposition requires far less production energy [Courret et al. 1998].

Codes and Standards 3.8.

Energy-efficiency standards for conventional daylighting systems (i.e., windows, skylights) are widely adopted and implemented in the industry; however, there are no specific standards for the daylighting systems noted in this source book. Conventional codes will either "prescribe" minimum or maximum levels for window properties (U-factor, g-coefficient, air leakage, etc.) or allow the designer to meet "performance" goals. In many European countries where cloudy skies predominate, codes regulate the minimum window size, minimum daylight factor (for commercial and residential buildings), and window position in order to provide view to all occupants and to create a minimum interior brightness level.

The performance goal approach will likely be most appropriate for advanced technologies, such as daylighting systems. To meet performance requirements, a designer must simulate the building's energy consumption with the advanced daylighting system, which, in turn, requires that standardised rating methods and design tools be available to reliably determine product performance. Single manufacturer tests and calculations are insufficient. Standardised industry ratings are critical to ensure code compliance and consumer protection. In addition, field verification protocols are required to ensure proper implementation by code officials. At present, this infrastructure is not routinely in place for daylighting systems in most countries, so there is no way to prove the system's performance. Proof of performance is necessary, however, if the daylighting system is to get credit under energy codes.

Construction and Systems Integration 3.9.

3.9.1. Product Data

When assessing a daylighting system for use within a building, a designer must review architectural, structural, and construction technical data related to the system's use. Most of these data will be available directly from the manufacturer. Other data regarding structural issues (thermal expansion), fire safety (flammability, toxic fumes, melting, breakage), or property safety (bullet-, intrusion-, shatter-resistance, etc.) may not be provided by the manufacturer and thus need to be inferred from experience and knowledge about the materials that make up a system. The architectural appearance of daylighting systems can be conveyed via photographs, line drawings (plans, sections, elevations), product samples, full-scale mock-ups, and other visualisation methods.

Durability is a measure of the degradation of material or system performance resulting from moisture, sunlight, and operating temperatures, as a function of time. This parameter quantifies how key operational, optical, and other parameters will change within the expected lifetime of the product, typically 15-20 years. For example, oxidation may affect the reflectivity of prismatic films. Ultraviolet solar radiation may break down certain plastics. Weathering or corrosion, particularly in locations near the ocean or in industrial settings, may lead to degradation of performance. Durability tests are generally conducted by an independent laboratory that uses standard test procedures.

3.9.2. Systems Integration

Daylighting systems must be designed within the context of all building systems. Interior light shelves, for example, must be considered in the context of overhead electric light because they may create shadows at night. Spray from fire sprinklers or air from mechanical system diffusers may also be blocked by horizontal obstructions such as light shelves. Integrated electric light and daylighting solutions can incorporate ambient or task lighting within the underside or below the light shelf. This may reduce commissioning and tuning costs and can improve the reliability of system performance.

Additional design features that are peripheral to the principal design objective can increase a system's usability within typical building contexts, increase the chances that users will find the system acceptable, and add functionality to a daylighting system. The definition and importance of "usable" features depend on building type. Two usable features are:

Natural Ventilation. For moderate climates and during some periods in all climates, natural ventilation and access to fresh air are amenities that can improve occupants' environmental satisfaction in low-rise commercial buildings, such as schools and small offices. For these building types, daylighting systems that enable a user to fully operate a window or that enable the designer to combine the system with operable windows meet this criterion.

Blackout Option. For some spaces (schools, conference rooms, etc.), complete blackout of daylight is desired for viewing of audiovisual presentations or other activities that require a dark interior space. It is important to provide occupants with operable shades to control daylight when necessary.

3.9.3. User Considerations

Users can react negatively or positively to the physical appearance, operation, and visual quality of daylighting systems. Daylighting effects that occur with conventional window systems are generally expected and acceptable. The degree of acceptance of unusual effects depends on the building type (e.g., occupants will have different expectations regarding the lighting effects in a church than in an office) and the mentality of the occupants.

Documentation of operating features is necessary for sustained performance. User options should be made clear. For example, if a light-redirecting system needs to be adjusted seasonally, there should be clear instructions to the building manager or individual occupants to explain this fact to the users. If there are automatic controls, these features should also be documented as well as explained to the users, especially if these features are essential for accurate or acceptable control. Maintenance, recommissioning, and fine tuning are required for sustained, acceptable performance.

Some systems that involve moving parts and motors may generate unacceptable noise. Daylighting systems that operate within the background noise threshold of the building type are generally considered successful. It should be emphasised, however, that moveable parts are usually not recommended in buildings because of higher failure risks and maintenance costs than for systems without moveable parts.

Daylighting Systems 4.

Introduction 4.1.

This chapter describes the characteristics of advanced daylighting systems, to aid building professionals in choosing a system. Following this introduction, which summarises the key elements of the decision-making process for daylighting systems, Section 4.2 consists of a detailed matrix of daylighting systems classified into two general groups: those with and without shading. The technical descriptions in Sections 4.3 through 4.14 give details about the design and application of each system, the physical principles on which it is based, as well as information about controls, maintenance, costs and energy savings, examples of use, and simulation or measurement results of the performance associated with each system.

The systems in this chapter represent the large range of advanced daylighting systems now available to the building profession. Some of these systems are still in the development or prototype stage and some systems are architectural concepts rather than products (see Chapter 2).

All of these systems have different characteristics related to the major performance parameters discussed in Chapter 3. Because these parameters may have different importance in real-life design cases, it is impossible to develop a unified rating scale or to define a clear-cut selection method for choosing the best daylighting system in a given situation. Nonetheless, there are some general strategies for making decisions about using a daylighting system in a design.

First, a designer should focus on these questions; Chapter 2 discusses in detail the conditions that will govern the answers:

- Is it useful to apply a daylighting system in my case?
- What kind of problems can I resolve with a daylighting system?

- What benefits could I achieve with a daylighting system?

If the use of a daylighting system appears to be a promising option based on this initial screening, the next question is:

- Which system should I choose?

This chapter presents the most comprehensive and up-to-date information available, including measured performance data and expert analysis, to assist designers in answering that question.

The key parameters to consider in choosing a system are:

- Site daylighting conditions—latitude, cloudiness, obstructions
- Daylighting objectives
- Daylighting strategies implied in the architectural design
- Window scheme and function
- Energy and peak power reduction objectives
- Operational constraints—fixed/operable, maintenance considerations
- Integration constraints—architectural/construction integration
- Economic constraints

It is also important to focus on the major objectives for applying daylighting systems:

- redirecting daylight to under-lit zones
- improving daylighting for task illumination
- improving visual comfort, glare control
- achieving solar shading, thermal control.

It is very important that a reader who wishes to compare the merits of different systems understand the context of the results given in this chapter. Some measurement results come from scale-model experiments under simulated light conditions while others come from full-scale test rooms under real sky conditions at different locations around the world (see testing facility descriptions given in Appendix 8.4). Because experimental test rooms and conditions differ so significantly from site to site, we cannot compare the numerical results from different experimental sites. The general conclusions drawn for each system are valid, but specific details, such as the absolute magnitude of illumination levels, cannot be compared among systems tested at different sites.

4.2. System Matrix

The matrix that follows covers two groups of daylighting systems—those with and without shading.

Daylighting Systems with Shading

Two types of daylighting systems with shading are covered: systems that rely primarily on diffuse skylight and reject direct sunlight, and systems that use primarily direct sunlight, sending it onto the ceiling or to locations above eye height.

Shading systems are designed for solar shading as well as daylighting; they may address other daylighting issues as well, such as protection from glare and redirection of direct or diffuse daylight. The use of conventional solar shading systems, such as pull-down shades, often significantly reduces the admission of daylight to a room. To increase daylight while providing shading, advanced systems have been developed that both protect the area near the window from direct sunlight and send direct and/or diffuse daylight into the interior of the room.

Daylighting Systems Without Shading

Daylighting systems without shading are designed primarily to redirect daylight to areas away from a window or skylight opening. They may or may not block direct sunlight. These systems can be broken down into four categories:

> **Diffuse Light-Guiding Systems** redirect daylight from specific areas of the sky vault to the interior of the room. Under overcast sky conditions, the area around the sky zenith is much brighter than the area close to the horizon. For sites with tall external obstructions (typical in dense urban environments), the upper portion of the sky may be the only source of daylight. Light-guiding systems can improve daylight utilisation in these situations.

> **Direct Light-Guiding Systems** send direct sunlight to the interior of the room without the secondary effects of glare and overheating.

> **Light-Scattering or Diffusing Systems** are used in skylit or toplit apertures to produce even daylight distribution. If these systems are used in vertical window apertures, serious glare will result.

> **Light Transport Systems** collect and transport sunlight over long distances to the core of a building via fiber-optics or light pipes.

Some Notes on the Information in the Matrix

Some systems included in the matrix can fulfil multiple functions and are therefore shown in more than one category. Light shelves, for instance, redirect both diffuse skylight and beam sunlight.

Selected column headings from the matrix that are not self-explanatory are described in detail below:

Under the heading "Glare protection," the following questions were considered: Does the system prevent glare when viewed directly from the interior, glare from direct sun, and glare from veiling reflections?

In evaluating "View outside," the matrix considers the following questions: Does the system permit a transparent, undistorted view when used in its primary design position? For example, the systems known as anidolic zenithal openings do not permit a clear unobstructed view to the exterior (they are typically used above a transparent window which does permit an unobstructed view).

For the column headed "Light-guiding into the depth of the room," the matrix answers the question: Does the system achieve light redirection to depths that are greater than conventional perimeter window systems?

In the column "Homogeneous illumination," the matrix addresses the question: Does the system achieve a uniform distribution of daylight throughout a space (walls and ceiling)? In assessing "Savings potential (artificial lighting)," the matrix answers the question: Does the system effectively displace the use of artificial lighting compared to conventional systems?

In the column headed "Need for tracking," the matrix answers the question: Are passive adjustments or mechanical systems needed to track the diurnal or seasonal movement of the sun throughout the day or year to maintain efficient performance?

"Availability" indicates whether the technology is commercially available (A) or is still in the testing stage (T). Contact information for manufacturers of commercially available systems is given in Appendix 8.6. Some systems that are labeled as available must be designed and constructed as an integral part of the building envelope, e.g., light shelves.

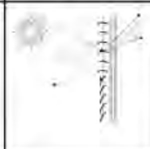
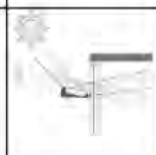
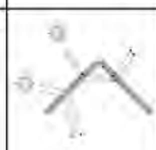
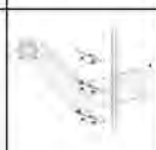
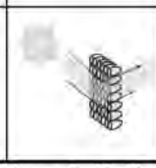
For most of the systems included, detailed information is given in the technical descriptions that follow the matrix. An important exception is light transport systems (group 2D), which were beyond the scope of this work.

1. Shading Systems

Category	Type/name	Sketch	Climate	Location	Criteria for the choice of elements: Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving potential (artificial lighting)	Need for tracking	Availability
1A Primary using diffuse skylight	Prismatic panels (→ 4.5)		All climates	Vertical windows, skylights	**D**	**N**	**D**	**D**	**D**	**D**	**A**
	Prisms and venetian blinds		Temperate climates	Vertical windows	**Y**	**D**	**Y**	**Y**	**Y**	**Y**	**A**
	Sun protecting mirror elements		Temperate climates	Skylights, glazed roofs	**D**	**N**	**N**	**Y**	**N**	**N**	**A**
	Anidolic zenithal opening (→ 4.12, 4.13)		Temperate climates	Skylights	**Y**	**N**	**N**	**Y**	**Y**	**N**	**T**
	Directional selective shading system with concentrat-ing Holo-graphic Optical Element (HOE) (→ 4.11)		All climates	Vertical windows, skylights, glazed roofs	**D**	**Y**	**N**	**D**	**Y**	**Y**	**T**
	Transparent shading system with HOE based on total reflection (→ 4.11)		Temperate climates	Vertical windows, skylights, glazed roofs	**D**	**Y**	**N**	**Y**	**Y**	**Y**	**A**

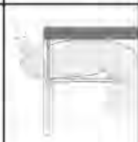
Y= Yes , D= Depends, N= No, A= Available, T= Testing phase, "→ n" = See section number n

1. Shading Systems

Category	Type/name		Climate	Location	Criteria for the choice of elements: Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving of energy for artificial light-ing	Need for tracking	Availability
1B Primary using direct sunlight	Light guiding shade (→ 4.7)		Hot climates, sunny skies	Vertical windows above eye height	**Y**	**Y**	**D**	**D**	**D**	**N**	**T**
	Louvres and blinds (→ 4.4)		All climates	Vertical windows	**Y**	**D**	**Y**	**Y**	**Y**	**Y**	**A**
	Light shelf for redirection of sunlight (→ 4.3)		All climates	Vertical windows	**D**	**Y**	**Y**	**Y**	**Y**	**N**	**A**
	Glazing with reflecting profiles (Okasolar)		Temperate climates	Vertical windows, skylights	**D**	**D**	**D**	**D**	**D**	**N**	**A**
	Skylight with Laser Cut Panels (LCPs) (→ 4.7)		Hot climates, sunny skies, low latitudes	Skylights	**D**		**Y**	**Y**	**Y**	**N**	**T**
	Turnable lamellas		Temperate climates	Vertical windows, skylights	**Y/D**	**D**	**D**	**D**	**D**	**Y**	**A**
	Anidolic solar blinds (→ 4.13)		All climates	Vertical Windows	**Y**	**D**	**Y**	**Y**	**D**	**N**	**T**

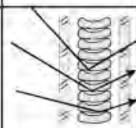
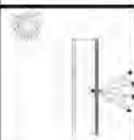
Y= Yes , D= Depends, N= No, A= Available, T= Testing phase, "→ n" = See section number n

2. Daylighting systems without shading included

Category	Type/name	Sketch	Climate	Location	Criteria for the choice of elements: Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving of energy for artificial lighting	Need for tracking	Availability
2A Diffuse light guiding systems	Light shelf (→ 4.3)		Temperate climates, cloudy skies	Vertical windows	**D**	**Y**	**D**	**D**	**D**	**N**	**A**
	Anidolic Integrated System (→ 4.12)		Temperate climates	Vertical windows	**N**	**Y**	**Y**	**Y**	**Y**	**N**	**A**
	Anidolic ceiling (→ 4.12)		Temperate climates, cloudy skies	Vertical facade above view-ing window		**Y**	**Y**	**Y**	**Y**	**N**	**T**
	Fish System		Temperate climates	Vertical windows	**Y**	**D**	**Y**	**Y**	**Y**	**N**	**A**
	Zenith light guiding elements with HOEs (→ 4.10)		Temperate climates, cloudy skies	Vertical windows (especially in court-yards), skylights		**Y**	**Y**	**Y**	**Y**	**N**	**A**
2B Direct light guiding Systems	Laser Cut Panel (→ 4.6)		All climates	Vertical windows, skylights	**N**	**Y**	**Y**	**Y**	**Y**	**N**	**T**
	Prismatic panels (→ 4.5)		All climates	Vertical windows, skylights	**D**	**D**	**D**	**D**	**D**	**Y/N**	**A**

Y= Yes , D= Depends, N= No, A= Available, T= Testing phase, "→ n" = See section number n

2. Daylighting systems without shading included

Category	Type/name	Sketch	Climate	Location	Criteria for the choice of elements						
					Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving of energy for artificial lighting	Need for tracking	Availability
2B Direct light guiding Systems	HOEs in the skylight		All climates	Skylights	**D**	**Y**	**Y**	**Y**	**Y**	**N**	**A**
	Sun-directing glass (→ 4.9)		All climates	Vertical windows, skylights	**D**	**N**	**Y**	**Y**	**Y**	**N**	**A**
2C Scattering systems			All climates	Vertical Windows, skylights	**N**	**N**	**Y**	**Y**	**D**	**N**	**A**
2D Light transport	Heliostat		All climates, sunny skies				**Y**		**Y**	**Y**	**A**
	Light Pipe		All climates, sunny skies				**Y**	**Y**	**Y**	**N**	**A**
	Solar Tube		All climates, sunny skies	Roof			**Y**	**D**	**Y**	**N**	**A**
	Fibres		All climates, sunny skies				**Y**		**Y**	**Y**	**A**

Y= Yes , D= Depends, N= No, A= Available, T= Testing phase, "→ n" = See section number n

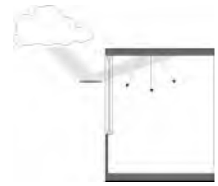
2. Daylighting systems without shading included

Category	Type/name	Sketch	Climate	Location	Criteria for the choice of elements						
					Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving of energy for artificial lighting	Need for tracking	Availability
2D Light transport	Light-guiding ceiling		Temperate climates, sunny skies				**Y**	**Y**	**Y**	**N**	**T**

Y= Yes , D= Depends, N= No, A= Available, T= Testing phase, "→ n" = See section number n

4.3. Light Shelves

A light shelf is a classic daylighting system, known to the Egyptian Pharaohs, that is designed to shade and reflect light on its top surface and to shield direct glare from the sky.



4.3.1. Technical Description

Components

A light shelf is generally a horizontal or nearly horizontal baffle positioned inside and/or outside of the window facade. The light shelf can be an integral part of the facade or mounted on the building.

Figure 4-3.1: Semi-transparent double light shelves made out of reflective glass [Littlefair 1996]

Production

Light shelves are not standard, off-the-shelf products. They must be made to fit the architectural situation in which they are used.

Location in Window System

A light shelf is usually positioned above eye level. It divides a window into a view area below and a clerestory area above. Light shelves sometimes employ advanced optical systems to redirect light to deep areas of the building interior. The light shelf is typically positioned to avoid glare and maintain view outside; its location will be dictated by the room configuration, ceiling height, and eye level of a person standing in the space. Generally, the lower the light shelf height, the greater the glare and the amount of light reflected to the ceiling.

Technical Barriers

An internal light shelf, which redirects and reflects light, will reduce the amount of light received in the interior relative to a conventional window. Both full-scale and scale model measurements have shown that windows with internal light shelves produce an overall reduced daylight factor on the work plane throughout the interior space compared to a non-shaded window of equal size [Aizlewood 1993, Christoffersen 1995, Littlefair 1996, Michel 1998]. In some cases, use of an external light shelf makes it possible to increase the total amount of daylight compared to that provided by traditional windows. An external light shelf increases exposure to the high luminance area near the sky zenith. Depending on the light shelf's geometry, available daylight will be more uniformly distributed by an external light shelf compared to a non-shaded window of equal size.

4.3.2. Application

Light shelves affect the architectural and structural design of a building and must be considered at the beginning of the design phase because they require a relatively high ceiling in order to function effectively. Light shelves should be designed specifically for each window orientation, room configuration, and latitude. They can be applied in climates with significant direct sunlight and are applicable in deep spaces on a south orientation in the northern hemisphere (north orientation in the southern hemisphere). Light shelves do not perform as well on east and west orientations and in climates dominated by overcast sky conditions.

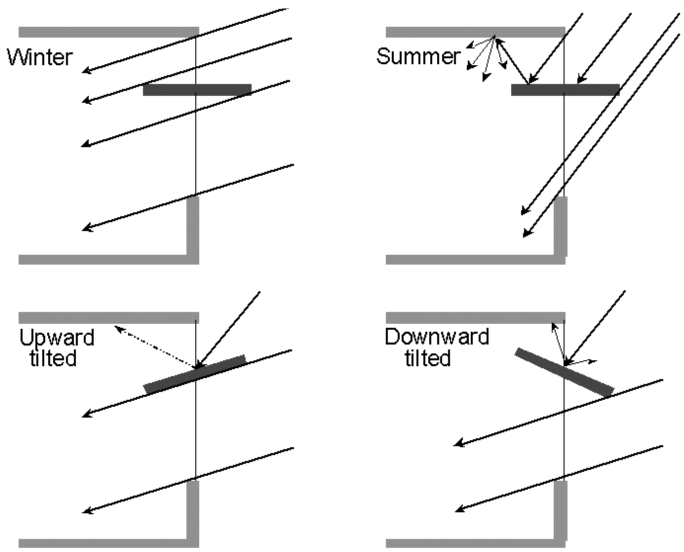


FIGURE 4-3.2: TOP SECTION OF AN INTERIOR AND EXTERIOR LIGHT SHELF WITH SPECULAR SURFACE, SHOWING THE PATH OF SUNLIGHT RAYS IN THE WINTER AND IN THE SUMMER. BOTTOM SECTION SHOWS HOW AN UPWARD- OR DOWNWARD-TILTED REFLECTIVE LIGHT SHELF INFLUENCES SHADING AND DAYLIGHT REFLECTION. NOTE THAT, IN WINTER, THE LIGHT SHELF ALONE DOES NOT ADEQUATELY CONTROL GLARE

4.3.3. Physical Principles and Characteristics

The orientation, position in the facade (internal, external, or combined), and depth of a light shelf will always be a compromise between daylight and shading requirements. An internal light shelf, which redirects and reflects light, will reduce the amount of light received in the interior. For south-facing rooms (in the northern hemisphere), it is recommended that the depth of an internal light shelf be roughly equal to the height of the clerestory window head above the shelf. Moving the light shelf to the exterior creates a parallel movement of shaded area towards the window facade, which reduces daylight levels near the window and improves daylight uniformity. The recommended depth of an external light shelf is roughly equal to its own height above the work plane [Littlefair 1995]. Glazing height and light shelf depth should be selected based on the specifics of latitude and climate.

At low latitudes, the depth of internal light shelves can be extended to block direct sunlight coming through the clerestory window at all times (see Figure 4-3.2). At higher latitudes and with east- or west-facing rooms, a light shelf may let some direct sunlight (low solar elevation) penetrate the interior, through the space between the light shelf and the ceiling, resulting in the need for additional shading devices. Increasing the depth of the shelf will reduce the problem but will also obstruct desired daylight penetration and outside view. Shading the window perimeter by tilting the shelf downward will reduce the amount of light reflected to the ceiling. Upward tilting will improve penetration of reflected daylight and reduce shading effects. A horizontal light shelf usually provides the best compromise between shading requirements and daylight distribution.

The ceiling is an important secondary part of the light shelf system because light is reflected by the light shelf towards the ceiling and then reflected from the ceiling into the room. The characteristics of the ceiling that affect this process are surface finish, smoothness, and slope. Although a ceiling with a specular surface will reflect more light into the room, care should be taken to avoid glare from the ceiling reflections near the light shelf. To avoid glare, the ceiling finish is usually white diffusing or low-gloss paint.

The penetration of light from a light shelf system depends on the ceiling slope. A gable style ceiling that slopes upwards from the window towards the centre of the building will dramatically increase the depth to which light from the light shelf penetrates into the building. For a flat ceiling, light from the light shelf is mostly reflected into the space near the window, so penetration of light into the room is more modest.

Conventional Light Shelf

A light shelf is usually a fixed, solid system, but some fixed external light shelves can incorporate slatted baffle systems with reduced upward reflection. The finish of a light shelf influences the "efficiency" and direction of light redirected from its top to the ceiling. A matte finish produces diffuse reflection with no directional control, in contrast to a specular reflection where the angle of incidence is (almost) equal to the angle of reflection. For a perfectly diffusive surface (Lambertian), only half of the reflected light will be distributed into the room, but, for an interior light shelf, some of the "lost" light is reflected towards the interior from the clerestory glass surface. A highly reflective surface (e.g., a mirror, aluminium, or a polished material) reflects more light to the ceiling than a diffuse surface but may reflect onto the ceiling an image of any dirt pattern on it [Lam 1986]. A semi-specular finish for the top of the light shelf may be better. Another possibility is a reflecting prismatic film to throw light further into the room [Littlefair 1996].

Optically Treated Light Shelf

Optically treated light shelves make two significant improvements over conventional light shelf designs for sunny climates, see Figure 4-3.3: 1) The light shelf geometry is curved and segmented to passively reflect sunlight for specific solar altitudes, and 2) commercially available, highly reflective, semi-specular optical films can increase efficiency [Beltrán et al. 1997]. Design objectives are to block direct sun at all times, to increase daylight illuminance levels up to 10 m from the window wall, to minimise solar heat gains through an optimally sized window aperture, and to improve daylight uniformity and luminance gradient throughout the room under variable direct sun conditions. For consistent performance throughout the year, the optically treated light shelf will project from the exterior wall by 0.1–0.3 m to intercept high summer sun angles. No active adjustment or control is required.

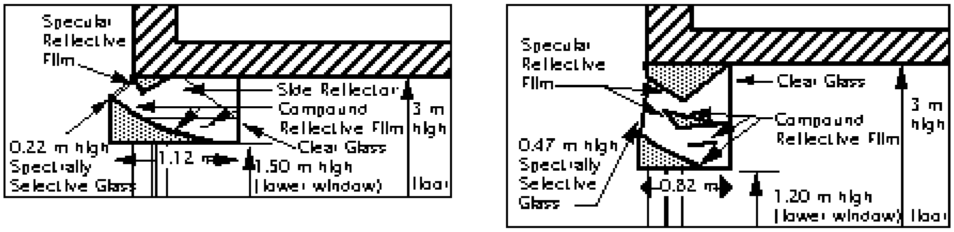


Figure 4-3.3: Section of light shelf: (left) single-level light shelf, (right) bi-level light shelf

The optically treated light shelf design consists of a main lower reflector and a secondary upper reflector. The lower segmented reflector consists of inclined surfaces that are finished with a daylight film. The film has linear grooves that reflect sunlight within a 12–15° outgoing angle at normal incidence to the grooves. The segments are inclined to reflect sun to the ceiling plane up to 10 m from the window wall for noon solstice and equinox sun angles (south-facing facades in the northern hemisphere). The upper reflector is placed above the main reflector at the ceiling plane near the window to intercept incoming low winter sun angles and to reflect these rays to the lower main reflector. This reflector is surfaced with a highly reflective specular film and may be a small-area source of glare.

This system has been developed conceptually using scale models. A full-scale modified skylight prototype has been built and installed in a small office building [Lee et al. 1996]. For vertical window applications, efficient performance of the system requires a room height greater than 2.5 m from floor to ceiling. It is possible to design and adapt an optically treated light shelf to existing buildings, but special care should be taken to integrate it with existing architectural features.

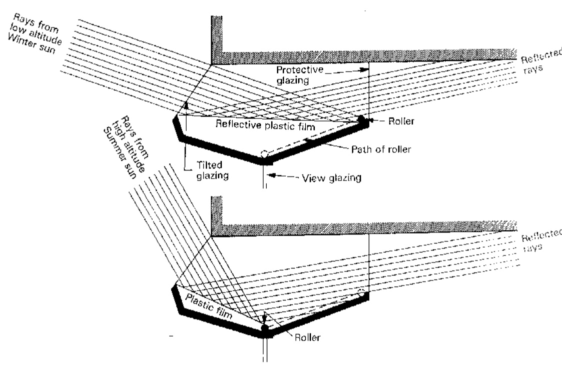


Figure 4-3.4: Winter and summer operation of the VALRA (Variable Area Light Reflecting Assembly) [Littlefair 1996, Howard et al. 1986]

Sun-Tracking Light Shelf

A variable area light reflecting assembly (VALRA) is a tracking light shelf system (see Figure 4-3.4) that reflects light into a building [Howard et al. 1986]. The system uses a reflective plastic film surface over a tracking roller assembly within a fixed light shelf. This system extends the projection capabilities of a fixed light shelf so that it functions for all sun angles. It has not been installed in a building to date. A simpler version of a light shelf that can be adjusted according to sun position or the sky luminance is the movable (pivotable), external light shelf (see monitored results from Denmark below).

4.3.4. Control

In general, movable light shelves are more expensive (especially if motorized) than fixed light shelves, but movable systems are more flexible in control and application. Downward tilted light shelves shade window perimeters and reduce the amount of light reflected to the ceiling. Upward-tilted light shelves improve penetration of reflected daylight but reduce the shading effect of the window perimeter. Exterior-mounted light shelves reduce cooling loads by providing more shading of direct sun to lower view apertures relative to what is possible with unobstructed windows with or without interior shades. With interior-mounted light shelves, there will be an increase in transmitted direct solar radiation through the non-shaded clerestory window above the light shelf, compared to the light transmitted by a window that has an interior shading device that covers the full height of the window. The type of glazing in the clerestory window and lower view window aperture will also affect solar heat gains.

4.3.5. Maintenance

Light shelves require regular cleaning. An internal shelf collects dust, and an external shelf can become dirty, collect snow, and provide nesting places for birds or insects. A specular surface requires maintenance to maintain its reflective properties. Optically treated light shelves are completely sealed from the interior and exterior environment and protected from dirt and occupant interference. They require no routine maintenance other than cleaning of the exterior and interior glass.

4.3.6. Cost and Energy Savings

Reduced light at a window wall can lead to increased use of electric lighting, but increasing the uniformity of light distribution in the same situation may cause the room to be perceived as relatively well lit, which may reduce the probability that occupants will switch on electric lights. The total amount of daylight can be enhanced by using an external light shelf, depending on the shelf's geometry and surface treatment. However, most traditional light shelves do not, in general, produce high levels of illuminance deep inside a space, so energy savings are modest.

The optically treated light shelf can introduce adequate ambient illuminance for office tasks in a 5 m to 10 m zone of a deep perimeter space under most sunny conditions with a relatively small inlet area. It has been found that a room with the optically treated light shelf can use less total annual electricity for lighting than one with a conventional light shelf.

4.3.7. Some Examples of Use

- De Montfort University Engineering, Leicester, UK: internal light shelf
- Greenpeace, London, UK: external light shelf
- South Staffordshire Water, Walsall, UK: internal and external (sloped) light shelf

- Sacramento Municipal Utility District (SMUD) Headquarters, Sacramento, California, USA: internal sloped Mylar sail light shelf (Figure 4-3.5)
- Lockheed Building 157, Sunnyvale, California, USA: south exterior light shelf with curved segmented shape and north interior flat light shelf (3.7 m deep)
- Palm Springs Chamber of Commerce, Palm Springs, California, USA: Skylight with optically treated light shelf (Figure 4-3.6)

Figure 4-3.5: View of interior/exterior light shelf at the SMUD Headquarters, California

Figure 4-3.6: South side of an optically treated skylight system, Palm Springs, California

4.3.8. Simulations and Measured Results

Measurements were made of three different conventional light shelves with various surface treatments and locations in the facade (interior and exterior).

A.	Exterior light shelf mounted on a pivot with semi-reflective surface	**Denmark**
B.	Interior fixed light shelf with semi-reflective surface	**Norway**
C.	Interior fixed light shelf with semi-transparent surface	**Norway**

Figure 4-3.7: The exterior semi-reflective light shelf in a downward-tilted position

A. Exterior Light Shelf with Semi-Reflective Surface (Denmark)

The Danish Building Research Institute, Denmark (DEN), tested an exterior light shelf (0.8 m deep), shaped like a "flight wing", and mounted on a pivot on the south facade. The surface of the shelf is polished aluminium with 75% reflectance.

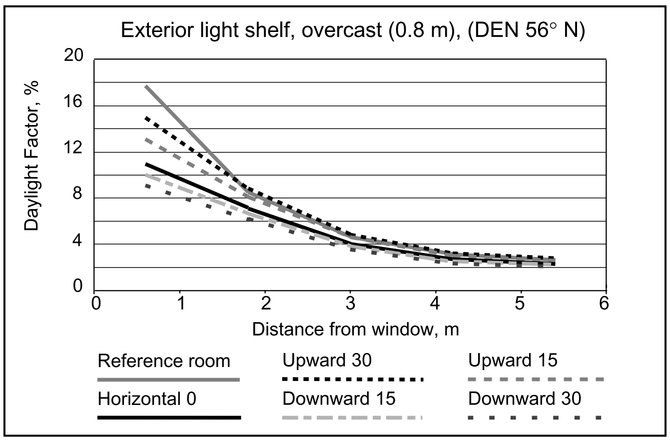
Two identical rooms at the institute were oriented 7° east of due south with some outside obstructions to the west. Each room has windows that extend the full height of the facade, but the lower part of the windows, from the floor to a sill height of 0.78 m, was covered during the measurements (see test room descriptions in Appendix 8.4). The reference room had clear, unshaded glazing.

Light Shelf - Exterior (0.8 m deep) **Denmark: 56°N** Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Horizontal - Overcast (DF%)	7.1%	8.6%	4.1%	4.7%	2.3%	2.7%	16.2	6.5
Upward tilted 15° - Overcast (DF%)	8.1%	8.4%	4.6%	4.6%	2.6%	2.6%	12.1	4.8
Upward tilted 30° - Overcast (DF%)	8.8%	8.4%	4.9%	4.6%	2.8%	2.6%	12.9	5.0
Downward tilted 15° - Overcast (DF%)	6.7%	8.5%	3.9%	4.7%	2.2%	2.7%	9.6	3.8
Downward tilted 30° - Overcast (DF%)	6.2%	8.6%	3.5%	4.8%	2.0%	2.7%	11.6	4.7
Horizontal - Clear winter: Noon	Sun	Sun	> 4,000	> 4,000	> 4,000	> 4,000	17.1	52.8
Horizontal - Clear winter: 15:00	880	1040	600	690	380	430	4.3	5.9
Horizontal - Clear equinox: Noon	Sun	Sun	> 4,000	> 4,000	> 4,000	> 4,000	38.6	95.1
Horizontal - Clear equinox: 15:00	6,510	7,250	> 4,000	> 4,000	3,060	3,450	27.5	58.4
Upward tilted 30° - Clear equinox: Noon	Sun	Sun	> 4,000	> 4,000	> 4,000	> 4,000	53.8	96.2
Upward tilted 30° - Clear equinox: 15:00	Sun	Sun	> 4,000	> 4,000	3,830	3,620	33.0	62.1
Horizontal - Clear summer: 9:00	4,030	4,370	2,500	2,760	1,540	1,760	69.5	40.7
Horizontal - Clear summer: Noon	6,700	6,630	3,770	> 4,000	2,270	2,730	96.8	66.5
Upward tilted 30° - Clear summer: Noon	6,400	5,580	> 4,000	> 4,000	3,240	2,670	102.3	70.8
Upward tilted 30° - Clear summer: 15:00	4,710	3,940	3,270	2,700	2,120	1,770	92.9	47.5
Downward tilted 30° - Clear summer: 9:00	2,570	3,350	1,650	2,220	1,040	1,440	71.6	39.3
Downward tilted 30° - Clear summer: Noon	3,190	4,990	2,160	3,610	1,380	2,300	101.5	67.8

Note: The window, intermediate, and rear zone sensors were 1.8, 3.0, and 5.4 m from the window, respectively. "Sun" indicates sunlight striking the sensors. ">4000" indicates that the sensors are at a state of saturation. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing 7° east of due south. DF% is the daylight factor.

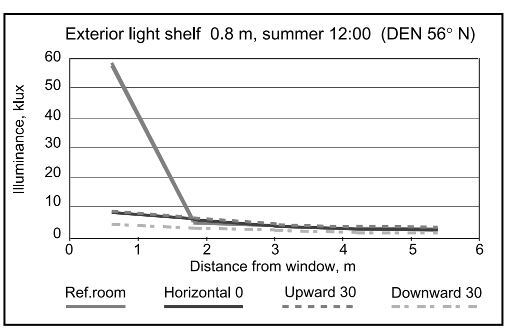
Overcast Sky

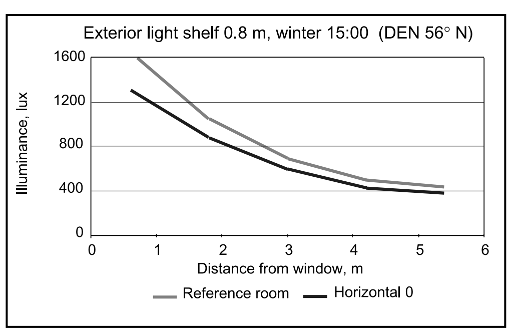
The exterior light shelf shades the window zone and evens out the luminance difference within the room. Five different slope angles were measured. Tilting the light shelf upward (-30°) increases the illuminance level in the intermediate zone compared to illuminance in the reference room which has an unshaded window of equal size. Thus there is, in general, some evening out of luminance variations between the window perimeter and the interior depth of the room.



Clear Sky

In summer, the exterior light shelf completely shades an area near the window from direct sunlight. Reflected sunlight illuminates the ceiling, but only the upward-tilted light shelf (-30°) boosts the illuminance level (10–20% in relative values) at the back of the room. The horizontal light shelf reduces the light level by 10% to 20% in most of the room, and the downward-tilted light shelf (30°) reduces the light level by 30% to 40%. At equinox, the exterior light shelf behaves much as in the summer. The semi-specular surface of the horizontal light shelf reflects sunlight further into the room and increases the illuminance level slightly at the back of the room. The upward-tilted light shelf (-30°) does not increase the illuminance level at the back as it does in summer. The illuminance level is the same as in the reference room because the light shelf does not block direct sunlight coming through the clerestory window. At low sun angles in winter, direct sunlight penetrates the interior through the space below and above the light shelf, resulting in a need for additional shading devices.





Conclusion (A)

A conventional light shelf has limited application in high-latitude countries because additional shading devices will be necessary during much of the year. If used in climates dominated with overcast sky conditions, the light shelf should be tilted. In sunny climates or low-latitude countries, the light shelf will protect areas near the window from direct sunlight with only a slight reduction in light levels throughout the rest of the room. To reduce cooling loads and solar gain, an exterior light shelf is the best compromise between shading requirements and daylight distribution.

B. Interior Light Shelf with Semi-Reflective Surface (Norway)

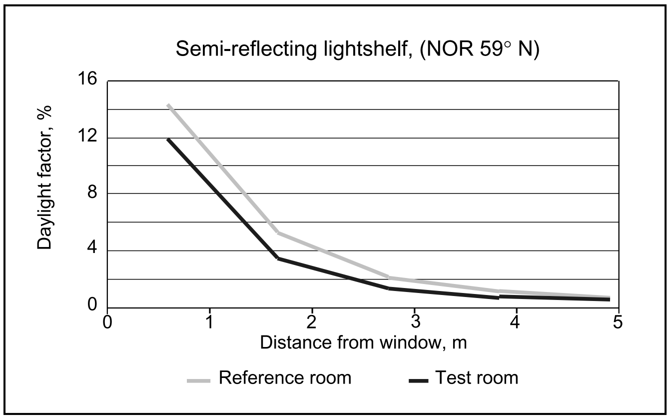
The Norwegian University of Science and Technology, Norway (NOR), tested an interior horizontal light shelf 1.0 m deep, the full width of the window, and mounted between the clerestory window (1.0 m^2) and the view window (2.2 m^2). The surface of the light shelf is covered with a semi-reflective, brushed aluminium sheet. The reference room had clear, unshaded glazing of equal size to the test room. Measurements were made in an occupied office building at Sandvika, Norway (near Oslo) at latitude 59ºN. See detailed test room description in Appendix 8.4.

Interior translucent blinds **UK: 52°N** Monitoring case and time	Interior Illuminance level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Horizontal 0° - Overcast (DF%)	3.6 %	9.0 %	1.7 %	2.9 %	0.5 %	0.7 %	19.6	7.8
Downward 45° - Overcast (DF%)	4.2 %	10.4 %	2.1 %	3.2 %	1.0 %	1.3 %	3.6	1.5
Closed 90° - Overcast (DF%)	2.0 %	8.9 %	0.8 %	2.7 %	0.3 %	0.7 %	8.5	3.4
Horizontal 0° - Clear winter: Noon	3,120	3,920	Sun	Sun	1,110	1,500	29.4	71.3
Horizontal 0° - Clear winter: 15:00	2,100	2,910	1,350	1,690	570	730	12.8	35.8
Horizontal 0° - Clear equinox: Noon	2,790	4,070	1,380	1,500	640	750	55.5	86.5
Horizontal 0° - Clear equinox: 15:00	2,310	3,530	1,150	1,760	520	790	35.1	66.5
Downward 45° - Clear equinox: Noon	1,810	2,390	930	1,130	460	570	77.1	77.4
Downward 45° - Clear equinox: 15:00	1,410	2,550	720	1,220	360	580	56.8	63.2
Closed 90° - Clear equinox: Noon	250	4,450	250	1,700	40	780	NA	NA
Closed 90° - Clear equinox: 15:00	200	3,300	90	1,440	20	640	NA	NA

Note: For overcast sky measurements, the window, intermediate, and rear zone sensors were 1.05, 2.89, and 6.34 m from the window, respectively. For clear sky measurements, the window, intermediate, and rear zone sensors were 2.7, 4.5, and 8.1 m from the window, respectively. The tilt angle is defined as the vertical angle from horizontal where a positive angle is downwards, with a view of the ground from inside the building. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

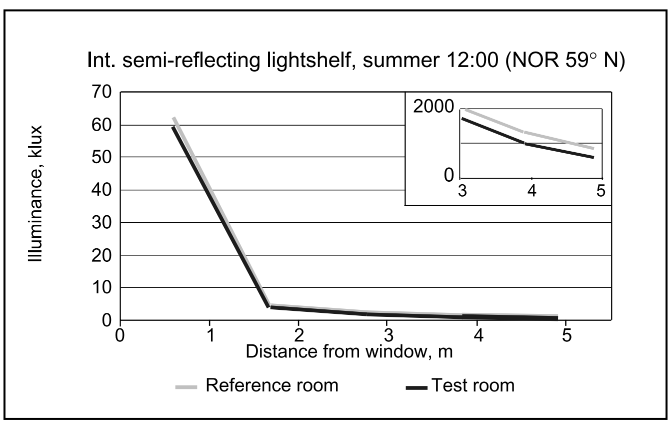
Overcast Sky

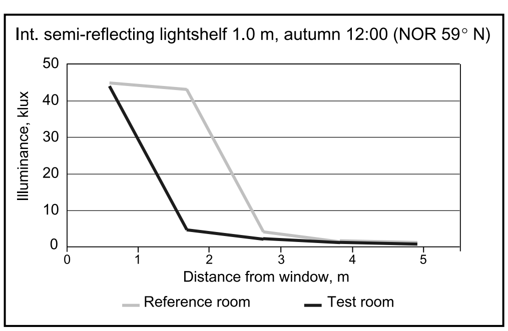
The internal light shelf reduces illuminance by 20% to 35% in the whole room. Even if the light shelf reduces the illuminance in the window zone, the daylight uniformity is not improved because the reduction is also considerable in the rest of the room.

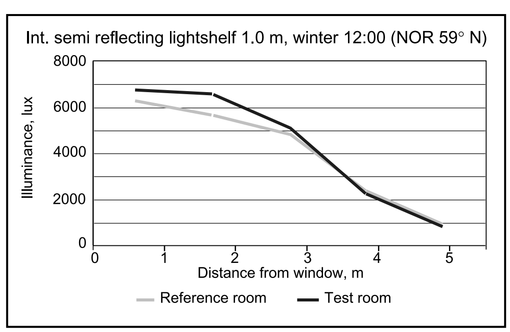


Clear Sky

Even at high sun angles in summer (53°), the light shelf does not protect areas near the window from direct sun. There is a small reduction in illuminance in the intermediate zone and a somewhat larger reduction in the rear wall zone (10–20%). In the spring and autumn, the light shelf shades direct sun in the window zone, but it also reduces illuminance by about 25% in the rear wall zone. At very low sun angles in winter, the illuminance increases in the window zone, probably because of inter-reflections between the desk and the underside of the light shelf (made of the same material as the upper side of the shelf). The light shelf does not increase the illuminance in the rear wall zone.







Conclusion (B)

The internal light shelf with semi-reflective surface does not increase the uniformity of daylight distribution in the room and it does not protect the window zone from direct sun. At low sun angles, an additional shading device is necessary to avoid glare problems. A deep horizontal light shelf installed just above head level may often also cause architectural or esthetic problems.

C. Interior Light Shelf with Semi-Transparent Surface (Norway)

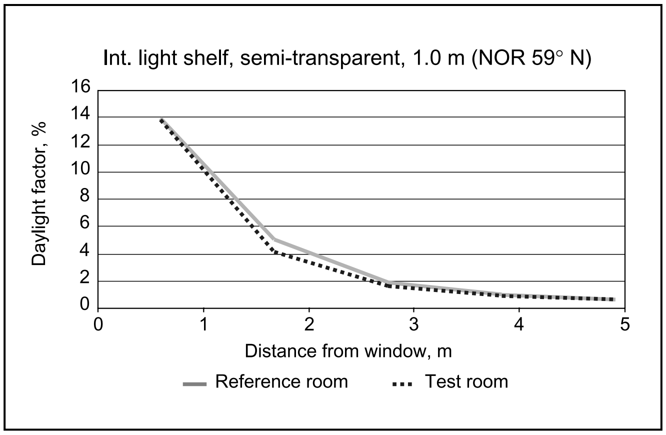
The Norwegian University of Science and Technology tested an interior horizontal light shelf 1.0 m deep, the full width of the window, and mounted between a clerestory window (1.0 m^2) and a view window (2.2 m^2). The light shelf is made of solar control glazing (Pilkington Kappa Sol Reflecta, now known as Pilkington Eclipse: light transmission 33%, reflection 43% or 50% depending on mounting), which gives the light shelf a semi-transparent surface. The reference room had clear, unshaded glazing of equal size to the test room. Measurements were made in an occupied office building at Sandvika, Norway (near Oslo) at latitude 59°N. See detailed test room description in Appendix 8.4.

Light Shelf - Interior (1.0 m deep) Norway: 59°N Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Horizontal - Overcast (DF%)	4.2%	5.0%	1.6%	1.9%	0.7%	0.7%	5.9	2.4
Horizontal - Clear winter: Noon	Sun	Sun	Sun	Sun	Sun	Sun	18.7	69.9
Horizontal - Clear equinox: Noon	Sun	Sun	2,330	1,930	1,110	970	68.5	90.7

Note: The window, intermediate, and rear zone sensors were 1.67, 2.75, and 4.91 m from the window, respectively. “Sun” indicates sunlight striking the sensors. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

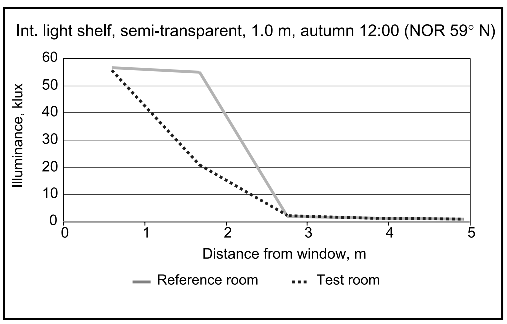
Overcast Sky

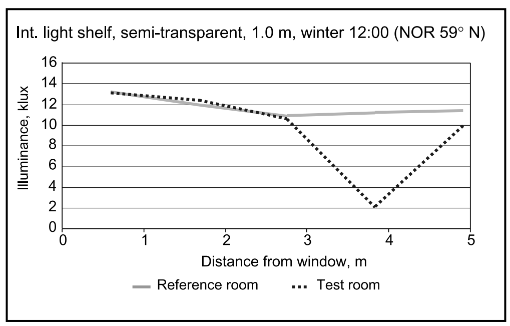
The internal light shelf reduces illuminance by about 15% in the intermediate zone. In the rear wall zone, the illuminance is equal to that observed in the reference room. The luminance difference is large in the area close to the window, and the daylight distribution in the window zone has a greater gradient in the test room than in the reference room.



Clear Sky

In spring or autumn, the light shelf shades an area near the window from direct sunlight, and the illuminance in the intermediate and rear wall zone is somewhat increased (10–20%). At very low sun angles, the internal light shelf does not shade or redirect direct sunlight. The whole work plane is exposed to direct sunlight.



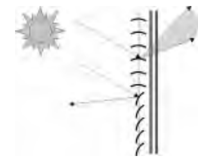


Conclusion (C)

The internal light shelf with semi-transparent surface does not increase the uniformity of daylight distribution in the room. At equinox, the light shelf may shade an area near the window from direct sunlight, but at low sun angles an additional shading device is necessary to avoid glare problems. A deep horizontal light shelf installed just above head height may often also cause architectural or aesthetic problems.

Figure 4-3.8: interior view of the test room with a semi-transparent, interior light shelf on an overcast winter day

4.4. Louvers and Blind Systems



Louvers and blinds are classic daylighting systems that can be applied for solar shading, to protect against glare and to redirect daylight.

4.4.1. Technical Description

Components

Louvers and blinds are composed of multiple horizontal, vertical, or sloping slats. There are various kinds of louver and blind systems, some of which make use of highly sophisticated shapes and surface finishes. Many of these specific types of systems are described below following a general description of conventional louvers and blinds.

Production

Exterior louvers are usually made of galvanised steel, anodised or painted aluminium, or plastic (PVC) for high durability and low maintenance. Interior venetian blinds are usually made from small- or medium-sized PVC or painted aluminium. The slats can be either flat or curved. Slats are usually evenly spaced at a distance that is smaller than the slat width so that the slats will overlap when fully closed. Slat size varies with the location of the blinds: exterior, interior, or between the panes in a double-paned window. Exterior slats are usually between 50 and 100 mm wide; interior slats are usually 10 to 50 mm wide.

Location in Window System

Louvers or blinds can be located on the exterior or interior of any window or skylight, or between two panes of glass. Louvers are generally situated on the exterior of the facade; blinds are fitted inside or between glazing.

Technical Barriers

Depending on slat angle, louvers and blinds partly or completely obstruct directional view to the outside. Vertical blinds allow a vertical view of the sky dome, and horizontal blinds reduce the vertical height of the exterior view. An occupant's perception of view can sometimes be obstructed by the small-scale structure of slats, which generates visual confusion as the eye sorts out the outside view from the blind itself. Many louvers and blinds are therefore designed to be fully or partially retracted.

Under sunny conditions, blinds can produce extremely bright lines along the slats, causing glare problems. With blinds at a horizontal angle, both direct sunlight and diffuse skylight can increase window glare due to increased luminance contrast between the slats and adjacent surfaces. Tilting the blinds upward increases glare as well as visibility of the sky; tilting the blinds downward provides shading and reduces glare problems. Glossy, reflective blinds may generate additional glare problems because sun and skylight may be reflected off the slat surface directly into the field of view. Some of these problems can be reduced by use of a diffuse slat surface.

4.4.2. Application

Louvers and blinds can be used in all orientations and at all latitudes and can be added to a window system whenever necessary. Exterior blinds affect the architectural and structural design of a building; interior blinds have less impact. In practise, horizontal louvers and blinds are generally used on all building orientations, and vertical blinds are predominantly used on east- and west-facing windows. Advanced designs have different requirements from conventional blinds.

4.4.3. Physical Principles and Characteristics

Louvers and blinds may obstruct, absorb, reflect and/or transmit solar radiation (diffuse and direct) to a building's interior. Their effect depends on the position of the sun and their location (exterior or interior), slat angle, and slat surface reflectance characteristics. Thus, the optical and thermal properties of a window with louvers or blinds are highly variable. Horizontal blinds in a horizontal position can receive light from the sun, sky, and ground. Upward-tilted slats transmit light primarily from the sun and sky, and downward-tilted slats transmit light primarily from the ground surface. Both louvers and blinds can increase penetration of daylight from direct sunlight. When skies are overcast, louvers and blinds promote an even distribution of daylight.

Fixed and Operable Louvers and Blinds

Fixed systems are usually designed for solar shading, and operable systems can be used to control thermal gains, protect against glare, and redirect daylight. On sunny days, downward-tilted slats will produce efficient shading of sunlight, but, under cloudy conditions, a fixed system may cause an unfavourable shading effect that significantly reduces indoor daylight. Movable systems need to be fully or partially retracted to operate optimally according to outdoor conditions. Depending on slat angle, slat surface treatment, and the spacing between slats, both sunlight and skylight may be reflected to the interior.

Translucent Blinds

Translucent blinds transmit a fraction of light when closed. Translucent vertical blinds are typically 100 mm wide and require little or no cleaning. Translucent blinds can be made of fabric, plastic, or perforated plastic material (typically offering various levels of light transmittance). If backlit, the blinds can act as a bright, large-area source of glare.

Light-Directing Louvers

There are many different types of light-directing or reflecting louvers, which generally consist of an upper surface of highly specular material that sometimes has perforations and concave curvature. Light-directing louvers are usually fitted between glazing and are typically 10–12 mm in width. These louvers have been designed to reflect the maximum possible amount of daylight to the ceiling while having a very low brightness at angles below the horizontal (Figures 4-4.1 and 4-4.2).

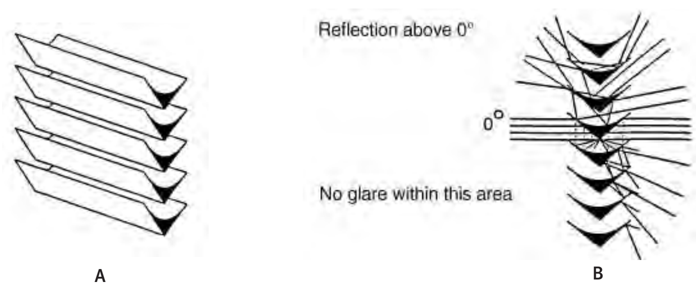


Figure 4-4.1: "Fish" system consisting of fixed horizontal louvers

The "Fish" system consists of fixed horizontal louvers with a triangular section that has been precisely aligned by special connections to the louver itself [Pohl and Scheiring 1998]. The system, designed only for vertical windows, is designed to limit glare and redirect diffuse light; additional shading is required (e.g., a roller blind) if heat gains and admission of sunlight are to be limited. The louvers are designed so that light from the upper quarter of the sky is transmitted to the upper quarter of the room (ceiling). Theoretically, the system without the glazing transmits 60% of diffuse light for an aluminium surface with 85% reflectance.

The "Okasolar" system, which is also a fixed system, consists of numerous equally spaced, three-sided, reflective louvers placed inside a double glazed unit. The system reflects light up towards the ceiling in the winter and has a shading effect in the summer. These blinds are designed to suit the latitude where they will be used.

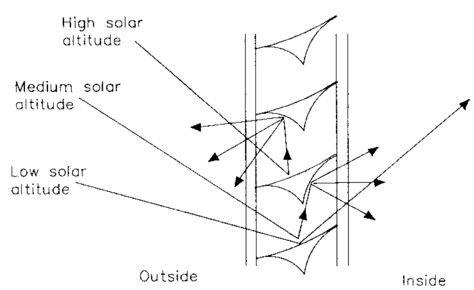


Figure 4-4.2: The Okasolar system consists of fixed, equally spaced, reflective louvers

4.4.4. Control

Louvers and blinds can be operated either manually or automatically. Automatically controlled louvers and blinds can increase energy efficiency, if controlled to reduce solar gain and admit visible daylight during daily and seasonal variations in solar position. However, automatic systems can produce discomfort in occupants who dislike the feeling of not having personal control over the system. Manually operated systems are generally less energy-efficient because occupants may or may not operate them "optimally" (e.g., operation may be motivated by glare or view, or systems may be left in position when the occupant is absent from the room). Research has found that occupant-preferred positions for louvers and blinds are relatively independent of daily, seasonal, and sometimes climatic conditions. Some studies have found a link between climate and the preferred positions for louvers and blinds [Rubin et al. 1978, Rea 1984, Inoue et al. 1988].

4.4.5. Maintenance

Maintenance of louvers and blinds can be difficult, especially when they have reflective slats. Interior slats collect dust; exterior slats can accumulate dirt and snow. Between-pane systems have an advantage of requiring little cleaning and are not as susceptible to damage (e.g., bending) as interior and exterior systems.

4.4.6. Cost and Energy Savings

Under sunny conditions, some systems can increase daylight penetration, reduce cooling loads, and make the variation more uniform between the brighter area near the window and darker interior zone. Cost and energy savings result from the more efficient use of light without added solar heat gains and cooling loads. For cloudy conditions, louver and blind systems can be energy-efficient if operated properly because most systems will provide less interior light than would be admitted by clear, unobstructed glazing. With reflective louver systems (e.g., those placed in the upper portion of a window to avoid reflected glare), illuminance levels can be increased under cloudy and sunny conditions when the sun is near-normal to the window.

4.4.7. Some Examples of Use

- Gartner Office Building, Gundelfingen, Germany: external mirrored blinds
- Riehle Office Building, Reutlingen, Germany: reflective louvers/blinds
- NMB Bank, Amsterdam, The Netherlands: reflective louvers
- Swanlea Secondary School, Whitechapel, London, UK: mirrored louvers
- Hooker Chemical Headquarters (offices), Buffalo, New York, USA: movable louvers
- Environmental Office of the Future, Watford, UK: motorised glazed louvers (Figure 4-4.3 and IEA SHC Task 21 *Daylight in Buildings: 15 Case Studies from Around the World*)
- Goetz Building, Wuerzburg, Germany: automated louver blinds

Figure 4-4.3: Motorised glazed louvers in the Environmental Office of the Future in Watford, UK

4.4.8. Simulations and Measured Results

One type of fixed louvers and five types of venetian blinds were tested.

A.	Standard light grey venetian blinds	**UK**
B.	Static and automated venetian blinds	**USA**
C.	Translucent venetian blinds	**UK**
D.	Fixed louvers–Fish system	**Austria**
E.	Inverted semi-silvered venetian blinds	**UK**
F.	Inverted semi-silvered translucent venetian blinds	**Denmark**

A. Standard, Light Grey Venetian Blinds (United Kingdom)

The Building Research Establishment, United Kingdom (UK), tested conventional 38-mm venetian blinds with a light grey finish. The blind system was monitored at three slat angle positions (fully closed, horizontal, and 45° downward tilted) in a south-facing mock-up office. The reference room was identical to the test room, but had unshaded, clear glazing.

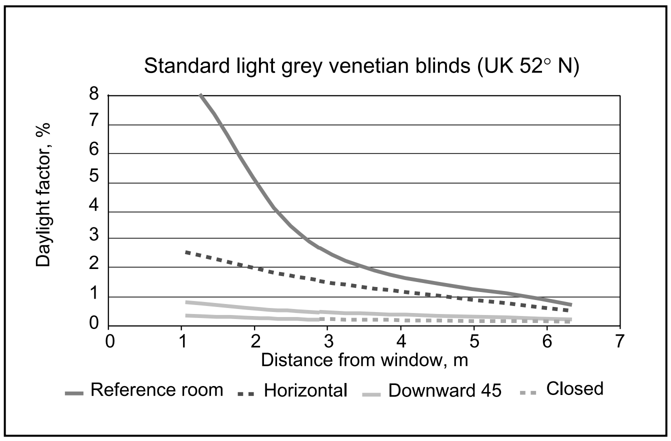
Interior light grey venetian blinds **UK: 52°N** Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Horizontal 0° - Overcast (DF%)	2.5 %	9.1 %	1.5 %	2.9 %	0.5 %	0.7 %	9.5	3.8
Downward 45° - Overcast (DF%)	0.8 %	8.7 %	0.4 %	2.5 %	0.1 %	0.7 %	6.6	2.7
Closed 90° - Overcast (DF%)	0.3 %	8.9 %	0.1 %	2.7 %	≈ 0.0 %	0.7 %	8.7	2.8
Horizontal 0° - Clear winter: Noon	Sun	Sun	Sun	Sun	1,110	1,500	30.2	74.9
Horizontal 0° - Clear winter: 15:00	1,230	1,780	830	1,050	320	420	8.1	20.3
Downward 45° - Clear winter: Noon	530	Sun	270	Sun	130	1,360	25.0	65.2
Downward 45° - Clear winter: 15:00	210	1,890	100	1110	40	410	8.5	21.6
Closed 90° - Clear winter: Noon	150	Sun	70	Sun	30	1,520	25.7	71.7
Closed 90° - Clear winter: 15:00	70	2,380	30	1,460	10	560	8.9	28.1
Horizontal 0° - Clear equinox: Noon	1,800	3,290	980	1,540	470	740	68.9	79.7
Horizontal 0° - Clear equinox: 15:00	1,360	2,890	730	1,380	350	640	47.3	60.7
Downward 45° - Clear equinox: Noon	210	2,430	90	1,150	30	550	76.4	81.7
Downward 45° - Clear equinox: 15:00	170	2,590	70	1,250	20	560	28.9	17.5
Closed 90° - Clear equinox: Noon	60	1,470	30	560	10	270	37.6	21.4
Closed 90° - Clear equinox: 15:00	60	1,540	30	700	10	320	25.4	20.2
Horizontal 0° - Clear summer: Noon	1,210	2,170	630	950	280	410	84.3	65.5
Horizontal 0° - Clear summer: 15:00	970	2,010	510	900	230	380	61.1	50.9
Downward 45° - Clear summer: Noon	660	2,400	350	1040	160	440	80.4	65.9
Downward 45° - Clear summer: 15:00	550	2,140	290	950	130	410	60.5	51.3
Closed 90° - Clear summer: Noon	160	2,180	70	940	20	410	87.3	59.0
Closed 90° - Clear summer: 15:00	130	1,860	60	820	20	360	64.5	43.7

Note: For overcast sky measurements, the window, intermediate, and rear zone sensors were 1.05, 2.89, and 6.34 m from the window, respectively. For clear sky measurements, the window, intermediate, and rear zone sensors were 2.7, 4.5, and 8.1 m from the window, respectively. The tilt angle is defined as the vertical angle from horizontal where a positive angle is downwards, with a view of the ground from inside the building. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

Overcast Sky

The daylight factor on the work plane for standard grey venetian blinds was measured at three slat angle positions (horizontal, 45° downward tilted, and fully closed). Measurements were made for 3 days in the reference room and then averaged.

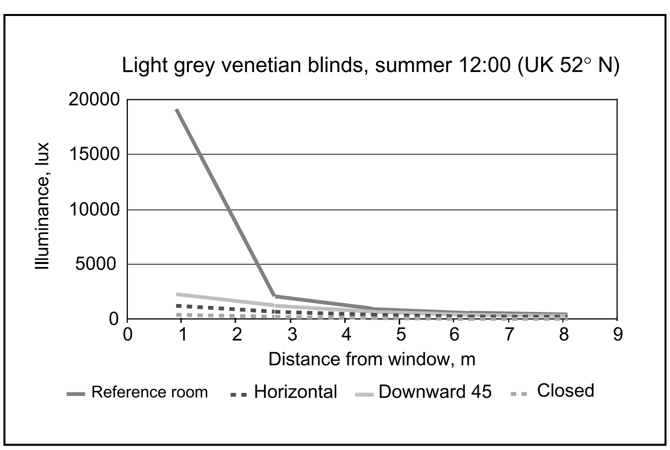
The conventional venetian blinds with a light grey finish in a horizontal slat angle position produced moderate, uniform variation in light between the window area and at the back of the room. The amount of light entering the room was reduced considerably in all cases, even when the slats were in horizontal position.

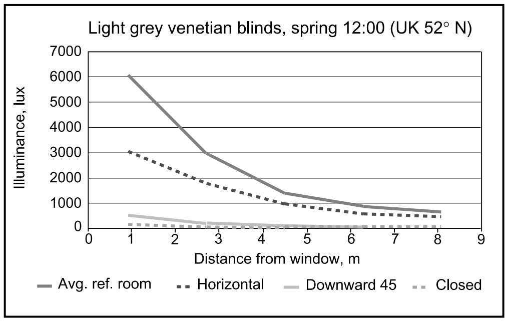


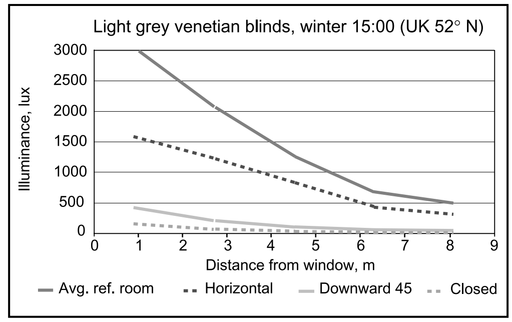
Clear Sky

The illuminance level was measured on the work plane for standard grey venetian blinds at three slat angle positions (horizontal, 45° downward tilted, and fully closed). Measurements taken over 3 days in the reference room were averaged to illustrate the magnitude in illuminance level.

At high sun positions the blind inhibited sunlight from entering the room and reduced the difference in illuminance levels between the window area and the rest of the room. At low sun position, the slats in horizontal position reflected the sunlight into the interior, increasing the illuminance considerably compared to the effect of the downward-tilted position.







Conclusion (A)

For conventional venetian blinds, there is no advantage for glare control in closing the slats beyond 45°, and there are significant disadvantages in terms of room illuminance levels. A design improvement would therefore be to limit the degree to which such blinds would close under normal operation while allowing users the option of completely closing the blinds if necessary under other conditions.

B. Static and Automated Venetian Blinds (USA)

The Lawrence Berkeley National Laboratory, USA, tested interior, semi-specular, white painted aluminium venetian blinds (17 mm wide, spaced 15 mm apart) in two identical rooms. The primary purpose was to test the performance of the control system; the daylighting performance of these blinds has been tested at other institutions.

In the test room, the slat tilt angle was automatically controlled to maintain interior daylight levels at 500 lux throughout the day (the venetian blinds were never retracted). In the reference room, a static blind angle was set to remain the same during the day: either horizontal (0°) or 45° downward tilted (view of ground from the interior). The rooms were oriented 62.6° east of south with partially obstructed views of nearby high-rise buildings. The windows spanned the full width of the room and had a head height of 2.58 m and a sill height of 0.78 m.

Interior static and automated venetian blinds **USA: 37°N** Monitoring case and time	Interior Illuminance Level (lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Auto 0°, Static 0° - Overcast (DF%)	NA	NA	NA	NA	NA	NA	4.2	NA
Auto 0°, Static 0° - Clear winter: 9:00	450	560	320	380	220	260	28.0	NA
Auto 48°, Static 0° - Clear winter: Noon	960	2,100	690	1510	420	990	57.0	
Auto 0°, Static 0° - Clear winter: 15:00	310	320	250	250	220	210	28.8	
Auto 70°, Static 0° - Clear equinox: 9:00	1,630	5,300	1150	3,360	720	2,010	43.2	NA
Auto 67°, Static 45° - Clear equinox: 9:00	2,030	2,420	1,460	1,790	960	1,210	53.0	
Auto 52°, Static 0° - Clear equinox: Noon	1,030	1,700	730	1,250	430	830	72.7	
Auto 48°, Static 45° - Clear equinox: Noon	900	1,020	660	760	390	460	74.9	
Auto 0°, Static 0° - Clear equinox: 15:00	420	400	350	340	290	290	53.5	
Auto 0°, Static 45° - Clear equinox: 15:00	390	160	330	130	290	100	51.5	
Auto 65°, Static 0° - Clear summer: 9:00	1,340	4,430	900	2,930	540	1,630	78.3	NA
Auto 67°, Static 45° - Clear summer: 9:00	1,560	1,660	1,090	1,180	690	750	64.6	
Auto 43°, Static 0° - Clear summer: Noon	750	1,130	550	840	320	570	106.0	
Auto 26°, Static 45° - Clear summer: Noon	790	690	610	510	400	280	86.1	
Auto 0°, Static 0° - Clear summer: 15:00	540	580	470	510	430	460	84.3	
Auto 0°, Static 45° - Clear summer: 15:00	510	220	440	180	380	120	67.5	

Note: The measured data in the test room column are for the automatically controlled blind; data in reference room column are for the static blind in a fixed slat angle position (e.g. Auto 0°, Static 0° means that both the automatic and static blind were in a horizontal position). The window, intermediate, and rear zone sensors were 1.5, 2.4, and 4.3 m from the window, respectively. The tilt angle is defined as the vertical angle from horizontal where a positive angle is downward, with a view of the ground from inside the building. Evg (klux) is global exterior horizontal illuminance. Evgs is not available (NA).

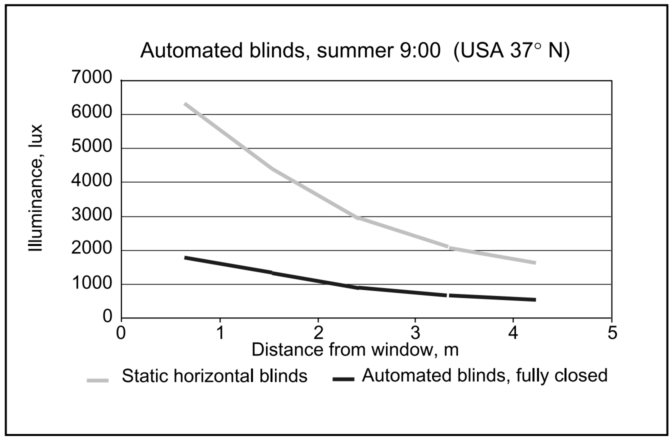
Overcast Sky

There were no comparative measurements taken under overcast sky conditions. Therefore, no conclusions were drawn for these conditions.

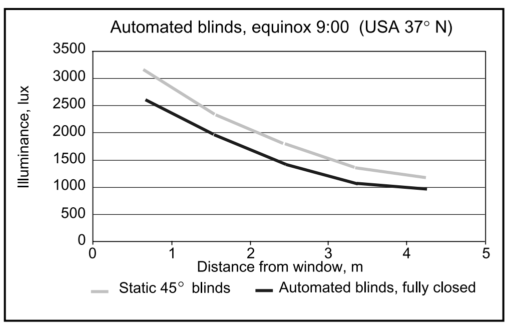
Clear Sky

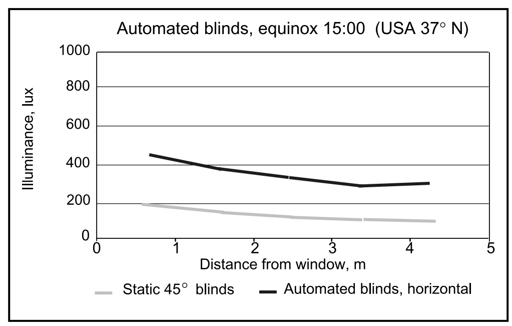
The Auto venetian blinds are more effective than both the horizontal (0°) and 45° static blinds at maintaining daylight illuminance levels at the specified design level of 500 lux. In the summer, the Auto venetian blind in a fully closed position yields more uniform maintained illuminance levels (540–1,340 lux) throughout the test room compared to the reference room with horizontal blind (between 1,630–4,430 lux). No redirection of light can be noted in the illuminance profile.

For the equinox, the same conclusions can be made as for the summer solstice period except that the magnitude of the difference in illuminance between the test and reference rooms is smaller because of decreased daylight availability.



Because the test rooms faced east-southeast, sunlight does not hit this facade in the afternoon. In this situation, the Auto venetian blinds at a horizontal tilt angle provide more daylight than partly closed blinds. Illuminance profiles for the two situations are given in the figures below at 9:00 and 15:00 respectively, for the same day.





Conclusion (B)

Auto control of venetian blind systems may perform well in all climates. However, the automatic control algorithm may need to be adjusted to accommodate the unique cooling- or heating-load-to-daylighting balance for the building location. For low-latitude countries in hot climates, the system may be more energy-efficient if controlled to provide less overall transmitted solar radiation or if placed on the exterior of the building. For high-latitude countries in cold climates, the system may be more energy-efficient if controlled to provide more daylight and solar radiation.

The test results show that it is important to control the blinds in response to available daylight. However, additional control to avoid glare from the exterior or from the blinds themselves was not investigated. Algorithms have been developed to reduce movement of blinds under partly cloudy conditions, but this should be packaged as a user-defined option to ensure occupant satisfaction.

C. Translucent Venetian Blinds (United Kingdom)

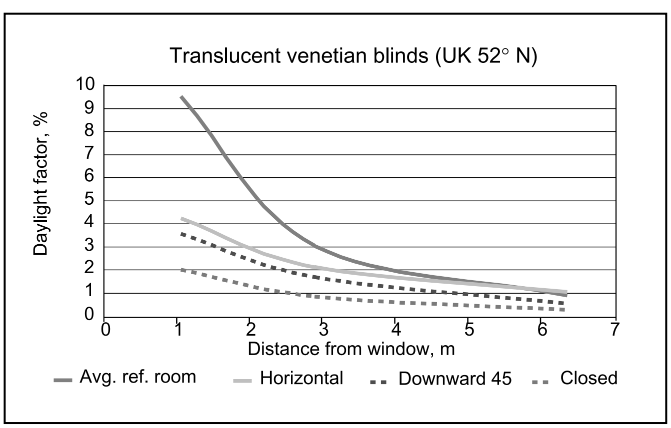
The Building Research Establishment, United Kingdom (UK), tested 25-mm-wide white translucent blinds with a transmission of less than 5%. The blind system was monitored (winter and equinox) at three slat angle positions (fully closed, horizontal, and 45° downward tilted) in a south-facing mock-up office. The reference room was identical to the test room, but had unshaded, clear glazing.

Interior translucent blinds UK: 52°N Monitoring case and time	Interior Illuminance level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Horizontal 0° - Overcast (DF%)	3.6 %	9.0 %	1.7 %	2.9 %	0.5 %	0.7 %	19.6	7.8
Downward 45° - Overcast (DF%)	4.2 %	10.4 %	2.1 %	3.2 %	1.0 %	1.3 %	3.6	1.5
Closed 90° - Overcast (DF%)	2.0 %	8.9 %	0.8 %	2.7 %	0.3 %	0.7 %	8.5	3.4
Horizontal 0° - Clear winter: Noon	3,120	3,920	Sun	Sun	1,110	1,500	29.4	71.3
Horizontal 0° - Clear winter: 15:00	2,100	2,910	1,350	1,690	570	730	12.8	35.8
Horizontal 0° - Clear equinox: Noon	2,790	4,070	1,380	1,500	640	750	55.5	86.5
Horizontal 0° - Clear equinox: 15:00	2,310	3,530	1,150	1,760	520	790	35.1	66.5
Downward 45° - Clear equinox: Noon	1,810	2,390	930	1,130	460	570	77.1	77.4
Downward 45° - Clear equinox: 15:00	1,410	2,550	720	1,220	360	580	56.8	63.2
Closed 90° - Clear equinox: Noon	250	4,450	250	1,700	40	780	NA	NA
Closed 90° - Clear equinox: 15:00	200	3,300	90	1,440	20	640	NA	NA

Note: For overcast sky measurements, the window, intermediate, and rear zone sensors were 1.05, 2.89, and 6.34 m from the window, respectively. For clear sky measurements, the window, intermediate, and rear zone sensors were 2.7, 4.5, and 8.1 m from the window, respectively. The tilt angle is defined as the vertical angle from horizontal where a positive angle is downwards, with a view of the ground from inside the building. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

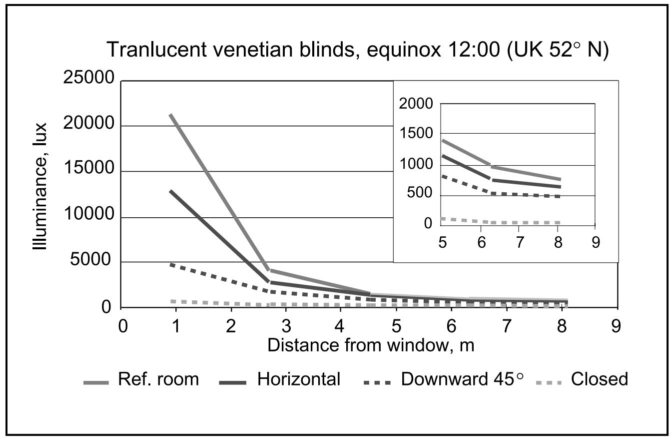
Overcast Sky

The daylight factors on the work plane for translucent venetian blinds are slightly higher than those measured for standard blinds at three slat angle positions (horizontal, 45° downward tilted, and fully closed). Measurements taken over three days in the reference room were averaged.



Clear Sky

Under sunny conditions, there are only small differences between the illuminance levels with translucent and standard blinds. The illuminance level on the work plane was measured for translucent venetian blinds at three slat angle positions (horizontal, 45° downward tilted, and fully closed). Measurements taken over three days in the reference room were averaged to illustrate the magnitude in illuminance level in the reference room.



Conclusion (C)

In general, translucent blinds let in more daylight than traditional blinds. The concept of translucent blinds might offer the possibility of complete glare control while allowing more diffuse daylight into the space than is possible with other systems. However, care must be taken that the blinds themselves do not become a secondary glare source.

D. Fixed Louvers – Fish System (Austria)

The Bartenbach Lichtlabor, Austria (AUT), tested a combined system that consisted of two different daylighting components in the upper and lower areas of the window. The upper area had "Fish" louvers, a fixed, reflective light-directing system (see Figure 4-4.1). The lower area had exterior, movable light-directing louvers to permit glare control. The reference room had 45° downward-tilted exterior venetian blinds, with window area of equal size to the test room. The main purpose of these tests was to compare illuminance levels and light distribution when the overall average interior luminances of the two windows were the same (low levels, no glare).

Fish system - between glazing **Austria: 47°N** Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Overcast (DF%)	2.6 %	1.5 %	2.3 %	1.2 %	1.5 %	0.9 %	19.4	8.0
Clear equinox: Noon	470	290	430	220	280	150	89.7	62.8
Clear equinox: 15:00	440	310	390	230	260	160	87.6	63.6
Clear summer: 9:00	70	110	60	90	40	60	55.2	8.4
Clear summer: Noon	280	250	230	190	160	130	97.1	40.0

Note: The window, intermediate, and rear zone sensors were 1.3, 2.0, and 3.4 m from the window, respectively. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

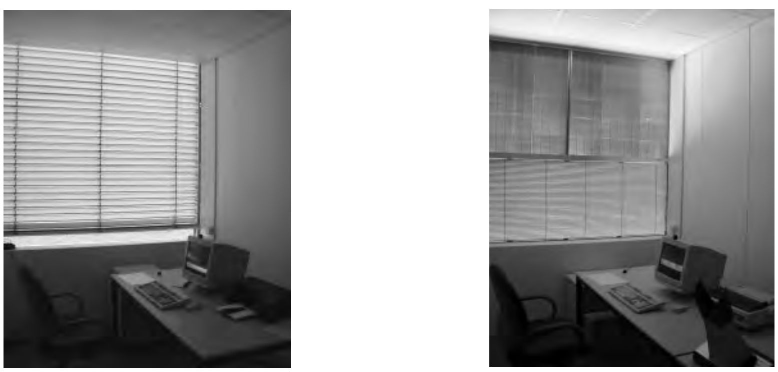
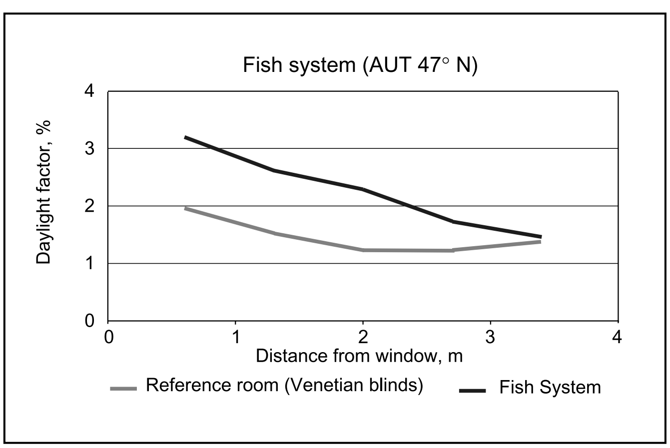


Figure 4-4.4: Interior view of test (right) and reference (left) rooms

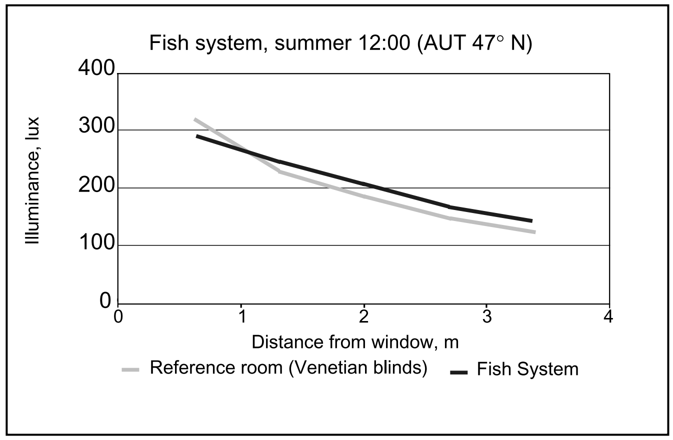
Overcast Sky

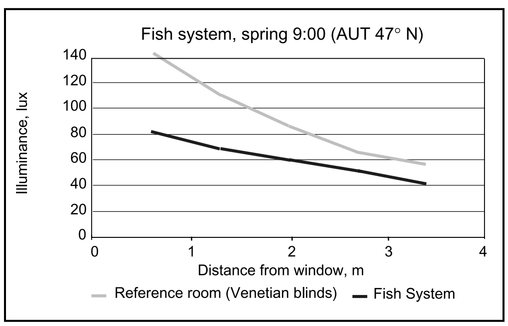
Measurements for the Fish system with an overcast sky showed almost twice the illuminance level in the whole room compared to that in the reference room with exterior downward-tilted venetian blinds. However, no measurements were made with clear, unobstructed glazing. Therefore care should be taken when comparing the results.

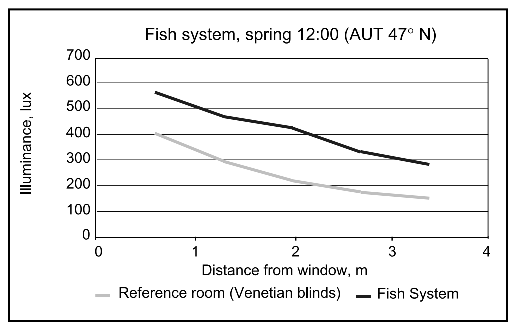


Clear Sky

Because the exterior blinds were partly closed, the overall illuminance levels were very low in both rooms. The clear sky summer measurements show a lower illuminance level for the test room in the morning but a higher illuminance level at noon. Light penetration appears to be highly dependent on the altitude and azimuth of the sun.







Conclusion (D)

The Fish system generally improves the illuminance distribution somewhat compared to ordinary, closed blinds. With the same window luminance level, higher work plane illuminance levels are achieved at high sun positions compared to those achieved by the reference system with exterior downward-tilted venetian blinds. It should be noted that the results only cover the combination of the Fish system with external blinds and only at very low internal illuminance levels. The Fish system was not investigated by itself.

E. Inverted Semi-Silvered Venetian Blinds (United Kingdom)

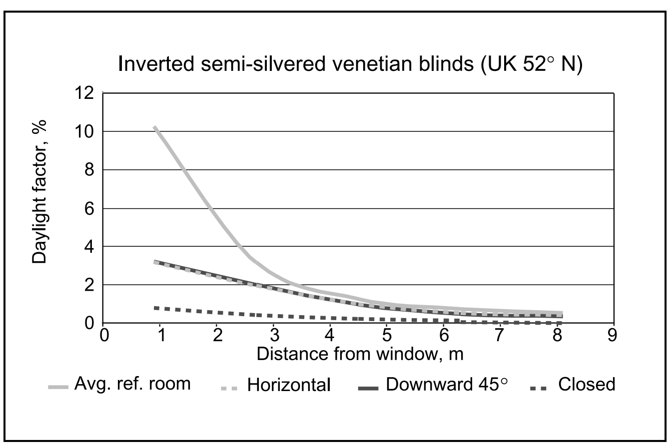
The Building Research Establishment, United Kingdom (UK), tested an experimental 38-mm-wide blind with the louvers inverted and painted silver on the upper (concave) side. The blind system was monitored (summer and equinox) at three slat angle positions (fully closed, horizontal, and 45° downward tilted) in a south-facing mock-up office.

Inverted semi-silvered blinds - Interior **UK: 52°N** Monitoring case and time	Interior Illuminance level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Horizontal 0° - Overcast (DF%)	1.9 %	3.2 %	1.0 %	1.3 %	0.4 %	0.5 %	15.0	6.2
Downward 45° - Overcast (DF%)	2.0 %	3.2 %	0.9 %	1.3 %	0.4 %	0.5 %	4.2	1.7
Closed 90° - Overcast (DF%)	0.4 %	3.0 %	0.2 %	1.2 %	0.1 %	0.5 %	14.2	5.7
Horizontal 0° - Clear equinox: Noon	2,840	3,190	1,490	1,510	690	730	56.3	85.4
Horizontal 0° - Clear equinox: 15:00	1,070	1,670	590	770	280	380	13.1	20.3
Downward 45° - Clear equinox: Noon	750	Sun	390	1850	190	960	42.6	78.9
Downward 45° - Clear equinox: 15:00	380	2,590	190	1150	90	470	16.3	35.0
Closed 90° - Clear equinox: Noon	30	1,060	10	640	4	380	13.6	11.7
Closed 90° - Clear equinox: 15:00	10	310	5	130	2	170	9.4	5.7
Horizontal 0° - Clear summer: Noon	1,720	2,070	850	900	380	440	87.3	57.1
Horizontal 0° - Clear summer: 15:00	1,200	1,850	610	830	290	400	68.9	45.2
Downward 45° - Clear summer: Noon	350	2,930	170	1,190	90	530	46.8	39.8
Downward 45° - Clear summer: 15:00	130	900	60	390	30	190	27.7	13.2
Closed 90° - Clear summer: Noon	230	2,590	110	1,090	40	490	86.9	56.3
Closed 90° - Clear summer: 15:00	180	2,030	80	890	30	400	61.2	40.2

Note: The window, intermediate, and rear zone sensors were 2.7, 4.5, and 8.1 m from the window, respectively. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

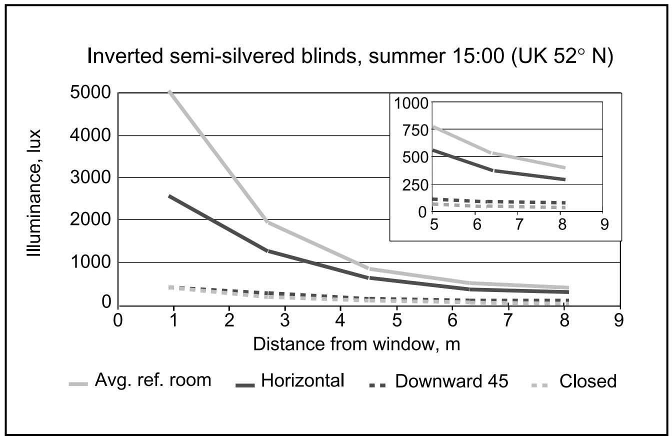
Overcast Sky

The daylight factor was measured on the work plane for inverted semi-silvered venetian blinds at three slat angle positions (horizontal, 45° downward tilted, and fully closed). Measurements taken over three days in the reference room (clear glass) were averaged. The illuminances at 45° and horizontal are almost the same.



Clear Sky

Clear sky at 15:00: The illuminance level was measured on the work plane for inverted semi-silvered venetian blinds at three slat angle positions (horizontal, 45° downward tilted, and fully closed). Measurements taken over three days in the reference room were averaged to illustrate the magnitude in illuminance level. The horizontal slats allowed high illuminance levels (300–2,500 lux) while evening out the difference between the window zone and the rest of the room.



Conclusion (E)

Compared to conventional blinds, inverted silvered blinds give extra daylight when the slats are horizontal, especially at high sun angles (summer). Silvered blinds always involve potential glare problems and can normally only be used in a daylight window above eye height.

F. Inverted Semi-Silvered Translucent Venetian Blinds (Denmark)

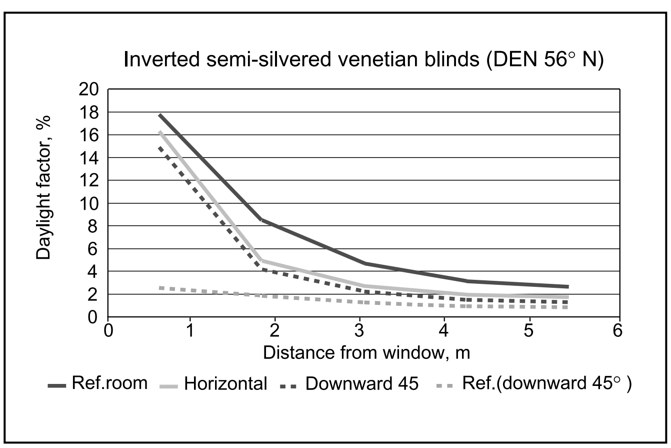
The Danish Building Research Institute, Denmark (DEN), tested a translucent, 50-mm venetian blind (made by Hüppe) with a transmission lower than 10%. The slats are inverted and silvered on the upper (concave) side and are light grey on the downward side. The blinds were monitored in summer, winter, and at equinox for two slat positions (horizontal and 45° downward tilted). The system was positioned above eye height for a standing person (1.8 m) with no supplementary system below this height. For clear sky measurements, the reference room was shaded by standard white venetian blinds tilted 45° down-ward and covering the entire window area. For overcast sky measurements, the reference room had a clear, unobstructed window.

Inverted semi-silvered blinds - Interior Denmark: 56°N Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Horizontal 0° - Overcast (DF%)	4.9 %	8.6 %	2.7 %	4.6 %	1.7 %	2.6 %	19.3	7.6
Downward 45° - Overcast (DF%)	4.1 %	8.5 %	2.2 %	4.7 %	1.3 %	2.7 %	7.5	3.0
Standard Downward 45° - Overcast (DF%)	1.8 %	8.5 %	1.3 %	4.7 %	0.8 %	2.7 %	7.5	3.0
Downward 45° - Clear winter: 9:00	5,480	2,070	2,320	1,290	1,670	900	8.7	38.2
Downward 45° - Clear winter: Noon	Sun	3,710	> 4,000	2,540	> 4,000	1,820	29.3	87.7
Horizontal 0° - Clear equinox: 9:00	5,640	2,410	3,650	1,610	2,310	1,070	40.4	67.6
Horizontal 0° - Clear equinox: Noon	7,830	3,360	> 4,000	2,280	3,730	1,540	66.9	94.0
Downward 45° - Clear equinox: 9:00	4,130	2,340	2,770	1,600	1,040	1,830	38.4	65.1
Downward 45° - Clear equinox: Noon	4,950	3,320	3,710	2,300	2,790	1,520	65.5	92.6
Horizontal 0° - Clear summer: 9:00	3,820	1,690	2,340	1,150	1,470	760	66.7	46.9
Horizontal 0° - Clear summer: Noon	5,650	2,540	3,710	1,720	2,320	1150	91.6	69.3
Downward 45° - Clear summer: 9:00	2,470	1,530	1,560	1,040	980	690	74.0	44.8
Downward 45° - Clear summer: Noon	3,480	2,380	2,330	1,620	1,440	1,083	98.7	65.8

Note: The window, intermediate, and rear zone sensors were 1.8, 3.0, and 5.4 m from the window, respectively. “Sun” indicates sunlight striking the sensors. “>4000” indicates that the sensors are at a state of saturation. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing 7° east of due south. DF% is the daylight factor.

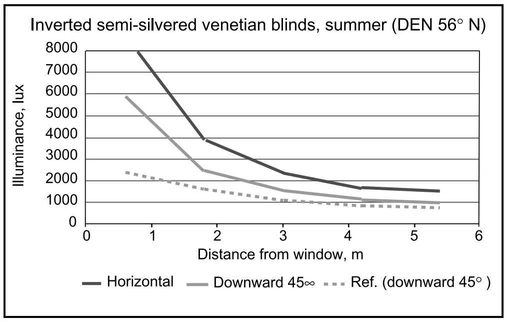
Overcast Sky

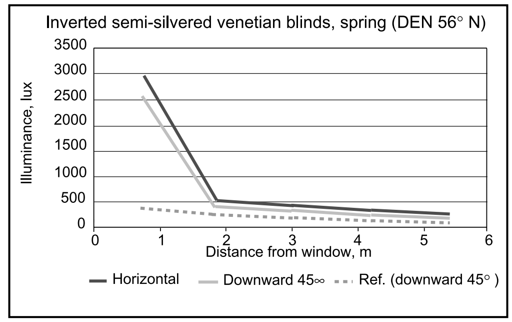
The blinds reduced the interior illuminance level on the work plane throughout the interior compared to the reference room with an unshaded window of equal size. The smallest light reduction occurred when the slats were in the horizontal position. However, for real-life applications, some additional shading for the view window will be necessary because the silvered blinds cause glare problems themselves if used below eye height. The lower curve is for the reference room with 45° downward-tilted blinds in full height of the window.



Clear Sky

Both in summer and at equinox, most of the reflected light illuminates the ceiling and increases light levels in the intermediate and rear wall zones of the room compared to the effect of a standard downward-tilted blind. Sunlight reflected to adjacent walls and ceiling can create visual disturbance, i.e., distracting, distorted patterns of light bands. Closing the blinds or using a different surface treatment may reduce this problem. The reference room has downward-tilted (45°) standard venetian blinds.

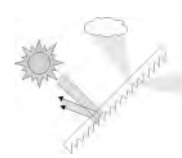




Conclusion (F)

The spacing between the slats is smaller than for standard blinds, which reduces the view to the outside even when the slats are in the horizontal position. However, because of the translucency of the blinds, some sense of connection with the outside is maintained when the blinds are tilted. The shape of the slats and reflecting surface treatment implies that the system should be implemented in a daylight window only in order to avoid glare problems. It will then perform similar to a mirrored louver system.

4.5. Prismatic Panels



Prismatic panels are thin, planar, sawtooth devices made of clear acrylic that are used in temperate climates to redirect or refract daylight. When used as a shading system, they refract direct sunlight but transmit diffuse skylight. They can be applied in many different ways, in fixed or sun-tracking arrangements, to facades and skylights.

4.5.1. Technical Description

Components

A linear prismatic panel consists of an array of acrylic prisms with one surface of each prism forming a plane surface known as the prism backing. There are two refracting angles. Very often these prismatic systems are inserted in a double-glazed unit to eliminate maintenance.

Production

Currently, two different manufacturing processes are used to make prismatic panels:

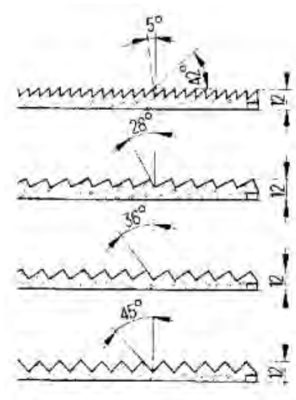


Figure 4-5.1: Four types of commercially available prismatic panels

Injection moulding. Prismatic panels are produced from acrylic polymer in four different configurations (different refracting angles). Some panels are partially coated with an aluminium film with high specular reflectance on one surface of each prism.

Specialised etching. This etching process produces prisms that are spaced less than a millimeter apart. The resulting acrylic film is lightweight yet still has good optical properties. This film can be applied on the inside of a double-glazed unit.

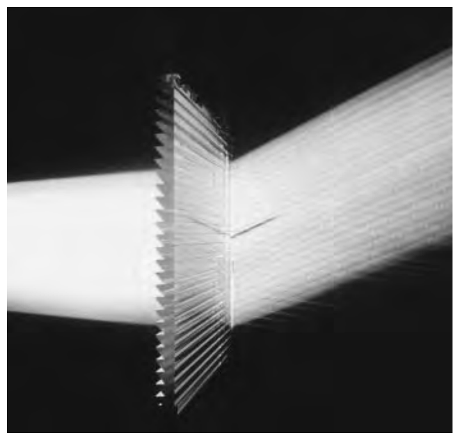


Figure 4-5.2: Cross-section of a linear prismatic panel and visualisation of the light redirection achieved by the panel

Location in Window System

Prismatic panels are used in fixed and movable configurations. Depending on the daylighting strategy being used, they can be positioned in the window pane (fixed configuration) on the exterior and/or interior side. The panels offer a transparent but distorted view to the outside. An extra view window will usually be needed unless the panel can open to allow a view.

Prismatic panels have two very different functions: a) solar shading, and b) redirection of daylight. Their location in relation to the facade or the roof is very dependent on the specific application.

Technical Barriers

If prismatic panels are used as sun-shading devices in a fixed configuration, additional components are needed to prevent colour dispersion. These could include, for example, an etched sheet of glass (slightly diffusing) behind the system.

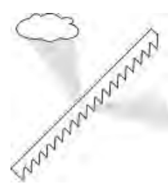
If used for redirecting sunlight, currently available prismatic panel designs may redirect some sunlight downward, causing glare. Computer analysis shows that for a vertical, fixed prismatic panel, some downward sunlight is inevitable at some times of the year. With correct profile and seasonal tilting, these downward beams can be avoided, however.

Historically, the effect of prismatic panels on daylight has been well known. There are patents on this technology dating from the beginning of the 20th century. However, production was a significant barrier in the past. With the advent of acrylic polymer, it became possible for the first time to produce very precise panels. In addition, covering single surfaces of a prism with reflective coatings has expanded the possibilities of prismatic systems. Still, cost is an important barrier to the panels' wider use.

The panels' high coefficient of expansion usually requires that they be designed to allow for thermal expansion. Since acrylic burns, fire regulations must be checked when prismatic panels are used.

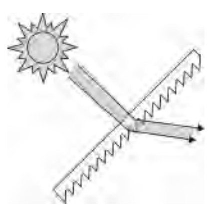
4.5.2. Application

As a light-directing system, prismatic panels can be used to guide diffuse daylight or sunlight.



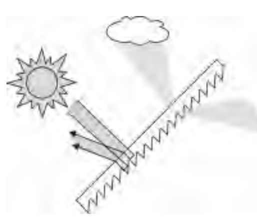
Diffuse Daylight

Prismatic panels are normally used in the vertical plane of the facade to redirect light from the outside sky to the upper half of the inside room, usually the ceiling. Simultaneously, the panels reduce the brightness of the window. With this profile, the panels operate best as an anti-glare system with a simultaneous light-directing function. For sunny facades, however, additional sun shading is necessary in front of the panels.



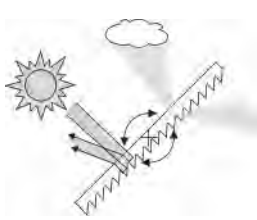
Sunlight

Prismatic panels can also be used to direct sunlight into a room. To prevent glare and also colour dispersion, the correct profile and a seasonal tilting of the panels are essential. See Section 4.5.8 for test room studies at the University of Sydney, Australia.



Fixed Sun-Shading System

This application is usually found in glazed roofs. The prismatic structure is designed according to the movement of the sun, and the panels are integrated into a double-glazed unit. See Section 4.5.8 for measurements made at Bartenbach LichtLabor, Austria.



Moveable Sun-Shading System

For this application, prismatic panels are used in louver form. They are placed in front of or behind double glazing, in a vertical or horizontal arrangement (a double glazed unit is no longer necessary). This application will control glare from the sun but not the sky; in other words, it acts only as a sun-shading device.

4.5.3. Physical Principles and Characteristics

The main function of light-directing prismatic glazing is to achieve deep penetration of natural light. The prismatic panel uses both reflection and refraction to enable the controlled use of daylight in buildings. The system can be designed to reflect light coming from a certain range of angles while transmitting light coming from other angles. Refraction and total internal reflection (based on the critical angle of the material) can be used to change the direction of transmitted light rays. The fractions of reflected and refracted light depend on the angle of incidence, the indices of refraction, and the state of polarisation of the incident light.

For deep penetration of sunlight, a prismatic panel must accommodate a wide range of solar altitudes. The refracted light should emerge at an angle less than 15° above the horizontal to obtain maximum penetration without creating descending rays of sunlight that create glare. The panel's performance is therefore determined by an appropriate configuration of the refracting angles. A specific configuration for the prismatic profile is usually required for different geometric and geographic situations, to achieve high illuminance levels at the back of a room. In addition, a good surface texture with a high reflectivity is required for the ceiling, especially in the area near the window and for approximately one-third of the ceiling depth.

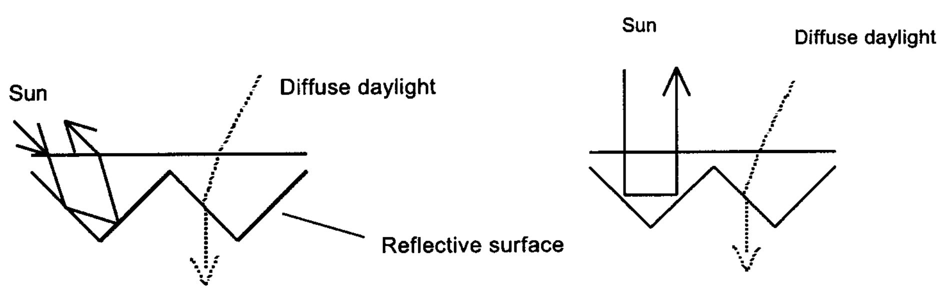


Figure 4-5.3: Behaviour of direct and diffuse components of daylight in a fixed prismatic sun-shading device (left) and in a movable prismatic sun-shading device (right). The phenomenon of total internal reflection is used to reflect the sun's rays

4.5.4. Control

When prismatic panels are applied as a movable sun-shading system, one-axis automatic tracking of the panels according to the movement of the sun is generally required. For many light-redirection applications, only seasonal adjustments are needed.

4.5.5. Maintenance

Prismatic panels inside a double-glazed unit do not require any maintenance other than the normal washing of the exterior and interior glazing surfaces. If the panels are exposed, they must be very carefully cleaned so as not to damage the optical surfaces.

4.5.6. Cost and Energy Savings

Costs for a prismatic panel alone are in the range of 200 euros (for high-volume production) to 400 euros (for low-volume production) per square metre. The cost of prismatic film is 40 to 80 euros per square metre. Potential energy savings can be derived from the measurement results in Chapter 4.5.8.

4.5.7. Some Examples of Use

- 3M Centre, Building 275, St. Paul, Minnesota, USA: light guides and light emitters made from prismatic film
- 3M Office Building, Austin, Texas, USA: rooflight reflectors fitted with prismatic film at the top of the atrium

Figure 4-5.4: SBV, Biel, Switzerland. The structure in front of the glass curtain wall, one storey above ground level, supports movable prismatic panels. Behind these panels, there are also light-directing prismatic panels

Figure 4-5.5: Sparkasse, Bamberg, Germany. Fixed sun-shielding and light-redirecting prismatic panels inside double glazing

Figure 4-5.6: German Parliament Building, Bonn, Germany. Movable sun-shading prismatic panels

4.5.8. Simulations and Measured Results

Test room data following the IEA Task 21 monitoring protocol are given for Norway and Germany. The remaining abbreviated results are given with references, as appropriate.

A.	Prismatic panel at vertical clerestory window	**Norway**
B.	Prismatic panels combined with inverted, semi-perforated blinds in a vertical window	**Germany**
C.	Light-directing and sun-shading prismatic panels	**Austria**
D.	Prismatic film and prismatic panel	**United Kingdom**

A. Prismatic panel (Norway)

Measurements of prismatic panels (Siteco 45°) were made by the Norwegian University of Science and Technology, Norway (NOR). The test rooms were 2.9 m wide, 5.5 m deep, and 2.7 m high. The test room window was separated into two: a full-width clerestory (1.0

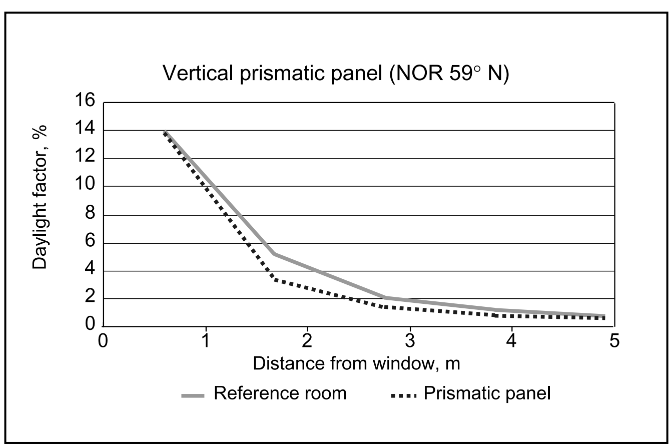
m^2) above a view window (2.2 m^2). Prismatic panels were mounted vertically between the two panes of the clerestory. The prismatic panel occupied 31% of the total glazing area. The reference room had clear, unshaded glazing. Results are presented for the case when the sun is perpendicular to the window facade. Measurements were made in an occupied office building at Sandvika, Norway (near Oslo) at latitude 59°N. For a detailed description of the test rooms, see Appendix 8.4.

Prismatic Panel Norway: 59°N Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Overcast (DF%)	3.4%	5.2%	1.4%	2.1%	0.6%	0.7%	3.4	1.4
Clear winter: Noon	Sun	Sun	Sun	Sun	Sun	Sun	11.0	51.1
Clear equinox: Noon	Sun	Sun	Sun	Sun	1,410	1,640	38.4	90.8
Clear summer:Noon	3,240	3,130	2,140	1,650	710	660	87.5	76.0

Note: The window, intermediate, and rear zone sensors were 1.67, 2.75, and 4.91 m from the window, respectively. "Sun" indicates sunlight striking the sensors. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

Overcast Sky

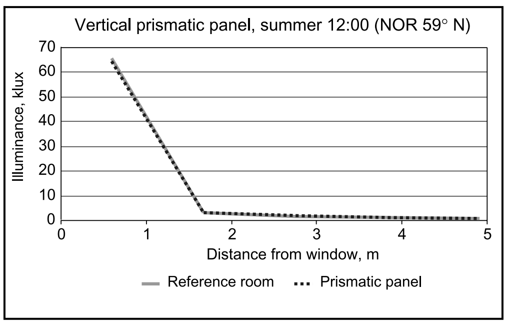
Under overcast sky conditions, the prismatic panels reduced the illuminance in all zones by 20–35%; daylight distribution was less uniform than in the reference room. The brightness of the upper part of the window was reduced.

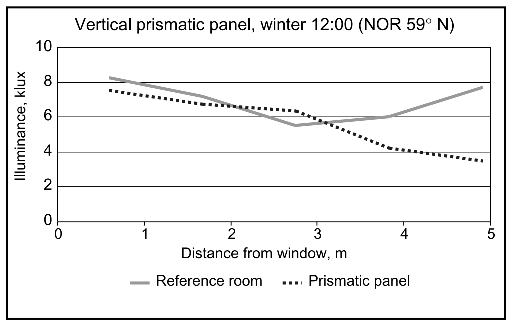


Clear Sky

For summer clear sky conditions, the prismatic panels provided more uniform daylight distribution in the room than under overcast skies. The illuminance in the intermediate zone was increased by up to 30%; in the rear wall zone, the average increase was about 14%.

In the reference room at low sun angles during the equinox and winter solstice, direct sunlight penetrated the entire depth of the room at low sun angles; in the test room, the prismatic panels reduced or prevented direct sun from reaching the rear wall zone. Consequently, the luminance differences in the rear zone of the test room were evened out. The prismatic panels also prevented direct sun dazzle for people first entering the room.





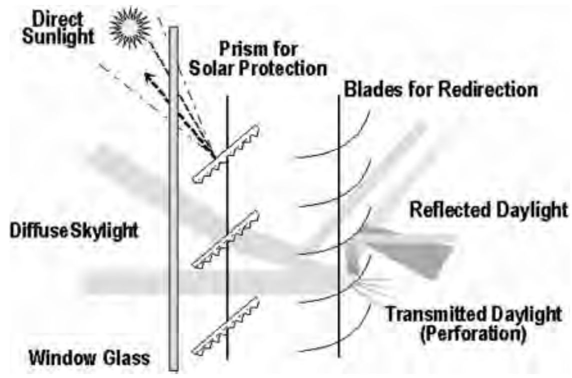
Conclusions (A)

Prismatic panels have limited applications in climates dominated by overcast sky conditions. For clear sky climates, the panels can direct sunlight into a room and provide a relatively uniform daylight distribution.

B. Prismatic Panels Combined with Inverted, Semi-Perforated Blinds (Germany)

Measurements of a Siteco 45/45 prismatic panel combined with a blind system were made at the Technical University of Berlin, Germany. The test rooms were 3.5 m wide, 4.7 m deep, and 3.0 m high. The test room was equipped with a window system (made by Hüppe) consisting of a layer of prismatic panels for sun shading and semi-perforated blinds for redirecting diffuse daylight. Both layers were installed inside the window and covered the full height of the window. For clear sky measurements, the reference room was equipped with a standard, outdoor, grey, 80-mm-wide venetian blind set at a slat angle of +45° (view of ground when inside the room). For overcast sky measurements, the reference room had clear, unshaded glazing. For a detailed description of the test rooms, see Appendix 8.4.

Figure 4-5.7: Diagram of the Hüppe system



Because of its complex construction, the Hüppe system must be installed inside the room. The slat angle of the prisms is automatically adjusted according to the current sun position. The micro-controller unit that is responsible for the adjustment must be pre-programmed by the manufacturer for the specific location and room orientation in which the system is to be used.

Prismatic panel combined with blinds Berlin (52°N)	Interior Illuminance Level (% of lux)						Exterior Condition (klux)	
	Window zone		Intermediate zone		Rear wall zone			
	Test Room	Ref. room	Test Room	Ref. Room	Test Room	Ref. room	Evg	Evgs
Clear equinox: Noon	1,660	1,240	1,280	840	770	520	65	61
Clear equinox: 9:00	1,020	860	720	530	390	320	46	37
Clear equinox: 15:00	500	440	360	290	200	200	33	32
Clear summer: Noon	1,400	860	1,050	570	620	350	98	57
Clear summer: 9:00	820	670	600	420	320	250	75	33
Clear summer: 15:00	470	490	340	310	200	190	75	35

Note: The window and rear zone sensors were 0.6 and 4.2 m from the window, respectively. The intermediate zone is an average of data taken at 1.8 and 3 m from the window. “Sun” indicates sunlight striking the sensors. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

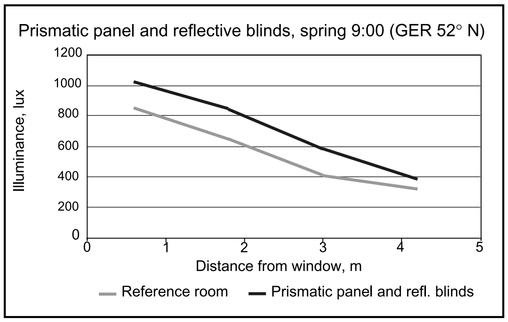
Overcast Sky

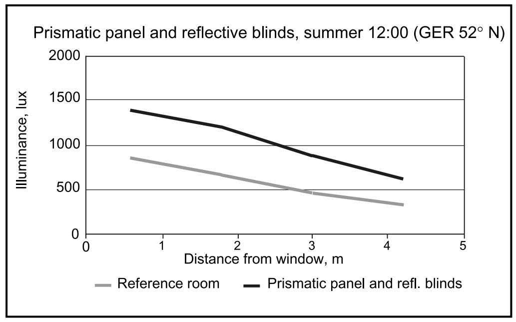
Under overcast sky conditions, the prismatic panel system was raised manually with the semi-perforated blind remaining. In this case, the illuminances were the same as in the reference room, which had no shading system. The window of the reference room is of equal size, clear, and nearly unobstructed.

Clear Sky

The results were compared with those for a reference room equipped with standard venetian blinds with a slat angle of 45°.

Under clear sky conditions, the Hüppe system increased the illuminance level in most cases. The system also works as a shading system, but due to the interior position of the prisms the shading factor was relatively low. The prisms and the slats allow only an extremely reduced view to the outdoors.





Conclusions (B)

For cloudy or overcast sky conditions without direct sunshine on the facade, the illuminance level was significantly reduced by the system. In this case, a sun sensor could be advantageous for automatically adjusting the slats or for lifting up and retracting the prisms to allow for an unobstructed window.

C. Prismatic Panel (Austria)

The following measurements of transmitted luminous flux were taken of three different types of prismatic panels at Bartenbach LichtLabor, Innsbruck, Austria.

In the polar diagrams below (Figure 4-5.8a), the percentage of transmitted daylight is given as a function of incidence angle, where the outgoing altitude (θ=0-90°) and azimuth (φ= -180° to 180°) angles are relative to the surface of the prismatic panel. The structured or serrated side of the panel is oriented to the exterior. In the interior light distribution diagrams (Figure 4-5.8b), the interior light distribution (percentage of the exterior luminance produced by a diffuse hemispherical light source) is given as a function of altitude and azimuth angles relative to the inside surface of a vertical window. A vertical section through the window falls along the -90°/+90° azimuthal axis, and the inward surface normal has an altitude of 90°. See Appendix 8.3 for a more detailed description of these types of measurements.

Light-Directing Panel (Siemens 48/5)

This panel is designed to redirect daylight deeper into a room and towards the ceiling. Normally, it is used in a vertical opening above eye level. In this case, the prismatic structure is oriented to the outside. The average diffuse transmittance of the panel is 48%. From

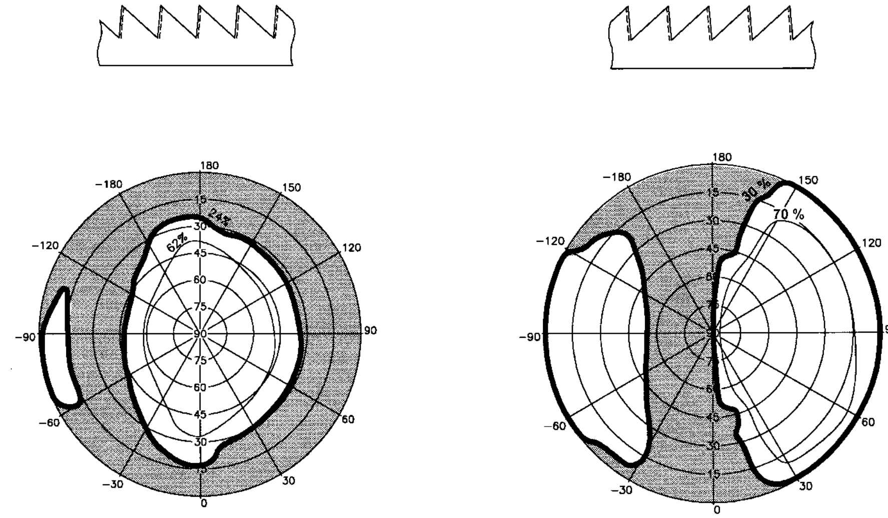


Figure 4-5.8: a) left: transmission of light as a function of incidence angle, where the structured side is oriented to the outside, ground is 90°, and zenith is -90°; b) right: inside light distribution based on a diffuse hemispherical light source on the structured side of the panel, ground 90°, zenith -90°

Figure 4-5.8a, it can be seen that the panel transmits light primarily at angles normal to the surface of the panel. The shaded area denotes values less than 24%. Figure 4-5.8b shows that most of the transmitted light is distributed into the right-hand side of the diagram, i.e., the upper part of the room, if the panel is oriented correctly. The shaded area denotes values less than 30% of the exterior luminance.

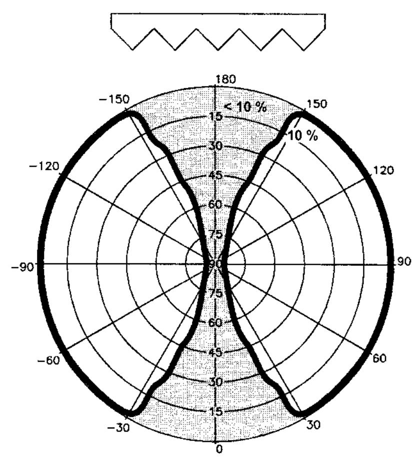


Figure 4-5.9: Angle-dependent transmission of the Siteco 45/45 sun-shading panel

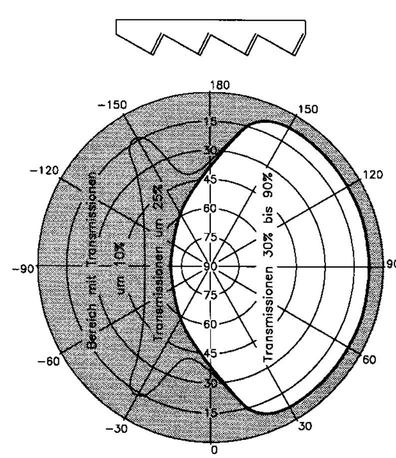


Figure 4-5.10: Angle-dependent transmission of the Siteco 62/28 sun-shading panel

Sun-Shading Panel (Siteco 45/45)

This panel is used as a movable sun-shading device. The average diffuse transmittance of the panel is 56%. In Figure 4-5.9, the shaded central portion of the diagram shows the outgoing angles where sun shading occurs. Therefore, the panel must be adjusted daily and seasonally so that sun can be blocked within this outgoing angular area.

Sun-Shading Panel (Siteco 62/28)

This panel is used as a fixed sun-shading system. The diffuse transmittance is 56% (panel only). A coated surface has been added to the prismatic structure (see Figure 4-5.10) so that the angle-dependent transmission diagram shows a larger angular area with low transmission. This means that the panel can remain in a fixed position. The shaded area denotes values less than 30%.

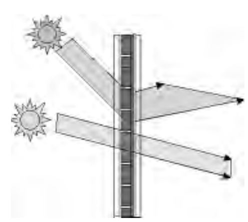
D. Prismatic Film and Prismatic Panel (United Kingdom)
The Building Research Establishment (BRE) tested two separate systems in its mock-up office facility in Garston near London, United Kingdom (UK) [Aizelwood 1993]: a prismatic film system (prism angles 62° and 78°) and a Siemens prismatic light-directing panel (prism angles 45° and 90°).

In direct sun (summer and equinox), the prismatic film refracted sunlight and illuminated the ceiling in the centre of the room. Compared to clear glazing, the prismatic film raised illuminance levels in the middle and at the back of the room by about 10 to 20%. For low sun elevations (winter), the bright patch on the ceiling was nearer to the window, which reduced the illuminance level at the back by 30 to 40%. The film also performed less well under cloudy conditions (10 to 30% reduction), but provided glare control.

Under overcast conditions, the prismatic light-directing panel provides a uniform reduction in illuminance levels throughout the room of 35 to 40%. On clear summer days, the panel generally excluded sunlight, which reduced overall light levels in the room. On clear equinox days, illuminance levels were increased at the back of the room by more than 100%. However, this performance of the prismatic panel was rarely replicated during the study period. On clear winter days, as the sun got lower in the sky, light levels at the very back of the room were reduced by 50% because the sunlight that would have penetrated deep into the room was redirected onto the ceiling at the front. The prismatic panel provided good glare control in all conditions without the need for venetian blinds.

Laser-Cut Panel 4.6.

The laser-cut panel is a daylight-redirecting system produced by making laser cuts in a thin panel made of clear acrylic material.



4.6.1. Technical Description

Components
A laser-cut panel is a thin panel that has been divided by laser cutting into an array of rectangular elements. The surface of each laser cut becomes a small internal mirror that deflects light passing through the panel. The principal characteristics of a laser-cut panel are: (a) a very high proportion of light deflected through a large angle (>120°), (b) maintenance of

Figure 4-6.1: View through a laser-cut panel

view through the panel (see Figure 4-6.1), and (c) a flexible manufacturing method suitable for small or large quantities.

Light is deflected in each element of the panel by refraction, then by total internal reflection, and again by refraction (see Figure 4-6.2). Because all deflections are in the same direction, the deflection is highly efficient. The panels are usually fixed inside glazing units, but they may also be used as external glazing if the cut surface is protected by lamination between glass sheets. Normally the panels are cut at an angle perpendicular to the surface, but it is possible to make the cuts at a different angle for added control over the direction of the deflected light [Edmonds 1993, Reppel and Edmonds 1998].

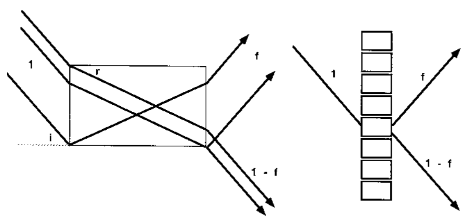


Figure 4-6.2: Showing the fraction "f" of light deflected in a prism and an array of prisms. The fraction f is given as a function of incidence angle in figure 4.6.5

Production

Panels are produced by laser cutting a sheet of clear acrylic (PMMA). They are designed to include a solid periphery and support sections. The laser cutter is programmed with the design.

Laser cuts are usually made right through the panels because this method requires less control of cutting speed and laser power than other approaches. For this reason, it is necessary to design the panel so that solid regions 10-20 mm wide are left to support the cut sections. For example, a panel 1000 mm x 600 mm that has laser cuts right through a 6 mm thick acrylic panel requires a 20-30-mm-wide solid periphery and two vertical solid support sections that are 10-20 mm wide. It is possible to cut only partway through the panel, e.g., 75% depth. However, a solid periphery is still necessary for structural strength.

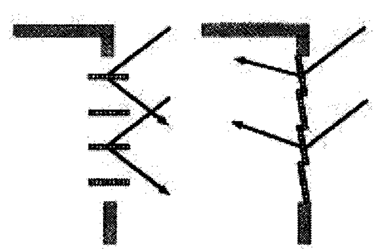


Figure 4-6.3: In louver or venetian form, laser-cut panels may be adjusted to the open, summer position to reject light or to the closed, winter position to admit light

Location in Window System

Laser-cut panels may be used in fixed and movable arrangements within a window system. There is view through the panels. However, even though laser-cut panels maintain high transparency with limited distortion of the view out, they should mainly be used for daylight apertures and not for view windows, or at least not when occupants are close to view windows. Because the panels redirect downward incoming light in an upward direction, it is desirable that they be installed above eye level in windows to avoid glare.

The panels may also be used in louver arrangements or, if produced in narrow widths, as venetian style arrangements. As movable louvers, the system rejects sunlight when the panels are in the open louver position (see Figure 4-6.3, above left) and redirects light when the panels are in the closed louver position (see Figure 4-6.3, above right). Whether in louver or venetian form, laser-cut panel panels may be adjusted to the open, summer position to reject light or to the closed, winter position to admit light.

Technical Barriers

The main technical barrier to laser-cut panels is their cost, approximately 100 euros per square metre. At present, the panels are designed and cut to suit the size and shape of specific windows. They can also be produced in a laminated sheet that can be cut to size, but this process has not yet been established commercially.

4.6.2. Application

Laser-cut light-deflecting panels can be applied as:

- a fixed sun-shading system for windows, as shown in Figure 4-6.4,
- a light-redirecting system (fixed or movable), as shown in Figure 4-6.8, or
- a sun-shading/light-directing system for windows (in louvered or venetian form) as shown in principle in Figure 4-6.3.

FIGURE 4-6.4: LASER-CUT PANELS THAT ARE 20 MM WIDE PANELS CAN BE INSTALLED VENETIAN STYLE BETWEEN TWO GLASS PANES TO FORM A DOUBLE-GLAZED WINDOW. THIS ANGLE-SELECTIVE FORM OF WINDOW REJECTS A HIGH PROPORTION OF INCIDENT SUNLIGHT WHILE MAINTAINING GOOD VIEWING CHARACTERISTICS. (SEE FIGURE 4-6.7 FOR IRRADIANCE VERSUS TIME OF DAY FOR AN EAST-FACING WINDOW AT THE LATITUDE OF PARIS, 48.8°N.)

4.6.3. Physical Principles and Characteristics

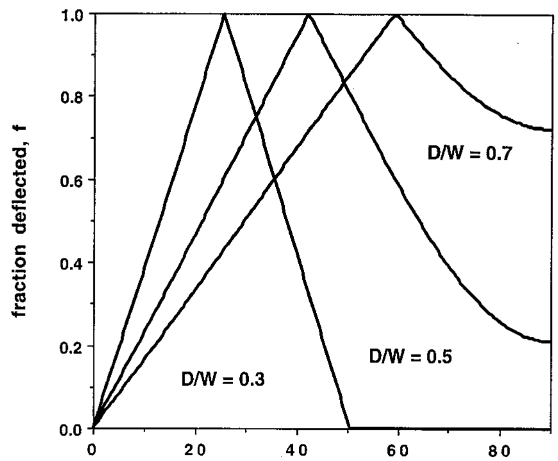
Fixed Light-Directing System

A laser-cut panel with a cut spacing to cut depth ratio (D/W) of 0.7 that is fixed vertically in a window will deflect nearly all light incident from above 45° and transmit most light incident from below 20° (see Figure 4-6.5). Thus, a high fraction of light is deflected by the panel onto the ceiling which then acts as a secondary source of diffuse reflected light in a similar way to a light shelf.

Light-Directing System in Windows

A vertical laser-cut panel strongly deflects light incident from higher elevations, >30°, while transmitting light at near normal incidence with little disturbance, thus maintaining view. Figure 4-6.5 shows the fraction of light deflected versus elevation angle of incident light on a vertical laser-cut panel. The panel has very low glare because the deflected light is directed strongly upwards while the undeflected light continues in the same downward direction as the incident light. The scattered light is low because no rounded surfaces are produced in the manufacturing process. Nevertheless, it is desirable to use laser-cut panels in the upper half of windows.

Figure 4-6.5: The fraction of light deflected versus elevation of incident light for a vertical laser-cut panel with three different cut spacing (D) to cut depth (W) ratios



Sun-Shading System in Windows

If an array of narrow panels is mounted horizontally in a window, i.e., with the face of the panels horizontal, then sunlight from higher elevations is deflected back to the outside. Thus, this system is very effective for excluding sunlight while being entirely open for viewing (See Figures 4-6.6 and 4-6.7).

Figure 4-6.6: Horizontal laser-cut panels form an angle-selective window that deflects light to the outside

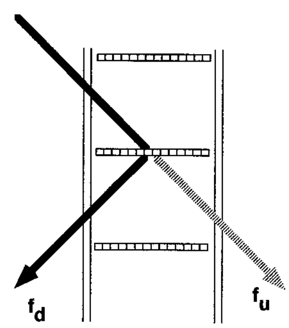
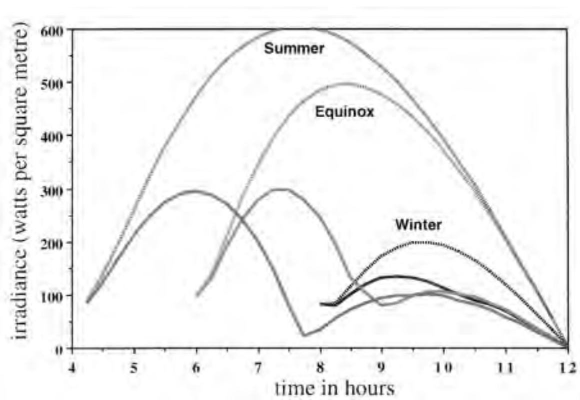


Figure 4-6.7: The irradiance through an east-facing angle- selective window at the latitude of Paris (48.8°N)



4.6.4. Control

Laser-cut panels are usually fixed as a second internal glazing in windows or skylights. However, when laser-cut panels are installed as an internal glazing in awning windows, then, as the awning windows are tilted open to the outside, high-elevation light is deflected more deeply into the room. In principle, the tilt of the panel can be continuously adjusted to obtain optimum penetration of sunlight. (Figure 4-6.8 illustrates the deflection of sunlight over the ceiling of a room by laser-cut panels in awning windows.)

4.6.5. Maintenance

If the panels are fixed inside of existing glazing or skylights, no maintenance is required. When panels are laminated between thin sheets of glass and installed as single glazing, the maintenance is the same as for glass.

4.6.6. Cost and Energy Savings

The cost of the panels is approximately 130 euros per square metre for small areas of panel (< 20 m^2). For larger areas, the cost approaches 100 euros per square metre.

Energy savings depend on the application. For example, laser-cut panels fixed in the upper half of a window to deflect light deeply into a room may increase the natural light by 10% to 30% depending on sky conditions. If the panels can be tilted out from the window, both light collection and penetration into the building can be dramatically increased.

4.6.7. Some Examples of Use

Figure 4-6.8: Laser-cut panels in awning windows deflecting sunlight over the ceiling of a classroom (Kenmore South State School, Brisbane, Australia)

4.6.8. Simulations and Measured Results

Test room measurements were conducted for laser-cut panels at two test sites. Norway conducted tests on a vertical panel. Germany conducted tests on an exterior, 20° tilted panel.

Algorithms have been developed to incorporate laser-cut panels into the lighting simulation programme ADELINE and Radiance.

A. Vertical Laser-Cut Panel (Norway)

The Norwegian University of Science and Technology (NTNU) tested a vertical laser-cut panel in an occupied office building at Sandvika, Norway (near Oslo) at latitude 59ºN. In the test room, the laser-cut panel was installed in the upper part of the window (Figure 4-6.9). The reference room had clear, unshaded glazing of equal size to the test room. See detailed test room description in Appendix 8.4.

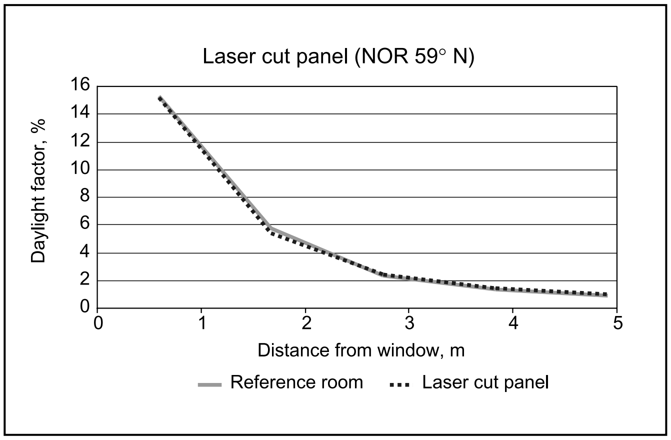
Figure 4-6.9: View to the outside from the test room with laser-cut panels installed in the upper, horizontal window (sunny day). A centre line aluminium section is used to locate measurement points

Laser-cut panel **Norway: 59°N** Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Overcast (DF%)	5.4%	5.8%	2.5%	2.3%	1.0%	0.9%	12.2	5.5
Clear winter: Noon	Sun	Sun	Sun	Sun	2,230	1,240	23.4	78.8
Clear winter: 15:00	1,400	1,150	680	480	320	190	5.2	23.4
Clear equinox: Noon	7,620	4,730	4,200	2,540	1,710	1,220	58.5	96.6
Clear equinox: 15:00	2,720	2,630	1,370	1,120	720	460	38.7	62.7
Clear summer: Noon	4,790	3,700	2,660	1,800	970	700	85.7	77.1
Clear summer: 15:00	1,470	1,360	790	630	390	260	63.9	48.4

Note: The window, intermediate, and rear zone sensors were 1.67, 2.75, and 4.91 m from the window, respectively. "Sun" indicates sunlight striking the sensors. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

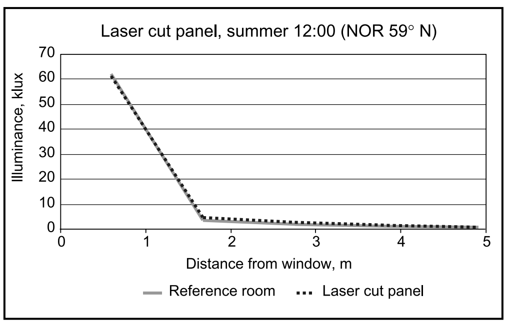
Overcast Sky

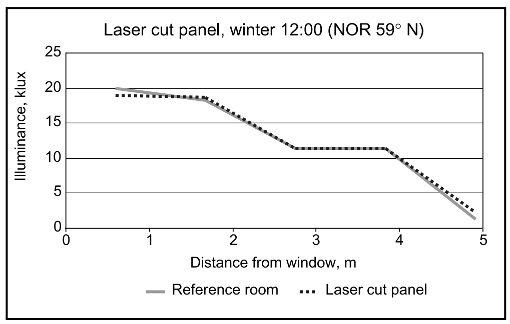
The test room and the reference room windows are identical except for the upper glazing area where a laser-cut panel is installed in the test room. As can be seen from the graph below, the laser-cut panel makes almost no change in the lighting level or distribution in the room.



Clear Sky

Under clear skies, the laser-cut panel increases the lighting level in all seasons of the year and throughout most of the day, especially in the intermediate zone of the room.





Conclusion (A)

The reduction of the light penetration through the laser-cut panel compared to an unobstructed window is smaller than what is normally experienced with blind systems. Even in the fixed position, the laser-cut panel improves the light distribution somewhat through most of the day and year.

B. Exterior, Tilted Laser-Cut Panel (Germany)

An exterior laser-cut panel covering the upper one-third (60 cm) of a glazing area was tested at Technical University of Berlin (TUB) in unfurnished mock-up offices in Berlin (latitude 52°N, longitude 13°E). The panel was tilted 20° to achieve a best compromise between light penetration and glare in summer.

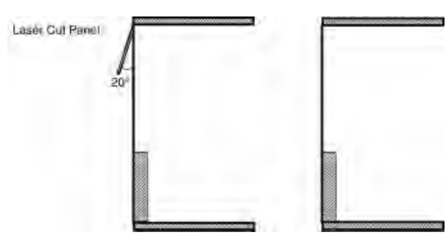


Figure 4-6.10: Section of facade of the test room (left) and reference room (right)

Production

Panels are produced by laser cutting a sheet of clear acrylic (PMMA). They are designed to include a solid periphery and support sections. The laser cutter is programmed with the design.

Laser cuts are usually made right through the panels because this method requires less

Laser-cut panel (20° tilt) Berlin: 52.47°N, 13.4°E Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Overcast (DF%)	11.0	14.9	3.8	4.9	1.7	2.1	25	9
Overcast (DF%)	11.5	16.1	3.8	5.3	1.6	2.2	39	12
Clear equinox: Noon	2,650	1,460	Sun	1,000	1,320	570	74	77
Clear equinox: 9:00	1,900	1,010	1,180	600	630	340	51	46
Clear equinox: 15:00	1,100	480	670	300	360	190	48	46
Clear summer: Noon	2,730	830	1,600	550	920	330	97	58
Clear summer: 9:00	1,660	630	910	390	450	230	75	34
Clear summer: 15:00	1,220	500	720	320	390	200	75	36

Note: The window and rear zone sensors were 0.6 and 4.2 m from the window, respectively. The intermediate zone is an average of data taken at 1.8 and 3 m from the window. "Sun" indicates sunlight striking the sensors. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing south. DF% is the daylight factor.

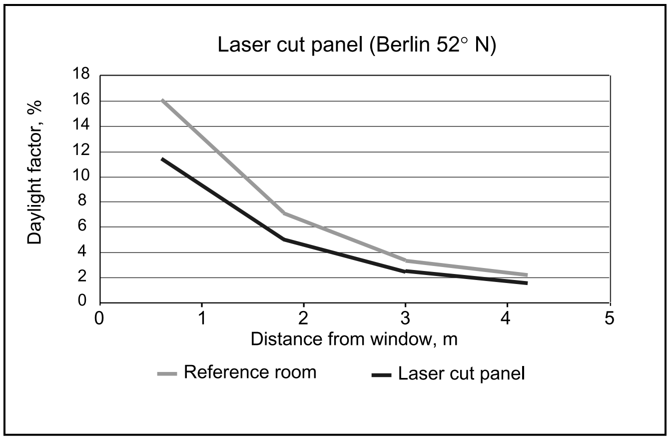
control of cutting speed and laser power than other approaches. For this reason, it is

Figure 4-6.11: Interior view of the TUB test room with the tilted laser-cut panel in the upper third of the glazing. The lower part of the glazing has no other system (overcast sky case)

necessary to design the panel so that solid regions 10-20 mm wide are left to support the cut sections. For example, a panel 1000 mm x 600 mm that has laser cuts right through a 6 mm thick acrylic panel requires a 20-30-mm-wide solid periphery and two vertical solid support sections that are 10-20 mm wide. It is possible to cut only partway through the panel, e.g., 75% depth. However, a solid periphery is still necessary for structural strength.

Location in Window System

Laser-cut panels may be used in fixed and movable arrangements within a window system.

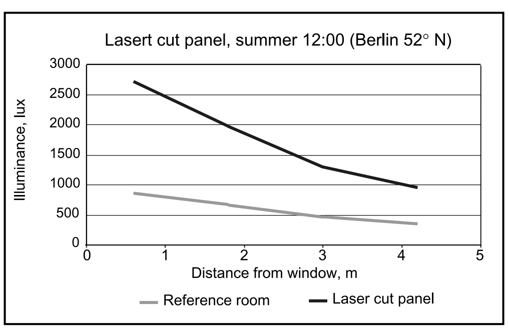


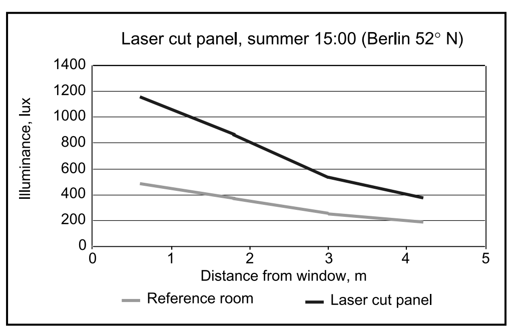
Clear Sky

Under clear skies, the lower two-thirds of the test room window and all of the reference room window were covered with exterior venetian blinds with slightly curved slats, downward tilted at a +45° slat angle. The slats were 80 mm in width, with a grey, diffusely reflecting surface. The position of the blinds caused a partly obstructed directional view to the outside.

Figure 4-6.12: The TUB test room with the tilted laser-cut panel in the upper third of the glazing. The lower part of the glazing has an exterior blind to protect against direct sun (clear sky case)

Under clear skies, the illuminance level is distinctly increased compared with that in a reference room equipped with standard exterior venetian blinds. Direct sun is admitted for some sun positions (e.g., equinox at noon). To avoid this, the tilt angle of the laser-cut panel will have to be adjusted seasonally.





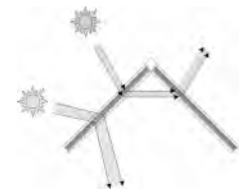
Conclusions (B)

Under overcast sky conditions, the laser-cut panels do not change daylighting level or light distribution dramatically compared to clear glazing.

Under clear sky conditions, daylighting performance can be significantly improved if the position of the panels is adjusted depending on time of day and year (relative to sun position). Adjustment of the tilt angle also improves the system's ability to redirect light and to work as a shading device. Because the system is not suited for view windows, supplementary protection against direct sun and glare is necessary. No colour dispersion has been observed.

4.7. Angular Selective Skylight (Laser-Cut Panel)

The angular selective skylight (Figure 4-7.1) incorporates a pyramid or triangle configuration of laser-cut panels within the transparent skylight cover to provide angular selective transmission.



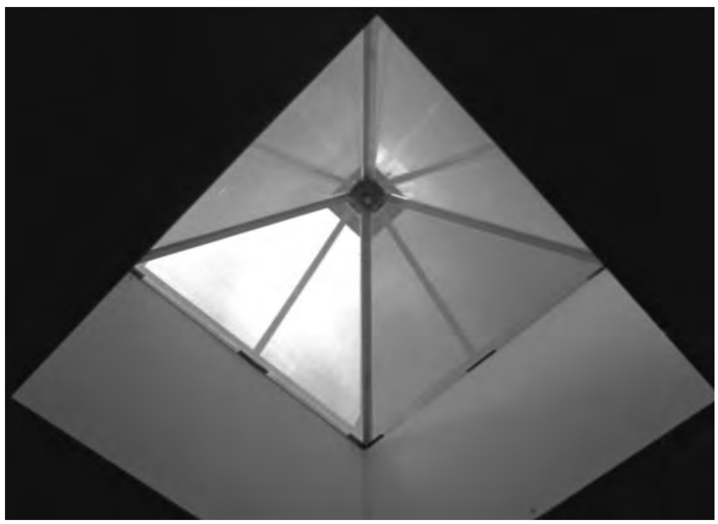


Figure 4-7.1: The skylights used at the Waterford School in Brisbane, Australia, use laser-cut acrylic panels to achieve angular selective transmittance. Light from high sun angles is reflected while diffuse, low-angle skylight and sunlight penetrate the skylights

4.7.1. Technical Description

Components

An angular selective skylight is a conventional clear pyramid or triangular type skylight. Laser-cut light-deflecting panels are incorporated inside the clear outer cover forming a double glazing (Figure 4-7.2). This system transmits more low-elevation light and less high-elevation light. Normally, a diffusing panel is used at the ceiling aperture.

Production

Laser-cut panels are produced by making fine cuts through a thin panel of acrylic (PMMA) [Edmonds et al. 1996]. Four panels, each cut to a triangular shape, are fixed inside a pyramid-type skylight. For a triangular or gable-type skylight, the panels are cut to rectangular form and fixed to the interior of the skylight frame. Usually the panels are cut from 6-mm-thick acrylic, and the cuts are spaced 4 mm apart. Useful tilt angles for the panels in the skylight range between 45° and 55° for the tropics and subtropics where rejection of high-elevation sunlight is critical. For high latitudes where admittance of low-elevation light is more important, tilt angles between 25° and 35° are used.

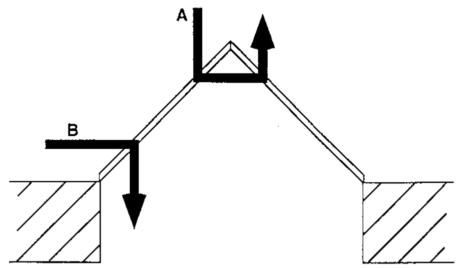


Figure 4-7.2: High-elevation light, A, is rejected and low-elevation light, B, is deflected to the interior

Angular selective skylights are manufactured and sold under licence in Australia by Skydome Ltd., Sydney, in sizes ranging from 0.8 m^2 to 2.4 m^2.

Location in Window System

Skylights are installed in the roof of a building. The primary function of an angular selective skylight is to provide relatively constant irradiance to the interior during the day and to reduce the tendency to overheat the building on summer days.

Technical Barriers

Because angular selective skylights reject high-elevation light, they are not suitable in climates with predominantly overcast skies. They were designed specifically for low-latitude climates with clear skies. However, the design may be applied in high-latitude, clear sky climates such as Canada to boost the irradiance from low-elevation winter sunlight. These skylights are not suited to high-angle roofs because a curb must be used to keep the aperture horizontal, and this adds to their cost.

4.7.2. Application

Angular selective skylights are especially suited for natural lighting of ventilated or air-conditioned buildings with extensive floor area and low-angle roofs, such as supermarkets and schools (see Figure 4-7.5).

Low Latitudes

At low latitudes in subtropical climates, it is important to reject high-elevation sunlight to avoid overheating at midday. Thus the tilt angle of the skylight panels is greater than 45°, as in Figure 4-7.2. As illustrated in Figure 4-7.3 for a triangular skylight (panel tilt angle = 55°), the transmission of skylight falls rapidly as the elevation of incident sunlight approaches 90°, demonstrating that this type of skylight enhances low-elevation input and rejects high-elevation input.

High Latitudes

At high latitudes, it is important to enhance the input of low-elevation sunlight and to maintain the input of high-elevation diffuse skylight. Thus, for high latitudes, the tilt angle of the laser-cut panels is 35° or less. As illustrated in Figure 4-7.3 for a triangular skylight (panel tilt angle 30°), the enhancement of low-elevation light input is considerable, and the input of high-elevation light is only slightly decreased.

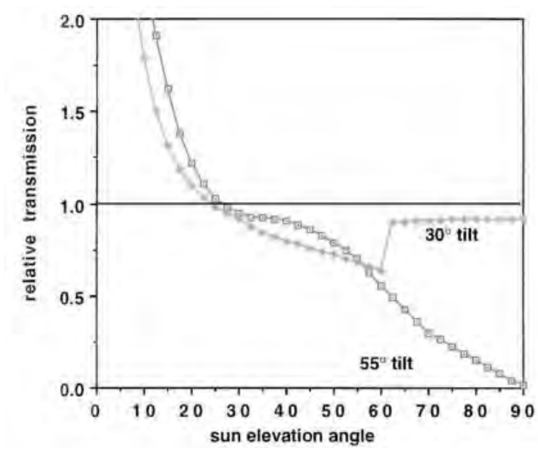


Figure 4-7.3: Transmission of an angular selective skylight relative to an open skylight for tilt angles of 30° and 55°

Skylights

Skylights in buildings with low ceilings usually provide too much light directly below the skylight and too little to the sides of the skylight. If laser-cut panels are used in an inverted V or inverted pyramid structure below a skylight, downcoming light may be deflected over the ceiling, improving the distribution of light to the interior (see Figure 4-7.6 for an example of a light-spreading skylight installed in a very large room).

4.7.3. Physical Principles and Characteristics

Conventional skylights strongly transmit high-elevation light and weakly transmit low-elevation light. The pyramid or triangle configuration of laser-cut panels in angular selective skylights (Figure 4-7.1) deflects low-elevation light down into the skylight and increases transmittance of this light to the building interior. When the tilt angle of the laser-cut panels is greater than 45°, they reduce transmittance of high-elevation light by deflecting it from one panel across to the opposing panel and back out of the skylight (Figure 4-7.2). The detailed performance of angular selective skylights depends on the spacing of the laser cuts in the panel, the tilt angle of the pyramid or triangle configuration of the panels, the well depth of the skylight, the time of day and season, and the sky conditions. As the skylight well depth increases, its performance at low-elevation light angles increases rapidly. The most useful measure of performance is to compare the irradiance through an angular selective skylight with the irradiance through an open skylight as a function of the time of day (Figure 4-7.4 for a skylight with zero well depth).

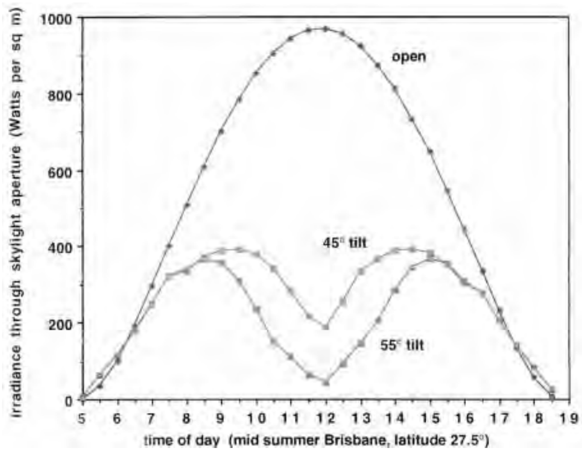


FIGURE 4-7.4: Irradiance versus time of day through the aperture of open and angular selective skylights with tilt angle 45° and 55° in mid summer at latitude 27.5°

4.7.4. Control

Angular selective skylights are always used as fixed systems; their angle-dependent transmittance provides time-dependent control of irradiance to the building's interior.

4.7.5. Maintenance

No maintenance is required beyond normal skylight maintenance.

4.7.6. Cost and Energy Savings

An angular selective skylight is essentially a conventional skylight with a double glazing of laser-cut panels added. The extra cost may be calculated based on 100 euros per square metre for laser cut panel. Typically, the installed cost of a 0.8 m^2 conventional pyramid skylight is about 500 euros whereas the installed cost of a 0.8 m^2 angular selective pyramid skylight is 600 euros.

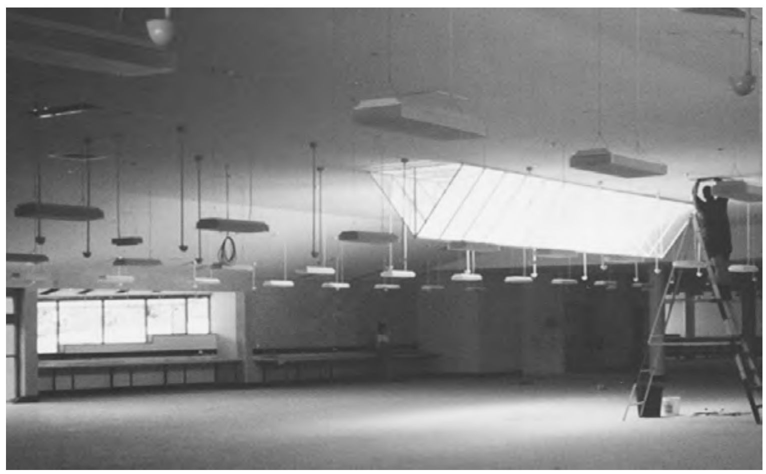
Energy savings can be significant since angular selective skylights can reduce overheating. Electrical lighting use can also be reduced compared to buildings with no skylights or buildings that use smaller skylights to control overheating.

4.7.7. Some Examples of Use

- Waterford State School, Brisbane, Australia (Figure 4-7.5)
- Konica Office Building, Sydney, Australia
- Canugra Parish Church, Queensland, Australia
- Mount Cootha Herbarium, Brisbane, Australia (Figure 4-7.6)

Figure 4-7.5: Angular selective skylights in a classroom at Waterford State School, Brisbane, Australia

Figure 4-7.6: Laser-cut panels installed in "V" form below a skylight aperture. Downcoming light from the skylight is deflected over the ceiling, distributing light more evenly within the room (Mount Cootha Herbarium, Brisbane)



4.7.8. Simulations and Measured Results

An installation of angular selective skylights at Waterford School was selected to test the technology because two identical-size school buildings, each 14 m x 9 m, were available. One was used as the trial building with eight 0.8-m^2 skylights (Figure 4-7.5) and the other with no skylights as the reference building. Both buildings had strong external shading, including absorbing glass, on the windows.

These measurements did not follow the monitoring protocol. Measured illuminances at desk-top level along the central axis of each building are shown in Figures 4-7.7 and 4-7.8. Figure 4-7.7 compares illuminance levels in the trial and reference building under overcast skies at about 15:00 (horizontal ambient illuminance about 20 klux). Figure 4-7.8 compares illuminance under extremely bright summer conditions near noon (direct plus bright cloud-reflected light, horizontal ambient illuminance about 140 klux). While the external illuminance varies by about seven times, the internal illuminance varies by only three times. Simulations were also performed [Edmonds et al. 1996].

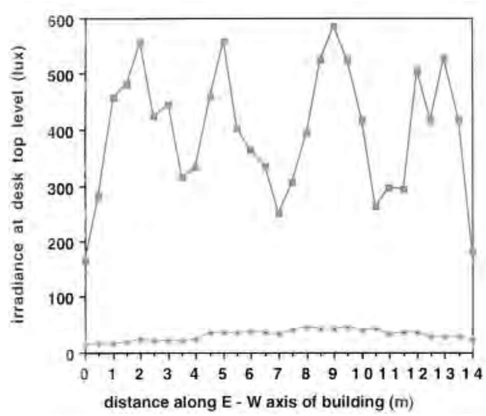


Figure 4-7.7: Illuminance at desk-top level in the trial building (upper curve) and in the reference building (lower curve) for overcast conditions

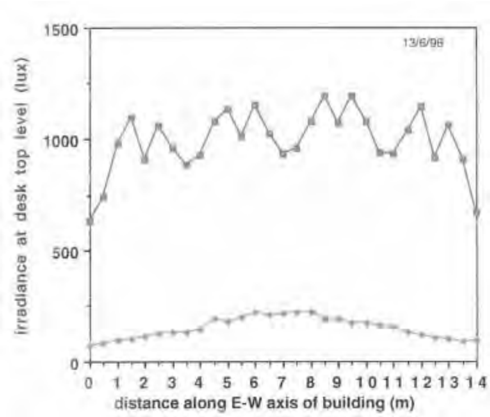
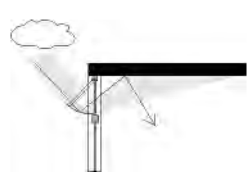


Figure 4-7.8: Illuminance level at desk-top level in the trial building (upper curve) and in the reference building (lower curve) for very bright conditions

Light-Guiding Shades 4.8.

A light-guiding shade is an external shading system that redirects sunlight and skylight onto the ceiling.



4.8.1. Technical Description

Components

A light-guiding shade consists of a diffusing glass aperture and two reflectors designed to direct the diffuse light from the aperture into a building at angles within a specified angular range (Figure 4-8.2). Usually the angular range of light distribution in the building is designed to extend from horizontal up to an elevation of about 60°. The lower elevation is set at zero or horizontal to avoid glare. The light-guiding shade is fixed in the same way as an external shade over a window; it shades the window from direct sunlight as a normal shade does.

Figure 4-8.1. Light-guiding shades mounted on the north windows of the Mount Cootha Herbarium, Brisbane, Australia

Production

Light-guiding shades are more complicated and more precisely defined than conventional shades. Highly reflective material, such as bright-finish aluminium, must be used for its inner surfaces. However, the method of light-metal fabrication is essentially the same for both types of shades.

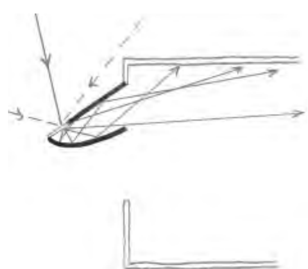


Figure 4-8.2. Principle of the light-guiding shade

Location in Window System

Light-guiding shades are installed over the upper one-third or one-half of a window system. The shades have vertical side panels for support and additional shading.

Technical Barriers

The principal barrier to light-guiding shades is that they cost more than conventional shades, primarily because of the cost of the high-reflectance metal sheet from which the light guiding shade is manufactured and the requirement that the reflective material be formed accurately to limit the spread of output light. One problem observed in practise is that light-guiding shades tend to leak water. This problem can usually be corrected with small drain holes.

4.8.2. Application

In the subtropics, windows are almost always shaded by wide eaves, external and internal shades, and reflecting or absorbing glass. Consequently, the daylight entering a window is much reduced. Daylight levels in shaded subtropical buildings are well below levels in buildings with unshaded windows in more temperate climates. It is possible to adapt the form of an external shade so that it guides into the building some of the light that falls onto the shade. If this adaptation is made carefully so as to avoid glare and to direct light deep into a room, it is possible to enhance the room's daylighting while shading direct sunlight. This is a light-guiding shade's objective (Figure 4-8.1).

Light-guiding shades may be used in any building that uses external shading of windows. All daylight that enters through the light-guiding shade is directed over the ceiling; therefore the shade is a source of diffuse light, which is non-luminous when viewed by occupants of the room and is therefore entirely free of glare. Figure 4-8.3 compares the illuminance of rooms with a conventional shade and with a light-guiding shade of the same size. It is evident that daylighting is greatly improved and that the daylight source is free of glare when a light-guiding shade is used. The ceiling from which the light is reflected may become a source of glare if gloss paint is used, however. Usually a ceiling painted in flat white prevents glare problems.

Figure 4-8.3: compares the daylight in a trial room with a conventional shade (left) and a light-guiding shade (right). The outer edge of the shade is the horizontal yellow band visible through the lower window. Note the low luminance of the output aperture of the light-guiding shade which is directing light only to the ceiling (right photo, upper aperture)

4.8.3. Physical Principles and Characteristics

Light-guiding shades are designed to improve the daylighting of rooms in subtropical buildings that have external shading to reduce radiant heat gain through windows. Therefore, their daylighting performance should be measured relative to a shaded window, not an open window.

The input light to the light-guiding shade comes from a wide range of directions. However, because the input aperture is diffusing, the directional dependence of the input light is removed. Because the light entering the input aperture is diffuse, it is possible to use the principles of non-imaging optics to design the light-guiding reflectors so that the output light falls within an exactly defined angular range. This range can be as narrow or as wide as desired. However, a very narrow output angular range requires a long reflective light guide and a small input-aperture-to-output-aperture ratio. Thus, for a narrow output range, the system is able to collect only a small fraction of the light incident on the shade; as a result, the potential for improved daylighting is small. A compromise must be made between the precision with which light is directed into the room and the amount of light being directed. Because light-guiding shade systems are designed to boost the daylight from the very low level in strongly shaded rooms, it is desirable to direct the light into a relatively wide-output angular range, e.g., 0° to 60°, and to use a larger input-aperture-to-output-aperture ratio—usually in the ratio of 1:2 to maximise total daylight input. Much of the daylight falls on the ceiling close to the window, but because light levels close to the window are often very low, the light-guiding shade can improve interior lighting levels.

If the shade's reflective surfaces are accurately manufactured, then the output beam is very well-defined. If the system is designed so that no light is emitted below the horizontal, then the light-guiding shade source appears dark when viewed from inside the building (Figure 4-8.3). Although this is ideal for reducing glare, occupants who are not familiar with the system may think it is not working. Therefore, there may be a good reason to direct a small amount of light downward, e.g., an angular range from -5° up to +50°. The design equations are outlined in the patent [Edmonds 1992].

4.8.4. Control

Light-guiding shades are fixed in position. Control of the light direction is achieved by the optics.

4.8.5. Maintenance

There is no maintenance other than occasional cleaning of the external input aperture glazing.

4.8.6. Cost and Energy Savings

The cost of a light-guiding shade should be compared with the cost of a conventional external shade or equivalent shading system. Manufacturing costs are much higher than the costs for conventional shades because of the precisely shaped, high-reflectance surfaces required. However, installation and maintenance costs are the same, and the daylighting performance is much superior to that of conventional shades (Figure 4-8.3).

There is a considerable energy benefit from light-guiding shades. Conventional external shades significantly reduce daylight input and are designed to exclude all direct sunlight. Typically, the average daylight level in a room with a strongly shaded window is less than 50 lux. Under clear sky conditions, a light-guiding shade can produce a work plane illuminance of more than 1000 lux at a 5-m room depth. Under overcast sky conditions, the average illuminance obtained would be about five times smaller, i.e., 250 lux. Thus, a light-guiding shade can boost daylight levels in a 5-m-deep room to regulation levels. This example illustrates the gains possible with a light-guiding shade system. In practise, gains will depend on the shape and size of the window; the slope and reflectance of the ceiling, walls, and floor; the type of glazing on the window; and the ambient conditions.

Figure 4-8.4: Light-guiding shade on a building at Regents Park State School, Brisbane, Australia

4.8.7. Some Examples of Use

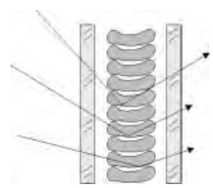
- Regents Park State School, Regents Park, Queensland, Australia (Figure 4.8.4)
- Mount Cootha Herbarium, Brisbane, Australia

4.8.8. Simulations and Measured Results

Test room studies were conducted at Brisbane, Australia, but these measurements did not follow the monitoring protocol.

Sun-Directing Glass 4.9.

Concave acrylic elements stacked vertically within a double-glazed unit redirect direct sunlight from all angles of incidence onto the ceiling.



4.9.1. Technical Description

Components

The main component of a sun-directing glass system is a double-glazed sealed unit that holds the acrylic elements. This sealed unit is normally placed above the view window. The unit's solar heat gain coefficient is 0.36, and its U-value is about 1.3 W/m^2K (depending on the combination of glass and gas fill). A sinusoidal pattern on the interior surface of the window unit can be used to spread outgoing light within a narrow horizontal, azimuthal angle. A holographic film on the exterior glass pane can also be used to focus incoming daylight within a narrow horizontal angle [Kischkoweit-Lopin 1996].

An important part of the system is the ceiling, which receives the redirected light and reflects it down to the task areas. Tilted reflective elements in the ceiling can be used to concentrate reflected light to specific task areas. A simple matte white ceiling also works well to redirect light; the resulting illumination will be more diffuse.

Production

Light-guiding acrylic elements are produced by extrusion. The elements are stacked and placed in an ordinary, sealed, double-glazed unit. When holograms are used for horizontal deflection of daylight, they are produced using a holographic film that is exposed to an interference pattern of two or more laser beams. The film is then placed between two sheets of glass which form the outer pane of the sealed unit. The sinusoidal surface can be produced online during the extrusion process by a CO_2-laser beam or afterwards by laser, mechanically.

Figure 4-9.1: Sun-directing glass attached above the normal viewing window in the ADO office building, Cologne, Germany

Location in Window System

Sun-directing glass is placed in the window area above eye height in order to avoid glare and other visibility effects. It can also be placed in front of the facade, or behind it in retrofit situations. The height of the area with sun-directing glass should in most cases be about 10% of the height of the room. The normal lower viewing window can be shaded by conventional blinds.

Sun-directing glass can also be placed in rooflights to aid penetration of sunlight in atria or halls. The glass should be sloped at an angle of about 20° to redirect sunlight from lower sun positions (Figure 4-9.3).

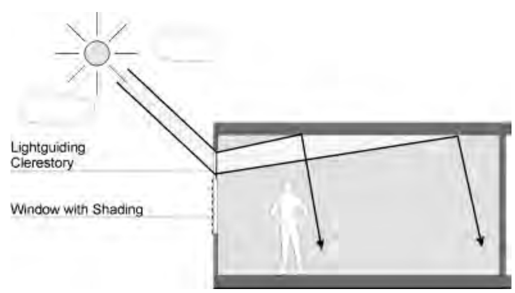


Figure 4-9.2: Sun-directing glass in the clerestory portion of the window

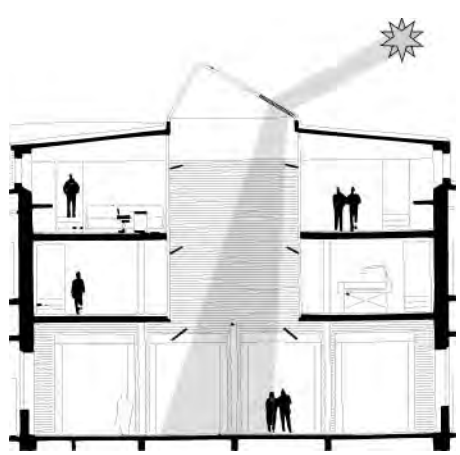


Figure 4-9.3: Sun-directing glass used in a rooflight to daylight an atrium

Technical Barriers

Sun-directing glass is commercially available. The only real barrier to its use is cost. Sun-directing glass also looks different from a normal window; it may appear to be somewhat "milky", which may interrupt the design of the facade, especially if most of the facade is transparent glass.

4.9.2. Application

The system is designed for use in direct sunlight. The best orientation on a facade is south in moderate climate zones (in the northern hemisphere). On west or east facades, it is only useful in the morning or afternoon. The system also deflects diffuse light, but the illuminance level achieved is much lower than with direct sunlight. Thus, for north facades, the elements have to be larger.

The profile of the acrylic elements has been designed for specific latitudes. The optimum sun altitude for the sun-directing glass is between 10–65° (Figure 4-9.4). In tropical regions where sun altitudes are higher, the sun-directing glass should be installed at a tilted vertical angle so as to redirect more light. In this case, the geometry of the sun-directing elements will have to be changed to prevent glare. A light-directing rooflight should be installed with a slope of about 20° towards the sun.

4.9.3. Physical Principles and Characteristics

Sun-directing glass deflects light in the horizontal plane as well as the vertical. Thus, light can reach the depth of a room for all solar positions without the need for movable parts in the building facade. Vertical deflection is achieved by the shape of the acrylic elements. Horizontal deflection is achieved either by holographic optical elements or by a sinusoidal glazing surface.

Vertical Deflection

Incoming light is focused by the first surface of the acrylic elements (Figure 4-9.4) and redirected by total reflection at the lower surface of the profile. It is spread slightly towards the ceiling when it leaves the elements.

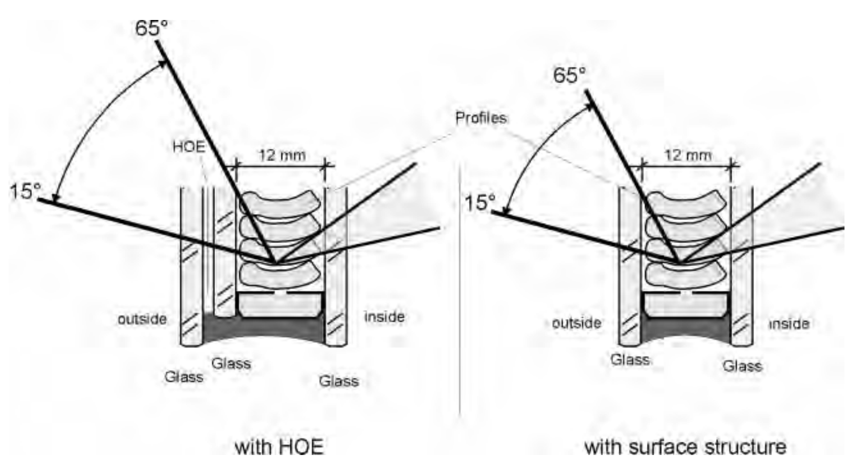


Figure 4-9.4:

Vertical section

Horizontal Deflection

To spread the light more broadly across the width of the room, holographic optical elements or a certain sinusoidal surface structure at the interior glass pane can be used to deflect light horizontally within the room.

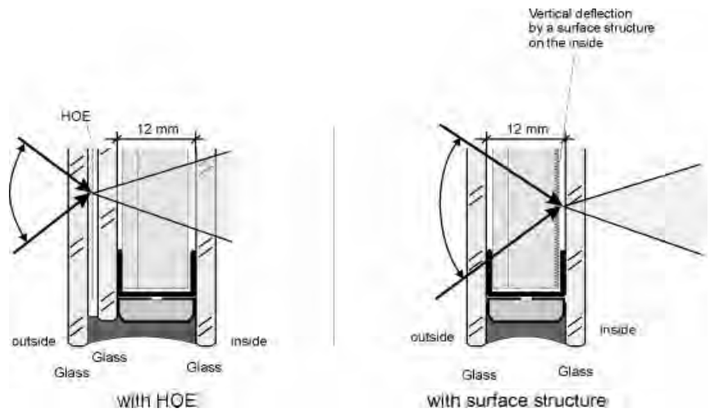


Figure 4-9.5: Horizontal section (plan view)

4.9.4. Control

Sun-directing glass does not include any movable or adjustable parts, so there is no need for control.

4.9.5. Maintenance

As the sun-directing profiles are installed between two glass panes, no maintenance is necessary other than cleaning the glass.

4.9.6. Cost and Energy Savings

The price difference between sun-directing glass and standard insulated double glazing is about 200 euros per square metre for the sun-directing element itself (about 12 euros per square metre floor area). This price is expected to decrease for large-scale production. Sun protection is not necessary in front of the sun-directing glass, so these costs can be reduced.

4.9.7. Some Examples of Use

- Geyssel office building, Cologne, Germany (see Section 4-9.8)
- Office building ADO, Cologne, Germany

The ADO office building was refurbished with sun-directing glass. The glass was installed in some places by replacing the existing window glazing and in other places by mounting the units in front of the existing windows (Figure 4-9.1). The ceiling was white and diffusely reflecting. The electric lighting was controlled by a photosensor on the roof (open-loop control strategy). See the *IEA SHC Task 21 Daylight in Buildings: 15 Case Studies from Around the World.*

4.9.8. Simulations and Measured Results

Measurements were made of the sun-directing glass in vertical windows. The measurements were not made according to the monitoring protocol.

A. Sun-Directing Glass with Reflective Interior Ceiling (Germany)

Sun-directing glass was applied in the new Geyssel office building in Cologne within a ground floor office room approximately 9 m long and 7 m deep. The ceiling height was 3 m. There was a reflecting ceiling with aluminium lamellas tilted towards the window to distribute the light onto the work plane with minimum loss. The electric lighting supplemented the daylight to achieve an illuminance of 500 lux. The electricity demand for electric lighting was monitored continuously for a year. Significant lighting energy savings from sun-directing glass were measured, but the reference room without the daylighting system was in this case without automatic lighting controls (see IEA SHC Task 21 *Daylight in Buildings: 15 Case Studies from Around the World* and *Survey of Architectural Solutions* on this book's CD-ROM).

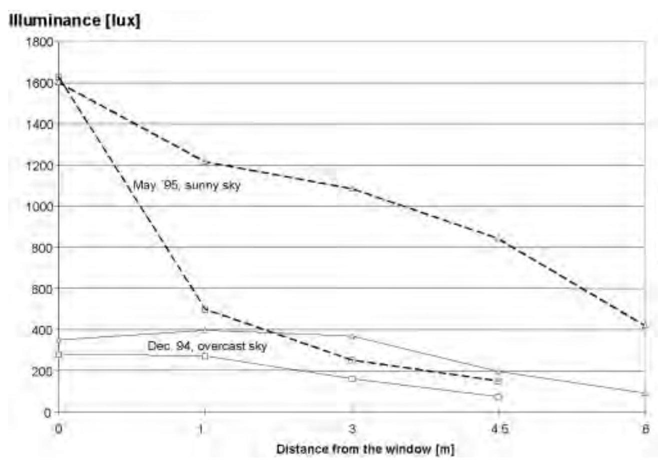


Figure 4-9.6: Measured interior illuminance on December 9, 1994 (overcast) and on May 3, 1995 at 14:30. The lower window shades were closed

B. Sun-Directing Glass (Germany)

The Institute for Light and Building Technique (ILB) at the University of Applied Science in Cologne, Germany, tested sun-directing glass mounted at a height of 2.05 m in the test room. The sun-directing elements themselves were 40 cm high and were installed behind the existing window. In front of the lower viewing section of the window of the test room, a black venetian blind was installed. In the reference room, black venetian blinds completely covered the window. During clear sky measurements, the slats in both rooms were tilted at the same angle to block direct sun: 40° in the summer, 80° in winter, and 60° during the equinox. During overcast sky measurements, the slat angle was horizontal (0°) in both rooms.

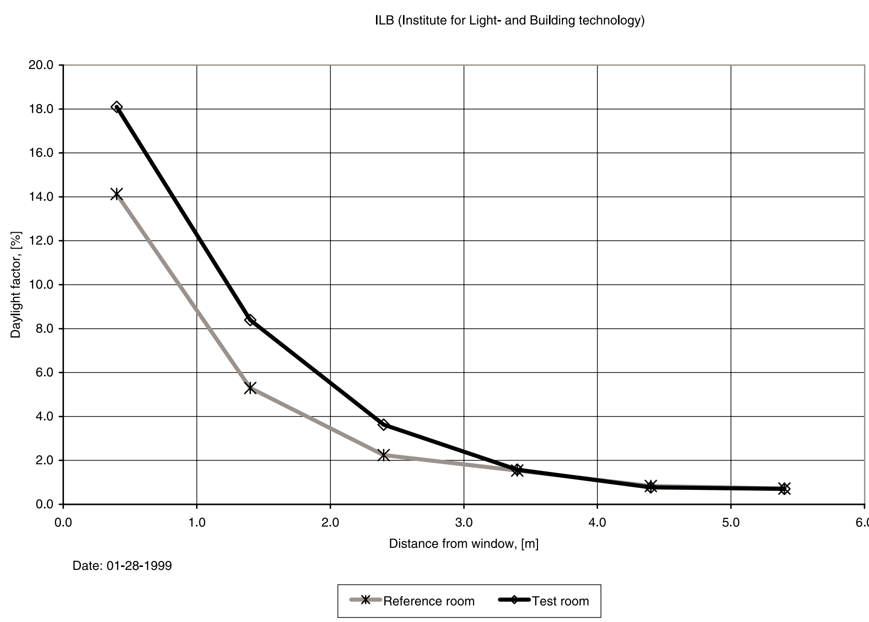
Figure 4-9.7: Interior view of the Geyssel office building in Cologne, Germany with sun-directing glass in the upper windows

Sun-directing glass **Germany: 51°N** Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Overcast (DF%)	8.4%	5.3 %	1.6%	1.5%	0.7%	0.7%	8.0	3.3
Clear winter: Noon	1,514	510	607	344	329	249	24.6	67.3
Clear winter: 15:00	179	83	73	47	41	26	7.8	10.8
Clear equinox: Noon	1,570	680	840	388	574	285	60.4	70.1
Clear equinox: 15:00	908	360	432	213	273	155	44.6	41.7
Clear summer: Noon	1,971	1,213	753	614	502	365	79	54.0
Clear summer: 15:00	663	416	234	194	157	110	59	24.0

Note: The window, intermediate, and rear zone sensors were 1.4, 3.4, and 5.4 m the window, respectively. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

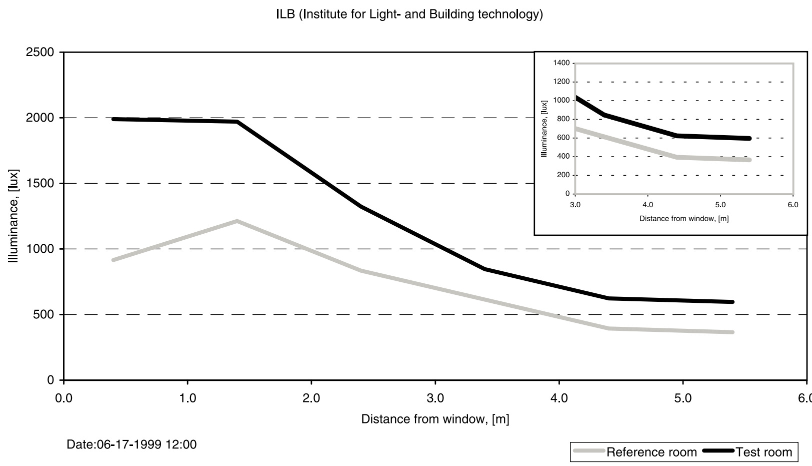
Overcast Sky

During overcast days, the sun-directing glass increases interior illuminance levels up to a 3 m depth from the window.



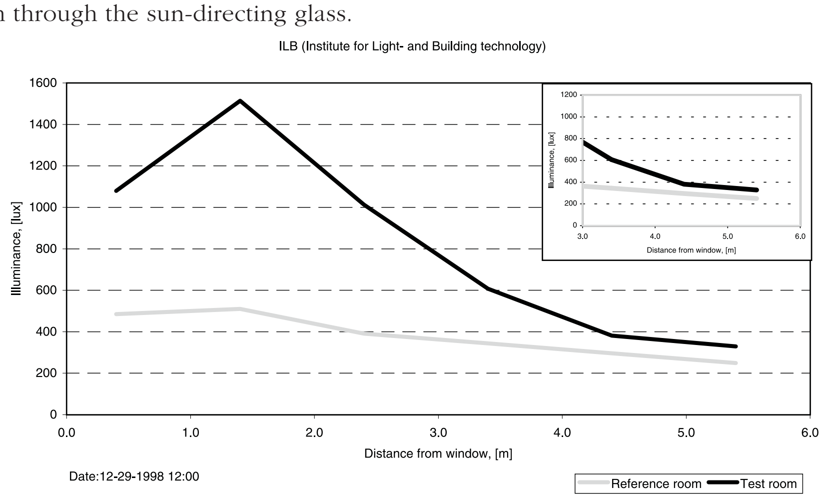
Clear Sky

At higher summer solstice sun positions, the illuminance level is sufficient in the whole room. A level of more than 500 lux was achieved even at the rear zone.



On the equinox, the illuminance level is sufficient in the entire room. Because the sun altitude is lower than in summer, the peak illuminance is located at a distance of 1.5 m from the window.

During winter, the illuminance level is much lower in both rooms than other times of the year because of decreased exterior illuminance. As a result of low sun positions, the venetian blinds' cut-off position to block direct sun is closed (80°) so that light can only enter the room through the sun-directing glass.



Conclusions (B)

As might be expected, the sun-directing system works best in sunnier climates and on building facades that receive direct sun. For overcast sky conditions or exposure to clear sky only, the effect of the sun-directing glass is small. The main improvement can be observed near the window with negligible impact beyond a distance of 3 m from the window.

On sunny days for the hours when the sun faced the building facade, the illuminance levels were often above 500 lux throughout most of a typical 5-m-deep room, allowing electric lighting to be dimmed or turned off. Compared to a conventional glazing system with partly closed blinds, the sun-directing system allowed higher illumination levels and relatively even daylight distribution. During winter, equinox, and summer, the sun-directing glass increased the illuminance in the back of the test room by 100 to 300 lux. Although a reference window without any blind system would have higher light levels if used as a reference case, it would also have very high illuminances from direct sun penetration and large potential glare problems.

During equinox and winter when solar altitude angles are lower, the redirected sunlight substantially increased illumination in the front two-thirds of the room and provided more moderate increases in the back of the room. In the summer months with higher sun altitudes, the sun-directing glass did not provide as much of a relative advantage as in the other seasons. Because sun-directing glass performance depends on solar altitude, it works best at mid-latitudes where the typical solar altitude is in the range of 15–65°.

In addition to providing more light throughout a space and enhanced light in the back of a room under given exterior conditions, the higher light levels resulting from sun-directing glass should provide better light balance throughout the space; thus, the technology should be easily accepted by users.

C. Sun-Directing Glass in a Clerestory Window (Germany)

Sun-directing glass covering the upper one-fourth (40 cm) of the vertical window was tested in unfurnished mock-up offices at the Technical University of Berlin (TUB, latitude 52°N, longitude 13°E). The sun-directing glass had a sinusoidal surface pattern on the interior surface of the window unit. It was installed vertically (interior to the existing double-pane

Figure 4-9.8: Interior view of the TUB test room with sun-directing glass (left) and reference room with clear, unshaded glazing (right) under overcast sky conditions

clear glazing) after determining that the depth of light penetration was nearly independent of sun position and the inclination of the glazing unit.

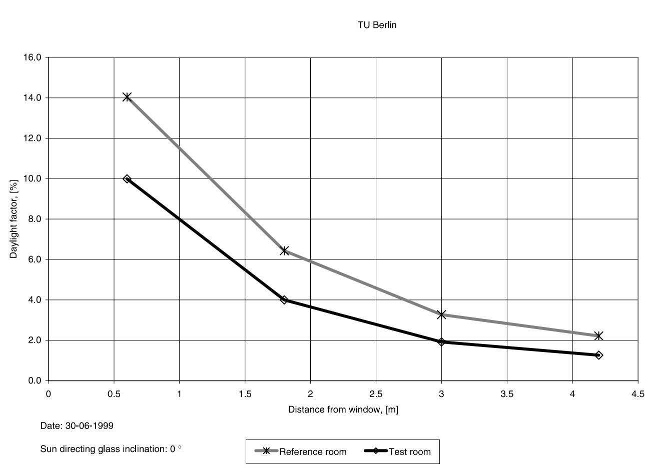
For the overcast sky measurements, the reference room had clear, unshaded glazing. For the clear sky measurements, exterior, diffuse-reflecting, light grey, 80-mm-wide, 45° tilted venetian blinds were extended over the full height of the window in the reference room and over the lower, 120-cm-high view window in the test room. In all other respects, the test and reference room windows were identical except for a 25-cm-high opaque frame that separated the test room's upper window from the lower view window (Figure 4-9.8). The interior ceiling was diffusing. A detailed test room description is given in Appendix 8.4.

Sun-directing glass Berlin: 52.47°N	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
Monitoring case and time	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Overcast (DF%)	10.0%	14.0%	3.0%	4.9%	1.3%	2.2%	35	15
Clear equinox: Noon	2,540	1,240	1,330	840	710	520	65	61
Clear equinox: 9:00	1,650	860	920	530	520	320	46	37
Clear equinox: 15:00	820	440	490	290	270	200	33	32
Clear summer: Noon	1,450	800	890	530	500	330	99	55
Clear summer: 9:00	1,010	650	640	400	360	250	77	32
Clear summer: 15:00	640	380	370	250	210	170	74	31

Note: The window and rear zone sensors were 0.6 and 4.2 m from the window, respectively. The intermediate zone is an average of data taken at 1.8 and 3 m from the window. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing south. DF% is the daylight factor

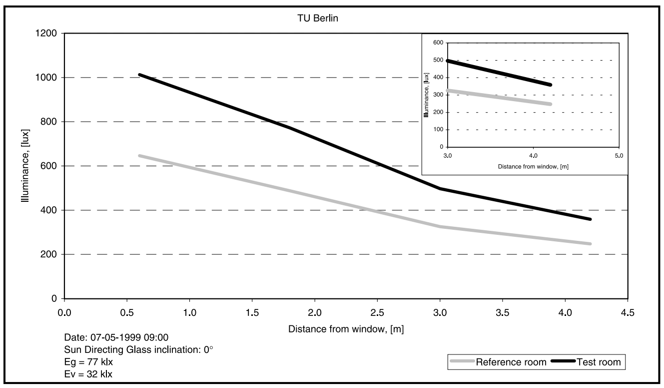
Overcast Sky

As expected, compared to a clear, unobstructed window, the sun-directing glass decreased interior work plane illuminance levels throughout the 4.5 m depth of the room. Towards the rear of the room, interior illuminance levels were reduced by ~39% compared to the reference case. The lower illuminance levels in the test room can be attributed to both the lower transmission of the sun-directing glass and the opaque 25-cm-high mullion that is used to divide the upper clerestory window from the lower view window in the test room.

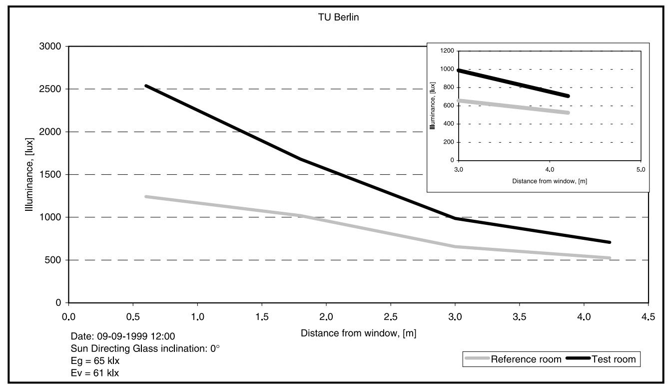


Clear Sky

Interior work plane illuminance levels in the test room were significantly greater than the reference room throughout the day for both the equinox and summer solstice conditions. No data were collected for the winter clear sky condition. Significant increases in illuminance levels occurred throughout the depth of the space. Light redirection was made apparent by the diffuse, upward-angled light patterns on the side walls (Figure 4-10.9). The large differences between the two rooms may be diminished with the use of a higher reflectance blind.



Summer, 9:00, Clear Sky



Equinox, 12:00, Clear Sky

Continuous surface luminance maps were made on clear days using a CCD camera. The luminance of the sun-directing glass varied between 2,000–10,000 cd/m^2 over the equinox and summer solstice days, compared to 800–600–1,800 cd/m^2 of the opaque portions of the grey venetian blind (direct views of the sky between the slats were comparable in luminance to the sun-directing glass). The sun-directing glass will create more direct source glare for some task locations and view angles.

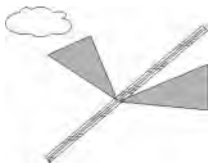
Figure 4-9.9: Luminance (cd/m^2) map of the TUB test room with sun-directing glass on September 9 at noon, E_{VG}= 46 klux, E_{VGS}= 37 klux.

Conclusions (C)

Under overcast sky conditions, the sun-directing glass decreased interior illuminance levels. Under clear sky conditions, interior illuminance levels were significantly increased compared to a grey venetian blind. The bright luminance of the sun-directing glass may cause glare.

Zenithal Light-Guiding Glass with Holographic Optical Elements 4.10.

Zenithal light-guiding glass redirects diffuse skylight into the depth of a room.



4.10.1. Technical Description

Components

The main component of zenithal light-guiding glass is a polymeric film with holographic diffraction gratings, which is laminated between two glass panes. The holographic element redirects diffuse light coming into the building from the zenithal region of the sky. Because the system may cause colour dispersion when hit by direct sunlight, it should only be used on facades that do not receive direct sunlight.

Figure 4-10.1: Outside view of zenithal light-guiding glass with holographic optical elements

Production

Zenithal light-guiding glass is produced when a holographic film is exposed to an interference pattern of two laser beams. After development, the pattern is fixed in the film as a periodic variation of the refractive index. The film is laminated between two glass panes for mechanical stability and protection against humidity.

Location in Window System

Zenithal light-guiding glass can be integrated in a vertical window system or attached to the facade in front of the upper part of the window at a sloping angle of approximately 45°. Because zenithal light-guiding glass slightly distorts view, it should only be applied to the upper portion of the window.

Technical Barriers

Zenithal light-guiding glass is designed for use with diffuse light only. If direct sunlight reaches the film, glare and colour dispersion may occur. Light-guiding holographic optical elements for direct light are under development.

4.10.2. Application

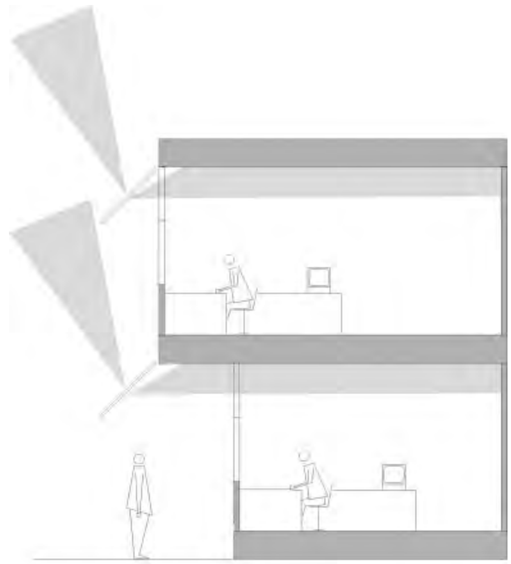


FIGURE 4-10.2: EXAMPLE OF APPLICATION OF A ZENITHAL LIGHT-GUIDING ELEMENT

Because zenithal light-guiding glass is integrated into the building envelope, architectural integration is required. The glass is installed in a building like a normal window or structural glazing unit. Installation does not require specific equipment or knowledge.

The system can be used in facades that are not exposed to direct sunlight. It is most useful in situations where the sky view is heavily obstructed (i.e., urban environments) and in cloudy climates with high sky luminances.

4.10.3. Physical Principles and Characteristics

The luminance level of the zenith region of the overcast sky is typically much higher than the level in the horizontal region, so zenithal light-guiding glass is a promising strategy for predominantly cloudy climates to redirect light from the sky zenith into the depth of a room [Kischkoweit-Lopin 1999]. Tilting the element at an angle of approximately 45° from the facade increases its exposure to the sky, so more light is redirected into the room. Thus, zenithal light-guiding glass is especially appropriate for buildings with external obstructions, e.g., in a courtyard situation.

The incident light from a specific area of the sky is diffracted by the grating in the refractive index of the holographic film and guided to the ceiling of the room. Because of the range of angles of the incident light, colour dispersion is mixed, so only small colour effects occur. When there is incident direct sunlight within the active angle of the element, glare occurs and colour dispersion cannot be prevented. Visibility through the holographic optical element is possible except in the general direction of the active angle.

4.10.4. Control

Zenithal light-guiding glass is a fixed daylighting system; therefore, no controls are required.

4.10.5. Maintenance

No maintenance is needed other than cleaning.

4.10.6. Costs and Energy Savings

A zenithal light-guiding system was installed for the first time in July 1996. The cost for the elements was about 900 euros per m^2. Prices may decrease with large-scale production.

Figure 4-10.3: Office with light-guiding element

4.10.7. Some Examples of Use

The first installation was in the ADO office building in Cologne, Germany. Zenithal light-guiding glass was attached to a north facade in front of three windows. A comprehensive evaluation of the ADO office building can be found in the IEA SHC Task 21 *Daylight in Buildings: 15 Case Studies from Around the World*.

Distance from the facade	0.2 m	1.2 m	2.2 m	3.2 m	4.2 m
Without HOE	15.78%	4.10%	1.35%	0.75%	0.57%
With HOE	14.71%	3.09%	1.40%	0.86%	0.72%

Table 4-10.1: Daylight factor with and without holographic daylight redirecting element

4.10.8. Simulations and Measured Results

The system has not been monitored in test rooms according to the IEA Task 21 monitoring protocols. The table above shows the daylight factor in an office with and without a holographic daylight-redirecting element. Although the system reduces daylight in the window area, daylight increases slightly in the depth of the room.

Holographic optical elements have shown promising laboratory results, but no significant energy savings have yet been demonstrated in a real building.

4.11. Directional Selective Shading Systems Using Holographic Optical Elements (HOEs)

Directional selective shading systems reject incident light from a small angular area of the sky vault. Thus, the system can redirect or reflect incident beam sunlight while transmitting diffuse light from other directions. This selective shading provides daylight to building interiors without seriously altering view from windows.

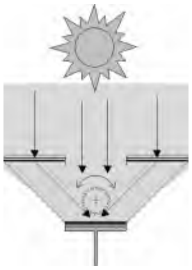


FIGURE 4-11.1: Holographic transparent shading system at REWE Supermarket Headquarters. above: Interior view of the glazed roof with external movable lamellas. below: Exterior view of movable lamellas

4.11.1. Technical Description

Components

Holographic diffraction gratings embedded in a glass laminate can be used in two different ways to provide shading control for large glazed areas.

In **Transparent Shading Systems,** the holographic optical elements are designed to directly reflect incident sunlight within a relatively narrow angular range normal to the surface. If the glass that incorporates these elements is rotated to follow the sun, direct sunlight is effectively shielded from entering the space while light incident from other angles passes through the system.

In **Sunlight-Concentrating Systems,** the holographic elements are designed to redirect and concentrate direct sunlight onto opaque stripes on a second set of glass elements. At these elements the sunlight is reflected, absorbed, or converted to electricity or thermal energy. This design allows the construction of a shading system that blocks direct sunlight while being transparent for diffuse light and viewers looking out.

In both designs, the whole shading element has to track the sun's path to achieve optimal shading, so a single-axis tracking system is necessary.

Production

The critical functional element in both types of directional selective shading systems is the holographic layer. A holographic film is exposed to an interference pattern of two laser beams. After development, the pattern is fixed in the film as a periodic variation of the refractive index. The film is placed between two glass panes for mechanical stability and protection against humidity. One or more glazings containing these holographic optical element panes are then integrated with other structural and tracking elements to create the linear modules described above.

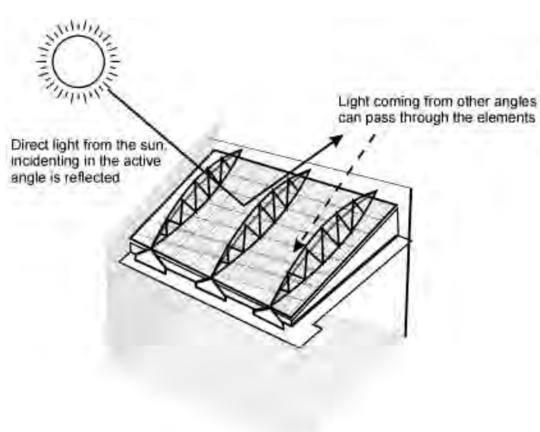


FIGURE 4-11.2: Roof application of transparent shading system at REWE headquarters in Cologne, Germany

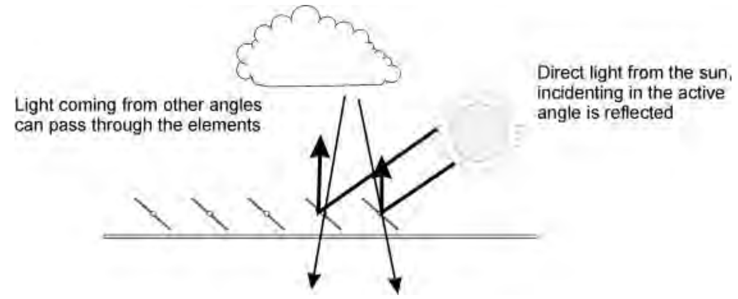


Figure 4-11.3: Principle of directionally selective shading in a roof application of the transparent shading system

Location in Window System

The movable glass element incorporating the holographic coating would normally be attached in front of the primary vertical glass facade or roof opening as a shading system. In some applications, these shading elements may be applied in the building's interior if solar gain can be vented through the roof structure; this arrangement reduces the weathering requirements for the single-axis tracking system. Whether on the interior or the exterior, the operable shading system needs to be integrated into the technical and architectural design of the building.

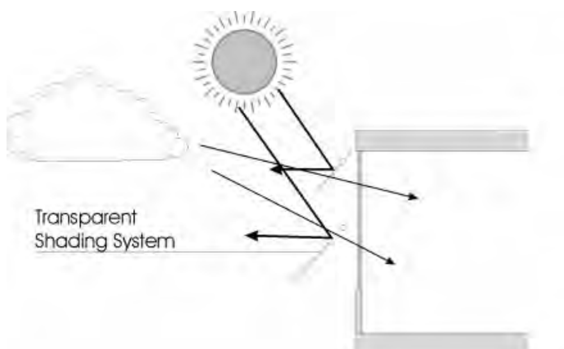


Figure 4-11.4: Computer-generated image of selective concentrating shading system with holographic optical element

Technical Barriers

Holographic optical elements are in the early stages of development; there is little long-term experience with their performance over time in harsh outdoor conditions. The mechanical systems that are needed to track and control the panels represent cost and maintenance barriers similar to those faced by other operable tracking systems.

Figure 4-11.5: HOE transparent shading system

4.11.2. Application

The holographic optical elements are designed for use as a transparent shading system, which allows penetration of diffuse light for illumination purposes and good view out while blocking the intense rays of the direct sun. These elements are most applicable where a large glazed area is desirable but where glare or overheating from direct sun may be a problem. While many opaque operable shading systems are commercially available, these transparent shading systems have the potential advantage of maintaining a high degree of transparency for the overall building structure and providing good solar control. They can be installed to rotate about the horizontal or vertical axis, either on a vertical facade or over a glass roof. Colour effects may be caused by dispersion within the holographic optical element. With proper system design, this colour dispersion may not be noticed indoors unless the panels are not correctly aligned or adjusted.

Sunlight-concentrating systems utilise opaque elements to block direct sunlight. The opaque elements may directly reflect the light or light may be absorbed for thermal conversion and use, or absorbed by a photovoltaic panel for conversion to electricity. In these latter applications, there will be added integration requirements for the thermal conversion or photovoltaic systems [Müller 1996].

4.11.3. Physical Principles and Characteristics

Transparent Shading System (Total Reflection)

Incident light within the active angular range is redirected by the HOE at a very oblique angle towards the back of the glass laminate layer. After a ray bounces off the back glass surface by means of total internal reflection, the holographic layer redirects it back out the front surface. The holographic optical element is inactive for all other angles of incidence, so diffuse light can penetrate the HOE to provide daylight to the space behind the glazing. The view to the outside of the building is not significantly altered by the holographic element (Figure 4-11.1). For the system to operate at maximum effectiveness, the glass panel (which may have a horizontal or vertical axis) must track the sun's motion over the course of the day.

Sunlight-Concentrating System

Holographic optical elements redirect normal incident sunlight onto the opaque surface of a lower strip of glass or other material (e.g., photovoltaic), thus effectively blocking intense direct solar radiation. The holographic elements are optically inactive or transparent to all other angles of incidence, so diffuse light can penetrate through the elements to illuminate the building interior. The view out through the panels is reduced by the opaque strips (30 to 50% of glass area).

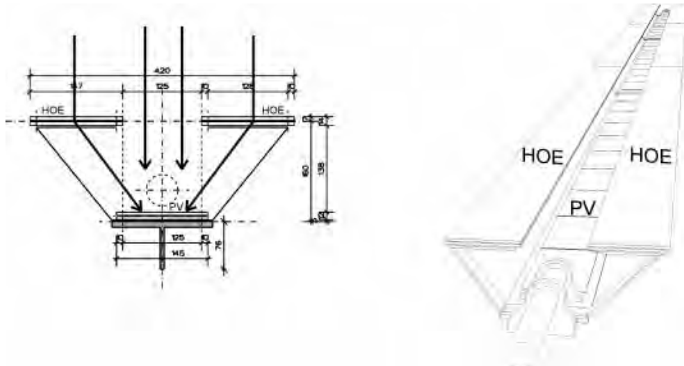


Figure 4-11.6: Advanced light-concentrating selective-shading lamella with solar cells. HOE = holographic optical element, PV = photovoltaic solar cells

4.11.4. Control

Both sunlight-concentrating and transparent shading elements have to track the sun's path. Tracking would normally be realised by a computer-controlled automated system similar to systems that operate motorised louvers. The sun's position can be pre-calculated and stored in a look-up table or directly determined with various lighting sensors. Generally the controls for such a system would be automated with some options for manual override.

4.11.5. Maintenance

The maintenance of the glass elements themselves involves infrequent cleaning in most environments. However, past experience has shown that maintenance of electromechanical systems to reliably operate a large number of movable glass panels is likely to be difficult.

4.11.6. Costs and Energy Savings

The cost of directional selective shading systems is high because the holographic elements are not yet produced in volume and the control systems are complex and costly. The first systems cost about 1,500 euros per square metre of the complete system including the cost of special mounting and tracking systems. Reliable energy savings figures are not yet available.

4.11.7. Some Examples of Use

Internationale Gartenbau-Ausstellung (IGA) Row Houses, Stuttgart, Germany – Light-Concentrating Shading Systems

The first generation of sunlight-concentrating systems incorporating photovoltaic (PV) cells was installed in 1993 and tested for three years at a demonstration building in Stuttgart. In 1996, new systems were installed using larger and cheaper PV elements. The sunlight-concentrating system used in row houses at the IGA has been shown to reduce temperatures in the courtyard area on sunny summer days. Figure 4-11.8 shows that the systems can control direct sunlight while admitting diffuse skylight on partly cloudy days.

REWE Headquarters, Cologne, Germany – Transparent Shading Systems

A first application of the transparent shading system is the courtyard of the REWE headquarters in Cologne (Figures 4-11.1, 4-11.2, 4-11.3 and 4-11.6).

Figure 4-11.7: Glazed courtyard of the REWE headquarters (Figure 4-11.1 shows more detail about this application of reflecting holographic elements)

4.11.8. Simulations and Measured Results

Directional selective shading systems have not yet been monitored in test rooms using the monitoring protocols of IEA SHC Task 21. Therefore, detailed performance data are not yet available for these systems. The solar transmission is 0.2 for the sunlight-concentrating elements and 0.27 for the transparent shading elements (both values for direct radiation only). In other words, these systems reject 70 to 80% of incident direct solar energy and reduce building cooling loads.

Measurements in the IGA row houses in Stuttgart and at REWE headquarters show that good shading control can be provided (for solar gain control) while good daylight illumination is maintained. The users at the two sites were satisfied with the lighting conditions, comparing them with sitting in the shade of a tree in summer.

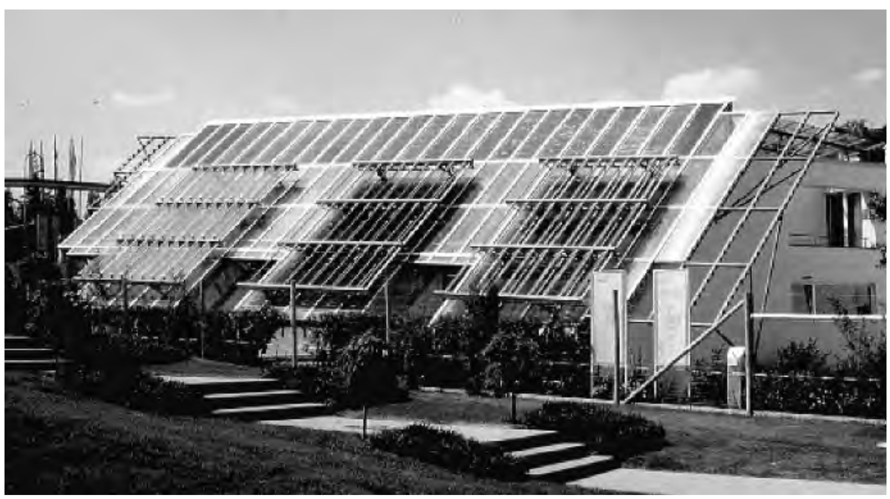
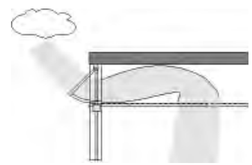


Figure 4-11.8: Sunlight-concentrating system applied at the IGA row houses in Stuttgart

Holographic directional selective shading systems of various designs may be used in any climate, but the greatest impact will be achieved in buildings with large glazed facades under sunny conditions. The transparent shading system is particularly useful where architectural requirements favour a transparent solar control solution rather than a conventional blind system. At the moment, the high cost and mechanical complexity of the tracking systems limit their use primarily to demonstration projects or high-profile buildings.

Anidolic ceiling systems use the optical properties of compound parabolic concentrators to collect diffuse daylight from the sky; the concentrator is coupled to a specular light duct above the ceiling plane, which transports the light to the back of a room. The primary objective is to provide adequate daylight to rooms under predominantly overcast sky conditions.



4.12.1. Technical Description

Components

An anidolic ceiling consists of daylight-collecting optics coupled to a light duct in a suspended ceiling. The system is designed for side lighting of nonresidential buildings. Anidolic (non-imaging) optical elements are placed on both ends of the light duct. On the outside of the building, an anidolic optical concentrator captures and concentrates diffuse light from the upper area of the sky vault, which is typically the brightest area in overcast skies, and efficiently introduces the rays into the duct. At the duct's exit aperture in the back of the room, a parabolic reflector distributes the light downward, avoiding any back reflection. The daylight is transported deeper into the room by multiple specular reflectors lining the light duct, which occupies most of the area above the ceiling. On sunny days, direct penetration of sunlight is controlled by a blind that can be deployed over the entrance glazing. The entire anidolic ceiling system is shown in schematic form in Figure 4-12.1.

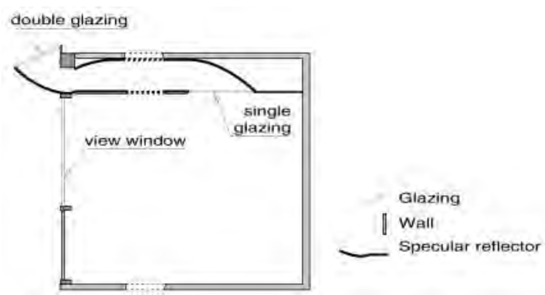


Figure 4-12.1: Schematic vertical section of an anidolic ceiling showing exterior anidolic collector, blind for sun control, specular duct in ceiling, and interior exit optics

Availability

Reflectors in the anidolic elements consist of anodised aluminium surfaces (reflectance $\rho = 0.9$) attached to shaped frames to produce the desired optical control. The prototype frames have been made of wood, but, if production volumes increase, other metal, plastic, or composite materials could be used. The ducts are enclosed by glazing to keep the reflective surfaces clean. The operable blind must be properly integrated into the system.

Location in Window System

An anidolic ceiling system is designed to be located on a vertical facade above a view window. Because the external anidolic device collects diffuse light rays with high optical efficiency, the anidolic ceiling is suitable for lighting rooms with diffuse daylight during overcast conditions. The system is designed to collect diffuse light from the sky vault, so it can be used in any latitude if solar blinds are installed to protect against glare and overheating from direct sunlight.

Technical Barriers

In its present application, the primary objective of the system is to provide adequate daylight under overcast sky conditions. In order to collect sufficient luminous flux, the anidolic collector must typically span the full width of the room facade, and the light duct must completely occupy the void above the suspended ceiling in the room. No other building systems or structural elements should be placed in this space. If they are, the luminous performance will decrease. In addition, because the use of anidolic ceilings directly affects many other building components, the use of this system requires additional coordination in planning and construction.

4.12.2. Application

The system is best used on vertical facades in buildings that are located in predominantly overcast conditions and that have limited access to direct sunlight or face obstructions in a large portion of the sky vault. Design requirements include:

- Available daylight must be efficiently collected from the sky vault and guided into the light duct, even during the worst overcast conditions (usually winter).
- Glare risks must be reduced by channeling the daylight from the facade into the room and redistributing it downward from the ceiling in a conventional manner (like electric light).
- Light duct dimensions must be compatible with available building space.

Channeling the light in a duct above the ceiling reduces the potential for undesired glare. When direct sunlight is the main daylight source, a high concentration factor is feasible, allowing a smaller duct system which will occupy less of the ceiling plenum (see Optically Treated Light Shelves, Chapter 4.3). Because the goal of the current application is to provide daylighting under overcast conditions and with the sky as a diffuse source, concentration is limited to a factor of 2 or 3 so a large light duct is required. The present design has been optimised on this basis, to accommodate a light duct that fills the entire ceiling plenum cavity.

Anidolic ceilings can be used in densely built-up urban as well as rural areas. Their relative effect is more impressive in an urban environment because obstructions around a building increase the importance of collecting diffuse light from the upper sky vault. Anidolic ceilings can be used in both clear and cloudy skies as long as proper shading is provided to control sunlight.

Anidolic ceilings can be used in commercial, industrial, or institutional buildings. Specific design solutions will vary with climate and latitude. Application to the renovation of buildings with deep ceiling plenum spaces or high ceilings may be appropriate if there are no large obstructions and interference with other building systems.

4.12.3. Physical Principles and Characteristics

The field of non-imaging optics has established reliable, efficient methods for designing solar concentrators, which have almost reached the theoretical limit of solar concentration (46,000 dictated by the law of thermodynamics [Welford and Winston 1989]). The same optical principles can be used to develop systems that maximise use of diffuse light from the sky vault (Figure 4-12.2). Features of such systems include:

- The "bundle size" of the light rays delimited at the entry aperture by the angles θ and θ' (given design parameters) is fully transmitted at the exit aperture. Existence angles include all hemispherical directions.
- The number of reflections can be minimised through an appropriate design (which explains the high optical efficiency achieved by the system).
- An accurate selection of incoming rays at the system's entry aperture, as well as an accurate control of emerging rays at the exit aperture, can be achieved (high angular selectivity).

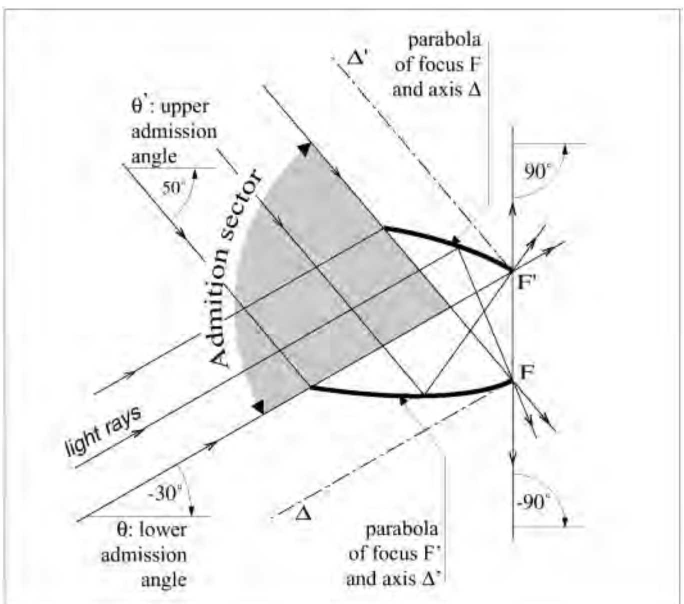


Figure 4-12.2: Principles of two-dimensional, non-symmetric anidolic system (Compound Parabolic Collector)

Because the system is based on reflection from a highly reflective surface (e.g., anodised aluminium), it does not introduce any optical dispersion, even with direct sunlight. The anidolic ceiling was developed with the above principles:

- an anidolic daylight collector was designed and placed in front of the light guide to collect and concentrate the daylight at the entrance of the duct;
- another anidolic device was installed at the end of the duct to distribute the flux of daylight into the room, so as to avoid visual discomfort.

When the sky is the light source, light concentration is essential for the anidolic ceiling system's performance. Although the concentration factor under overcast skies is limited to between 2 and 3, this is adequate for the desired interior daylight illuminance levels. At the interior end of the duct, light is "deconcentrated" by a second anidolic device to direct the flux towards the work plane.

4.12.4. Control

If an exterior blind is used to control direct sun and excessive glare, manual or automated controls are needed. The anidolic ceiling itself requires no additional controls.

4.12.5. Maintenance

The basic anidolic ceiling system typically needs no maintenance. In normal atmospheric conditions (i.e., not particularly dusty) and with typical air quality in an urban environment, rain is enough to clean the system's entrance pane to maintain normal performance levels. Operation of an anidolic ceiling system for approximately three years without significant performance losses has confirmed this (Figure 4-12.4). When a blind is installed for solar control, the blind system has to be maintained as well.

4.12.6. Costs and Energy Savings

The anidolic ceiling system requires additional first costs, relative to a conventional window, to create the optical collector system at the facade and to build the reflective plenum with the emitting optical element. We assume that blinds and lighting controls would be included in a conventional system, so these are not considered an additional cost. Energy consumption for electric lighting was monitored in two 6.6-m-deep identical mock-up offices (see Section 4.12.8A) equipped with the same dimmable light controller and suspended lighting fixtures (two rows of two 36-W fluorescent tubes). One room was fitted with the anidolic ceiling (test room) and the other with a conventional double-glazed facade (reference room). Both facades were unshaded and oriented due north during the monitoring period. Both rooms used clear glazings. The task illuminance (300 lux ± 15%) at 5 m from the window was balanced in both rooms by the continuously dimmable electric lighting control. Figure 4-12.3 shows results from monitoring lighting energy consumption. The office test room with anidolic ceiling used 31% less electricity for lighting during this monitored period than the reference office room for a conventional depth (6.6 m in the present case). Even greater relative savings could be expected in a deeper room.

These monitoring results agree well with the lighting savings figures calculated for this technology using the Swiss method for daylighting (ASE 8911.1989), which predicts yearly lighting savings of 30%. The Swiss method allows the statistical calculation of lighting energy use for a given required desk illuminance (300 lux in this case) on the basis of the daylight factor.

It must be emphasised that this savings figure assumes fully automatic control of the electric lighting (i.e., perfect daylight-responsive dimming), independent of user behaviour. Depending on user behaviour, the utilisation of solar blinds as well as lighting control can lead to different results, especially for south-oriented or other facades that receive direct sunlight.

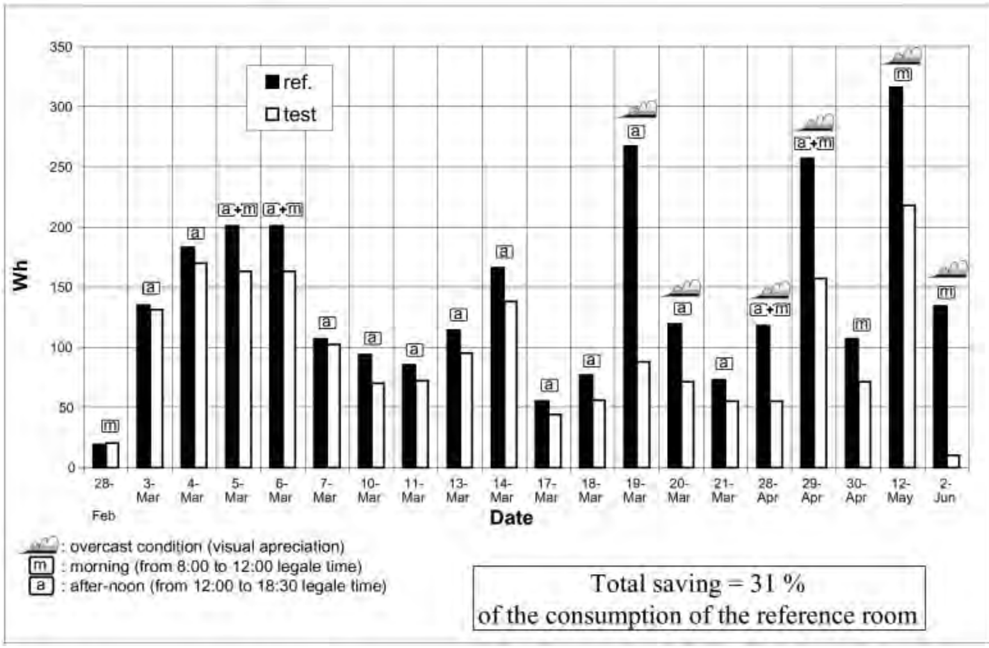


Figure 4-12.3: Lighting energy consumption monitored in the test and reference rooms from February to June (both rooms are equipped with the same dimming controller)

4.12.7. Some Examples of Use

- Module de demonstration en éclairage naturel (DEMONA) daylighting test modules, Lausanne, Switzerland
- LESO Solar Experimental Building, Lausanne, Switzerland

See the following section for monitored results from these two examples.

4.12.8. Simulations and Measured Results

A. DEMONA Daylighting Test Modules (Switzerland)

An anidolic ceiling was installed in a 1:1 scale office test module and was placed next to a reference module equipped with a conventional double-glazed facade. The modules had identical interior photometric properties (ρ_{walls}=0.80, $\rho_{ceiling}$=0.80, ρ_{floor}=0.15) and identical dimensions (3.05 x 6.55 x 3.05 m). Figure 4-12.4 gives a front view of the two modules, placed on a rotating circular platform and facing the same direction. More information about these test rooms can be found in Section 8.4 and Courret [1999].

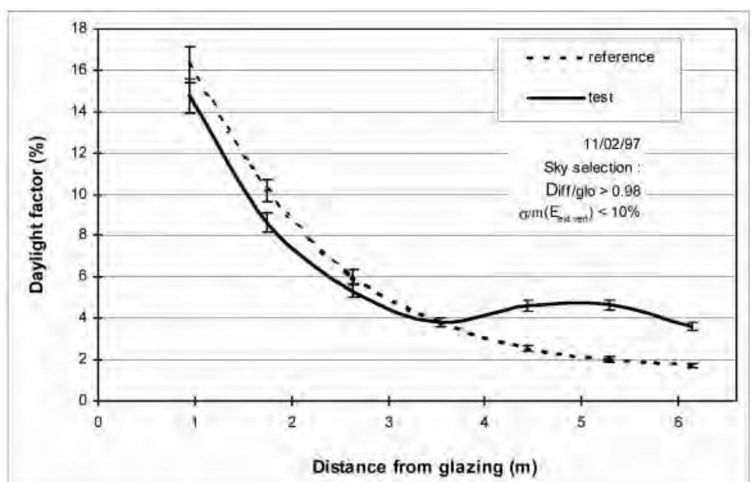
The anidolic system used an insulated double low-E glazing (visible transmittance of 0.81) at the entry aperture for thermal reasons. The entrance pane had a tilt angle of 25°,

Figure 4-12.4: Front view of the two daylighting modules. Foreground: test module (anidolic ceiling); Background: reference module (double-glazed facade with blinds lowered). This south-facing, shaded configuration was not used for the test results shown here

which contributed to its cleaning by rainfall and provided a more favourable incident angle for light rays from the upper sky dome (the bright part of the sky). All the external parts of the system were thermally insulated to avoid thermal bridges and water condensation. A single clear plastic panel (visible transmittance of 0.9) was placed at the interior ceiling exit aperture for maintenance purposes. The system, built in 1996, has shown no significant degradation of performance or mechanical troubles during a period of three years.

In the test room with the anidolic system, the daylight factor on the work plane at 5 m from the window is more than double the value in the reference room under overcast conditions. Both rooms had no exterior or interior shading and both rooms had clear glass. The rooms were oriented due north. The average daylight factor in the back half of the rooms is improved by a factor 1.7 to reach more than 4% in absolute value. In an urban environment with obstructions of 40° elevation, simulation results show that this improvement ratio could reach 2.8. The uniformity of daylight distribution is improved because the overhang of the anidolic system reduces light levels in the front of the room (CIE uniformity ratio goes from 0.3 to 0.6). More extensive data on the overall performance of the system can be found in Courret [1999].

Figure 4-12.5: Comparison of daylight factor profiles in the test room (anidolic ceiling) and in the reference room (double-glazed facade) under overcast skies. The average and standard deviation shown on the graph represents a sample of 43 separate measurements within a period of 40 min.



In addition to the lighting monitoring study, human factors tests were carried out on a group of 33 subjects in the same two test rooms. For these studies both modules were oriented due south. This orientation was chosen to take into account possible glare risks from direct sun penetration into the modules. Furniture, desks, and VDTs were identical in both rooms to permit an objective comparison of the luminous work environment in the two modules.

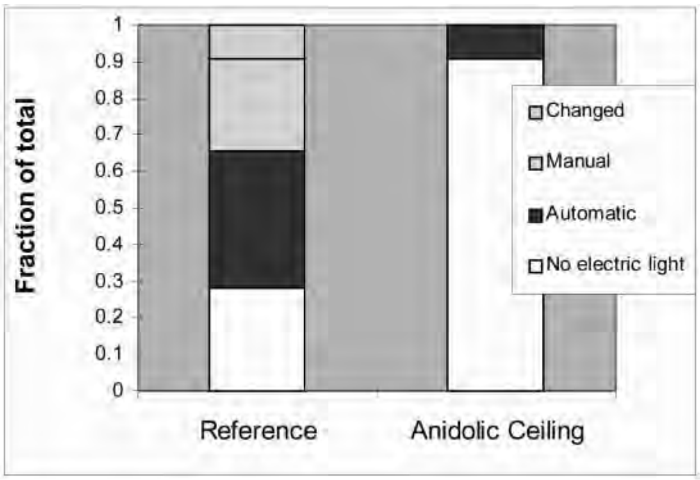


Figure 4-12.6: Lighting mode used by the subjects in the different rooms (subjects could choose lighting modes at their convenience)

The work planes were located in the rear of the rooms 5 m from the window. Their orientation was chosen so that the main view axis of the occupants was parallel to the window. The occupants were provided with varying degrees of control over the electric lighting. The electric lighting system is described in Section 4.12.6. Three different types of response tests were conducted:

- a test of acuity based on black/white document reading,
- a test of acuity based on VDT reading,
- a questionnaire on user acceptance.

The acuity test for document reading showed that a subject makes, on average, 38% fewer reading errors in the room with an anidolic ceiling than in the reference room. Analysis of the lighting/daylighting modes chosen by the subjects showed a considerable difference between the two rooms. In the test room with anidolic ceiling, daylight was strongly preferred as the light source (Figure 4-12.6). In the reference room, occupants selected a variety of electric lighting control strategies.

The acuity test for VDT reading showed that less luminance contrast is necessary to read a number on a VDT screen in the test room than in the reference room (a 10% lower contrast threshold). This tendency is consistent with the assessment of visual comfort, suggesting that visual performance enhancement is probably the result of a more appropriate luminance ratio of the surroundings to the VDT screen in the test room.

The user acceptance questionnaire was the basis for comparison of the perceived visual atmosphere in the two rooms. The study concluded that:

- The visual atmosphere was perceived to be brighter in the test room.
- The colours in the test room were found to be more pleasant although they were physically the same as those in the reference room.

The anidolic system provides improved control of daylight distribution in a room relative to a conventional window. Measurements were made under an overcast sky as well as sunny conditions with the blinds pulled down both for the view glazing and at the entrance of the anidolic collector. Luminance scanning at the work plane in the rear of the offices showed that:

- The anidolic ceiling contributed to a more uniform luminance distribution on the walls and ceiling, thus slightly improving the perceived luminous environment at the desk (lower luminance gradient).
- The additional daylight flux brought in by the anidolic ceiling improved the luminance ratio in the field of view (ratio closer to unity).

These two effects significantly increase visual comfort for reading tasks involving paper as well as VDTs.

Conclusion (A)

By introducing additional daylight in the back of the room, the anidolic ceiling improves overall light levels as well as uniformity from front to back. The absolute figures achieved by the system (a daylight factor of more than 4% at a distance of 4 to 6 m from the facade under overcast conditions) are better than those for most existing side lighting systems. With appropriate electric lighting controls, this system can produce significant lighting energy savings, especially for climates dominated by overcast conditions. Studies with building occupants have demonstrated improved working and lighting conditions, which may translate into better productivity and visual amenity for users.

Figure 4-12.7: View of the renovated south facade of the LESO solar experimental building with its external anidolic system

B. LESO Solar Experimental Building (Switzerland)

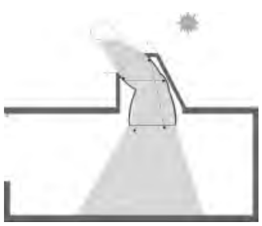
The LESO solar experimental building is a mid-size non-residential building (780 m^2 of heated floor area), which hosts researchers at the Solar Energy and Building Physics Laboratory (LESO-PB) of École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. The building was built in 1980-81, using principles of energy conservation and passive solar design; it is characterised by a thermally insulated envelope and a highly glazed south facade (200 m^2), which collects passive solar energy during the winter.

The facade was fully renovated in 1998-99. On the south facade, the existing glazing was replaced with insulating double glazing that has a selective coating (U=1.1 W/m^2K) and, on three building floors, 25-m-long anidolic collectors were installed, similar to the one described earlier. The upper and lower glazing have blinds to provide shading and sun control when needed.

Because of the rather shallow depth of the offices (less than 4.5 metres deep) at EPFL, the use of a ceiling light duct was not considered appropriate. Instead, diffuse daylight along with sunlight collected by the device are redirected towards the ceiling instead of being sent through the duct. Under overcast conditions, a daylight factor of 2% is achieved at a distance of 3.5 m from the facade, comparable to the performance of a more conventional facade, but the system provides more uniform daylight distribution in the room than a conventional facade would.

Anidolic Zenithal Openings 4.13.

The anidolic zenithal opening is a daylighting system based on non-imaging optics. This anidolic device's high angular selectivity (see Chapter 4.12) is used to collect diffuse daylight from a large portion of the sky vault without allowing direct sun penetration. This form of skylighting system is best utilised to provide daylight to single-storey buildings, atrium spaces, or the upper floor of multi-storey buildings.



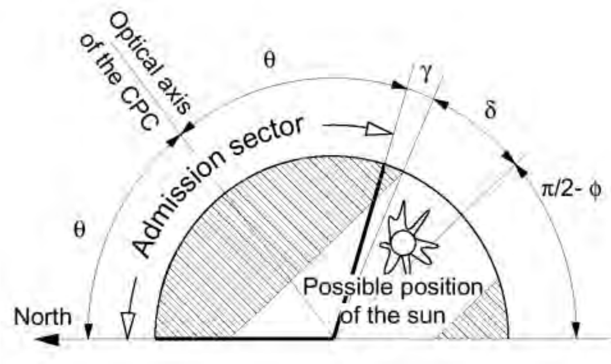
4.13.1. Technical Description

Components

The anidolic zenithal opening system is composed of an optical concentrating element and a "deconcentrating" or emitting element. The collector is based on a linear, two-dimensional, non-imaging, compound parabolic concentrator whose long axis is oriented east-west. The opening is tilted northward for locations in the northern hemisphere and designed so that the sector where it admits light includes the whole sky between the northern horizon and the highest position of the sun in the southern sky during the year. As shown in Figure 4-13.2, the sun never comes inside the admission sector, except at the beginning and end of the day, between the spring equinox and the autumn equinox. Solar protection is completed with a series of vertical slats uniformly laid over the aperture and spaced at 0.5 m.

Figure 4-13.1: Scale model of an anidolic zenithal opening located on a roof

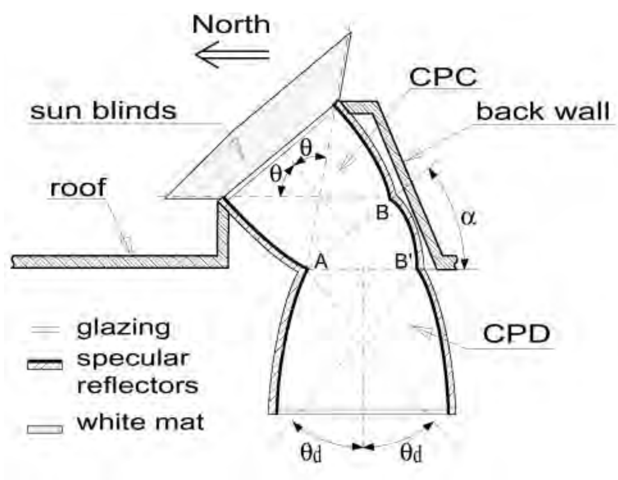
Figure 4-13.2:
Admission sector of an anidolic zenithal opening designed for 47°N; ϕ is the latitude (47°N), δ the maximal declination (23.5°), and γ an arbitrary angle



The admission angle, θ, is equal to 50°, and the tilt angle, α, from the horizontal is equal to 40° (see Figures 4-13.2 and 4-13.3). These angles can be determined using a simple equation given in Courret [1999] and depend on the latitude of the site (47°N in this case).

A compound parabolic deconcentrator, similar to the compound parabolic concentrator mentioned above but reversed, is placed at the emitting end of the opening to guide the daylight flux towards the bottom of the room. In the situation illustrated in Figure 4-13.3, it points vertically downward. The connection between the concentrator and deconcentrator is made with a section of cylindrical reflector. The whole device makes up the anidolic zenithal opening shown in Figure 4-13.3. The exit angle of the device, θ_d, is equal to 40° and is truncated at 45° to reduce its length. The anidolic zenithal opening does not constitute a direct glare source for building users under normal circumstances. In order to prevent the reflectors from gathering dust, the device is enclosed between two layers of glazing (visible transmittance of 0.9).

Figure 4-13.3:
Cross-section of an anidolic zenithal opening



Production

The reflector surfaces consist of sheets of anodised aluminium (specular reflectance of 0.9), which are placed on shaped frames made of wood or other structural materials. With the economics of volume production, the frame could be made of a composite material, for example fibreglass/epoxy, coated with a film of anodised aluminium. The specular reflective surfaces must be protected during the construction process. No extra precision is needed in construction and assembly compared to what is required by conventional building practises.

Location in Window System

This system is designed to be located in roofs with an east-west longitudinal axis. Its entry aperture is tilted to the north in the northern hemisphere and to the south in the southern hemisphere (see Figure 4-13.4).

Technical Barriers

The anidolic zenithal opening must be designed as part of a roof system over a task area or atrium space, so the system must be integrated into the building design process in its early stages. Construction details such as sealing and waterproofing would be similar to those for other rooflighting systems.

4.13.2. Application

The anidolic zenithal opening is designed for roof applications. Like any roof opening oriented to the north (in the northern hemisphere), this device has the advantage of providing daylight that is only weakly dependent on changes in the luminance distribution of the sky resulting from motion of clouds or the sun. Because the luminous output will not vary as widely as that of systems admitting direct sunlight, the anidolic zenithal opening should produce less glare and provide improved visual comfort. It should thus find favour in applications where there are clear indoor spaces for which visual comfort is essential (e.g., sport halls, museums, atria, and markets). It may, however, require larger aperture areas than systems that are designed to admit direct sunlight.

4.13.3. Physical Principles and Characteristics

The system design is based on non-imaging optics and is similar to the design of any anidolic daylighting system. A more detailed description of the underlying optical principles is given in Chapter 4.12. (Anidolic ceiling).

4.13.4. Control

Anidolic zenithal openings provide efficient protection against direct solar radiation without using movable parts. This protection has been demonstrated in tests on a scale model. Even though anidolic zenithal openings have no moving parts, the daylight they transmit throughout the year should be less variable than that transmitted by either fixed or movable systems that must control direct sunlight.

4.13.5. Maintenance

Because anidolic zenithal openings have no movable parts and because image transmission is not an issue, they have no particular maintenance issues. Under normal atmospheric conditions (i.e., not particularly dusty) and in a middle-latitude, European rainfall should be sufficient to clean the entrance glazing.

Table 4-13.1: Daylighting autonomy (%) calculated from mean daylight availability under overcast skies in Switzerland. Opening ratio is the ratio of glazing area to total roof area

opening ratio (%)	10			15			20			25			30			35			40		
Shed with blinds	10	0	0	45	5	0	60	25	0	65	40	5	75	50	20	80	60	35	82	65	45
Shed without blinds	30	0	0	60	25	0	70	45	10	80	60	30	82	65	45	84	72	55	85	75	60
Anidolic systems	55	20	0	74	52	25	82	65	45	85	75	65	87	80	65	88	82	72	89	84	75

lighting need: 300 Lux 500 Lux 750 Lux

4.13.6. Costs and Energy Savings

In temperate climates, overcast sky conditions occur frequently, particularly in the winter, spring, and fall. Under these conditions, an adequate daylight factor is necessary to achieve lighting energy savings. The efficiency and optimisation of light transmission, however, should not take priority over visual and thermal comfort. Anidolic zenithal openings were compared to two types of conventional skylight systems: horizontal diffusive glazing and sawtooth roof glazings [Courret et al. 1996] using computer simulations. "Daylighting autonomy" was calculated for different opening ratios and lighting set points (mean horizontal illuminance) for each of these three designs. Daylighting autonomy is the percentage of time when the overcast sky is sufficiently bright to enable the electric lights to be switched off during the working hours of 8:00–18:00. If one multiplies this parameter by the time frequency of overcast sky conditions and lighting power consumption, one can obtain an estimate of annual lighting energy use. The results are presented in Table 4-13.1. In order to achieve a task illuminance of 500 lux with a 50% daylight autonomy an opening ratio of 30% of the roof area is required with clerestories ("shed with blinds"); with anidolic openings, the required ratio is only ~15%.

Under clear sky conditions and in a semi-temperate climate (Geneva) with a 20% opening ratio, interior daylight levels reach 500 lux during 79% of the hours of building occupancy.

4.13.7. Some Examples of Use

An anidolic zenithal opening was incorporated into the design for the atrium of the new building for the Archives Cantonales du Tessin in Switzerland. In order to integrate the opening into the roof, several modifications were needed because the atrium was not oriented east-west. A cross-sectional view, shown in Figure 4-13.4, gives the overall proportions. In the original building design, daylight was provided only by a series of vertical windows placed at the top of the atrium. Introducing the anidolic zenithal opening increased the horizontal illuminance at the bottom of the atrium by 64%; the opening ratio increased by only 11%. Although these design studies appeared favourable, the anidolic zenithal opening was not incorporated into the final building design.

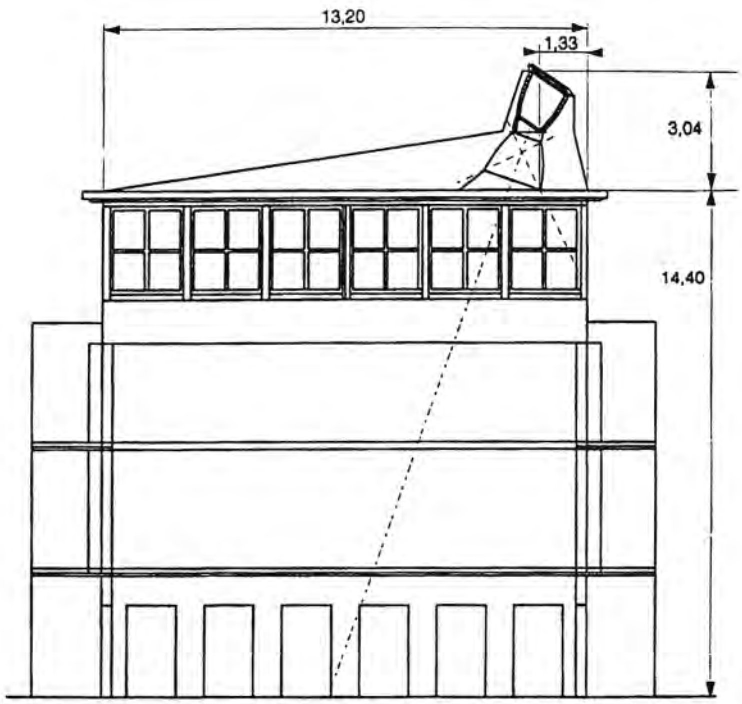


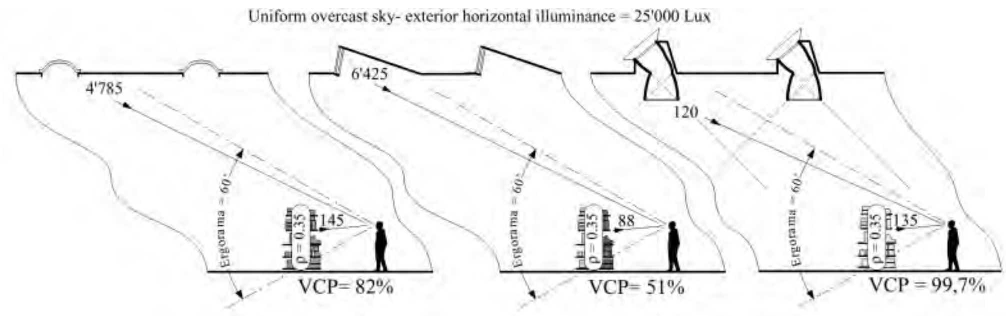
Figure 4-13.4: Cross-section of the atrium of the Archives Cantonales du Tessin (Switzerland) with an anidolic zenithal opening incorporated into the design

4.13.8. Simulations and Measured Results

Potential application of an anidolic zenithal opening to a 10 x 15 x 7-m test building has been studied through numerical simulations [Courret et al. 1996]. A roof opening utilising an anidolic zenithal opening provides twice as much daylight on a horizontal task as is provided by vertical clerestories of similar size. The anidolic zenithal opening's daylighting performance is equivalent to that provided by a horizontal diffusing skylight aperture with a 58% transmittance. However, unlike with a conventional skylight system, the anidolic zenithal opening prevents overheating from sun penetration.

Anidolic zenithal openings can provide required illuminance without excessive glare at the ceiling level. For example, as shown in Figure 4-13.5, the anidolic zenithal openings with a luminance value of 120 cd/m^2 are not brighter than the task in the working area (contrast ratio approximately equal to 1). This is not the case in the two other situations where the brightness ratio for the diffusive horizontal glazing and the sawtooth rooflights are 30 and 70 times brighter, respectively, than the tasks in the field of view. The skylight luminance levels could be reduced with a light well; however, in that case, daylight illuminance would also be reduced.

Figure 4-13.5: Guth's visual comfort probability for three alternative roof light designs (luminance values in cd/m^2)

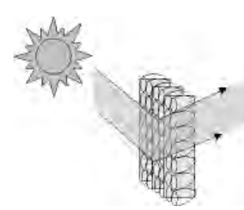


Conclusion

The anidolic zenithal opening applies the principles of non-imaging optics to skylight systems to produce a design that provides adequate illuminance levels by capturing diffuse sky light from a northerly sky view. The optical design of the device offers efficient protection against direct solar radiation transmission throughout the year without use of movable parts. The performance of the system was validated using scale-model tests. Numerical simulations show that this type of roof opening can be twice as efficient as vertical clerestories of similar size. Daylight autonomy of 50% is achieved for 500-lux illuminance levels using only a 15% glazing opening/roof ratio. The daylighting performance of the anidolic zenithal opening is equivalent to that of a horizontal aperture covered with a 58% transmitting diffusive glazing, but the anidolic zenithal opening has the added advantage that overheating from sun penetration is prevented. The anidolic zenithal opening provides better glare control and improved visual comfort than conventional skylights. It should thus find favour in applications where there are clear indoor spaces in which visual comfort is essential (sport halls, museums, atria, and markets, for instance). Because anidolic zenithal openings must be properly integrated into a building's design, they must be considered early in the design process.

4.14. Anidolic Solar Blinds

Anidolic solar blinds consist of a grid of hollow reflective elements, each of which is composed of two three-dimensional compound parabolic concentrators. The blinds are designed for side lighting and provide angular-selective light transmission to control sunlight and glare. The design is, at present, in the prototype and demonstration phase.



4.14.1. Technical Description

Components

The innovative feature of anidolic solar blinds compared to other anidolic systems (anidolic ceilings, anidolic zenithal openings) is their use of three-dimensional reflective elements (see Figure 4-14.1) and their small scale. The optics of the admitting portion of the blinds are designed to reject most high-solar-altitude rays from direct sun but to transmit lower-altitude diffuse light or winter sunlight. Figure 4-14.1 shows the fraction of rejected rays as a function of altitude and azimuth. The design of the portion of the blinds that admits light can be adapted to the specific facade orientation and the typical diurnal cycles of the outdoor temperature (e.g., more solar penetration is needed before noon than after). The optics of the portion of the blinds that emit light are designed to direct daylight into the upper quadrant of the room towards the ceiling and to spread the light horizontally within ±25° of the window surface normal. This design helps diffuse the transmitted sunlight without creating glare.

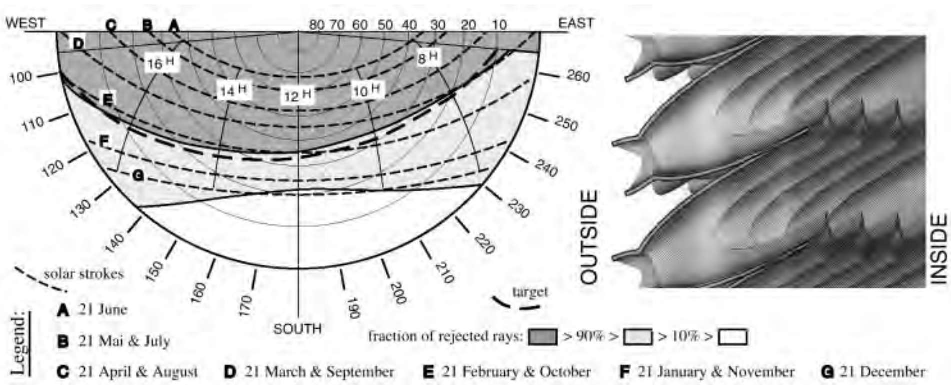


Figure 4-14.1: Comparing desired and calculated fraction of rejected rays (left); section of three-dimensional computer model of anidolic solar blinds (right)

Production

The elements of the blind system can, in theory, be produced at any scale (greater than daylight wavelength) and should be optimised for each latitude and orientation. In the present study, the facade is assumed to face due south (latitude 47°N).

Computer simulation based on ray tracing was used to assess the final performance of the device, whose shape had to be modified to fulfil the manufacturing requirements (laser stereo-lithography). The transmittance of the anidolic solar blinds was also assessed experimentally by means of an integrating sphere. The angular selectivity of the device with regard to the different possible directions of incoming rays was also evaluated.

A series of 20 pieces (31 x 35 x 10 cm) of 48 hollow elements each was manufactured in plastic by means of “vacuum cold moulding” in a mould of silicon. The initial “mother” piece was created through laser stereo-lithography from a computer model. Mirrored surfaces were created by depositing an aluminium coating by vacuum vapour deposition. Figure 4-14.2 shows the appearance of a section of the blinds.

Location in the Window System

The anidolic solar blind system can be applied either as a fixed louver to window openings that were principally designed to collect daylight (i.e., the view through them is blurred), or can be placed in the upper part of a normal window if view to the outside must be maintained through a lower portion of the window. In either application, anidolic solar blinds would typically be placed between two panes of glass for protection against dust.

FIGURE 4-14.2: PHOTOGRAPH TAKEN BEHIND THE EXIT APERTURE OF THE DEVICE. A CELL LOOKS BRIGHT ONLY IF THE VIEW DIRECTION BELONGS TO THE EMITTED ANGULAR SECTOR

Technical Barriers

A number of production problems have to be solved before the system could be readily available at low cost. An efficient process would have to be developed to translate the design criteria for a particular application into the mould and then to produce the final product in large panels. Improved methods of applying and maintaining the reflective coating are also needed.

4.14.2. Application

Anidolic blinds are a fixed system to control daylight and thermal gains in south-facing or other facades that receive extensive sunlight. The blinds are intended to increase daylight penetration under a wide range of conditions while preventing the interior space from overheating. They do not use any moving parts. Although the system is mainly designed to control daylight in sunny climates, it may be used under predominantly cloudy skies.

4.14.3. Physical Principles and Characteristics

The system design is based on non-imaging optics and is similar to other anidolic systems except that it is made of three-dimensional elements. A more comprehensive description of non-imaging optics is given in Chapter 4.12 (Anidolic Ceiling) and in Courret [1999].

Experimental results (see Figure 4-14.3) show that the anidolic solar blind system's maximum transmittance reaches 26% in the central part of the admitting zone. This value corresponds to the ratio of the effective areas of the apertures for the most favourable angles of incidence. The discrepancy between theoretical and measured angular selectivity is mostly a result of the process of producing the prototype.

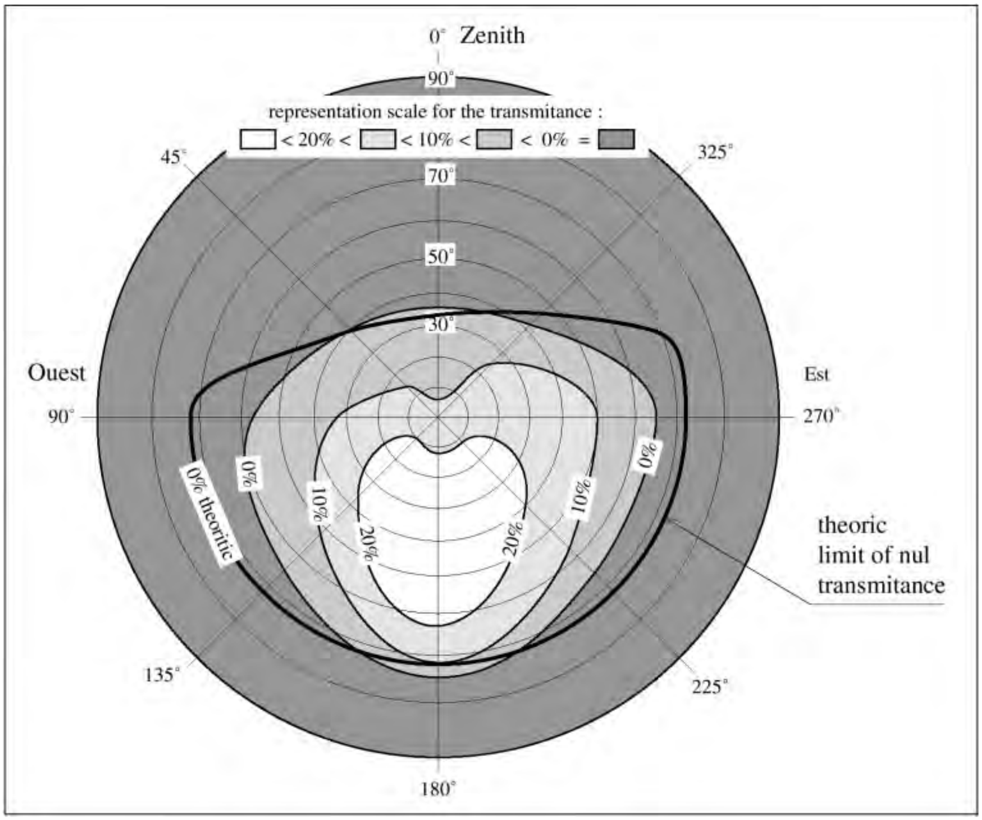


Figure 4-14.3: Comparison of measured and theoretical angular admission selectivity of a three-dimensional anidolic window element (height angle is relative to the normal of exit aperture; azimuth is relative to the vertical side of the prototype)

4.14.4. Control

The anidolic solar blind system is explicitly designed to control sunlight penetration for specified sun positions (see Technical Description above and Figure 4-14.1). It can remain in a fixed position and does not have to be moved like a conventional fabric or lamella blind.

Solar gain or illuminance levels can be increased by tilting the device from its vertical position. This possibility was tested experimentally (18° upward tilting), and performance improvements were confirmed.

4.14.5. Maintenance

Because the anidolic blind is a fixed system that is protected against dust and dirt by glazing on both sides, no particular maintenance is required.

4.14.6. Costs and Energy Savings

Because of its performance requirements, the system's required three-dimensional shape is more complex than two-dimensional anidolic systems such as the anidolic ceiling and the anidolic zenithal opening. Cost depends largely on the details of the manufacturing process. The current device could, in principle, be designed and manufactured with a high degree of automation and mechanisation, resulting in cost reductions. The manufacturing process for anidolic solar blinds is more complex, and the cost for this device is therefore likely to be higher than for the other devices. However, because the optics of anidolic solar blinds should function at almost any scale, the possibility remains that the solar blind panel could be made at large volume and low cost.

Primary energy savings are achieved by controlling electric lighting energy use when daylight from the anidolic blind is available. Greater energy savings can be expected from use of direct sunlighting than from diffuse daylighting. Because the problem of glare is solved by redirecting light to the ceiling, the blinds can also provide substantial heat gain in winter without adverse visual impact. Their very efficient summer-shading function reduces air-conditioning energy consumption as well as peak installed cooling capacity and peak power requirements.

4.14.7. Some Examples of Use

Anidolic solar blinds have not yet been used in a building.

4.14.8. Simulations and Measured Results

Simultaneous daylighting measurements were taken in side-by-side 1:1 full-scale test rooms to assess the comparative performance of the solar blinds. The two test modules were each 6.5 m deep and 2.65 m high. The mock-up office rooms have identical photometric properties (r_{walls}=0.8, $r_{ceiling}$=0.8, r_{floor}=0.15), which correspond to good room lighting design (2% daylight factor deep in the room for the reference module).

The reference test room utilised a high-quality white venetian blind whose slat tilt angle increases from top to bottom to allow penetration of daylight while simultaneously protecting work spaces from sun penetration and glare. The venetian blind slats were set to provide the same solar protection as the anidolic device (e.g., no penetration of sun rays with an incidence angle of more than 45°). A set of seven horizontal illuminance sensors was placed along the centre of each room at desk height.

Clear Sky

Light levels were low near the front of the room because the roller blind obstructed the lower two-thirds of the window. The illuminance increased in the rear of the room thanks to the deflecting function of the anidolic elements and the reflections on the ceiling and back wall. This enhancement meant that light levels measured in the front part of the room equal those in the back (Figure 4-14.4).

The illuminance level was lower in summer (corresponding to a 65° solar altitude) than in winter (corresponding to a 29° solar altitude), so the desired seasonal selectivity was clearly achieved.

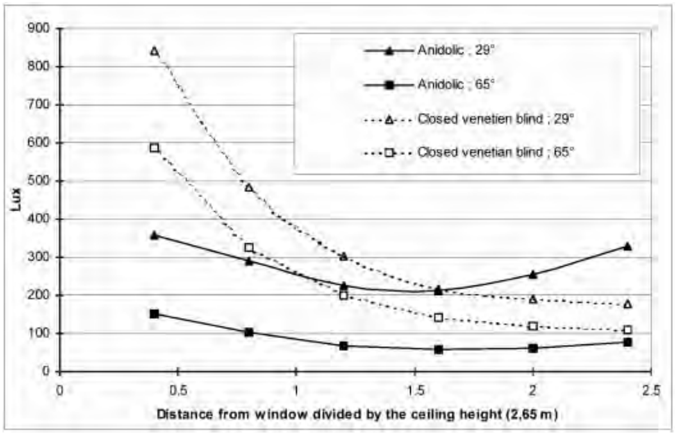


Figure 4-14.4: Indoor illuminance for two solar altitudes, 29° and 65° (sun azimuth = 0°) under clear sky conditions. The illuminance on the facade reached 85 and 41 klux, respectively.

Comparing illuminance levels for sun positions that are symmetrical around solar noon showed differences that favour the morning sun positions, as the system was originally designed (see Figure 14-4.1). At an altitude of 34°, if, for example, we compare an azimuth of 30° to the east of south to an altitude of 30° west of south, a ratio of 1.08 is measured between the two averaged levels of illuminance.

Figure 4-14.5 (left) shows an external view of the test module, equipped with the anidolic solar blind on the upper window. A fabric roller blind (made of thick dark brown fabric with a visible transmittance of 4%) was left in place behind the lower part of the window. Figure 4-14.5 (right) is a fish-eye view of the room interior, taken on a clear day, showing the system's redirection of sunlight deep into the room. The luminance mapping in the figure (corresponding to the field of view of a user seated at the rear desk in the room) confirms the glare control achieved by the system.

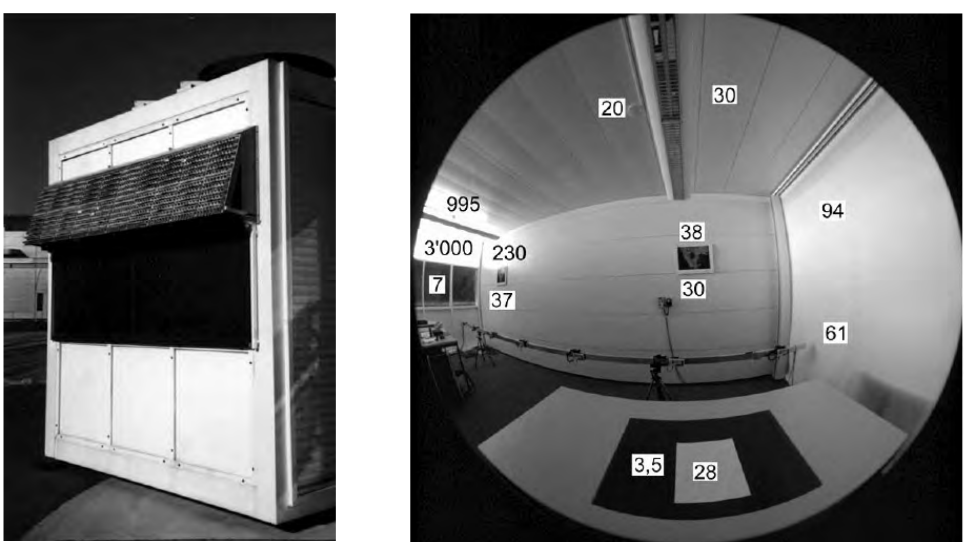


Figure 4-14.5: View of the experimental facade (left); view-field at desk in the rear of the room – luminance in cd/m^2 (right)

Conclusion

The performance of anidolic solar blinds is optimised to introduce sunlight for daylighting without glare. Its redirection and selectivity of sun rays offers significant promise for making sunlighting strategies more effective in mild and sunny climates. These benefits are not offered by other anidolic daylighting systems, which were optimised to work under overcast conditions with diffuse daylight.

Daylight-Responsive Controls 5.

Introduction 5.1.

This chapter for *Daylight-Responsive Lighting Control Systems* is an introduction and adjunct to the *IEA SHC Task 21 Application Guide*. It contains general information on the nature of daylight and electric light and their integration, the application of shading and electric lighting control systems in situations where daylighting systems are being used, and the benefits of controlling daylight and electric lighting. The chapter also includes information on probable occupant behaviour when these systems are used and the importance of taking user awareness into account.

There are at least two dimensions to daylight-responsive controls: the control of the daylight input to the space, and the control of the electric lighting output. The first is critical for providing adequate quantity and quality of daylight in interior spaces. The second saves energy and improves the overall distribution of light when daylight is insufficient. For both of these systems, user satisfaction and acceptance is extremely important. Annoyances caused by the system, such as glare, temporary reductions or sudden changes in brightness, or irritating mechanical noise, will reduce the system's effectiveness.

However, maintaining a constant illumination level or luminance at some reference plane or point in a room by means of controls is not always desirable and is often impossible. The illuminance provided by the sky is variable compared to the illuminance provided by electric lighting. Skylight varies continuously; this variation creates one of the fundamental differences between daylighting and electric lighting design. The sky luminance and resultant illuminances vary with latitude, time of day, and the seasons; random variations in sky luminance also result from the density and movement of clouds. In sidelit rooms, the illuminance at points near windows is rarely more than one-tenth of that outdoors and is often considerably less at points far from the window. Nevertheless, the daylight in an interior space is of sufficient magnitude to be a useful contribution to the lighting of building interiors for much of the year. The introduction of target illuminance or luminance levels and variability about those targets is therefore a practical solution to the lighting of building interiors.

Daylighting and daylighting systems can no longer be considered isolated elements of a building design. It is necessary at an early stage to consider the implications and interactions of daylighting design decisions with other design criteria such as energy consumption (electric lighting, mechanical heating and cooling), heat loss and heat gain, sound transmission, and economics. The *IEA SHC Task 21 Application Guide* classifies and describes types of electric lighting control systems that are currently available, installation and maintenance procedures, methods for predicting energy savings from the use of these control systems, user reaction to the systems, and methods for selecting an appropriate system for a specific situation. The guide also presents an overview of all the systems that have been tested within the IEA SHC Task 21 programme and the methods used to evaluate these systems.

5.2. Daylight and Electric Light

5.2.1. Daylight Variations

Daylight is a dynamic source of lighting. As noted above, the illuminance from the sky is not constant, and the variations in daylight can be quite large depending on season, location or latitude, and cloudiness. As a result, both daylight and electric lighting control systems will be needed from time to time to adapt the lighting systems to changing lighting conditions.

The CIE International Daylight Measurement Programme (IDMP) has undertaken worldwide recording of daylight fluctuations in global and diffuse illuminances. Much has been done in the statistical processing of these data to make them accessible to users [Kittler et al. 1992]. Different skylight levels can be found under the same sunlight conditions, and, even when the sky pattern remains the same, the range of solar illuminances may increase as a result of a momentary turbidity filter or scattering of particles over the sun. In consequence, any prediction system has to be flexible to allow for the multivariate changes that characterise the combination of sunlight and skylight. A proposal for universal sky models of reference daylight conditions based on 15 new sky standards has been introduced [Kittler et al. 1999] and is now being adopted by the CIE. This universal daylight system will enable comparison and characterization of the daylight climate in any location, either by analysing measured data or simulating illuminance conditions using the 15 sky standards.

5.2.2. Electric Light Sources

Electric lighting is a major energy end use in commercial buildings and can affect cooling and heating loads. The internal generation of heat from lighting, equipment, and occupants will often result in a cooling load for most of the year during daytime occupancy hours. It is possible to conserve this energy by increasing the use of daylight and also using daylight-responsive lighting controls, provided that solar heat gain is also controlled [Rubinstein et al. 1991, Lee et al. 1998a].

Using higher-efficiency lamps and ballasts and improving the effectiveness of fixtures and layout can increase the efficiency of building illumination and reduce adverse environmental impacts of electricity generation. Using daylighting systems with appropriate shading and electric lighting controls can substantially add to those energy and cost savings by reducing lighting energy consumption and moderating peak demand in non-residential buildings. To achieve optimum results, a room or interior space needs to be zoned for optimal placement of luminaires and sensors, with luminaires parallel to the windows. Another essential consideration is how lighting is positioned relative to the work spaces. Both task and ambient lighting need to be considered in this respect.

Some types of electric lighting, e.g., most HID sources, cannot be dimmed or safely switched on/off. Such sources are widely used in industrial buildings, swimming pools, and sports halls. Fluorescent lighting is the light source generally used with electric lighting controls, but consideration should be given to the fluorescent lighting's colour-rendering ability and colour appearance, if it is to be used with daylighting. Fluorescent lamps with a colour temperature within 3,000-4,500°K are most likely to be in agreement with the colour temperature of daylight. Daylight, climate, and individual preferences must be taken into account; in high-latitude countries, which are predominantly cloudy, there is a preference for warm-white lamps whereas in sunny (low-latitude) countries, there is a preference for cold-white sources. The latter colour temperatures may, however, be seen as too cold for night-time use.

When both daylight and electric light are used, care should be taken to minimise luminance differences between the window area and its surroundings to ensure visual comfort. Interior surfaces need to be light in colour to maximise the inter-reflection of light. In addition, particular care should be taken because of specular reflection that results from the shiny or mirrored surfaces that are sometimes used as components of the daylighting system and/or shading device [Zonneveldt and Mallory-Hill 1998].

5.3. Electric Lighting Control Systems

Photoelectric controls can be very effective in reducing lighting, heating, and cooling loads in some types of spaces, such as offices, restaurants, shops, industrial buildings, and schools. Control by switching or dimming is now one standard way to control lighting and allow the energy-saving potential of daylight to be realised in practise. Prediction methods have been developed to assess the potential energy benefits of these controls [Littlefair 1984, Littlefair and Heasman 1998].

During the past ten years, the use of electric lighting controls has shown potential to significantly reduce lighting energy use and to moderate peak demand in commercial buildings compared to conventional systems without controls [Rubinstein et al. 1991]. Lighting control strategies have included automatically dimming the lights in response to daylight, dimming and switching luminaires on or off according to occupancy, and performing lumen maintenance, i.e., automatic compensation for long-term lumen losses. However, these systems have proved in some instances difficult to calibrate and commission in actual practise.

Lighting controls that are now becoming available offer potential solutions to these difficulties: lighting energy monitoring and diagnostics, easily accessible dimming capabilities, and the ability to respond to real-time utility pricing signals. Research using an advanced electric lighting control system has found that daylight-linked control systems can bring about sustainable reductions of 30–41% in electrical energy for an outermost row of lights in a perimeter zone, and 16–22% for the second row of lights [Rubinstein et al. 1998]. However, it should be noted that if the cost of dimming controls is based on the system’s ability to produce a cost-effective reduction in lighting energy, the installed cost of the lighting controls should not exceed about 10 Euros per square metre floor area (for a payback period of three to four years).

With the advent of inexpensive handheld remote controls, occupant-controlled dimming is becoming an affordable option and has received a high occupant satisfaction rating [Maniccia et al. 1998]. In a study comparing the energy savings and effectiveness of various control techniques in offices during a period of seven months in a building in San Francisco, controls yielded 23% savings for bi-level switching, 45% savings for occupant sensing with task tuning, 40% savings with occupant sensing and manual dimming, and 44% savings for occupant sensing and automatic dimming. The last figure for savings is low because of the high light levels required by the occupants [Jennings et al. 1999].

Energy savings from occupant sensing versus dimming depend to a large extent on the behaviour of occupants (see Section 5.6). In offices where occupants remain at desks during the day, dimming controls will save more energy. An occupant’s immediate lighting requirements will also vary with the type of work being undertaken.

Daylighting controls are being increasingly linked to whole building management systems. As a component of a more comprehensive control system, daylight may be even more cost effective in applications where it would be otherwise difficult to justify on a financial basis.

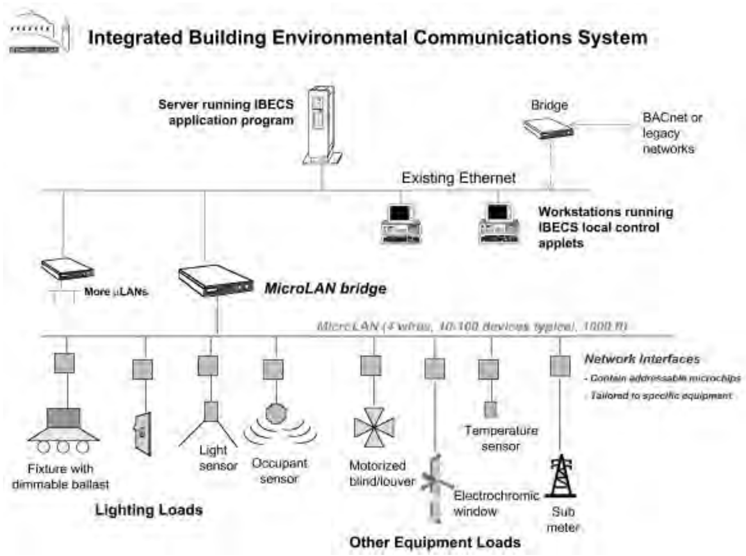


Figure 5-1. Building communications network [Rubinstein et al.1999]

5.3.1. A Building Communications Network

It is now possible to use computer software to programme the response of ballasts through a remote centralized control system. Depending on occupants' needs, a programmable system could save more energy than a directly controlled system. Setting up a programmable system is more costly in wiring and commissioning than a directly controlled system, but with a programmable system, building managers have the ability to adjust lighting levels from a remote location in response to an occupant's request and thus save maintenance staff the time that would be necessary to respond to the complaint. This new area of control technology is now being researched with the aim of providing a low-cost building communication network that will allow individual lighting loads to be controlled via an existing enterprise network (e.g., Ethernet). A building communications network enables both occupant-based and building-wide control of lighting systems and provides the hardware and software infrastructure for controlling and integrating the operations of most electrical loads in a building [Rubinstein et al. 1999]. A currently available system (Ergolight) also addresses the needs of office workers and energy management by offering electronic controls and energy management software in an integrated package.

Figure 5-1 shows a conceptual system that allows the light output from an overhead fluorescent light to be dimmed from a PC via a low-cost building control network. In this concept, the MicroLAN bridge couples an existing Ethernet network to the new MicroLAN, which networks together all lighting and other loads for that building zone.

5.3.2. New Installations and Retrofits

New installations and retrofits require different approaches. With a new installation, performance targets can be set and a light source and shading device can be chosen based on economic, ergonomic, and technical considerations, e.g., an acceptable payback period. With existing installations, choices will be limited by the building constraints and the availability of daylight.

5.3.3. Components of an Electric Lighting System

Apart from saving energy, a lighting control system must also 1) not disturb occupants, 2) be reliable, 3) conform to lighting standards, and 4) have a reasonable payback period.

Various systems for electric lighting control are available; these systems are either centrally or locally controlled. It is possible to control each luminaire or an entire building or floor area by a connected centralised system. Centrally controlled systems usually rely on a single daylight sensor that is often located on the ceiling (or sometimes the wall) of a large area in the centre of a circuit (or with a luminaire) and is calibrated on site within the sensor itself or within the controller to maintain a constant illuminance level. Controls can be adjustable in their preset levels, i.e., the range of light levels, with stepped or continuous ranges of lighting. Different types of controls can be used with different space functions; e.g., in circulation spaces, a simple on/off control may be all that is necessary, whereas in a large office, dimming controls may be the answer.

In locally controlled systems, a light sensor estimates the luminance on the work surface and adjusts the light output of the lamp to maintain a preset level. In general, localised systems perform better than centralised systems. However, one of the shortcomings of using these sensors is the problem of reflectance factors, e.g., when a large white sheet of paper is spread out on the work surface. This problem can be overcome by proper placement of sensors or can be reduced by using sensors with a large view angle.

Photoelectric Sensors

A key element of all types of photoelectric control is the sensor, which detects the presence or absence of daylight and sends a signal to a controller that will adjust the lighting accordingly. The location of the sensor is important because it influences the type of control algorithm used.

The photoelectric cell or sensor is often located on the ceiling and is calibrated on site to maintain a constant illuminance level. A single sensor that dims large areas can cause problems if some parts of the interior space are overshadowed by buildings or trees. It has been found that with innovative daylighting systems such as light shelves, a partially shielded sensor (shielded from the window only) is not susceptible to sky conditions and direct light from the window [Littlefair and Lynes 1999].

Controllers

A controller is located at the beginning of a circuit (normally the distribution board or the ceiling space) and incorporates an algorithm to process the signal from the photosensor and convert it into a command signal that is received by the dimming or switching unit.

Dimming and Switching Units

A dimming unit smoothly varies the light output of electric lights by altering the amount of power flowing to the lamps. If daylight is less than the target illuminance, the control tops up the lighting to provide the right amount on the work plane. Dimming controls can save more energy than switching if they are linked to daylight and if lamps are dimmed at the start of their lifetimes to compensate for their increased output. Dimming controls are also less obtrusive to occupants than switching, but a manual override is recommended in areas where occupants expect to have control [Slater et al. 1996]. Switches can also be used instead of dimmers, but this is not recommended except for limited applications because they are more obtrusive and may use more energy than dimming switches. High-frequency dimming produces the greatest savings in all but the most well daylit rooms.

A problem with photoelectric switches is rapid switching on and off when daylight levels fluctuate around the switching illuminance. This can annoy occupants and reduce lamp life. Various techniques have been developed to reduce the amount of switching. Differential switching control uses two switching illuminances, one at which the lights are switched off and another, lower illuminance level at which the lights are switched on. Photoelectric switching with a time delay can also introduce a delay in the switching process.

Occupancy Sensors

Recent studies have shown that workers are out of their offices 30–70% of the time during working hours [Newsham et al. 1995, Opdal and Brekke 1995, Love 1998]. A conservative estimate of savings possible from controls is about 30%, once time delays on occupancy control systems are taken into account. The actual savings will depend on the nature of the organisation using the space and the number of occupants in an office. Occupancy sensors are well suited to buildings where people are often away from their offices for a longer time than a few minutes. A weak point in this system is that the switching off of a certain zone, in a room where other people remain working, is generally experienced as disturbing. Recently developed systems allow a very smooth dimming down (or up after the return of the occupant) instead of sudden switching, which can help overcome this problem in group offices and thus increase user acceptance.

5.3.4. Types of Control Strategies

The general classification of control systems includes: closed loop systems (individual or with a limited number of luminaires) and open loop systems (central systems). Open and closed loop systems can also be stepped or continuous dimming systems. The calibration and the photosensor locations are quite different for these two systems because each system's algorithm expresses a different relationship between the photosensor signal and the output of the electric lights.

A control system is considered to be closed loop when the photosensor is located so that it is able to detect both the electric light that the system controls and the available daylight. In this case, the sensor needs to allow for the output of the lighting system that it controls. In contrast, an open loop control system's photosensor is designed and located so that it detects only daylight and is insensitive to the electric light that it controls. Although a lighting control system focuses on sensor placement and zoning, both of which are critical, other factors should be considered, including occupant override of controls, integration of controls with task and ambient systems, and design of the control system to accommodate skylights or light shelves.

5.4. Shading Controls

Shading can be used to control glare caused by the sun and/or high sky luminances as well as to control heat gain. Some shading systems can operate independently of a daylighting system; others, such as the transparent sun-excluding system (Figure 5-2), can be included in the daylighting system. In Chapter 4, daylighting systems are described as either shading systems (i.e., these are designed to provide both shading and daylighting) or as unshaded systems. In the latter classification, shading systems may need to be added, particularly in the tropics and in the summer season, to restrict solar heat gain and glare from direct sunlight.

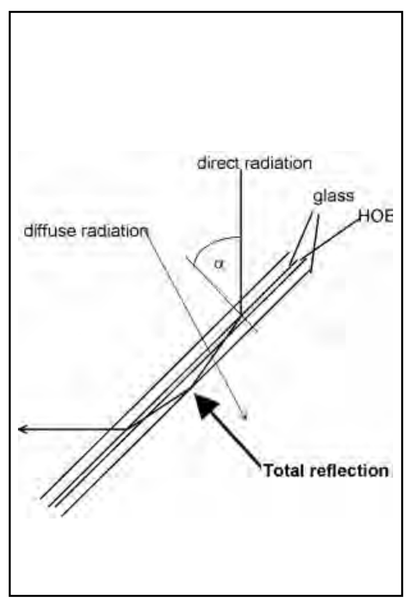


Figure 5-2: This transparent sun-excluding system consists of holographic optical elements (HOE) laminated between glass. The HOE redirects incident sunlight at the angle of total reflection, and only diffuse light penetrates the glass

A variety of strategies can be used to control a shading system automatically. Most current shading devices are manually controlled. However, when occupants are given only manual control of shading systems, the systems are often left closed, which eliminates all potential benefits from daylighting. External shading systems can be automatically controlled through a centrally controlled master switch that opens, tilts, or closes all shading devices at once. It is also possible to gauge the amount of light available to determine when shading is required. See Section 5.5.1 for a description of integrated shading controls.

An Integrated Approach 5.5.

Daylight, electric lighting, and shading systems cannot be considered separately because daylighting affects electric lighting use and introduces direct sunlight and glare that may be uncomfortable for building occupants. In fact, daylighting is fundamentally a systems integration challenge involving the building siting and orientation, window and/or skylight design, and lighting and shading control systems design, as well as ongoing maintenance. This requires cooperation between architects and lighting engineers. The deficiencies of both daylight and electric light are seldom optimally addressed unless they are seen as an integral part of the overall energy optimisation program.

5.5.1. Integrated Systems

The potential of an integrated dynamic envelope/lighting control system with automatic control of daylight and electric lighting was demonstrated in experimental studies at the Lawrence Berkeley National Laboratory (LBNL) in California, USA [Lee et al. 1998b] and at the École Polytechnique Fédérale de Lausanne, Switzerland [LESO-PB/EPFL 1996, Guillernin and Morel 1999].

Integrated control systems for blinds and electric lighting systems are characterized by: 1) their capacity to optimise the use of daylight under changing conditions, 2) their consideration of other factors such as avoiding solar gain, and 3) their continuous adaptation to user wishes with override priority granted to the user.

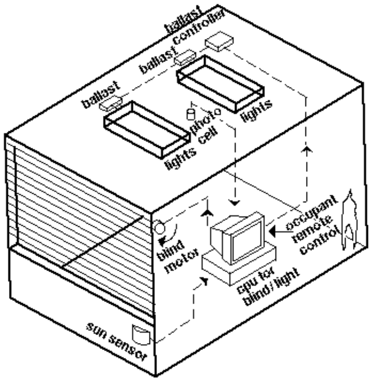


Figure 5-3: Schematic view of integrated venetian blind/electric lighting system

In the preliminary experimental work carried out at LBNL, daylight–responsive dimming of fluorescent lamps was coupled with automatically controlled venetian blind slats that exclude sunlight by automatically varying the slat angle. This system was designed to balance cooling loads and daylight admission by preventing direct sun penetration, actively

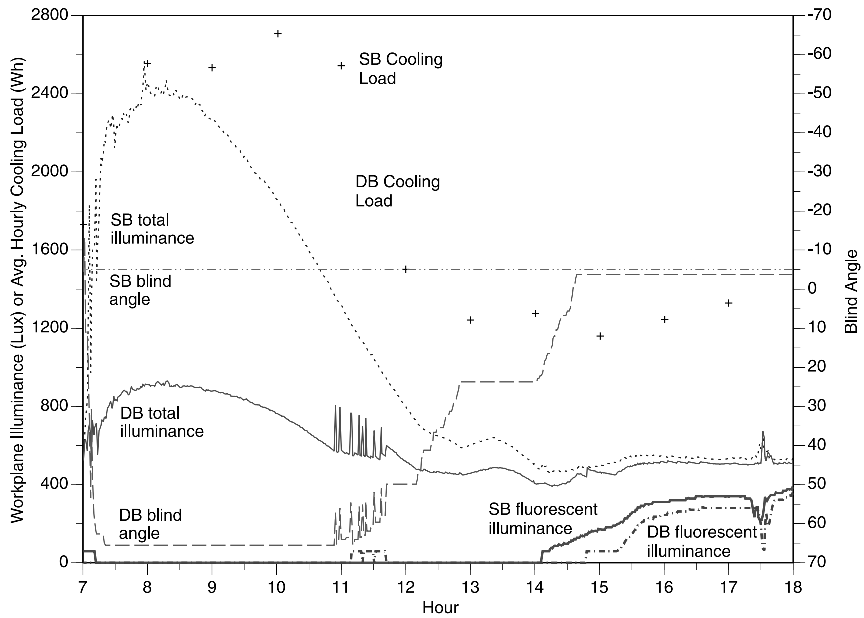


Figure 5-4: Monitored total work plane illuminance, electric lighting illuminance, angle of blinds of the static horizontal blind (SB) and the dynamic venetian blind (DB) on a clear day in California, USA.

managing daylight and electric light to provide 500–700 lux on the work plane, and permitting view when possible. The venetian blinds were polled by the system and activated every 30 seconds, if necessary, to block direct sun and maintain the target daylight illuminance at the work plane if daylight was available. A schematic diagram of the system is shown in Figure 5-3.

Energy, control, and illuminance data were collected for one year. Sample performance is shown in Figure 5-4; for this clear day, daily cooling load savings were 2,917 W (21%), peak cooling load reductions were 332 W (13%), and daily lighting energy savings were 127 Wh (21%) compared to a static horizontal blind with the same dimmable lighting system.

In LESO-PB/EPFL experiments in Switzerland, a venetian blind controller using fuzzy logic was developed, simulated, and measured [LESO-PB/EPFL 1996]. Fuzzy logic allows the formulation of operation rules that take into account various environmental factors. The EDIFICIO project [Guillemin and Morel 2001], which is currently being carried out under the EU Joule-Thermie Programme, tests a more elaborate integrated controller for heating and cooling, ventilation, blinds, and electric lighting in a room.

5.6. Occupant Behaviour

Experience has shown that manual controls are not used effectively. Many occupants leave electric lighting on once it is switched on even if the illumination from daylight is at a level that would be considered adequate if the occupant were entering the space [Hunt 1980, Andersson et al. 1987]. Although most case studies of lighting controls have focused on energy savings, a major factor in choosing lighting controls should be the improvement of visual comfort. A pilot study of human factors has indicated that satisfaction with lighting controls increases if users can alter settings using a remote-control device. In a study using a remotely controlled dimmable lighting system, the lights were dimmed more frequently than switched off in winter, switching decisions seemed to be mostly related to the amount of daylight available, and occupants seemed to have different personal preferences regarding settings. A recent post-occupancy evaluation of offices in Denmark by Statens Byggeforskningsinstitut (SBI) was based on a comprehensive questionnaire focusing on daylight, sunlight, and electric lighting. This study determined that the use of electric lighting depended on the time of year and the number of persons in the office [Christoffersen et al. 1999]. Post-occupancy evaluations were also conducted within this IEA Task 21 [Hygge and Löfberg 1999].

User-controlled systems enable occupants to set workplace conditions according to performance, activity, and location. A range of devices is available to allow users to control their lighting levels. These typically consist of a hand-held or wall-mounted controller that communicates to a dimming ballast by hard wire or by infrared signals.

The advantages of human and automatic (occupancy) controls could be exploited in a combined system that would build on the advantages of each [Crisp 1984]. Empirical studies [Hunt 1980, Andersson et al. 1987] have shown that, for much of the time, occupants in spaces with relatively glare-free daylighting are satisfied with lower work plane illuminances than are stipulated for automatic control systems. A combined system could be taken a step further to include manually controlled blinds designed to improve the combination of daylight admission and glare control; the device could cost less than a motorised blind. The system would switch off or dim the lights using occupancy-linked controls, reactivating them on a manual signal, and leaving the judgement of lighting adequacy to the user [Love 1998]. This type of combination is directed at providing quality daylight and encouraging the occupant to assess the need for supplementary lighting when entering an interior space.

Benefits 5.7.

5.7.1. Savings Parameters

Energy savings cannot be realised in daylit buildings unless the electric lights are dimmed or switched in response to the amount of available daylight. The energy savings achieved with daylight-responsive lighting controls will depend on the daylight climate, the sophistication of the controls, and the size of the control zones. An evaluation of currently available responsive control systems is presented in the *IEA SHC Application Guide*. This evaluation has shown that daylight-responsive systems used up 40% less than non-controlled systems (Figure 5-5). Cooling load reductions have also been noted, which can save an additional 2–3% of electrical energy consumption. Savings can be larger than 40% especially in toplighted spaces. In hot climates, the cooling savings can also be larger.

FIGURE 5-5: LIGHTING POWER FOR FIRST ROW OF LIGHTING FIXTURES IN THE SOUTH ZONE VERSUS TIME OF DAY FOR CLEAR (CLR) AND OVERCAST (OC) DAYS IN JULY, SEPTEMBER, AND DECEMBER IN SAN FRANCISCO [RUBINSTEIN ET AL. 1999]

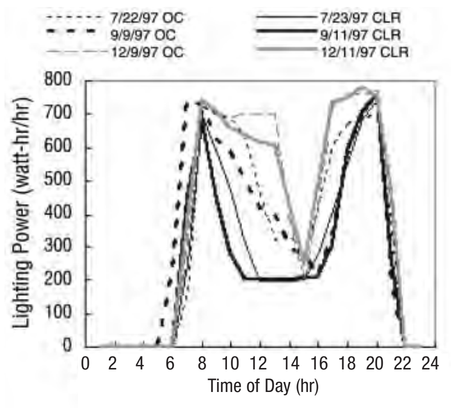


Figure 5-5 shows a graph for the south side of a building in San Francisco with lighting power as a function of time of day. The first row of lights in the perimeter zone shows significant dimming during daylit hours, dropping from 780 Watts to 200 Watts for several hours each day. Even on an overcast day, there is a significant reduction for a few hours.

5.7.2. Energy and Cost Estimates

The prediction of energy savings from the use of daylight-responsive controls is complex. An accurate estimate requires much information and detailed calculations (see Chapter 3). A simplified method demonstrated in the *IEA SHC Task 21 Application Guide* calculates savings omitting the complex factors such as the reduction of cooling loads. A computer can perform the calculation, which can be split into several factors that permit the user to understand the factors influencing the energy consumption. In this simplified method, the control characteristics of systems are evaluated under a number of sky conditions, and the results are extrapolated to estimate yearly savings. The validity of the extrapolation depends strongly on the type of control.

5.8. User Awareness

Researchers have found that physical and perceived performance of a daylight control system can differ quite remarkably. If the user finds the environment created by the system to be uncomfortable or disturbing in any way (noisy or too abrupt in its on-off switching), the system is likely to be rejected or an attempt will be made to compromise it. Energy savings are therefore directly related to a system's acceptance and proper operation by the user. Noisy or hard-to-operate systems are likely to be compromised. In addition, inappropriate ambience can result in rejection of the system. View aesthetics are also an important consideration. Users often do not accept daylight without view. In addition, the quality of light is important as is the avoidance of high contrasts and absolutely uniform lighting.

System Awareness 5.9.

An important but often overlooked aspect of control installations is the training of maintenance personnel and building occupants in the operation and purpose of a daylight-responsive control system. Although most manufacturers provide technical support during and for a period following installation of their systems, it is easier and more economical if those managing and occupying the building can address most problems.

Building and facility managers need to be aware of how to operate the system and adjust it. They need to understand the system's performance. Building occupants should receive information about the purpose of the system.

Installation and Maintenance 5.10.

5.10.1. Calibration of Sensors

The installation of luminaires with factory-installed sensors does not differ greatly from the installation of conventional luminaires. At the installation site, installers need only measure the illuminance on the work surface at night and during the daytime under each luminaire and to adjust the sensor until the desired lighting level is achieved. When there is one daylight level sensor controlling multiple luminaires in a single zone or room, then the placement of the sensor is critical. Generally, the sensor should view a representative luminance on a work surface, should not be able to "look outside," and should be located where it will not receive light from upward-directed lamps when indirect lighting is used. The most appropriate location for a sensor in small spaces (private offices) is usually on the ceiling near the primary work area. Calibrating an occupant sensor means setting the sensitivity and time delay for appropriate operation in the particular space where the unit is installed [Rubinstein et al. 1997].

In more sophisticated systems, calibration may be accomplished by software. Further details on the installation of luminaires with built-in sensors, room-based systems, and calibration of sensors can be found in the *IEA SHC Task 21 Application Guide*.

5.10.2. Maintenance

The need for maintenance depends on many factors. The most obvious is lamp life, i.e., the number of hours that a lamp is expected to burn. If as a result of switching or dimming a lamp burns fewer hours per day than normal, lamp life increases in terms of the number of days between relamping but decreases in terms of the total number of lamp hours. Aging of sensors can also influence system performance. In some cases, systems may require recalibration to account for degradation of the sensors. Photodiodes are known to be very stable, but certain types of plastic used in the white-diffusing covers of photosensors may degrade.

When lamps are replaced or cleaned as part of normal maintenance, the sensors can also be cleaned. Whenever extensive relamping takes place, luminance measurements should be taken and sensors recalibrated.

The daily control, management, and behaviour of shading systems also needs to be considered in case of failure, such as the short-circuiting of sensors. These issues are discussed in more detail in the *IEA SHC Task 21 Application Guide*.

Design Tools 6.

Introduction 6.1.

Daylighting design is a creative process. It aims to generate appropriate architectural and/or technical solutions to achieve an enjoyable and productive built environment while simultaneously reducing the energy consumption of buildings through the substitution of daylight for electric light.

Daylighting design is both an art and a science. Qualitative information and visual feedback on a given daylighting concept are usually as important for the building designer as the quantitative figures that reflect the engineering aspect of daylighting design.

Design tools are intended to help designers with the qualitative and quantitative elements of daylighting design through features that commonly include:

- visualisation of the luminous environment of a given daylighting design;
- prediction of daylight factors in a space lit by diffuse daylight;
- identification of potential glare sources and evaluation of visual comfort indices;
- prediction of potential energy savings achievable through daylighting;
- control of the penetration of the sun's rays and visualisation of the dynamic behaviour of sunlight.

By providing all information of this type, design tools play a significant role in the decision-making process that characterises daylighting design. These tools support designers throughout the sequence of decisions, from formulation of the daylighting concepts to final implementation of daylighting strategies and innovative techniques in real buildings.

Design tools must therefore fit the significant phases of architectural projects during which important decisions regarding daylighting strategies are made. These tools must suggest appropriate architectural solutions that meet the architectural objectives of the project. The capability of design tools to analyse a given daylighting scenario, based on a detailed physical description of the project, are especially significant when advanced daylighting systems are considered.

This chapter gives an overview of the state of the art of daylighting design tools. Special emphasis is placed on tools that address the advanced daylighting systems investigated by IEA SHCP Task 21.

6.2. Simple Tools

Simple design tools give a designer clues about basic design decisions without requiring extensive time or detail. These tools are normally used to check performance or estimate the impact of specific design elements on daylight performance in an early design stage. They do not require advanced equipment or knowledge and thus non-experts can use them. Simple tools cannot model complex daylighting strategies and therefore are not suitable for fine-tuning daylighting designs.

Many traditional simple tools focus on the daylight factor as a design criterion; these tools should only be used in predominantly cloudy climates. A new generation of “simple” computer tools embodies complex evaluation models, though these tools are nonetheless simple from the user’s point of view. A common characteristic of all simple daylighting design tools is the restriction of input parameters to key design properties such as interior

Table 6-1:

Survey of simple design tools carried out as part of IEA Task 21 [de Boer and Erhorn 1998]

TYPE	SUBJECT: Daylight Factor for Sidelit Rooms	Daylight Factor for Rooflit Rooms	Window Design	Rooflight Design	Atria Design	Energetic Behaviour / Daylight Autonomy	Shadow and Reflection Analysis / Sunshine Duration	Visual Comfort	TOOL
1. Formulae f(x)		■		■					2.1.1
	■	■	■	■					2.1.2
2. Tables	■		■						2.2.1
		■		■					2.2.2
3. Nomograms	■	■	■	■	■				2.3.1
	■				■				2.3.2
4. Diagrams	■	■	■	■		■	■	■	2.4.1
	■		■						2.4.2
						■			2.4.3
						■			2.4.4
5. Protractors	■	■	■	■					2.5.1
6. Computer Tools	■	■	■	■		■	■		2.6.1
							■		2.6.2
							■		2.6.3
						■			2.6.4
	■	■	■	■		■			2.6.5
7. Typology	■	■	■	■			■	■	2.7.1
8. Scale Models 1:X	■	■	■	■	■		■	■	2.8.1

reflectance, the size and the location of windows and skylights, and the proportions of the space and exterior obstructions.

Several surveys have been carried out during the past few years to identify the simple design tools available to practitioners and to estimate the market impact of these tools [Baker et al. 1993, McNicholl and Lewis 1994, Kenny and Lewis 1995, Aizlewood and Littlefair 1996]. Table 6-1 gives the results of one such survey, conducted recently as part of IEA Task 21 [de Boer and Erhorn 1998].

Most of the tools listed in Table 6-1 are based on practical experience or simple calculation methods, e.g., the lumen input method or the split-flux method [CIBSE 1987]. Although older tools, such as empirical equations, tables, nomograms, diagrams, and protractors, reflect historical conditions when computer technology was not available, new simple design tools are typically computer-based.

Another category of simple tools is dedicated to estimating the impact of obstructions on daylight availability at a construction site or on a facade. These tools generally provide a method of superimposing a sun chart or daylight availability chart on a representation of obstructions. Several instruments have been developed specifically for this purpose, but none of them has had great success.

A fisheye lens with an equidistant projection offers a quick means of analysing obstructions. When the camera is positioned at the location in question and the lens is pointed at the sky's zenith, the photograph is a circular representation of the sky hemisphere including all obstructions. This photograph can be superimposed on a sun chart either manually or by using a computer. Attention should be paid to precisely positioning the sun chart to the true north of the location. The fisheye representation of the surroundings can also be generated by using a computer-aided design (CAD) system rather than a camera. In this case, all obstructions need to be included in the model.

Because decisions in the early stages of building design have a large impact on a building's daylight performance, simple design tools are essential to help designers navigate this phase. Simple tools offer hints about key design parameters but cannot be used to evaluate a strategy in detail or to model advanced systems.

Computer-Based Tools 6.3.

With the advent of personal computers (PCs), powerful processors that can handle complex calculation algorithms and lighting simulation techniques are available to nearly all practitioners. In addition to the first generation of simple design tools, which were translated into numerical programmes, several new pieces of software have been developed since the 1980s to address the complexity of light propagation into building spaces.

Many of these pieces of more complex software were developed by researchers for mainframe computers: They have fewer limitations than simple tools in their ability to address the geometry and the photometry of the modeled architectural space and they offer more and richer graphic output options (e.g., illuminance contours and mapping). Image-based daylighting computer tools have improved these output features by providing synthetic imaging of modeled spaces.

Most of these tools have now been ported to the PC world, mainly for Microsoft Windows operating systems. Some of them have also been linked to commonly used architectural CAD programmes, whose graphical means for entering geometric data are much easier to handle than the conventional numerical input for xyz-coordinate systems used in most of the older stand-alone daylighting tools. Some tools offer more elaborate graphical user interfaces which significantly facilitate and speed up the daylighting design and

Table 6-2: Overview of daylighting computer design tools [Lighting Design and Application 1996]

		IEA ECBCS/ SHC ADELINE 3.0	Lawrence Berkeley Lab RADIANCE 2.4	Lawrence Berkeley Lab SUPERLITE 2.0	Electric Power Research Institute BEEM 1.01	Electric Power Research Institute LIGHTCAD 1.0	Cooper Lighting LUXICON 1.1	Lighting Technologies Inc. LUMEN-MICRO 6.0
General Applications	Indoor	X	X	X	X	X	X	X
	Outdoor	X	X				X	
Hardware	Operating System	Windows 95 & NT	UNIX	DOS	DOS	DOS	WINDOWS	DOS
	Operates Inside AUTOCAD							
	System Memory Required					X		
	Hard Disk Space Required							
	Minimum/Recommended Processor	32MB	16M	600K	512K	4M	8M	565K
		50-80MB	30M	1M	500K	3.5M	26M	8M
		Pentium	ANY 32-BIT RISC	8086/368-387	8088/386	386-387/486	486/ Pentium	386/486
Type of Analysis	Horizontal Point-by-Point Illumination	X	X	X			X	X
	Vertical Point-by-Point Illumination	X	X	X			X	X
	Interreflected Calculations	X	X	X			X	X
	Direct Calculations	X	X	X			X	X
	Room Surface Luminance or Exit	X	X	X			X	X
	Analysis Plane Can be Titled	X	X	X			X	
	Lightmeters Can Be Titled	X	X					
	Avg. Indoor Illuminance (zonal cavity)				X	X	X	X
	Avg. Outdoor Illuminance (lumen method)							
	Daylighting	X	X	X	X	X	X	X
	Visual Comfort Probability	X	X				X	X
	Relative Visual Performance						X	X
	Economic Analysis				X	X	X	X
	Unit Power Density	A			X	X	X	A
	Advanced Statistical Analysis						X	
	Image Synthesis	X	X				X	X
	Walk-thru Image Synthesis							SLIDE
Special Features	Automatic Layout					X	X	X
	Generate Schedules					X	X	
	CAD Interface	X	X		X	X	X	X
	Building Shadowing	X	X	X			X	X
	Interior Obstructions	X	X	X			X	X
	Shape of Room (plan view)	ANY	ANY	ANY		X	ORTH	ORTH
	Shape of Room (section view)	ANY	ANY	ANY		X	ORTH	ORTH
	Batch Processing		X				X	X
	Max. Number of Calculation Areas	Unlimited	Unlimited	3	100		Unlimited	5
	Max. Luminaire Types per Run	Unlimited	Unlimited	10		100	Unlimited	8
User Interaction	Tabular Entry	X			X	X	X	X
	Graphical Entry	X				X	X	X
	Metric Input and Output	X	X	X			X	X
	Input Device	KM	KM	K	KM	KM	KM	KM
	Context-Sensitive Help Screens	X	X		X		X	X
Types of Output	Point-by-Point	X	X	X			X	X
	Iso-Contours	X	X				X	X
	Scaled Output	X	X			X	X	X
	Templates	X	X					X
	3D Model View	X	X			X	X	X
	Plotter Output					X	X	
	Color Output	X	X			X	X	
	Graphics Printer as Plotter	X	X			X	X	X
	Shaded Printout	X	X				X	X
	Any Shape Printout or Masking					X	X	
International	Language Calculations			X				
Photometric Database	Photometric Data Manager					Within	Within	Within/Ext.
	Photometric Graphic Viewer						X	X
	Photometric Format	IESNA Eulumdat	IESNA			IESNA	IESNA, Other	All&LTL-1

analysis process. Pre- and post-processors extend the capabilities of the core lighting algorithms — for instance enabling one to link daylighting analysis with the building energy simulation.

Recent surveys have shown that these tools are increasing in number and use for architectural design. Table 6-2 gives an overview of the existing daylighting computer design tools in the more complex category. More recent overviews can be found in the IES publication, *Lighting Design and Application,* and in other publications.

Two main categories of computer-based tools can be distinguished based on the calculation methods they use: the radiosity technique and the ray-tracing technique.

6.3.1. Radiosity Method

The radiosity method is probably one of the first lighting calculation techniques applicable to the evaluation of the interchange of light among all the surfaces defining an architectural space. This method has a significant advantage over former analytical techniques because it allows for light inter-reflections between surface walls.

Originally developed for energy calculations, the radiosity method was used to determine the energy balance of a set of surfaces exchanging radiant energy (Figure 6-1). Some of its basic hypotheses and limitations are that:

- wall surfaces must be subdivided into small finite elements characterised by homogeneous photometric properties (e.g., reflection coefficient);
- all elements must be perfect diffusers (Lambert's law);
- similar hypotheses must be applied to all of the external obstructions situated in front of windows and openings.

The radiosity method is used to determine the illuminance and luminance of a set of points located at the centres of different surface elements. This determination can be made independent of view, before any surface rendering is made from a desired viewpoint.

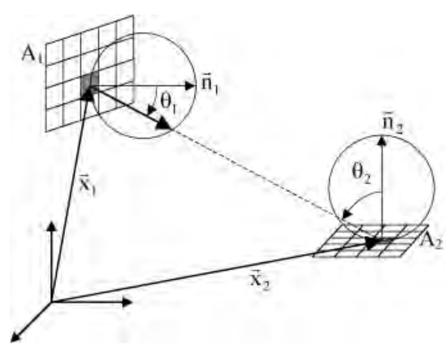


Figure 6-1: Surface elements exchanging light (or radiant energy) in the radiosity method

The SUPERLITE programme was one of the first widely available daylighting computer tools based on the radiosity method. The current version can handle both daylighting and electric lighting as well as rather complex room geometries (e.g., L-shaped rooms). Only perfectly diffusing surfaces can be considered; glazings can be transparent or diffusing, and windows can have shades.

Figure 6-2 gives an example of a visualisation of a daylighting calculation created using the radiosity method (SUPERLITE programme): Surface finite elements are visible in the picture.

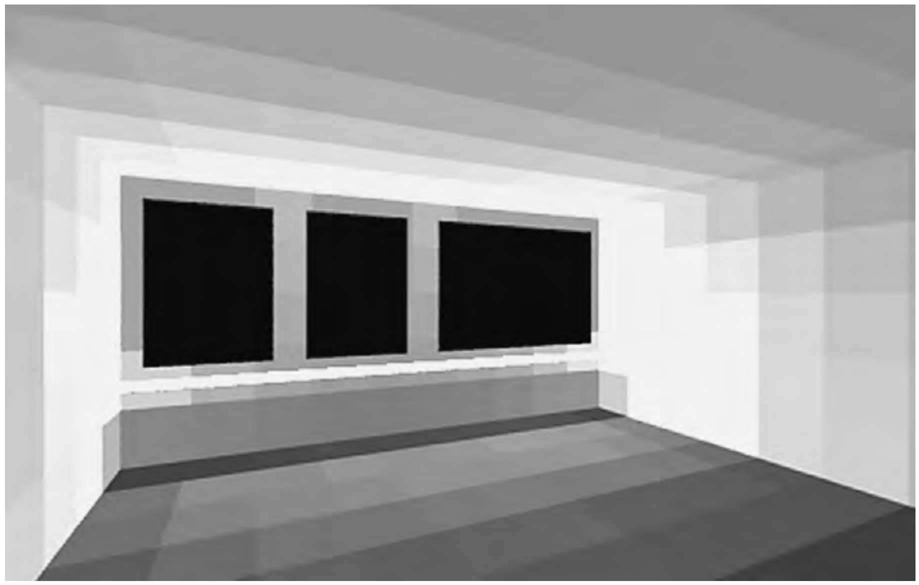


Figure 6-2: Visualization of a daylighting calculation made using a program that relies on the radiosity method [Compagnon 1993]

In spite of its weaknesses, the radiosity method has some advantages compared to the other well-known image rendering method, the ray-tracing technique. These include the radiosity method's view-independent calculation and the pre-eminence of major light sources in the images it renders.

6.3.2. Ray-Tracing Techniques

The ray-tracing technique determines the visibility of surfaces by tracing imaginary rays of light from a viewer's eye to the objects of a rendered scene. A centre of projection (the viewer's eye) and an arbitrary view plane are selected to render the scene on a picture plane. Thanks to the power of novel computer algorithms and processors, millions of light rays can be traced to achieve a high-resolution rendered picture.

Originally developed for imaging purposes, some ray-tracing programmes (e.g., RADIANCE, GENELUX, and PASSPORT) were adapted and optimised for calculation of daylighting within building spaces [Ward and Rubinstein 1988]. In this case, light rays are traced until they reach the main daylight source, which is usually the sun position (clear and intermediate skies) or the sky vault (cloudy skies). Figure 6-3 illustrates the principle of ray tracing, showing the viewpoint (P) and view direction of the observer as well as the main light source, represented by the sun.

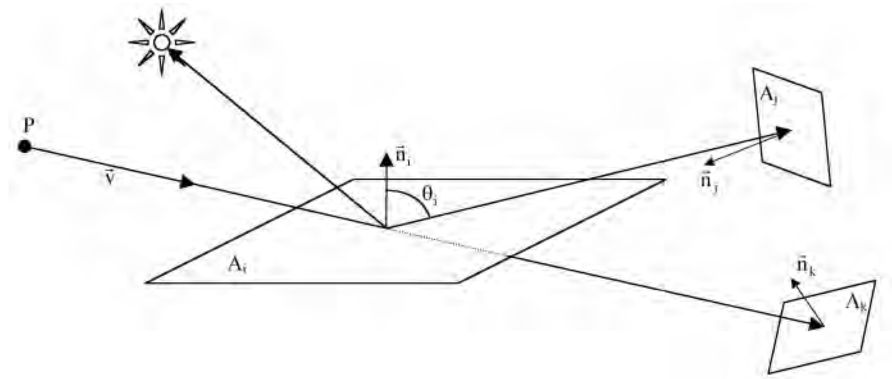


Figure 6-3: Tracing light rays from the viewpoint, P, to different surfaces and to the main light source (the sun)

Most daylighting and electric lighting calculation programmes currently use this backward ray-tracing technique (from the viewpoint to the source). A slightly different technique is used by some software to improve daylighting calculations, especially for clear sky conditions (with sun). A forward rather than backward ray-tracing technique is used by the GENELUX programme to follow rays from the light source to a scene.

The principal features of the ray-tracing technique for all types of light calculations are the following:

- the method accounts for every optical phenomenon that can be analytically expressed by physical equations;
- the method can consider specular materials, like window panes and glossy surfaces;
- the method can effectively simulate non-homogeneous textures and surface points.

Thanks to their large range of applications, ray-tracing techniques play a significant role in the design and simulation of advanced daylighting systems. Figure 6-4 shows the numerical simulation of a room equipped with two different daylighting systems (a conventional window pane and a zenithal anidolic collector) created by a programme using a backward ray-tracing technique (RADIANCE); this simulation allows comparison of the luminous performance of the two daylighting systems.

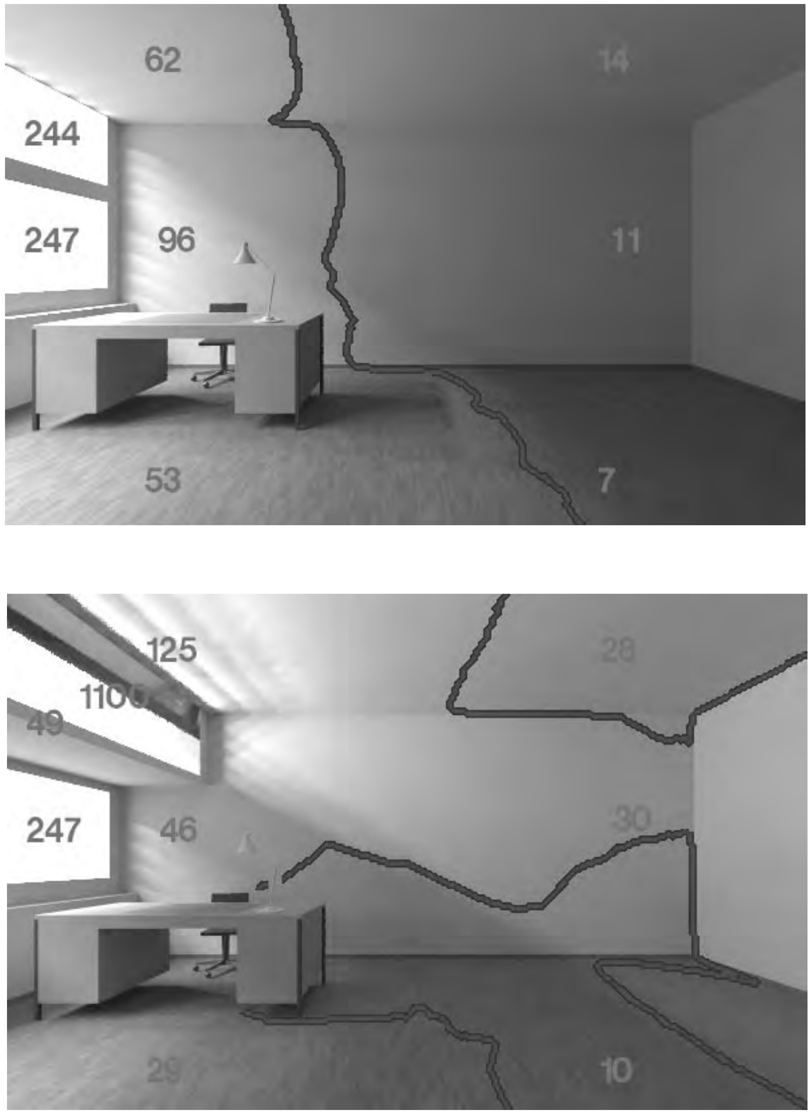


Figure 6-4: Computer simulation and image of an office space created using a ray-tracing technique.
Top: Reference room with double-pane window
Bottom: Anidolic zenithal collector

Several validations of ray-tracing programmes have demonstrated their reliability for daylighting performance assessment and advanced systems design [Compagnon 1993, Fontoynont 1999].

6.3.3. Integrated Software Environments

The use of daylighting and artificial lighting simulation programmes to calculate complex systems and models in the design practise often is impeded by the fact that the operation of these programmes, especially the model input, is extremely complicated and time-consuming. Programmes that are easier to use generally do not have the calculation capabilities required in practise. A second obstacle arises as the lighting calculations often do not allow any statements regarding the interactions with the energy and thermal building performance.

Both problems are mainly due to a lack of integration of the design tools of other building design practitioners as well as to insufficient user interfaces. The programme package ADELINE (Advanced Daylight and Electric Lighting Integrated New Environment) [Erhorn and Dirksmöller 2000] which has been further developed in the scope of IEA SHC Task 21 presents a promising approach to solving these problems.

The objective was to develop an integrated lighting analysis tool for building design purposes which is intended to assist the building designer and consultant in all issues associated with daylighting and electric lighting design. The general structure of the integrated programme system is depicted in Figure 6-5. The lighting calculations are executed using the algorithms of Superlite and Radiance. Several different pre- and post-processors around these core algorithms facilitate daylighting design and analysis during different design stages:

Simple Input

Early design phases account for the basic and often irreversible decisions concerning the daylight supply. The general floor layout, size and position of daylight openings decide whether daylight supply is sufficient or not. A tool to be used at this stage thus should allow for fast handling and quick access to the requested information while avoiding complex geometric modeling. ADELINE supports, as shown in Figure 6-6, a set of simple floor plan layouts which rely only on parametric input. Daylighting studies and design parameter variations can be performed in a fraction of the time usually required when applying CAD tools. The parametrically defined layouts can be used within ADELINE as starting point for more complex models.

Graphical Scene Editor

The graphical scene editor, depicted in Figure 6-7, allows for an interactive graphical composition of models made up of different predefined objects. Single objects or groups of objects can be copied, translated, rotated, and scaled. The graphical representation is based on a wire frame representation with hidden line removal. The scene editor gives direct access to libraries of furniture, materials, and luminaires. Views which will later be rendered can be defined — camera-like — directly in the wire frame representation.

Object Libraries

A material database with numerous opaque and transparent or translucent materials is included. Access to luminaire databases is provided. Using furniture in simulations enables more realistic and representative visualisations. Individual libraries can be established or existing ones can be used. More than 350 objects such as tables, chairs, and office equipment, Figure 6-8, can be selected from a furniture library to allow for representative visualisations. Selection and preview dialogues allow the convenient placement and arrangement of objects within the graphical scene editor.

Comprehensive Graphical Output

Light distributions can be displayed through either two- or three-dimensional graphics, and results are given as iso-lux or iso-daylight-factors curves as depicted in Figure 6-9. Light penetration can be analysed through two-dimensional sections of the building. This is very powerful for estimating the impact of each opening. Radiance renderings allow for detailed illuminance and luminance analysis as shown in Figure 6-12.

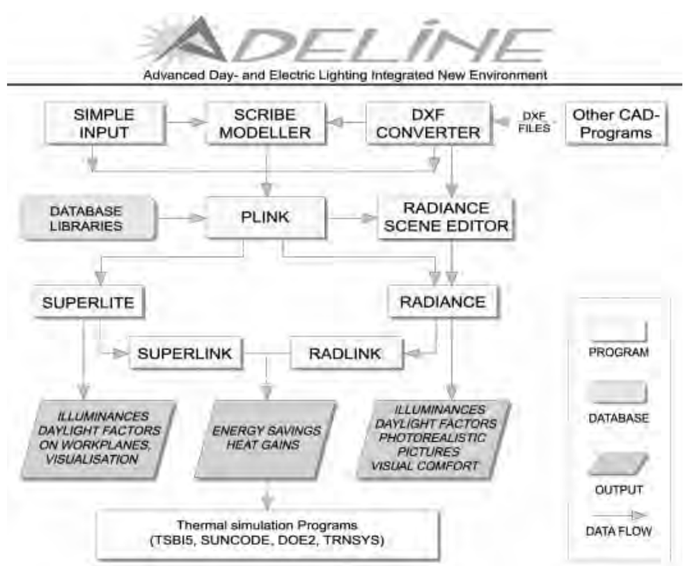
Integrated Energy Approach

SUPERLINK and RADLINK are programmes used to obtain estimates of the interaction between daylighting, artificial lighting, and the dynamic thermal building performance. The simulation is based on daylighting calculations with SUPERLITE or RADIANCE. SUPERLINK and RADLINK produce hourly values for additional artificial lighting input into a building over a complete year, taking into account:

- several lighting control strategies,
- different lamp types,
- desired work surface illuminance,
- user-defined work schedule,
- hourly sunshine probability.

A typical outcome of this calculation is shown in Figure 6-10. The hourly lighting energy input can be used to perform hourly thermal simulation with dynamic building simulation programs such as tsbi5, SUNCODE, DOE2, or TRNSYS.

Figure 6-5: ADELINE 3 Programme System



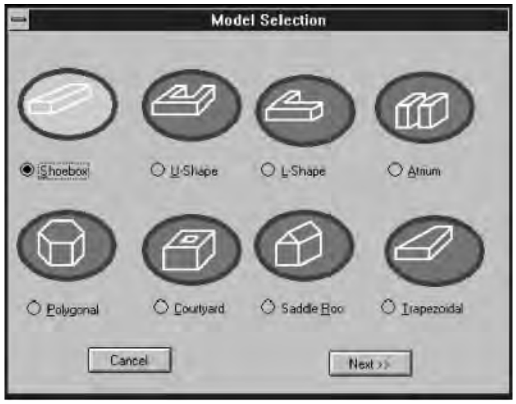


Figure 6-6: Parametrically definable basic geometries of the Simple Input Mode

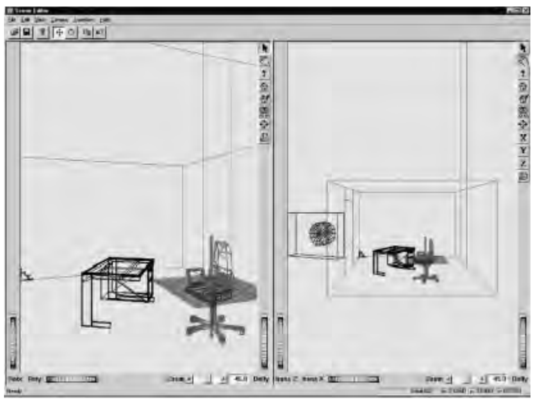


Figure 6-7: Wire Frame representation of Radiance Scene Editor

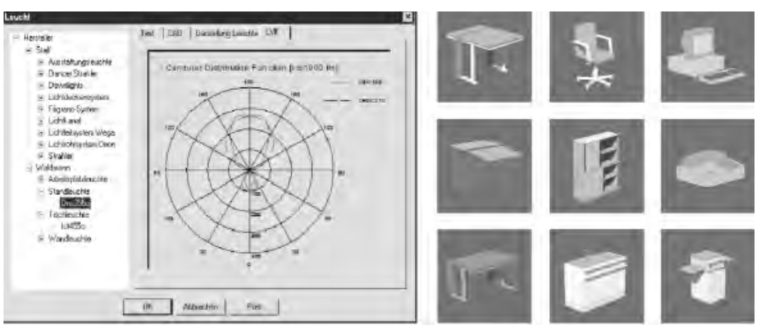


Figure 6-8: Examples from the luminaire and furniture database

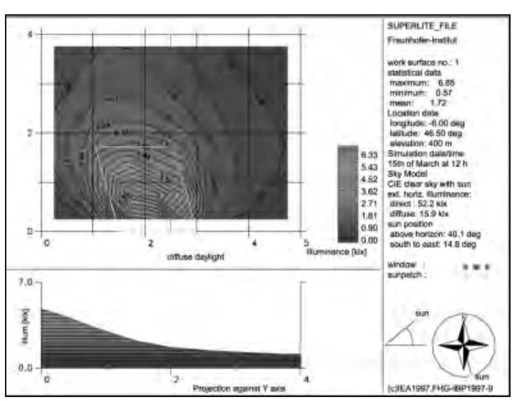


Figure 6-9: Iso-contour line representation of illuminances in a working plan

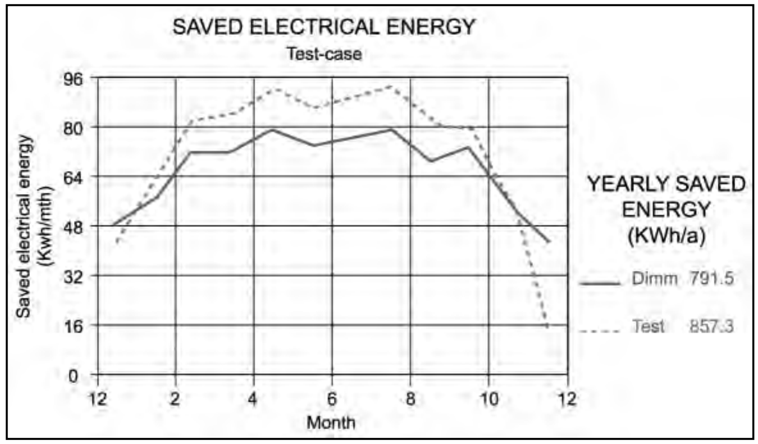


Figure 6-10: Annual electrical energy saved as a function of different daylight-dependent artificial lighting control strategies results calculated with SUPERLINK

6.3.4. Simple Computer-Based Calculation Tools

From a user's point of view, the main differences between the advanced computer tools described above and simple computer-based tools are that the latter allow less freedom in the complexity and detail of input, and the results are less accurate. Most simple tools can only handle shoe-box type room geometry, and many permit daylight apertures in only one wall. Input for these programmes may, however, be very easy.

Simple computer-based design tools can only handle calculations for diffuse skylight, CIE or uniform luminance distribution or both. The algorithms commonly used for direct sky and external reflected components are based on the solid angle formulas derived from double integrals [Hopkinson et al. 1966]. Some tools have "computerised" simple manual tools, such as BRS protractors, Waldram diagrams, or other diagrams or tables. For the internal reflected component, these tools will often rely on the BRS split flux or other applications of the integrating sphere theory, sometimes with some sophisticated corrections added.

These programmes can produce highly accurate direct and external reflected component calculations given that the cases to be analysed have very simple geometry. Serious inaccuracies may, however, result in calculation of the internal reflected component. In the critical dark deep zones of a room, this component is a major contributor to the daylight factor. Thus, simple calculation tools have problems with accuracy in this zone.

Although computer design tools can play a substantial role in daylighting design, most are more appropriate for analysis of daylighting performance. An accurate physical description is often required for the device to be analysed (e.g., for ray-tracing simulation) at stages where designers usually need suggestions for appropriate architectural and technical solutions.

To overcome this problem and provide users with optimal support during different design phases, daylighting decision tools were developed based on the theory of information [Paule et al. 1995]. Fuzzy logic was used to offer the possibility of characterising room geometry and photometric properties through linguistic values (fuzzy subsets) (Figure 6-11).

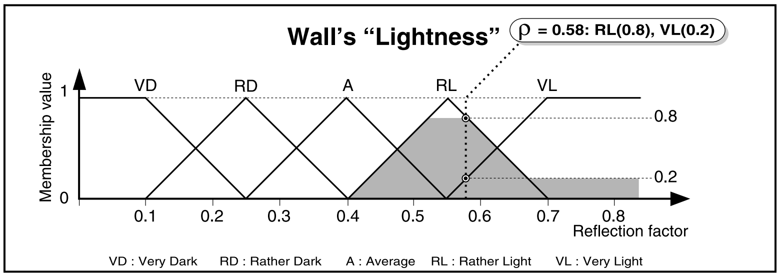


Figure 6-11: Fuzzy characterisation of the brightness of walls using fuzzy subsets

The international version of the program LESODIAL, which was developed as part of IEA Task 21, uses this novel approach. Based on fuzzy logic, this daylighting decision tool, described in Figure 6-12, has the following features:

- it takes into account imprecise parameters, expressed in vague terms, during architectural pre-design phases;
- it facilitates problem description through graphical and linguistic expressions;
- it uses fuzzy inference rules to give daylighting diagnosis and recommendations for a design;
- it compares and outranks architectural reference objects by means of fuzzy outranking relations from a building database.

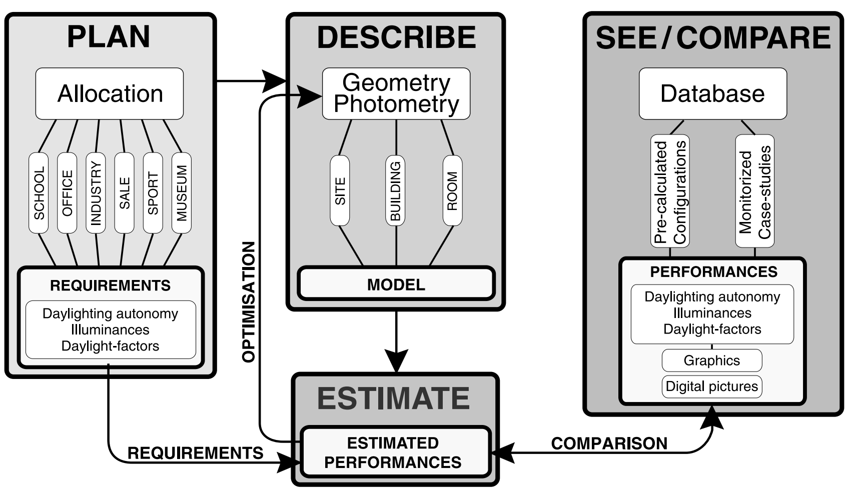


Figure 6-12: Flow chart of a daylighting decision tool based on fuzzy logic

In addition, the programme calculates daylight factors and the percentage of the year when daylight is sufficient by means of an analytical (BRE split-flux) method and statistical climate data. Diagnosis and recommendations to improve the daylighting design are provided in the form of graphics and verbal comments. A vocabulary of lighting terminology helps designers to use the programme with very little tutoring.

6.4. Physical Models

Scale models of buildings are used all over the world for daylighting design. The main advantages and interest of this approach compared to other design methods are that:

- architects use scale models as design tools to study various aspects of building design and construction;
- it is a "soft technology," well known to and shared by architects and other building professionals;
- when properly constructed, scale models portray the distribution of daylight within the model room almost as exactly as in a full-size room.

All these features are a result of the extremely small size of light wavelengths (380–780 nanometers). Thus, the physical behaviour of light is absolutely the same for a 1 m^2 area in a full-size room as it is for the corresponding 4 cm^2 area of a 1:50 scale model. In other words, even the smallest of scale models can produce very accurate results.

Construction of a model must be preceded by choice of an appropriate scale, which is directly related to the model's particular purpose. Scales ranging from 1:500 to 1:1 can be considered, as shown by the different activities undertaken as part of IEA Task 21. Table 6-3 summarises the possible scale choices.

Table 6-3: Scale choice as a function of daylighting design purpose

Scale	Objectives
1: 200 - 1 : 500	for preliminary design and concept development to provide a gross sense of the massing of the project to study the shadow created by the future building or from a neighbouring building
1 : 200 - 1 : 50	to study direct sunlight penetration into a building (e.g., efficiency of solar protection) to study diffuse daylight in a very big space (e.g., an atrium)
1 : 100 - 1 : 10	to consider detailed refinement of spatial components to have highly detailed inside views (e.g., video or photos) to study accurately diffuse and direct daylight penetration
1 : 10 - 1 : 1	to integrate critical industrial components to consider daylighting devices that cannot be reduced in scale to proceed to final evaluation of advanced daylighting systems through monitoring and user assessment

Common rules must be applied, however, in the construction of any model, whatever its scale. The principal rules are:

Materials

- the walls of the model must be absolutely opaque, and all the joints must be light proof;

- model parts must be movable or replaceable to facilitate comparison of configurations and allow for the placement of sensors and cables;
- Optical properties of internal (walls, ceiling, and floor) and external surfaces must be as close as possible to those of the planned building;
- model glazing materials, i.e., thin sheets of glass or clear plastic, should be used in apertures if the angle of incidence transmissivity of glass is expected to be important for the distribution of daylight in the internal spaces;
- geometry and sizes must be as accurate as necessary to permit consideration of the design questions.

Other Criteria

- the overall dimensions and weight of the model must be such that it can be supported (e.g., on a heliodon) or moved (e.g., movable mock-up rooms);
- the size of the model must be reasonable with regard to the distance to light sources (e.g., 0.6 m in height for a 5-m-diameter sky dome);
- the fixing of the model parts should be strong enough to allow different movements (e.g., mock-up rooms) and even vertical positions (e.g., heliodon);
- access to the model's interior, through apertures or removable parts, must be possible for placing illuminance sensors or imaging devices.

Because of the difficulty in meeting all these requirements, physical modeling generally achieves relative rather than absolute results. The search for relative improvements in performance is thus a more appropriate goal than attempting to obtain accurate quantitative measurements.

These difficulties are even more important when models are placed under real sky conditions and not under sky or sun simulators, for example, in the case of on-site performance assessment and for mock-up room measurements, which depend upon the sky luminance distribution at the site. The use of a reference facade in conjunction with the facade is necessary to overcome this difficulty and produce a relative performance assessment. Indoor and outdoor testing situations will be considered in the following sections.

6.4.1. Sky Simulators

Sky simulators have been used for decades in daylighting design studies. Their main advantage is that they offer reliable and reproducible conditions that simulate daylighting under real skies. To allow comparisons among daylighting design studies carried out on different simulators, normalised sky luminance distributions (so-called "standard skies") are used. Table 6-4 gives an overview of the principal sky simulator configurations.

Table 6-4: Principle sky simulator configurations

Designation	Characteristics	Advantages	Disadvantages
Mirror sky	Most common configuration; mirror enclosure with a lighting ceiling (fluorescent tubes and opal diffuser)	• moderate cost • minimised horizon error	• only CIE overcast sky reproduced • inter-reflection disturbed by the scale model
Sky dome	Diameter between 3 and 9 m; made of white opaque hemisphere illuminated by light sources in a circular groove	• reproduction of different standard sky models (uniform sky overcast or clear CIE sky) possible • very easy scale model access	• hard and tiresome calibration (requires about 1 week) • high electric consumption and frequent maintenance problems
Spotlight sky simulator	Vault made of a multitude of incandescent lamps	• all types of sky reproducible	• calibration and maintenance complicated by different aging patterns of sources • high luminance discontinuity
	Line of 30 lamps mounted in a quarter-circle arc	• all types of sky reproducible • moderate cost	• model cannot be viewed under simulated daylight • slow measurement procedure
Scanning sky simulator	A sixth of the vault is constructed with 25 lamps. The whole hemisphere, based on Tregenza's model of 145 light zones, is rebuilt by a six-step scan. Quantitative (illuminance) and qualitative data (video digitised image) are added at the end of the process.	• a close match to the sky luminance measuring format (IDMP) • can reproduce all existing standard or statistical sky models • can achieve low construction, maintenance, and operation costs	• it is impossible to visualise or to measure instantaneously inside the model

Some proposed new sky simulator configurations are based on a scanning process [Tregenza 1989, Michel et al. 1995]. Of these, one uses a scanning process to rebuild the overall sky hemisphere, starting with a sixth of a hemisphere. This novel apparatus, shown in Figure 6-13, was used in IEA Task 21. Its numerous advantages are summarised in Table 6-4.

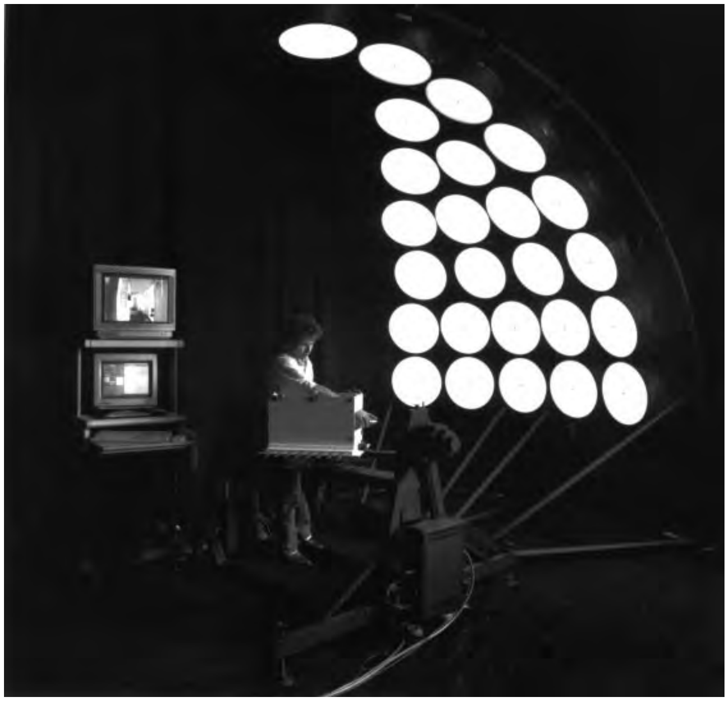


Figure 6-13: View of the EPFL scanning sky simulator (Switzerland), above, and the BRE mirror sky (UK), below

The novel principle on which the scanning sky simulator is based allows accurate reproduction of the luminance distributions of every type of sky. Some of these distributions, standardised by the CIE recommendations, are described by analytical functions. These distributions are used in daylighting studies and, although theoretical, have the important advantage of allowing comparison of results internationally. The main “standard skies” that can be reproduced on the simulator are:

- isotropic (uniform) sky
- CIE overcast sky
- CIE clear sky
- CIE intermediate sky

It is possible to reproduce statistical skies in addition to the different standard skies. Illuminance and luminance distributions of real sky measurements have been made available through the International Daylight Measuring Program (IDMP). The processing of these data allows the development of statistical skies that are representative of the daylight in a particular area. Monthly average skies as well as dynamic daily skies can be reproduced this way.

6.4.2. Full-Scale Test Rooms

Many quantitative daylighting design parameters can be assessed and optimised using scale models and simulators. Daylighting projects, however, have not only quantitative objectives (providing light, saving energy, etc.), but also qualitative requirements (perception of space, visual comfort, etc.). Some of these qualitative requirements can be formally expressed using structured, available scientific knowledge, including:

- perception and visual adaptation (ergo-ophthalmology)
- visual comfort and performance (visual ergonomy)
- light propagation, transmission, and reflection (photometry)

Several “occupancy-dependent” criteria and figures, which can be measured by appropriate physical instruments, can be outlined, which will lead to a relatively objective assessment of the human response to the luminous environment. Table 6-5 summarises the principal quantifiable figures that depend on occupants.

Table 6-5: Principle quantifiable criteria that depend on occupants

Objectives	Associated quantifiable figures
Visual performance	Illuminance (on working surface) Contrast object / background Object size
Visual comfort	Luminance contrast (task / background) Illuminance uniformity Colour temperature

Most of these quantifiable figures cannot, unfortunately, be assessed or measured in scale models because neither the occupants nor some objects that make up the luminous environment can be reduced in size (documents, view out, etc.). Full-scale test rooms in outdoor conditions must be used (see Appendix 8.4).

Because lighting conditions depend on the variable luminance distribution of the sky vault, two modules must generally be constructed:

- one is used as a reference room and equipped with a conventional facade (double glazing);
- the second is used as a test room and features novel daylighting systems.

A designer can optimise a daylighting system and room configuration using the assessment data. Most of the information gained by this procedure can be used to increase user acceptance of the designed system in the real building.

Conclusion 6.5.

Design tools play a significant role in the decision-making process that characterises daylighting design in a building project. These tools support designers through the sequence of decisions that leads from original daylighting concepts to their final implementation in a building.

To be efficient and accepted by practitioners, design tools must fit the most significant phases of the architectural projects where crucial decisions regarding daylighting strategies are made. These tools might even propose appropriate options.

Different types of daylighting design tools are available today for practitioners, providing qualitative and quantitative information. These tools include:

- simple tools, which are most appropriate for early design phases and are best suited for basic design problems;
- computer-based tools, which can handle advanced daylighting systems and provide a vast variety of output (images, visual comfort calculations, etc.);
- physical models, which are well-known and shared by architects and other building professionals.

No design tool will ever replace designers themselves, who must make the choices involved in the daylighting design of a building. However, these tools can accompany the designer in a creative process of devising an enjoyable and productive built environment while saving energy through the use of daylighting.

Conclusions 7.

Introduction 7.1.

This book is an introduction to advanced daylighting strategies for use in this millennium. For the first time, innovative daylighting systems have been evaluated on a comparative basis. The assessments, performed in real and scale-model buildings and in test rooms worldwide, show that the majority of the systems tested can produce potential energy savings when applied in the appropriate climates and on the appropriate orientations of a building.

A daylighting system should be selected according to climatic characteristics, e.g., the predominant sky type and the latitude at a building site. Actual energy savings depend on the daylighting system being designed as part of an integrated strategy that includes daylight-responsive controls. Careful integration of the daylighting system with the rest of a building's design should begin early in the design process to produce a high-quality work environment and provide building owners with a highly valued space.

The state of the art of designing daylit buildings in practise varies widely with climate and latitude. The design of buildings situated in higher latitudes, as embodied in typical design practise and building codes, places more emphasis on floor plans that are conducive to daylight admission where this resource is limited in availability. Buildings situated in lower latitudes, with an abundance of daylight and sunlight in most regions, must contend with the problem of cooling loads and therefore, in the past, have not relied as much on utilising daylight. Now with a renewed interest in reducing energy use and the improvement of working conditions, the use of innovative daylighting strategies is becoming a positive element in building design.

The advanced daylighting systems described in this book are intended to address the following challenges posed by traditional daylighting strategies:

- In predominantly overcast climates or in built-up urban areas, there is insufficient daylight flux to provide adequate interior daylighting.
- In some climates and orientations, poor control of glare from direct sunlight limits daylight applications.
- In hot and sunny climates, daylighting designs must manage sunlight to control cooling loads.
- There is widespread interest in extending the floor area that can be effectively daylit at a distance from windows and skylights.
- Given the ever-changing nature of tasks in buildings and the dynamic nature of daylight, design solutions that provide some degree of operational control are desirable.

These challenges shaped and defined the IEA SHC Task 21's Subtask A effort to study new technologies and designs that could address these needs. The study focused on both commercially available and experimental prototype technologies, so readers should verify the commercial status of any systems of interest. Current data on system costs and availability should be obtained from the appropriate commercial sources, some of which are listed in Appendix 8.6.

7.2. Performance

Participants of the IEA SHC Task 21 made a major effort to generate absolute and comparative performance data for innovative daylighting systems. A comprehensive set of test protocols was developed to ensure data quality and comparability (Appendix 8.5). Good comparative data were obtained for many systems in side-by-side testing with reference base cases under a variety of outdoor conditions. In some studies, occupant response data were also collected.

Although it was feasible to extend limited test room data to annual performance data, this was not always possible. Since the testing was carried out in different facilities in different countries, it was difficult to make comparisons between the data. In order to best utilise the results presented in this book and summarised below, a designer should carefully evaluate the performance data presented here in relation to the performance needs of a specific project. The "best" system for a particular project may turn out not to be useful for another project because of differing performance requirements.

The lighting energy savings potential of a daylighting system can be described as the system's capability to increase daylight as compared to a reference base case. The reference base case used in monitoring the daylighting systems in this project were either clear glazing or glazing shaded by venetian blinds at a specified tilt. Depending on the base case used and the sky conditions under which a system was tested, several systems demonstrated potential energy savings.

The main findings for each type of system studied are summarised below. The reader should refer to the appropriate section in the book for detailed information on each, taking into account the system's applicability and limitations.

7.2.1. Shading Systems Using Diffuse Light

Louvers. Fixed, mirrored louvers are designed principally for direct sun control. High-altitude sun and skylight reflected off the louvers increase interior daylight levels. Daylight levels from low-altitude skies (i.e., from the region of the sky approximately 10° to 40° above the horizon) are reduced. Fixed, mirrored louvers such as the "Fish" or "Okasolar" system can control glare but reduce daylight levels. They are a design option for shallow rooms in temperate climates.

Blinds. Standard venetian blinds provide moderate illuminance distribution. The optimum amount of slat closure is dictated by glare, direct sun control, and illumination requirements. Inverted, silvered blinds increase daylight levels if the slats are horizontal.

Automated Blinds. When an automated venetian blind is used to block direct sunlight and is operated in synchronisation with dimmable fluorescent lighting, energy savings are substantial compared to the energy used when a static blind is paired with the same electric lighting control system.

Holographic Optical Element (HOE) Shading Systems. These systems provide efficient solar shading while maintaining daylight illumination. The current high cost imposed by the required tracking system may limit the applicability of HOE shading systems.

7.2.2. Shading Systems Using Direct Sunlight

Light Shelves. Optically treated light shelves are an improvement over conventional internal light shelves. Optically treated shelves can introduce adequate ambient light for office tasks under most sunny conditions.

Light-guiding Shades. Light-guiding shades increase daylight illumination in the centre of a space as compared with the illumination provided by conventional shades. Light-guiding shades are suitable for hot, sunny climates.

Angular Selective Skylights. Angular selective skylights are best used in low latitudes because these systems reject direct sunlight at high altitude and redirect low-altitude daylight into a room, controlling heat gains and at the same time providing additional illumination from the sky.

7.2.3. Non-Shading Systems Using Diffuse Light

Light Shelves. External light shelves use not only diffuse light but also distribute (diffused) direct sunlight. An external, upward-tilted (30°) light shelf can increase daylight levels at the back of a room. An internal light shelf will decrease light levels.

Anidolic Ceiling. This system, which has an exterior, sky-oriented collection device, has been shown to increase the daylight factor below the light-emitting aperture of the system at a 5-m room depth. It requires a blind on the collection device to control sunlight on very sunny days.

Zenithal Light-guiding System with HOEs. This system increases illumination in the depth of a room and reduces it near the window at orientations where there is no direct sunlight.

7.2.4. Non-Shading Systems Using Direct Sunlight

Laser-cut Panel. Similar to the prismatic panel, the laser-cut panel increases light levels 10 to 20% in the depth of a room, particularly in sunny climates. When the panel is tilted, substantially higher levels are achieved. Tilting can also reduce the glare factor.

Sun-directing Glass. Sun-directing glass increases illuminance levels in the depth of a room in sunny climates. The system depends on the incident angles of the sun and is best used in temperate climates.

In general, among the systems tested, some, such as the selective shading systems that reconcile solar shading and daylighting, can save significant energy. Non-shading daylighting systems that are located above eye level and redirect sunlight to the room ceiling, such as laser-cut and prismatic panels, can save considerable electrical energy but require detailed design consideration, e.g., specific tilting to avoid glare. Under overcast or cloudy sky conditions, anidolic systems perform well.

Automatically controlled blinds and louvers have proven to be efficient shading systems with much greater energy savings potential than static systems. Systems with holographic optical elements are promising but require further development to reduce cost and improve performance.

IEA SHC Task 21 Subtask A Achievements 7.3.

EA SHC Task 21 Subtask A: Performance Evaluation of Daylighting Systems has documented the potential energy savings possible with advanced daylighting strategies that manage the flow of light and heat. The task has also laid the foundation for ongoing research and assessment by establishing testing facilities to monitor new systems, measure their physical characteristics for software input, and to evaluate systems when they are installed in actual buildings. As a result of this work, manufacturers of daylighting products can now test new devices using proven methods, develop these products further, and assess their performance using post-occupancy evaluation procedures.

Future Work 7.4.

Although the work documented in this book demonstrates that improved optical systems can provide better daylighting performance, greater occupant acceptance, and increased energy savings potential as compared with conventional systems, the rapid and continuing advances in materials science and production technologies promise additional performance improvements as well as reduced costs and maintenance.

Beyond advances in optical components, however, critical elements of daylighting design still need to be addressed. These include the successful integration of advanced daylighting systems with daylight-responsive lighting controls, and the consideration of occupant response to advanced daylighting strategies. Two key focuses for future research are the development of a comprehensive understanding of occupant needs and preferences in daylighted spaces, and the creation of models that describe the relationships among daylighting design parameters, occupant satisfaction, and control systems.

Past electric lighting energy savings mainly resulted from advances in the efficiency of lamps; future savings will be the result of using advanced daylighting systems and controls. Window and lighting system designs need to be integrated to maximise daylight while minimising cooling loads so that daylighting strategies can produce consistent energy savings. Cost-effective integrated design solutions are needed that have thermal impacts equal to or lower than those found in the best available conventional building designs. There is also the need for standards and guidelines to apply to these systems.

The work in this book is offered as a first step towards harmonising the needs of people with the advantages that technology can provide, and integrating the hardware and software elements of daylighting systems throughout the major phases of building life cycles.

Appendices 8.

Glossary 8.1.

Absorption

Transformation of radiant energy to a different form of energy by the intervention of matter.

Adaptation

The process by which the state of the human visual system is modified by previous and present exposure to stimuli that may have various luminances, spectral distributions, and angular subtenses.

Altitude

The angular distance of the sun measured upward from the horizon on the vertical plane that passes through the sun. Altitude is measured positively from horizon to zenith from 0° to 90°.

Angle of Incidence

The angle between a ray of light falling on a surface and a line perpendicular to the surface.

Atmospheric Turbidity

The scattering of solar radiation caused by air molecules, the scattering and absorption of solar radiation by larger particles known as aerosols, and the absorption of solar radiation by atmospheric gases and water vapour in the atmosphere. Atmospheric turbidity is usually expressed as the ratio of the total attenuation from molecules and aerosols in the atmosphere to that of molecules alone, using coefficients or optical thicknesses of molecular and particulate atmospheres. Atmospheric turbidity values of 3 to 6 are common even on days described as clear. A value of unity is equivalent to a Rayleigh atmosphere in which the size of particles is small compared with the wavelength of the radiation.

Atrium

An interior light space enclosed laterally by the walls of a building and covered with transparent or translucent material that permits light to enter interior spaces through pass-through components.

Azimuth

The azimuth of the sun is the angle between the vertical plane containing the sun and the vertical plane oriented to the north (direction of origin).

Brightness

The visual sensation by which an observer registers the degree to which a surface appears to emit or reflect more or less light. This subjective sensation cannot be measured in absolute units; it describes the appearance of a source or object.

Candela

The unit of luminous intensity. The luminance of a full radiator at the temperature of solidification of platinum is 60 candelas / cm^2.

Candela Per Square Meter

A unit of luminance in a particular direction recommended by the Commission Internationale de L'Éclairage (CIE).

CIE Standard Clear Sky

Cloudless sky for which the relative luminance distribution is described in Publication CIE No. 22 (TC 4.2) 1973 Commission Internationale de L'Éclairage (CIE).

CIE Standard Overcast Sky

A completely overcast sky for the luminance (cd/m^2) of any point in the sky at an angle of elevation γ above the horizon, is assumed to be given by the relation:

$$L\gamma = \frac{L_Z\,(1+2\sin\gamma)}{3}$$

where L_Z is the luminance at the zenith.

Clerestory

Daylight opening in the uppermost part of an exterior wall.

Contrast

The subjective assessment of the difference in appearance of two parts of a field of view seen simultaneously or successively. It can be defined objectively as:

$$(L_1–L_2) / L_1$$

where L_1 and L_2 are the luminances of the background and object, respectively.

Daylight

Visible global radiation. Daylight is the sum of sunlight and skylight.

Daylight Factor

Ratio, at a point on a given plane, of the illuminance that results from the light received directly or indirectly from a sky of assumed or known luminance distribution to the illuminance on a horizontal plane that results from an unobstructed hemisphere of this sky. The contribution of direct sunlight to both illuminances is excluded.

Daylight Opening

Area, glazed or unglazed, that is capable of admitting daylight to an interior.

Diffuse Illuminance From the Sky

Illuminance from the sky received on a horizontal plane from the whole hemisphere, excluding direct sunlight.

Diffuser

A device object or surface used to alter the spatial distribution of light.

Diffuse Reflection

The process by which incident flux is redirected over a range of angles.

Diffuse Transmission

The process by which the incident flux passing through a surface or medium is scattered.

Diffuse Transmittance

The ratio of the diffusely transmitted luminous flux leaving a surface or medium to the total incident flux.

Diffusion

The scattering of light rays so that they travel in many directions rather than in parallel or radiating lines.

Disability Glare

Excessive contrast, especially to the extent that visibility of one part of the visual field is obscured by the eye's attempt to adapt to the brightness of the other portion of the field of view; visibility of objects is impaired.

Discomfort Glare

Glare that causes annoyance without physically impairing a viewer's ability to see objects.

Emission

Release of radiant energy.

Fenestration

Any opening or arrangement of openings in a building for the admission of daylight or air.

Glare

A visual condition which results in discomfort, annoyance, interference with visual efficiency, or eye fatigue because of the brightness of a portion of the field of view (lamps, luminaires, or other surfaces or windows that are markedly brighter than the rest of the field). Direct glare is related to high luminances in the field of view. Reflected glare is related to reflections of high luminances.

Goniophotometer

Photometer for measuring the directional light distribution characteristics of sources, luminaires, media, or surfaces.

Integrating Sphere

Hollow sphere whose internal surface is a diffuse reflector that is as non-selective as possible.

Illuminance

The luminous flux incident on a surface per unit area. The unit is lux, or lumens per square foot.

Indirect Lighting

Illumination achieved by reflection, usually from wall and/or ceiling surfaces.

Latitude

Geographical latitude is the angle measured in the plane of the long meridian between the equator and a line perpendicular to the surface of the Earth through a particular point.

Light

Radiant energy evaluated according to its capacity to produce visual sensation.

Light Duct

An element of a building that carries natural light to interior zones. Duct surfaces are finished with highly reflective materials.

Longitude

The angular distance from the meridian through Greenwich, England, to the local meridian through a particular point. Longitude is measured either east or west from Greenwich through 180° or 12 hours.

Lumen

The unit of luminous flux. It is equal to the flux through a unit of solid angle (steradian) from a uniform point source of one candela or the flux on a unit surface all points of which are at a unit distance from a uniform point of one candela.

Luminaire

A complete lighting unit (fixed or portable) that distributes, filters, or transforms the light given by a lamp or lamps and that includes all the components necessary for mounting and protecting the lamps and connecting them to the supply circuit.

Luminance

The luminous intensity of any surface in a given direction per unit or projected area of the surface as viewed from that direction.

Lux

The International System (SI) unit of illumination. It is the illumination on a surface one square metre in area on which there is a uniformly distributed flux of 1 lumen.

Obstruction

Surfaces outside the building that obstruct direct view of the sky from a reference point.

Overcast Sky

Sky completely covered by clouds with no sun visible.

Radiation

Energy in the form of electromagnetic waves or particles.

Reflectance

The ratio of light reflected to incident light.

Reflection

Process by which radiation is returned by a surface or a medium without change of frequency of its monochromatic components.

Reflector

A device that returns incident visible radiation; used to alter the spatial distribution of light.

Refraction

Change in direction of propagation of radiation determined by change in the velocity of propagation as radiation passes through an optically non-homogeneous medium or from one medium to another.

Relative Sunshine Duration

Ratio of actual time to possible time when the sun is not obscured by clouds.

Shading

Use of fixed or movable devices to block, absorb, or redirect incoming light for purposes of controlling unwanted heat gains and glare.

Shading Coefficient

The dimensionless ratio of the total solar heat gain from a particular glazing system to that for one sheet of clear, 3-mm, double-strength glass.

Shading Device

Device used to obstruct, reduce, or diffuse the penetration of direct sunlight.

Skylight

An opening situated in a horizontal or tilted roof.

Toplighting

Daylight that enters through the upper portion of an interior space such as a clerestory or skylight.

Translucent Glass

A glass with the property of transmitting light diffusely.

Transmission

Passage of radiation through a medium without change of frequency of its monochromatic components.

Transmittance

Ratio of the transmitted radiant or luminous flux to the incident flux in the given conditions.

Veiling Reflections

Reflections that reduce the contrast between the task/object and the background when extremely bright reflections of light sources appear on the task object itself.

Window

Daylight opening on a vertical or nearly vertical area of a room envelope.

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Chapter 1.: Introduction

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8.3.: Optical Characteristics of Daylighting Materials

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8.3. Optical Characteristics of Daylighting Materials

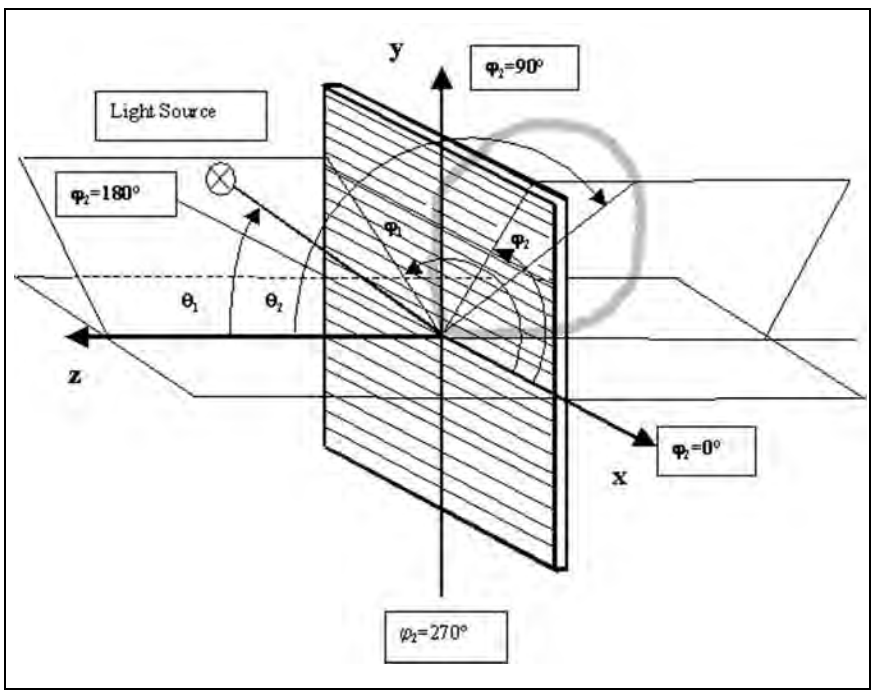
This appendix describes methods used to present and format measured optical performance data for daylighting systems, including 1) directional luminous transmittance measurements and 2) bi-directional transmittance distribution measurements. These data can be used in daylight simulation programs such as those described in Appendix 8.9 (on the CD-ROM).

8.3.1. Geometrical Description

In order to characterise any daylighting system with respect to different incident and observation angles, a coordinate system needs to be defined.

The origin is placed in the daylighting element. The z-axis will be orthogonal to the element's surface. Directions are defined by the azimuth angle φ and altitude angle θ (similar to spherical coordinates).

Figure 8-3.1: Coordinate system for material measurements



An angle's index indicates whether the angle is related to the incident or the observation direction; index 1 is the incident direction and 2 is the observation direction.

The range of the angle φ is from 0° to 360°; θ varies between 0° and 90° for light incidence and from 90° to 180° for light transmittance.

The relative position of any daylight element to this coordinate system is of significant impact to the measurement results. Therefore, not only the coordinate system needs to be well defined but also the orientation of the sample. If no additional information about the orientation is given in the measurement setup description, the following rules apply to the adjustment:

- The sample plane is parallel to a vertical window plane, i.e. the z-axis is pointing horizontally.
- The orientation of the sample within the x-y-plane is exactly like its orientation in the real daylight system, e.g. the linear structure of a laser-cut panel is usually horizontal, so $\varphi_1 = 0°$ in the experimental setup will show horizontal structures as well.
- The positive z-axis is the outside direction of the sample.

8.3.2. Luminous Transmittance (Directional) Measurements

Luminous transmittance measurements as a function of light incidence describe the ratio of transmitted luminous flux to the incident luminous flux. Since the two angles φ_1 and θ_1 change over a wide range, a large quantity of data has to be stored and, in subsequent steps, presented. A detailed description of the data format and the presentation of the results are given in the following sections.

Data Format

One of the most important aspects in storing any kind of data that should be accessed by many users is to have a device-independent format. Therefore, an ASCII file is suggested for the measurement results of luminous transmittance measurements. Such files can easily be read on nearly any operating system.

Since the results of the measurements sometimes show very high gradients, it is often not sufficient to store the data in a uniform incident angle grid. It makes a lot more sense to scan areas of interest with a smaller grid. To keep the file size quite small, such a grid does not necessarily need to be used for regions where the results do not change a lot. A uniform grid therefore allows both, a good description of the daylight element and no waste of disk space.

Note: A uniform grid is just a special case of a non-uniform grid. It is not forbidden to save the data in a uniform grid. In some cases (diffuse transmitting elements) it is recommended to have a uniform grid.

The data format for luminous transmittance measurements can be divided into two parts: header section and data section. The header contains basic information about the daylighting element and its symmetry (see example for details). Within the data section the range of the incident angles are given. After that each line of the file contains three values separated by the so-called tab-character (ASCII code 9). The first two values correspond to the incident angles φ_1 and θ_1. The third value is the luminous transmittance.

In the following lines the beginning of a typical luminous transmittance measurement file with a non-uniform grid is given:

Note: The lines in square brackets do not belong to the data file.

[HEADER SECTION]

```
#material: prismatic film
#manufacturer: 3M
#Isym=4 ! symmetry indicator: 0 no symmetry (phi_1 = 0°...360°)
#       1 rotary symmetry (only for one phi_1)
#       2 symmetry to phi=0°  and phi=180° (phi_1 = 0°...180°)
#       3 symmetry to phi=90° and phi=270° (phi_1 = -90°...90°)
#       4 symmetry to phi=0° & phi=180° and to phi=90° & phi=270° (phi_1=0°...90°)
#measurements done at TU-Berlin Institute of Electronics and Lighting Technology
#measurements by Ali Sit, Berit Herrmann and Sirri Aydinli
#date of measurements: 3. March 1998
#contact aydinli@ee.tu-berlin.de
#light incidence:
#phi_1-range: 0°...90° (azimuth)
#theta_1-range: 0°...70° (altitude)
#light transmittance for hemispherical light incidence : 0.49
```

[DATA SECTION]

```
#data
#phi_1           theta_1          tau
0.000000e+000    0.000000e+000    2.503987e-002
0.000000e+000    2.500000e+000    2.500000e-002
0.000000e+000    5.000000e+000    2.500000e-002
0.000000e+000    7.500000e+000    2.424242e-002
0.000000e+000    1.000000e+001    2.424242e-002
0.000000e+000    1.250000e+001    2.272727e-002
0.000000e+000    1.500000e+001    2.272727e-002
0.000000e+000    2.000000e+001    2.121212e-002
0.000000e+000    2.500000e+001    2.045455e-002
0.000000e+000    3.000000e+001    1.893939e-002
0.000000e+000    3.500000e+001    1.818182e-002
```

END

Presentation of Measurement Results

Due to the fact that two parameters are changed during the luminous transmittance measurements, a lot of data are obtained during the measurement. By looking at the values only, one cannot really see the information contained in the measurements. A graphical way to display the results is much more efficient, because the shape of a luminous transmittance body points out visually angle regions of interest.

Luminous Transmittance for Hemispherical Light Incidence

The luminous transmittance for hemispherical light incidence τ_{dif} is defined as the luminous transmission for an illumination with nearly uniform luminance from the hemisphere. This quantity could be measured using a hemisphere (or sphere) to illuminate the sample. It can also be derived from the integration of the luminous transmittance measurements:

$$\tau_{dif} = \frac{1}{2\pi}\int_{\varphi_1=0}^{2\pi}\int_{\theta_1=0}^{\frac{\pi}{2}}\tau(\varphi_1,\theta_1)\cdot\sin(2\theta_1)\cdot d\theta_1\cdot d\varphi_1$$

For a rotation symmetrical light transmittance:

$$\tau_{dif} = \int_{\theta_1=0}^{\frac{\pi}{2}}\tau(\theta_1)\cdot\sin(2\theta_1)\cdot d\theta_1$$

Filenames

All the data as well as the presentation of the sample measurements are included on the CD-ROM to this book. All measurements are put in one directory "PerformanceData/Directional" containing the data files (text files) and one WINWORD document which includes the presentation of the measurement results.

E.g. the filename "tub_3m.txt" contains the measurement results of the 3M-optical lighting film that were done at TUB.

8.3.3. Bi-directional Measurements

In contrast to luminous transmittance measurements, bi-directional measurements do not only change the incident light direction but scan the observation angles as well. *The Bi-directional Transmittance Distribution Function* (BTDF) is the spatial distribution of the luminance coefficient $q(\varphi_2,\theta_2)$. In theory, the integral value of the transmitted luminous flux calculated from the bi-directional data for a given light incidence corresponds to the value obtained by the luminous transmittance measurements.

$$\tau(\varphi_1,\theta_1) = \frac{1}{2}\int_{\varphi_2=0}^{2\pi}\int_{\theta_2=0}^{\frac{\pi}{2}} q(\varphi_2,\theta_2)\cdot\sin(2\theta_2)\cdot d\theta_2\cdot d\varphi_2$$

Much more data need to be stored since four parameters change their values. As a matter of fact, the presentation of bi-directional measurements is more complicated.

Light Incidence

It is agreed upon to limit the angles of light incidence according to the sky luminance distribution by Tregenza. This leads to 145 different light incidence directions which are shown in the figure and the table below.

Table 8-3.1: Light incidence for bi-directional measurements

θ_1	φ_1-step	φ_1	**Light incidents must be measured for:**
0°	-	0°	All samples
12°	60°	0°, 60°	All samples
24°	30°	0°, 30°, 60°, 90°	All samples
36°	20°	0°, 20°, 40°, 60°, 80°	All samples
48°	15°	0°, 15°, 30°, 45°, 60°, 75°, 90°	All samples
60°	15°	0°, 15°, 30°, 45°, 60°, 75°, 90°	All samples
72°	12°	0°, 12°, 24°, 36°, 48°, 60°, 72°, 84°	All samples
84°	12°	0°, 12°, 24°, 36°, 48°, 60°, 72°, 84°	All samples
			Additional Measurements if the sample is asymmetric to:
12°	60°	120°, 180°	φ_1= 90° / 270°
24°	30°	120°, 150°, 180°	φ_1= 90° / 270°
36°	20°	100°, 120°, 140°, 160°, 180°	φ_1= 90° / 270°
48°	15°	105°, 120°, 135°, 150°, 165°, 180°	φ_1= 90° / 270°
60°	15°	105°, 120°, 135°, 150°, 165°, 180°	φ_1= 90° / 270°
72°	12°	96°, 108°, 120°, 132°, 144°, 156°, 168°, 180°	φ_1= 90° / 270°
84°	12°	96°, 108°, 120°, 132°, 144°, 156°, 168°, 180°	φ_1= 90° / 270°
12°	60°	300°	φ_1= 0° / 180°
24°	30°	270°, 300°, 330°	φ_1= 0° / 180°
36°	20°	280°, 300°, 320°, 340°	φ_1= 0° / 180°
48°	15°	270°, 285°, 300°, 315°, 330°, 345°	φ_1= 0° / 180°
60°	15°	270°, 285°, 300°, 315°, 330°, 345°	φ_1= 0° / 180°
72°	12°	276°, 288°, 300°, 312°, 324°, 336°, 348°	φ_1= 0° / 180°
84°	12°	276°, 288°, 300°, 312°, 324°, 336°, 348°	φ_1= 0° / 180°
12°	60°	240°	φ_1= 0° / 180° **and** φ_1= 90° / 270°
24°	30°	210°, 240°	φ_1= 0° / 180° **and** φ_1= 90° / 270°
36°	20°	200°, 220°, 240°, 260°	φ_1= 0° / 180° **and** φ_1= 90° / 270°
48°	15°	195°, 210°, 225°, 240°, 255°	φ_1= 0° / 180° **and** φ_1= 90° / 270°
60°	15°	195°, 210°, 225°, 240°, 255°	φ_1= 0° / 180° **and** φ_1= 90° / 270°
72°	12°	192°, 204°, 216°, 228°, 240°, 252°, 264°	φ_1= 0° / 180° **and** φ_1= 90° / 270°
84°	12°	192°, 204°, 216°, 228°, 240°, 252°, 264°	φ_1= 0° / 180° **and** φ_1= 90° / 270°

Note: For rotation symmetrical samples, only measurements for θ1 = 0°, 12°, 24°, 36°, 48°, 60°, 72° and 84° need to be done.

Data Format

In order to store the measurement results, all the aspects of the data format for luminous transmittance measurements need to be taken into account (see also 8-3.2 Data Format), i.e. the file should be in ASCII-format for device independence. The header section contains all the information about the measurement setup and the sample. It is recommended to have a single file for each light incidence rather than one file for the whole measurement. Since the data cannot presented as a whole anyway, there is no need for storing the measurement results in one huge file. Further computation of the data becomes easier. The data section contains 3 columns in every line which are each separated by the tab character (ASCII code 9).

The solution of the light incident angles is given by the sky luminance distribution by Tregenza (see 8-3.3 Light Incidence). In order to minimise the disk space for the file without losing important information, a non-uniform grid of observation angles is acceptable. It is recommended to scan areas of high gradients in measurement values with an angle resolution of at least 1°.

Example:

Note: The lines in square brackets do not belong to the data file.

[HEADER SECTION]

```
#material: sun directing glass (Lumitop)
#manufacturer: Vegla
#Isym=3 ! symmetry indicator: 0 no symmetry (phi_1 = 0°...360°)
#       1 rotary symmetry (only for one phi_1)
#       2 symmetry to phi=0°  and phi=180° (phi_1 = 0°...180°)
#       3 symmetry to phi=90° and phi=270° (phi_1 = -90°...90°)
#       4 symmetry to phi=0° & phi=180° and to phi=90° & phi=270° (phi_1=0°...90°)
#measurements done at TU Berlin Fachgebiet Lichttechnik, TUB
#measurements and processing by Berit Herrmann, Sirri Aydinli
#date of measurement: 29. September 1998
#contact aydinli@ee.tu-berlin.de  for details
#light incidence:
#phi_1: 0° (azimuth)
#theta_1: 0° (altitude)
#light transmittance: 0.45
```

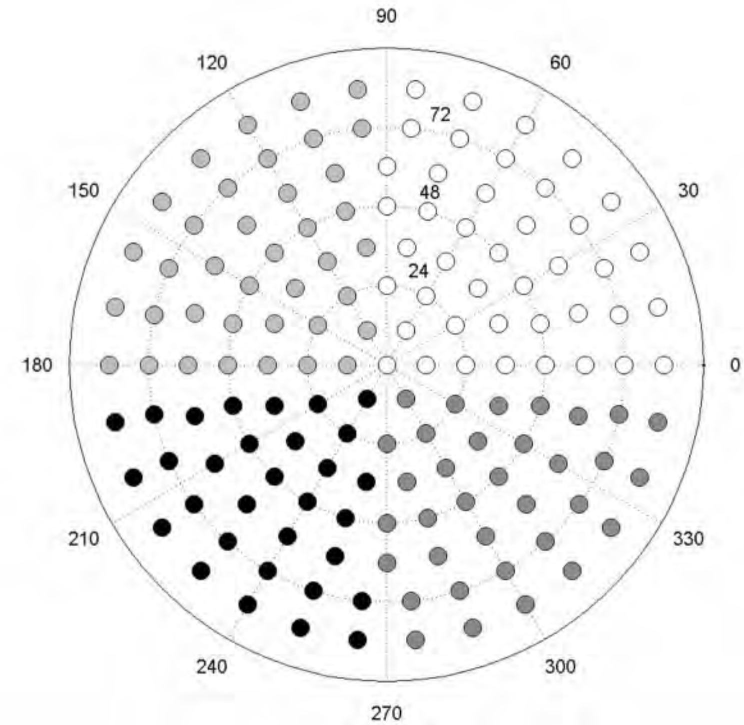
[DATA SECTION]

```
#data
#phi_2           theta_2          btdf
0.000000e+000    9.590000e+001    2.497359e-002
0.000000e+000    9.940000e+001    2.619607e-002
0.000000e+000    1.028000e+002    2.703650e-002
0.000000e+000    1.061000e+002    2.159965e-002
0.000000e+000    1.096000e+002    2.550889e-002
0.000000e+000    1.130000e+002    1.751997e-002
0.000000e+000    1.164000e+002    2.309398e-002
0.000000e+000    1.198000e+002    1.721820e-002
0.000000e+000    1.233000e+002    1.870304e-002
0.000000e+000    1.266000e+002    2.583353e-002
0.000000e+000    1.300000e+002    1.996848e-002
0.000000e+000    1.335000e+002    2.610528e-002
0.000000e+000    1.369000e+002    4.101757e-002
0.000000e+000    1.403000e+002    5.560827e-002
0.000000e+000    1.437000e+002    6.901417e-002
....
```

END

Figure 8-3.2:

Light Incidence for bi-directional measurements



Presentation of Measurement Results

Since there are four parameters for the bi-directional measurements, it is hard to present the results in a single plot. The system chosen here will include both a spatial distribution of the BTDF using spherical coordinates and the direction of the incident light (where required additional views are given).

Filenames

Bi-directional measurements collect a huge amount of data. A lot of files are created during the specification of a single material. Therefore, one should be careful with choosing the filenames. All the information about a sample and the light incidence is already included in the file's header section, but for convenience reasons, it is useful to put the filenames into a system. The filename contains four pieces of information: the institute carrying out the measurements, the material, and the light incidence angles θ_1 and φ_1.

All the data as well as the presentation of each sample measurement are included on the CD-ROM to this book. All the files necessary to characterise a sample are put together in a directory, e.g. "PerformanceData/Bi_directional/ Plexiglas" or "PerformanceData/Bi_directional/SunDirectingGlass". For each light incidence there is one text file. The presentation of the measurement results is put into a WINWORD document file.

E.g. the filename "tub_sdg_36_40.txt" contains the measurement results of the sun-directing glass that were done at TUB. The light incidence was: θ_1 = 36° and φ_1 = 40°. The corresponding presentation of this data can be found in the file "tub_sdg.doc".

Daylight measurements of different daylighting systems were conducted in Norway, Denmark, Germany, the United Kingdom, Austria, Switzerland, the United States, and Australia.

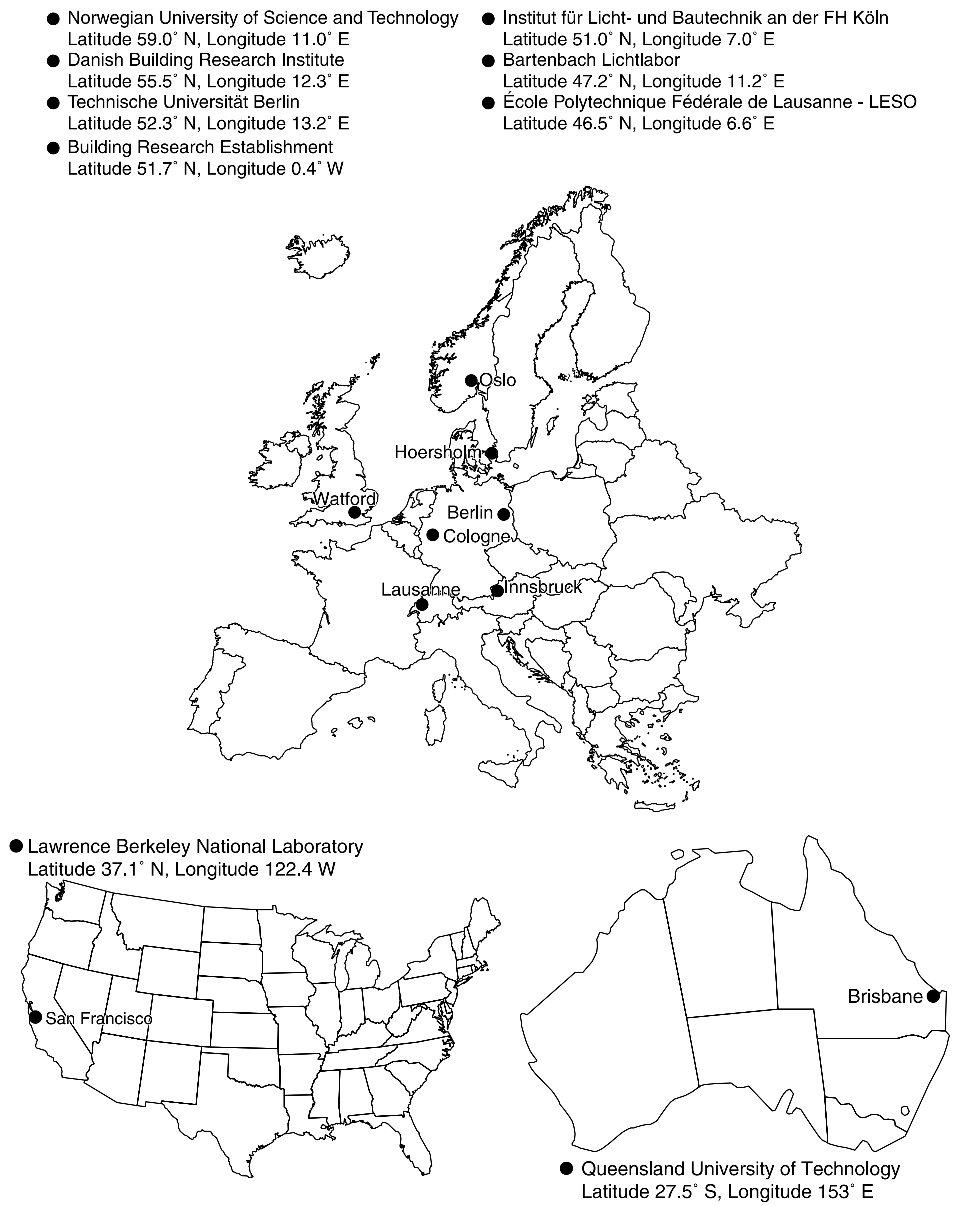


Figure 8-4.1: Map of test room locations

8.4.1. Technical University of Berlin (TUB), Germany

The experimental assessment of the daylighting systems was carried out in three unfurnished mock-up offices at the Technical University of Berlin (TUB). TUB is located in the centre of Berlin (latitude 52°N, longitude 13°E).

Geometry

The mock-up offices at TUB consist of 3 rooms (A, B, and D) with identical area. The test rooms are orientated 6° east of due south with some outside obstructions to the southeast. Each room has 3 separated windows and the sill height is 0.95 m above the interior floor level.

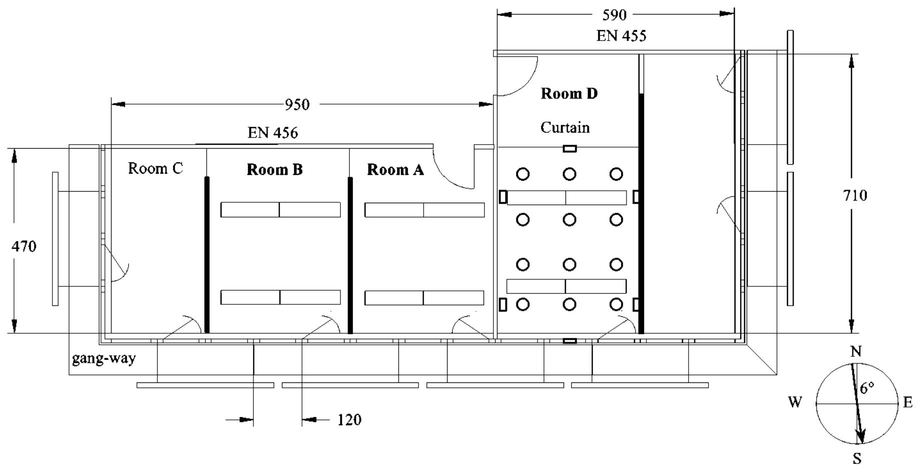


Figure 8-4.2: The mock-up offices are marked room A, B, and D. Grid sensor position is shown in room D. Dimensions are given in cm.

Test room: TUB	Length	Width	Height	Window area	Glazed area	Occupied
Geometry	4.70 m	3.50 m	3.00 m	7.00 m^2	5.30 m^2	No

Material Photometric Properties

The rooms are unfurnished with light-coloured surfaces (walls - grey, floor - grey, ceiling - white).

Test room: TUB	Reflectance			Transmittance of glazing		
	Walls	Floor	Ceiling	τ_{dif}	$\tau_{\perp}$	U-value
Surfaces	50 %	20 %	80 %	70 %	80 %	1.7

Note: τ_{dif} =transmittance for hemispherical irradiation;
$\tau_{\perp}$ = transmittance for normal irradiation;
U-value in W/m^2K.

Figure 8-4.3:
Exterior view of
TUB test rooms

Figure 8-4.4:
Interior view
of test room D
showing the window
configuration
and exterior
obstructions

Equipment for Measurement

All sensors used for interior and exterior illuminance measurements were photometer heads from PRC Krochmann and LMT GmbH, Berlin. Interior horizontal illuminance levels were measured in a grid (12 sensors) at a work plane height of 0.85 m. All sensors were connected to a data acquisition system (Delphin Instruments/Keithley) by use of PC board, and the data acquisition software was developed by TUB. Exterior illuminance measurements included global horizontal, shielded vertical (north, east, south, west) luminance distribution of the sky (sky scanner PRC, Krochmann GmbH, Berlin). Additional interior measurements were carried out by use of a CCD-Camera (TechnoTeam GmbH, Ilmenau).

8.4.2. Danish Building Research Institute (SBI), Denmark

The experimental assessment of daylight systems was carried out in two unfurnished mock-up offices at the Danish Building Research Institute (SBI). SBI is located north of Copenhagen (latitude 56°N, longitude 12°E).

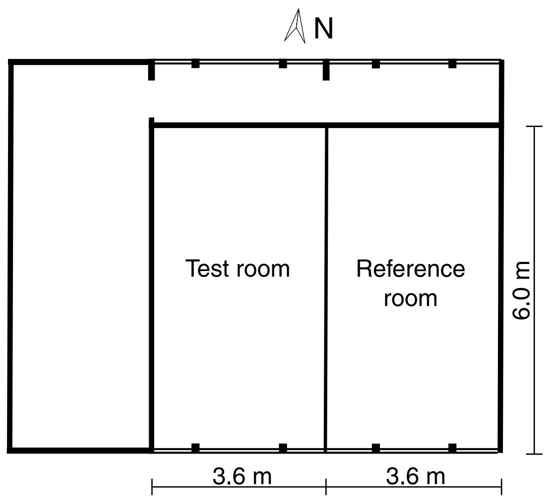


FIGURE 8-4.5:

FLOOR PLAN

Geometry

The mock-up offices at SBI consist of 2 rooms with identical area. The test rooms are orientated 7° east of due south with some outside obstructions to the west. Each room has windows in full height of the facade, but the lower part of the windows were covered during the measurements (sill height, 0.78 m above the interior floor level).

Test room: SBI	Length	Width	Height	Window area	Glazed area	Occupied
Geometry	6.00 m	3.60 m	3.00 m	7.80 m^2	6.60 m^2	No

Material Photometric Properties

The rooms are unfurnished with light-coloured surfaces (walls - white, floor - light grey, ceiling - white).

Test room: SBI	Reflectance			Transmittance of glazing		
	Walls	Floor	Ceiling	τ_{dif}	$\tau_{\perp}$	U-value
Surfaces	79 %	29 %	89 %	65 %	72 %	1.1

Note: τ_{dif} =transmittance for hemispherical irradiation;
$\tau_{\perp}$ = transmittance for normal irradiation;
U-value in W/m^2K.

Figure 8-4.6: Exterior view of test rooms with the exterior light shelf

Figure 8-4.7: Interior view of test room showing the window configuration, arrangement of furniture for user acceptance studies, and exterior obstructions

Equipment for Measurement

All sensors used for interior and exterior illuminance measurements were light-sensitive silicon diodes from Hagner, Sweden. Interior horizontal illuminance levels were measured in the centre line perpendicular to the window (6 sensors) at a work plane height of 0.85 m. All sensors were connected to a data acquisition system (Keithley) and the data acquisition software was developed by SBI. Exterior measurements included global horizontal and shielded vertical sky (south) illuminance.

8.4.3. Norwegian University of Science and Technology (NTNU), Norway

The experimental assessment of daylight systems was carried out in 5 (daily) occupied office rooms. The office rooms are situated in Sandvika, near Oslo, within the administrative building of the local energy company, Energiselskapet Asker og Bærum (latitude 59°N, longitude 11°E).

Geometry

The offices consist of 6 rooms with identical area. The test rooms have almost identical design, but every second room is laterally reversed (rooms 2, 4 and 6) compared to the reference room. The test rooms are oriented 9° east of due south with some outside obstructions to the east. The window function is separated into a full width clerestory window ("daylight window") above a view window. The window sill height is 0.85 m above the interior floor level.

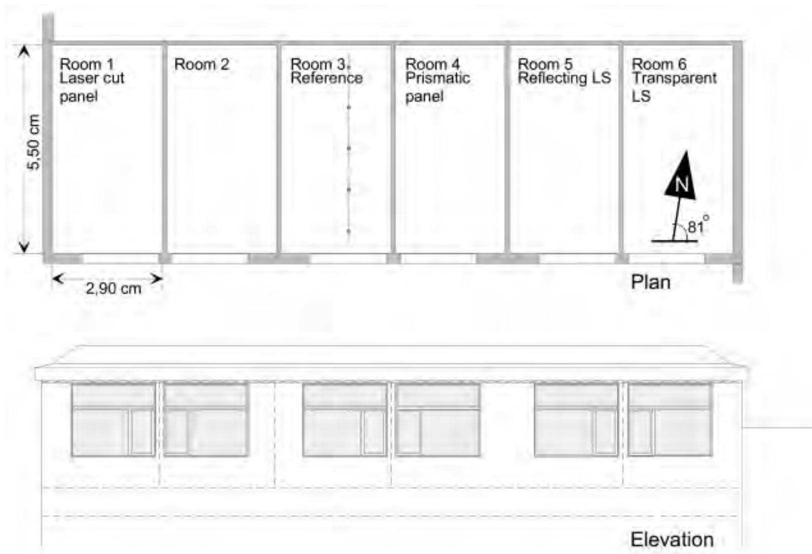


Figure 8-4.8: Plan and elevation of the Norwegian test rooms at the local energy company

Test room: NTNU	Length	Width	Height	Window area	Glazed area	Occupied
Geometry	5.90 m	2.90 m	2.70 m	4.30 m^2	3.20 m^2	Yes

Material Photometric Properties

The rooms are furnished with light-coloured surfaces (walls - white, floor - blue grey, ceiling - white). There are some differences in the furnishing of each room.

Test room: NTNU	Reflectance			Transmittance of glazing		
	Walls	Floor	Ceiling	τ_{dif}	$\tau_{\perp}$	U-value
Surfaces	69 %	18 %	82 %	77 %	NA	1.6

Note: τ_{dif} =transmittance for hemispherical irradiation;
$\tau_{\perp}$ = transmittance for normal irradiation;
U-value in W/m^{2}K.
NA = Not available.

Figure 8-4.9: The south facade of the Norwegian test rooms, located on the top floor. Daylighting systems were installed in the upper horizontal windows

Figure 8-4.10: View to the outside in the test room with laser-cut panels (sunny day). A centerline aluminium section is used for location of measurement points

Equipment for Measurement

All sensors used for interior and exterior illuminance measurements were light-sensitive silicon diodes (PRC Krochmann in Germany). The illuminance levels on the horizontal working plane were measured in the centre line perpendicular to the window at a work plane height of 0.8 m. In addition, a detector was mounted vertically on the rear wall at a height of 1.2 m above the internal floor. All sensors were connected to a data acquisition system (HP 34970A). Exterior sky measurements included global horizontal and one unshielded vertical detector for each orientation.

8.4.4. Lawrence Berkeley National Laboratory (LBNL), USA

Two side-by-side test rooms were used to conduct experimental evaluations of daylighting. The test rooms are located on the fifth floor of an existing high-rise building, located in downtown Oakland, California (latitude 37.1°N, longitude 122.4°W).

Geometry

The test rooms were designed with proportions typical of U.S. private offices. The south-east-facing windows are oriented 62.6° east of due south and have partially obstructed views of nearby high-rise buildings. The windows span the full width of each room, with a sill height of 0.78 m and a head height of 2.58 m.

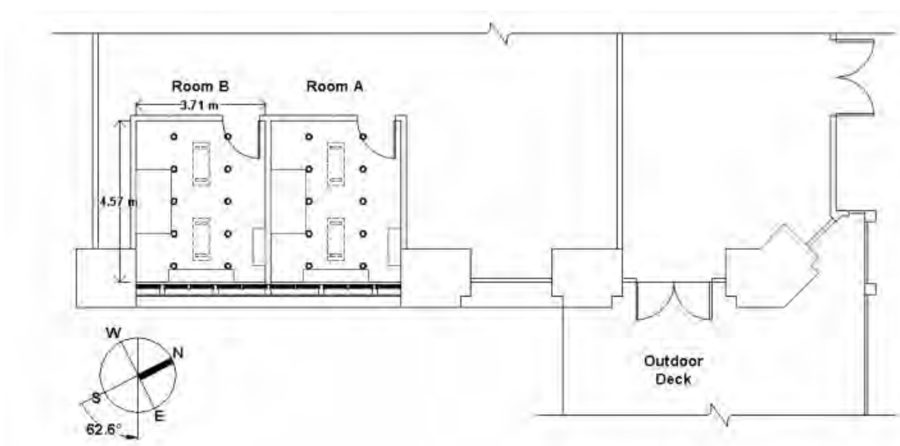


FIGURE 8-4.11: PLAN AND SECTION OF TEST ROOMS CONFIGURATION

Test room: LBNL	Length	Width	Height	Window area	Glazed area	Occupied
Geometry	4.57 m	3.70 m	2.58 m	8.50 m^2	7.52 m^2	No

Material Photometric Properties

The rooms are furnished with light-coloured surfaces (walls - white, floor - beige, ceiling - white). In each room, there is a large desk against one sidewall, a credenza against the window, and a bookcase against the opposite sidewall, all of dark-colored wood.

Test room: LBNL	Reflectance			Transmittance of glazing		
	Walls	Floor	Ceiling	τ_{dif}	$\tau_{\perp}$	U-value
Surfaces	88 %	17 %	88 %	69 %	76 %	6.4

Note: τ_{dif} =transmittance for hemispherical irradiation;
$\tau_{\perp}$ = transmittance for normal irradiation;
U-value in W/m^{2}K.

Equipment for Measurement

Interior and exterior illuminance were monitored using Li-Cor cosine corrected sensors. Ten work plane illuminance sensors were located in a 2x5 grid in each test room (height of 0.77 m) and monitored by National Instruments' LabView data acquisition software. Exterior global and diffuse horizontal illuminance, global horizontal irradiance, and outdoor temperature data were monitored on the roof of an adjacent 5-storey building wing using a Campbell Scientific CR10 data logger.

Figure 8-4.12: Exterior view of the test rooms. The 18-storey tower on the left houses the LBNL test rooms on the fifth floor, with an adjacent 5-storey building wing to the north or right

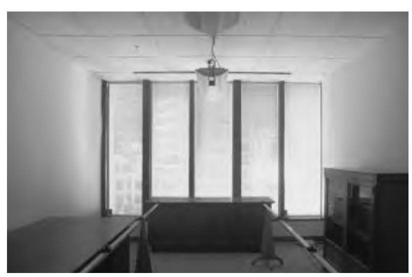


Figure 8-4.13: Views in the lbnl test room with partially closed venetian blinds on a sunny day

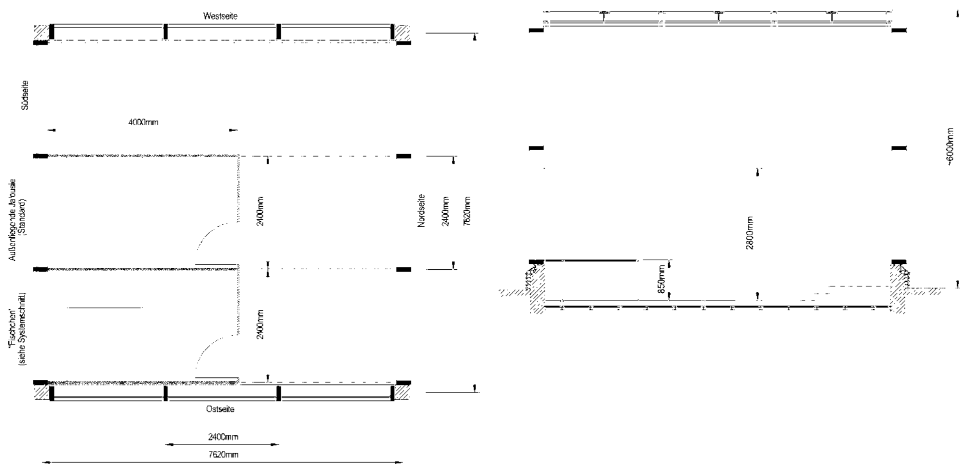
8.4.5. Bartenbach LichtLabor (BAL), Austria

The experimental assessment of daylight systems was carried out in two furnished mock-up offices at the Bartenbach LichtLabor (BAL). BAL is located southeast of Innsbruck, Austria (latitude 47°N, longitude 11°E).

Geometry

The mock-up offices at BAL consist of two rooms with identical area. The test rooms are orientated to south with high mountains in front. The average angle of obstruction is ~14°, with the highest mountain peak at ~18°. The mountains will reduce the sunny conditions during wintertime, especially at midday. Each room has full-height windows from the sill (0.85 m above floor level) up to the ceiling.

Figure 8-4.14: Plan and elevation of test room configuration



Test room: BAL	Length	Width	Height	Window area	Glazed area	Occupied
Geometry	5.00 m	2.30 m	2.80 m	4.50 m^2	4.50 m^2	No

Material Photometric Properties

The rooms are unfurnished with light-coloured surfaces (walls - white, floor - beige, ceiling - white).

Test room: BAL	Reflectance			Transmittance of glazing		
	Walls	Floor	Ceiling	τ_{dif}	$\tau_{\perp}$	U-value
Surfaces	80 %	30 %	80 %	85 %	92 %	-

Note: τ_{dif} =transmittance for hemispherical irradiation;
$\tau_{\perp}$ = transmittance for normal irradiation;
U-value in W/m^2K.

Figure 8-4.15: Exterior view of the test rooms at Bartenbach LichtLabor

Figure 8-4.16: Interior view of test rooms with the Fish system (left) and the reference room (right)

Equipment for Measurement

All sensors used for interior and exterior illuminance measurements were illuminance meter heads from LMT, Germany. Interior horizontal illuminance levels were measured in the centre line perpendicular to the window (5 sensors) at a work plane height of 0.85 m. All sensors were connected to a data acquisition system (Keithley Scanner and LMT Photometer) and the data acquisition software was developed by BAR. Exterior measurements included global horizontal, vertical sky, and vertical ground (south) illuminance.

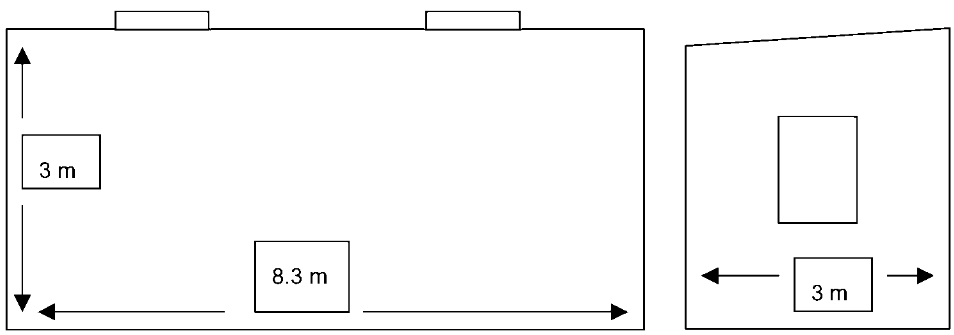
8.4.6. Queensland University of Technology (QUT), Australia

The experimental assessment of daylight systems was carried out in two unfurnished mock-up offices. QUT is located in Brisbane, Australia (latitude 28°S, longitude 153°E).

Geometry

The mock-up office at the test site consists of one building. The long axis of the test building is oriented 0° due north. There are minor outside obstructions not exceeding 5° in elevation. The building has a single glazed window (1.2 m x 1.2 m) with sill height 0.9 m in the northern end of the building. The building also has two skylight apertures (0.8 m x 0.8 m) in the roof for the comparison of skylight performance. For this skylight comparison, the building (8 m x 3 m x 3 m) can be divided into two rooms (4 m x 3 m x 3 m) by use of a temporary internal wall. Currently the window in the north end of the building is being increased in size to a window 1.6 m high and 2.4 m wide with sill height 0.9 m. The depth of the building from the window was made large (8 m), as the main thrust of daylighting research at QUT is towards improving the natural lighting within deep plan commercial buildings.

Figure 8-4.17: Elevations of the test room



Test room: QUT	Length	Width	Height	Window area	Glazed area	Occupied
Geometry	8.00 m	3.00 m	3.00 m	1.20 m^2	1.20 m^2	No

Material Photometric Properties

The rooms are unfurnished with light-coloured surfaces (walls - cream, floor - beige, ceiling - white).

Test room: QUT	Reflectance			Transmittance of glazing		
	Walls	Floor	Ceiling	τ_{dif}	$\tau_{\perp}$	U-value
Surfaces	60 %	30 %	80 %	85 %	92 %	-

Note: τ_{dif} =transmittance for hemispherical irradiation;
$\tau_{\perp}$ = transmittance for normal irradiation;
U-value in W/m^2K.

Figure 8-4.18: Exterior view of the test room at QUT with a light-guiding shade

Figure 8-4.19: Interior view of test room with light-guiding shade

Equipment for Measurement

Exterior irradiance was measured with two Middleton continuously recording pyrometers (one global and one diffuse). Internal illuminance was measured with cosine and spectrally corrected silicon diode detectors (8) linked to a 16-bit data acquisition system (Picolog). Calibrations were made with a Topcon IM5 photometer. Interior irradiance measurements were made with a Kipp and Zonen irradiance meter. Temperature measurements were usually made with miniature data loggers (Hobo) at suitable positions. The equipment is powered by a photovoltaic/battery power supply providing 240 V AC at about 1 amp.

8.4.7. École Polytechnique Fédérale de Lausanne (EPFL), Switzerland

The experimental assessment of daylight systems was carried out in two mock-up offices at the site of EPFL, located near Lausanne, Switzerland (latitude 46.5°N, longitude 6.6°E).

Geometry

The mock-up offices consist of two rooms with identical dimensions. The test rooms are movable and can be oriented in any direction. The angular altitude of external obstructions is lower than 5°. Each room has windows on the upper part of the facade, the lower part of the wall being opaque (sill height is 1.05 m above the interior floor); the overall facade can be fully glazed if necessary.

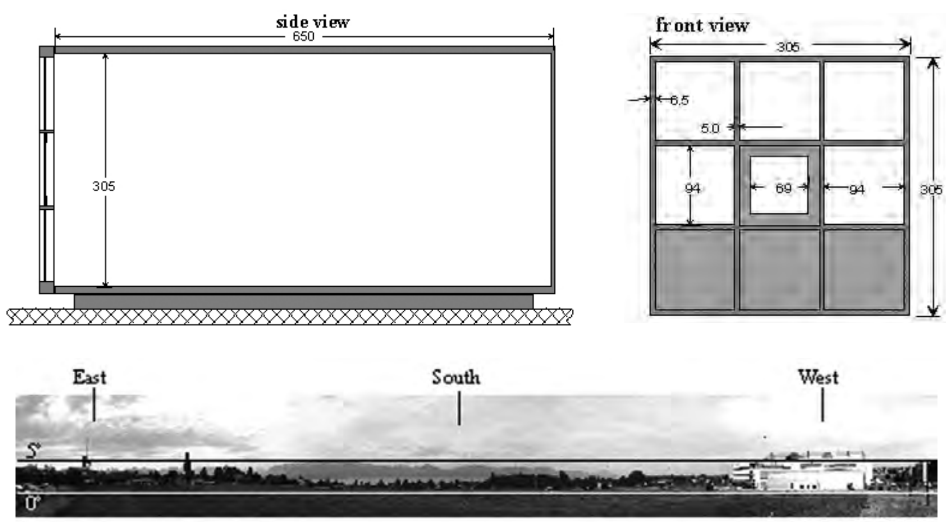


Figure 8-4.20: Elevations of the test rooms and view of the exterior obstructions. Dimensions are given in cm.

Test room: EPFL	Length	Width	Height	Window area	Glazed area	Occupied
Geometry	6.50 m	3.05 m	3.05 m	9.30 m^2	4.90 m^2	No

Material Photometric Properties

The rooms are furnished with neutral-coloured desks; walls, ceiling and floor surfaces are white to medium grey.

Test room: EPFL	Reflectance			Transmittance of glazing		
	Walls	Floor	Ceiling	τ_{dif}	$\tau_{\perp}$	U-value
Surfaces	81 %	16 %	81 %	70 %	80 %	2.9

Note: τ_{dif} =transmittance for hemispherical irradiation;
$\tau_{\perp}$ = transmittance for normal irradiation;
U-value in W/m^2K.

Figure 8-4.21: External view of the two test rooms

Figure 8-4.22: Internal view of test room with the anidolic system

Equipment for Measurement

Sensors used for interior illuminance measurements were two rows of 10 calibrated sensors BEHA 96408. Exterior illuminance data were collected by sensors mounted on black honeycomb stitch support (one horizontal LMT/BAP30 FCT, 4 vertical Hagner ELV641, plus one vertical sensor on each facade). All sensors were connected to a Campbell CR10 data acquisition system.

8.4.8. Institut für Lichtund Bautechnik (ILB), Germany

Test Room Description

The experimental assessment of daylight systems was carried out in two unfurnished and unoccupied mock-up offices at the Institute for Light and Building Technique at the University of Applied Sciences Cologne (ILB), Germany. ILB is located in the centre of Cologne (latitude 51°N, longitude 7°E). The test rooms are situated on the roof of the university on the 9th floor.

Geometry

The mock-up offices at ILB consist of 2 rooms with identical geometric measures. The test rooms face due south with few obstructions. Each room has windows in full height, but the lower part of the windows were covered during the measurements (sill height is 0.78 m above the interior floor level). The angle of obstruction was 0° during the measurement period.

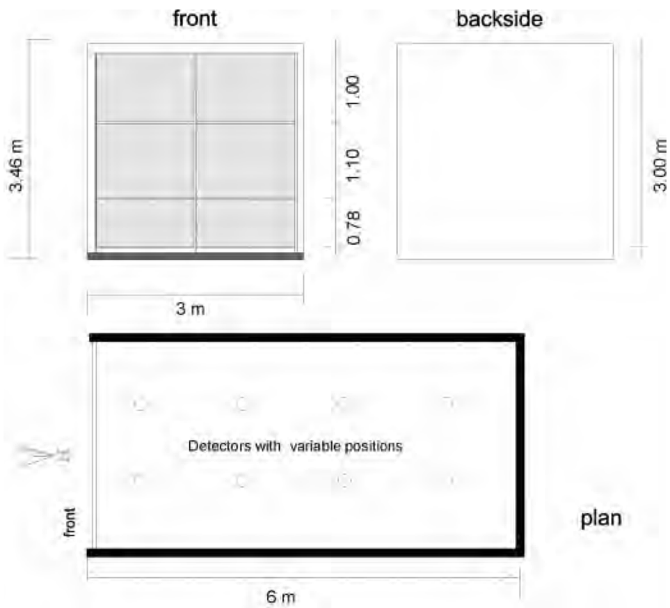


FIGURE 8-4.23:
ELEVATIONS OF TEST ROOM (ABOVE) AND FLOOR PLAN (BELOW)

Test room: ILB	Length	Width	Height	Window area	Glazed area	Occupied
Geometry	6.00 m	3.00 m	2.50 m	9.00 m^2	9.00 m^2	No

Material photometric properties

The rooms are unfurnished with light-coloured surfaces (walls - white, floor - grey, ceiling - white).

Test room: ILB	Reflectance			Transmittance of glazing		
	Walls	Floor	Ceiling	τdif	$\tau\perp$	U-value
Surfaces	70 %	30 %	80 %	70 %	80 %	3.0

Note: τ_{dif} =transmittance for hemispherical irradiation;
$\tau_{\perp}$ = transmittance for normal irradiation;
U-value in W/m^2K.

Figure 8-4.24:
Exterior view of test rooms of ILB (9th floor)

Figure 8-4.25:
Interior view of test room with sun-directing glass in upper aperture

Equipment for Measurement

All sensors used for interior and exterior illuminance measurements were light-sensitive silicon diodes with V(λ) calibration from PRC Krochmann, Germany. Interior illuminance levels were measured in a centre line perpendicular to the window (6 sensors) at a work plane height of 0.85 m. All sensors were connected to a PC-card-based self-developed data acquisition system. Exterior measurements included global horizontal and shielded vertical sky (south) illuminance.

8.4.9. Building Research Establishment (BRE), UK

Test Room Description

The experimental assessment of daylight systems was carried out in two unfurnished mock-up offices at the Building Research Establishment (BRE). BRE is located in Garston, near Watford, around 30 km north of London (latitude 51.7°N, longitude 0.4°W).

Geometry

The mock-up offices at BRE consist of 2 rooms of identical area. The test rooms are oriented around 10° west of due south. Each room has two windows (window head height is 2.6 m and sill-height is 1 m above the interior floor level) and the windows are almost the full room width, but have extensive glazing bars including a large central pillar. There is a tree to the east of the rooms, which shades the reference room window before 10:30 AM.

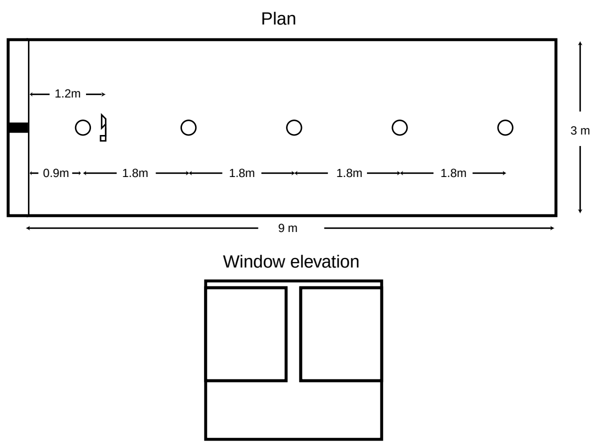


Figure 8-4.26: Plan and window elevation of a test room

Test room: BRE	Length	Width	Height	Window area	Glazed area	Occupied
Geometry	9.00 m	3.00 m	2.70 m	4.80 m^2	3.60 m^2	No

Material Photometric Properties

The rooms are unfurnished with light-coloured surfaces (walls - magnolia, floor - dark brown, ceiling - white).

Test room: BRE	Reflectance			Transmittance of glazing		
	Walls	Floor	Ceiling	τ_{dif}	$\tau_{\perp}$	U-value
Surfaces	80 %	9 %	80 %	85 %	95 %	-

Note: τ_{dif} =transmittance for hemispherical irradiation;
$\tau_{\perp}$ = transmittance for normal irradiation;
U-value in W/m^2K.

Figure 8-4.27: Exterior view of the test rooms. The four windows at the top right of the building belong to the two test rooms

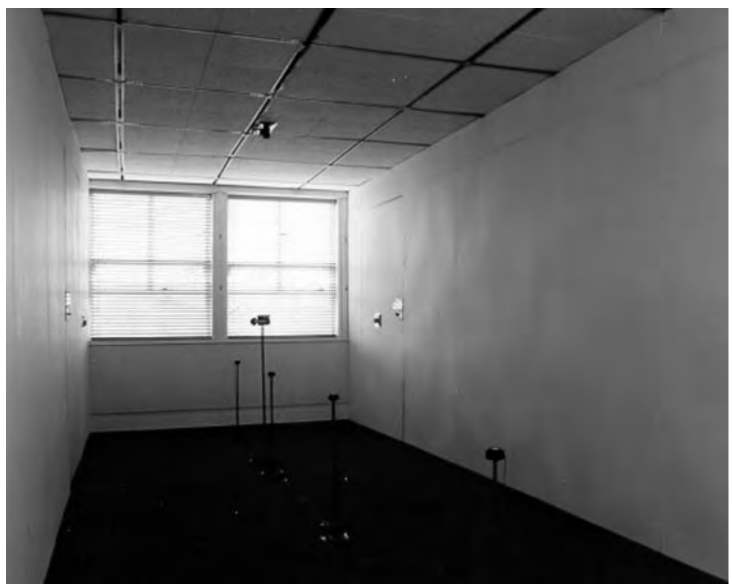


Figure 8-4.28: Interior view of test room

Equipment for Measurement

All sensors used for interior illuminance measurements were light-sensitive selenium diodes from Megatron, London, UK. Except for the direct normal illuminance, exterior illuminance sensors were silicon diodes supplied by LMT Lichtmesstechnik Berlin. The direct normal sensor was a Li-Cor silicon photocell mounted in an Eppley normal incidence pyrheliometer. Interior illuminance levels on the horizontal were measured in the centre line perpendicular to the window (6 sensors) at a work plane height of 0.7 m. All sensors were connected to a data acquisition system (using a Keithley A/D converter) and the data acquisition software was developed by Cambridge Consultants under contract to BRE. Exterior measurements included global horizontal, diffuse horizontal (using a shade ring), direct solar normal (using a solar tracker), and vertical total illuminance in the plane of the test room window. This was shielded from the ground-reflected light by a black honeycomb material.

8.4.10. Summary of Monitoring and Data Acquisition Systems

Description of Monitoring Equipment for Measurement

Institute	Manufacturer	Range klux	Calibration	Maximum calibration error	V(λ) (f_1')	Cosine response error (f_2)	Fatigue error (f_5)
Australia (QUT)	TopCon IM5	0.01 - 200	1998	± 2 %		± 5%	
Austria (BAL)	LMT	0.1 - 200	1994+1998	± 7 %	± 2%	± 2%	
Denmark (SBI)	Hagner	0.1 - 100	1993/1998		< 3%	< 3%	
Germany (ILB)	ILB	1.0 - 120		± 10 lux	< 3 %	< 0.4 %	< 1 %
Germany (TUB)	LMT	0.1 - 100	1996	± 0.6 %	< 3%	< 2%	
Norway (NTNU)	PRC Krochmann	50 - 200 2 - 100	1996	0.5 %	< 2%	< 1%	< 0.1 %
Switzerland (LESO)	BEHA	1.0 - 100	1996	2.5 %			2 %
	L.M.T.	1.0 - 100		3 %	3 %	2 %	
United Kingdom (BRE)	Megatron	0.01- 7.5/50 (depends on sensor position)	12 month interval	3 %	0.5%	3%	1%
USA (LBNL)	Li-Cor	0.0 - 150	1995	1%	-	1%	-

Description of Data Acquisition System

Institute	Manufacturer	Type	No. of differential analogue input channels	A/D converter resolution (in bits	Data acquisition software
Australia (QUT)	Pico Log	PC Board	8	16	Pico Log
Austria (BAL)	LMT, Keithley	Scanner + Photometer	20	16	BLL
Denmark (SBI)	Keithley SmartLink KNM - DVC 32	Datalogger	80	20	SBI
Germany (ILB)	ILB	PC Board	16	14	ILB
Germany (TUB)	Delfin Instr. / Keithley	PC Board	20	21	TUB
Norway (NTNU)	National Instruments	PC Board	16	12	LabView
Switzerland (LESO)	Campbell	Datalogger	32	12	PC 208 W
UK (BRE)	Keithley	PC Board	32	-	Cambridge consultants
USA (LBNL)	Campbell Scientific (CR10) and LabView	Datalogger/PC Board	25 (+3)	12	LabView National Instruments

8.5. Monitoring Procedures

IEA Task 21 Monitoring Procedures for Assessing the Daylighting Performance of Buildings

Monitoring of daylighting systems and daylight-responsive lighting control systems was carried out in test rooms in Australia, Austria, Denmark, Finland, France, England, Germany, the Netherlands, Norway, Switzerland, and the United States. A Monitoring Protocol, including monitoring procedures, was formulated for these studies; this protocol focuses on quantifying the performance of the systems evaluated. This appendix summarises the information that can be found in the IEA SHC Task 21 document "Monitoring Protocol" (appended to the CD-ROM of this book).

8.5.1. Objectives of the Monitoring Procedures

The objective of the monitoring procedures is to establish a basis for evaluating a daylighting or lighting control strategy compared to a reference situation in occupied and unoccupied rooms under real sky conditions. These procedures describe the parameters to be considered, and give guidance for measurements as well as procedures for user assessment. Different levels of monitoring are included. The monitoring level selected depends on the capacities of a test situation, i.e., available measurement equipment, and the daylighting system or control strategy to be tested. The Monitoring Protocol also includes recommendations for documentation of testing procedures and evaluation of the system's performance compared to a reference situation. This protocol can be used for studies in standard offices with only vertical window(s) and horizontal work planes.

8.5.2. Approach

Daylighting systems are used to redirect incoming sunlight or skylight to areas where it is required. Therefore, these systems need to be evaluated for their ability to control daylight levels and to redirect sunlight and skylight into the perimeter zone of a building under overcast and clear sky situations. Because a traditional window will often provide non-uniform daylight distribution, daylighting systems should also be evaluated for their ability to reduce the large variations in the daylight levels within a room.

Daylight-responsive artificial lighting control systems are generally designed to maintain an illuminance level set in the tuning procedure. By supplementing daylight when it is insufficient, these systems save energy. Therefore, illuminance levels on the work plane and lighting energy consumption both need to be monitored.

The overall performance of a daylighting or control system is determined by the capability of the system to meet the requirements mentioned above while maintaining visual quality in a room. Therefore, visual comfort and other related parameters are included in the monitoring procedures to assess user acceptance of the room illumination and the installed system(s). A system's capability is assessed by comparing a room where the system is installed to an identical reference room without the system, under the same sky conditions. Daylighting conditions in the two rooms and exterior conditions are monitored simultaneously.

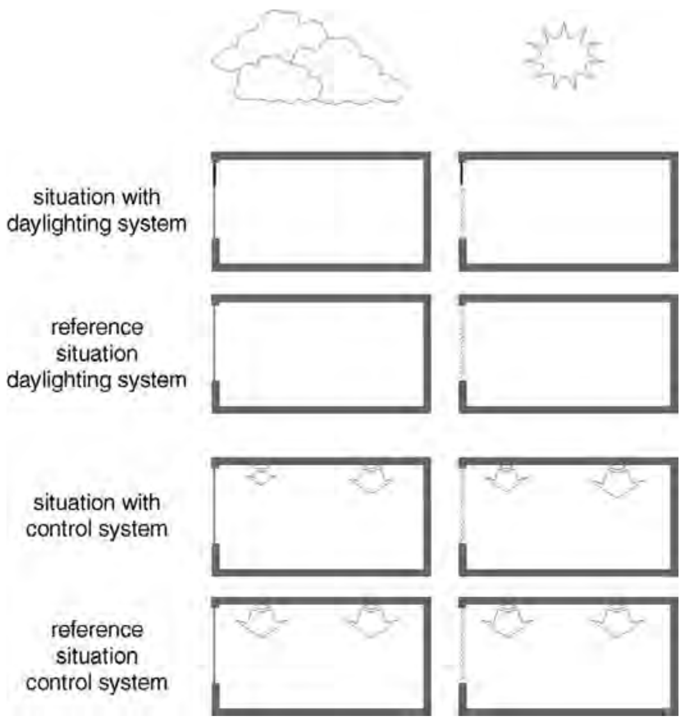


Figure 8-5.1:
Basic assumptions for reference situation

The reference room for testing a daylighting system under overcast skies has a double pane of clear glazing. For clear sky measurements, a shading system that is typical for the region should be included, e.g., downward-tilted venetian blinds. No artificial lighting is used.

The reference room for testing a daylight-responsive artificial lighting control system is equipped with existing luminaires that do not have the control system.

8.5.3. Monitoring Procedures

The monitoring procedures have four phases:

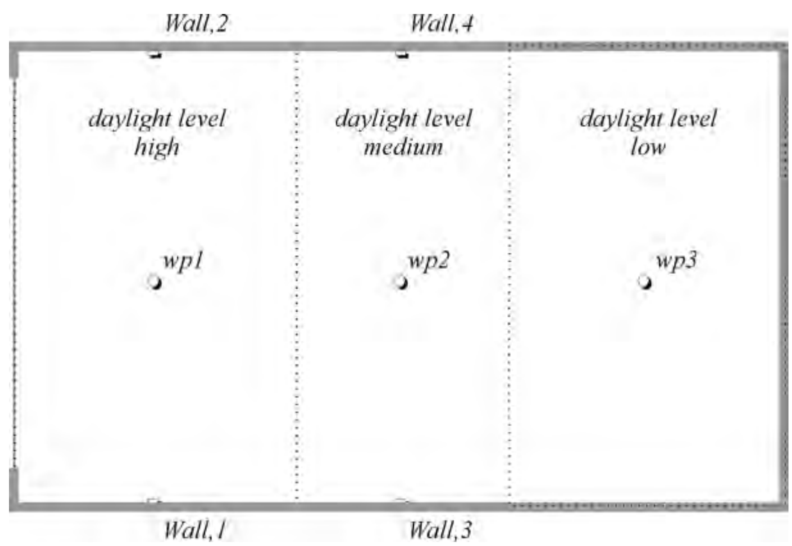
- A decision phase, in which choices are made regarding testing and the types of measurements to be carried out;
- A preparatory phase, in which the unchangeable conditions of the test rooms and monitoring equipment to be used are recorded in a descriptive document;
- A monitoring programme, which includes procedures for systematically verifying conditions and sensors; and

- A conclusion phase, in which the performance of the daylighting systems or daylight-responsive artificial lighting control system is determined based on the test results.

Minimum Measurements

Exterior measurements that will provide the minimum basis for evaluating a selected daylighting system include the horizontal global illuminance and the vertical sky illuminance. Interior work plane measurements should include those which enable one to check the system's ability to increase daylight penetration, provide "uniform" illuminance distribution, or maintain a certain illuminance level in the room (see, for example Figure 8-5.2). The height of the horizontal work plane should be consistent with the standard in the country where testing is performed (0.70–0.85 m above floor level).

Figure 8-5.2: Sensor position for monitoring a control system



The location of sensors depends on the number of sensors available and the monitoring level (minimal or with additional requirements). For monitoring a daylighting system, the locations will also depend on the daylighting system used. When a daylight-responsive artificial lighting control system is used, sensor locations depend on window size and transmittance.

Visual Comfort and User Acceptance

At a minimum, evaluation of visual comfort and user acceptance in a test room situation consists of observations in the occupied and unoccupied rooms. It includes the detection of sun patches areas with high luminance and glare.

For a more extensive evaluation of visual comfort and user acceptance, a standard questionnaire has been developed (see CD-ROM for more detailed monitoring procedures). When daylighting systems are tested, the questionnaire should include questions on glare (direct and indirect), illuminance distribution, illuminance levels at the work plane, and questions concerning satisfaction and acceptance of the system. When control systems are tested, the questionnaire should include questions on illuminance distribution, maintained illuminance level on the work plane, and questions related to the system.

Duration of Monitoring in Unoccupied Test Rooms

The time period for a minimum evaluation of a daylighting system or a control system is: One day under overcast sky conditions and three days (winter and summer solstices and equinox) when the sky is clear.

For overcast sky with ideal CIE sky luminance distribution, one measurement may be sufficient. However, it is recommended that a full day of measurements be carried out.

Measurements under clear sky conditions should be taken within eight weeks around the winter and summer solstices and the equinox.

Long-term monitoring is preferable for daylight-responsive artificial lighting control systems, to establish realistic energy saving potentials.

Additional Measurements For a More Detailed Evaluation

Additional measurements are suggested to monitor system-specific characteristics. Many daylighting systems are used to redirect daylight. Luminance and illuminance measurements on walls and ceiling can be used to monitor this ability. Monitoring can also include supplementary measurements to evaluate a daylighting system's capability to reduce discomfort glare.

Analysis of the Results

The performance of a daylighting system should be presented in comparison to the reference situation. Advantages and disadvantages can be assessed by comparison of absolute illuminance levels, daylight factors, and daylight distribution. Overall performance of a system should include assessment of user acceptance of the system.

The performance of daylight-responsive artificial lighting control systems can be expressed in terms of their capability to control artificial light in response to available daylight, to maintain the design illuminance level, and to reduce energy consumption. In addition, monitoring results should show duration, frequency, and magnitude of insufficient light levels. The overall performance of these systems should include an evaluation of user acceptance.

8.5.4. Conclusion

Until now, no standard monitoring procedures have been available for assessing and comparing performances of daylighting systems and daylight-responsive lighting control systems. The lack of monitoring protocols has been rectified by this documentation of the performance assessment of selected systems using standard monitoring methods in test rooms under real sky conditions.

The emphasis in the monitoring procedures used in the evaluation of daylighting and daylight-responsive control systems in IEA SHC Task 21 was on effective daylight utilisation, electrical energy savings, and user acceptance. These monitoring procedures have been proven to be effective; therefore they are a valuable method for future evaluations to determine system performance. The complete monitoring procedures are included in the CD-ROM appended to this book.

Prismatic Elements

3M (Scotch Optical Lighting Film)
3M Center Bldg. 225-2N06
St. Paul, MN 55144-1000
United States
Tel. +1 (612) 733-1898
Fax +1 (612) 736-3893
Prismatic film, light pipes,
mirror film

Siteco (formerly Siemens)
Beleuchtungsstarke GmbH
Ohmstrasse 50
83301 Traunreut
Germany
Tel. +49 8669 331
Fax +49 8669 33684
Prismatic glazing, mirrored
louvers, eggcrate microlouver,
reflective ceilings

Yazaki Co. Ltd.
1370 Koyasu-cho
Hamamatsu-shi
Shizuoka 435
Japan
Tel. +81 534-61-7111
Prismatic glazing

Bartenbach Lichtlabor
Rinner Str. 14
6071 Aldrans/Innsbruck
Austria
Tel. +43 512 386810
Fax +43 512 378048
Prismatic panels, louver and
blinds, light shelves

Redbus Serraglaze
3 The Quadrant
Coventry CV1 2DY
United Kingdom
Tel. +44 1203 243621
Fax +44 1203 243622
Stacked reflector/refractor
array prismatic sheet

Holographic Optical Elements

Institut fur Licht-und Bautechnik an der Fachhochschule Köln
Gremberger Straße 151a
50679 Köln
Germany
Tel. +49 221 831096
Fax +49 221 835513
Holographic glazing, transparent shading systems, light-guiding glass

Advanced Environmental Research Group
3681 S Lagoon View Drive
Greenbank, WA 98253
United States
Tel. +1 (206) 678 5439
Fax +1 (206) 678 5439
Holographic glazing

Autotype Limited
Grove Road
Wantage Oxfordshire
OX12 9BZ
United Kingdom
Tel. +44 1235 767777
Fax +44 1235 771196
Holographic glazing

Seele GmbH & Co KG
Gutenbergstraße 19
86368 Gersthofen
Germany
Tel. +49 821 2494 0
Fax +49 821 2494 100
Transparent shading

Louvers and Blinds

Altasol Ltd.
18 Gilmour Street
Burwood, Victoria 3125
Australia
Reflective louvres

Okalux Kapillarglas GmbH
Am Jöspershecklein
97828 Marktheidenfeld-Altfeld
Germany
Tel. +49 93 91 10 41
Fax +49 93 91 68 14

Colt International Limited
New Lane
Havant, Hampshire PO9 2LY
United Kingdom
Tel. +44 1705 451111
Fax +44 1705 454220
Moveable louvers

Hallmark Blinds Ltd
173 Caledonian Road
Barnsbury
London N1 0SL
United Kingdom
Tel +44 207 837 0964/8181
Fax +44 207 833 1693

SEA Corporation
2010 Fortune Drive, Suite 102
San Jose, CA 95131,
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Fax +1 (408) 954-1254

Synertech Systems Corporation
472 South Salina St. Suite 800
Syracuse, NY 13202
United States
Tel. +1 (315) 422-3828
Daylight microlouvers

Hunter Douglas Limited
Mersey Industrial Estate
Heaton Mersey, Stockport
Cheshire SK4 3EQ
United Kingdom
Tel. +44 161 432 5303
Fax +44 161 431 5087
Reflective blinds

Huppe Form GmbH
Sonnenschutz und Raumsysteme
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Germany
Tel. +49 441 402282
Fax +49 441 402 454
Reflective blinds

WAREMA Renkhoff GmbH
Vorderbergstraße 30
97828 Marktheidenfeld
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Tel. +49 9391 20600
Fax +49 9391 20279

Glas Schuler GmbH & Co.KG
Ziegelstraße 23-25
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Dasolas Internat. Productions
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Rosenheimer Glastechnik GmbH
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Brüder Eckelt + Co
Glastechnikgesellschaft mbH
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Heliostats

Bomin Solar
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79541 Lörrach
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Fax +49 7621 54368
Heliostats, mirrors, prisms, lenses

Alternate Energy Institute
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San Diego, CA 92108
United States
Tel. +1 (619) 692-2015
Heliostats

La Forêt Engineering & Information Service Co. Ltd.,
Himawari Building,
Toranomon 2-7-8
Minato-ku, Tokyo 105, Japan
Tel. +81 3 3593 0091
Fax +81 3 3593 0095
Himawari (heliostat and fibre optic)

Solartech
A. Kuzelka
Heugasse 8/1
2344 Maria Enzersdorf
Austria
Tel. 0664 481 14 12
Double mirror heliostat

Sumitomo Corporation
444 South Flower St.
Los Angeles, CA 90071-2975
United States
Tel. +1 (213) 489-0371
Fax +1 (213) 489-0300
Himawari (heliostats and fibre optics)

Zentrum für Sonnenenergie- und Wasserstofforschung
Hessbruhlstrase 2lc
70565 Stuttgart
Germany
Tel. +49 (711) 7870 222
Thermohydraulic heliostat

EGIS GmbH
Flutstr. 34-36
63071 Offenbach/Main
Germany
Tel. +49 (69) 85 83 27
Fax +49 (69) 85 78 63

Schlaich Bergermann & Partner
Stuttgart
Germany
Tel. +49 711 64 87 10

Light Pipes

The Sun Pipe Company
PO Box 2223
Northbrook, IL 60065
United States
Tel. +1 (800) 8444786
Fax +1 (708) 272 6972
Light pipes

Solartube Ltd.
5825 Avenida Enchinas, Suite 101
Carlsbad, CA 92008
United States
Tel. +1 (619) 929 6060
Light pipes

Monodraught Limited
6 Lancaster Court
Cressex Business Park
High Wycombe, Bucks HP12 3TD
United Kingdom
Tel. +44 1494 464858
Fax +44 1494 532465
Light pipes

Sanyo Electric Co. Ltd.
Air Conditioning and Refrigeration
Development Center
180 Sakata Oizumi-machi, Ora-gun
Gunma, Japan
Tel. +81 (276) 618122
Fax +81 (276) 618802
Double prism heliostats, light pipes

Skydome Ltd.
Unit 21
Springtown Industrial Estate
Springtown, Londonderry BT 46 OLY
United Kingdom
Tel. +44 1504 370270
Fax +44 1504 373411
Corrugated light pipe systems

LTI Lichttechnik
Heiko Schnetz GmbH
Konrad-Adenauer-Str. 25
50996 Köln
Germany
Tel. +49 221 35099 70
Fax +49 221 35099 71

LGM & Associates
PO Box 2613
Northbrook, IL 60062
United States
Tel. +1 (708) 272-6977
Light pipes

Laser-Cut Panels

Department of Physics
(Dr I Edmonds, Dr I Cowling)
Queensland University of Technology
GPO Box 2434
Brisbane Q 4001
Australia
Tel. +61 7 864 2329
Fax +61 7 864 1521
Laser-cut light deflecting sheets, stacked
curved daylight deflecting prisms

INGLAS - Innovative
Glassysteme GmbH & Co. KG
Im Winkel 4/1
88048 Friedrichshafen
Germany
Tel. +49 7544 6547 - 23
Special glazings

Skydome Skylight Systems Ltd
39 Antimony Street
Carole Park QLD 4300
PO Box 154 Goodna QLD 43400
Australia
Tel. 61 7 3271 3200
Fax 61 7 3271 4481
Angular selective skylights

Synergetics Inc.
122 Cox Avenue
Raleigh, NC 27605
United States
Tel. +1 (919) 832 4011
Variable area light
reflecting assembly

Anidolic Systems

Solar Energy and
Building Physics
Laboratory (LESO-PB)
Swiss Federal
Institute of Technology
in Lausanne (EPFL)
1015 Lausanne
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Tel. +41 21 693 45 45
Fax +41 21 693 27 22
Anidolic systems

Felix Constructions SA
Route de Renens 1
1030 Bussigny-Lausanne
Switzerland
Tel. +41 21 701 0441
Fax +41 21 701 31 68
Facade integrated
Anidolic systems

Summary: Appendices on the CD-ROM

This book entitled "Daylight in Buildings: A Source Book on Daylighting Systems and Components" is duplicated in entirety within the directory "Source Book" on the CD-ROM attached to the back of this book.

Additional appendices that supplement this book, but could not be included in the printed version of this book, are included in additional folders on the CD-ROM. This additional content includes the following reports which are explained in brief below:

8.3. Optical Characteristics of Daylighting Materials (Complete)
Performance Data

8.5. Monitoring Procedures for the Assessment of Daylighting Performance of Buildings (Complete)
Scale Model Daylighting Systems Evaluation
Scale Model Validation Data

8.7. Survey of Architectural Daylight Solutions

8.8. Applications Guide for Daylight Responsive Lighting Control Systems Summary

8.9. Results of Subtask C: Daylighting Design Tools
Survey: Simple Design Tools
Daylight Simulation: Methods, Algorithms, and Resources
ADELINE 3.0 Software Description
LESO DIAL Software description

8.10. Daylight in Building: 15 Case Studies from Around the World Summary
Example Case Study: Bayer Nordic Headquarters, Lyngby, Denmark
Daylighting Monitoring Protocols and Procedures for Building

8.3. Optical Characteristics of Daylighting Materials

The directory "8.3 Report" contains a more complete explanatory version of the source book's Appendix 8.3 on the optical characteristics of daylighting materials. Three-dimensional graphical depictions of the bi-directional properties of these optically-complex materials are also included.

The directory "8.3 Performance Data" contains raw and graphed optical data for various daylighting materials. The format of these data are explained in Appendix 8.3 of the source book and in the more complete report above.

8.5. Monitoring Procedures

Within the directory “8.5 Monitoring Procedures”, the file “8.5.1 Monitoring Procedures” contains a more complete version of the source book’s Appendix 8.5, which explains the procedures used to evaluate daylighting systems in full-scale test rooms and buildings.

The file “8.5.2 Scale Model Evaluation” explains the protocols for evaluating daylighting systems using scale models under an artificial sky. An example of these measurements is given in the file “8.5.3 Scale Model Validation Data”.

8.7. Survey of Architectural Daylight Solutions

This survey presents and reviews daylighting strategies of 25 commercial and institutional buildings located around the world in a variety of climates. Each two-page survey, rich with drawings and photographs, is linked from the introduction page, allowing the reader to easily navigate throughout the document. This survey is included in completion on the CD-ROM.

8.8. Application Guide for Daylight Responsive Lighting Control Systems

This summary explains the content and intent of the IEA Task 21 Subtask B product entitled: Application Guide for Daylight Responsive Lighting Control Systems. The application guide consists of two parts. The first part addresses general design considerations involving electric lighting and shading controls, installation procedures, and the prediction of energy savings and costs. The second part consists of the monitoring procedures used and the results of performance evaluations of lighting controls installed in test rooms. Information on how to obtain a copy of this book can be found on the IEA SHC Web site: http://www.iea-shc.org/task21/.

8.9. Daylighting Design Tools

This directory contains many of the final reports of the IEA Task 21 Subtask C. The objective of Subtask C: Daylighting Design Tools is to improve the capability, accuracy, and ease-of-use of daylighting design and analysis tools for building design practitioners covering all phases of the design process. The practitioners will be able to predict the performance of different daylighting systems and control strategies and to evaluate the impact of the integration of daylighting in the overall building energy concept by using these design tools. The following reports are included:

8.10. Monitored Case Studies

This directory contains a summary of the main IEA Task 21 Subtask D product: a book entitled Daylight in Building: 15 Case Studies from Around the World. Information on how to obtain a copy of this book can be found on the IEA SHC Web site: http://www.iea-shc.org/task21/.

While the "Survey of Architectural Solutions" given in Appendix 8.7 describes daylighting strategies, 14 selected case study buildings and one design case study have been monitored and evaluated in detail in this book. An example of a case study is included on the CD-ROM: "8.10.2 Example Case Study: Bayer Nordic Headquarters, Lyngby, Denmark".

The monitoring campaign in all 14 buildings was based on common monitoring procedures. These procedures are described in the report: "8.10.3 Daylighting Monitoring Protocols and Procedures for Buildings" which is also included on the CD-ROM. In five buildings, post occupancy evaluations have also been performed.