International Energy Agency
Energy Conservation in Buildings and Community Systems Programme

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Project Summary Report

Daylight in Buildings

Energy Conservation in Buildings & Community Systems
& Solar Heating and Cooling Programmes

ECBCS Annex 29 / SHC Task 21

Daylight in Buildings

ECBCS Annex 29 / SHC Task 21 Project Summary Report

Edited by Kjeld Johnsen and Richard Watkins

Based on the publications:
Daylight in Buildings: A Sourcebook on Daylighting Systems and Components
Survey of Architectural Daylight Solutions
Application Guide for Daylight Responsive Control Systems
Daylight simulation: Methods, algorithms, and resources
Daylight design tools
Daylight in Buildings: 15 Case Studies

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Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the twenty-eight IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D). The IEA co-ordinates research and development in a number of areas related to energy.

Energy Conservation in Buildings and Community Systems Programme

The mission of the IEA Energy Conservation for Building and Community Systems Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research.

The research and development strategies of the ECBCS Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Building Forum Think Tank Workshop, held in March 2007. The R&D strategies represent a collective input of the Executive Committee members to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy conservation technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in three focus areas of R&D activities:

- Dissemination
- Decision-making
- Building products and systems

Overall control of the program is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date the following projects have been initiated by the executive committee on Energy Conservation in Buildings and Community Systems (completed projects are identified by (*)):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)

Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HEVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings
Annex 45: Energy Efficient Electric Lighting for Buildings
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings
Annex 48: Heat Pumping and Reversible Air Conditioning
Annex 49: Low Exergy Systems for High Performance Buildings and Communities
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings
Annex 51: Energy Efficient Communities
Annex 52: Towards Net Zero Energy Solar Buildings
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods
Annex 54: Analysis of Micro-Generation & Related Energy Technologies in Buildings
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO)

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - Energy Efficient Communities

(*) – Completed

Solar Heating and Cooling Programme

The IEA Solar Heating and Cooling Programme was one of the first IEA Implementing Agreements to be established. Since 1977, its members have been collaborating to advance active solar and passive solar technologies and their application in buildings and other areas, such as agriculture and industry.

A total of 44 Tasks have been initiated, 35 of which have been completed. Each Task is managed by an Operating Agent from one of the participating countries. Overall control of the program rests with an Executive Committee comprised of one representative from each contracting party to the Implementing Agreement. In addition to the Task work, a number of special activities—Memorandum of Understanding with solar thermal trade organizations, statistics collection and analysis, conferences and workshops—have been undertaken. The Tasks of the IEA Solar Heating and Cooling Programme, both underway and completed are as follows:

Current Tasks:

Task 36:	Solar Resource Knowledge Management
Task 37:	Advanced Housing Renovation with Solar & Conservation
Task 38:	Solar Assisted Cooling Systems
Task 39:	Polymeric Materials for Solar Thermal Applications
Task 40:	Towards Net Zero Energy Solar Buildings
Task 41:	Solar Energy and Architecture
Task 42:	Compact Thermal Energy Storage
Task 43:	Solar Rating & Certification Procedure
Task 44:	Solar and Heat Pump Systems

Completed Tasks:

Task 1:	Investigation of the Performance of Solar Heating and Cooling Systems
Task 2:	Coordination of Solar Heating and Cooling R&D
Task 3:	Performance Testing of Solar Collectors
Task 4:	Development of an Insolation Handbook and Instrument Package
Task 5:	Use of Existing Meteorological Information for Solar Energy Application
Task 6:	Performance of Solar Systems Using Evacuated Collectors
Task 7:	Central Solar Heating Plants with Seasonal Storage
Task 8:	Passive and Hybrid Solar Low Energy Buildings
Task 9:	Solar Radiation and Pyranometry Studies
Task 10:	Solar Materials R&D
Task 11:	Passive and Hybrid Solar Commercial Buildings
Task 12:	Building Energy Analysis and Design Tools for Solar Applications
Task 13:	Advance Solar Low Energy Buildings
Task 14:	Advance Active Solar Energy Systems
Task 16:	Photovoltaics in Buildings
Task 17:	Measuring and Modeling Spectral Radiation
Task 18:	Advanced Glazing and Associated Materials for Solar and Building Applications
Task 19:	Solar Air Systems
Task 20:	Solar Energy in Building Renovation
Task 21:	Daylight in Buildings
Task 23:	Optimization of Solar Energy Use in Large Buildings
Task 22:	Building Energy Analysis Tools
Task 24:	Solar Procurement
Task 25:	Solar Assisted Air Conditioning of Buildings
Task 26:	Solar Combisystems
Task 28:	Solar Sustainable Housing
Task 27:	Performance of Solar Facade Components
Task 29:	Solar Crop Drying
Task 31:	Daylighting Buildings in the 21st Century
Task 32:	Advanced Storage Concepts for Solar and Low Energy Buildings
Task 33:	Solar Heat for Industrial Processes
Task 34:	Testing and Validation of Building Energy Simulation Tools
Task 35:	PV/Thermal Solar Systems

Completed Working Groups:
CSHPSS, ISOLDE, Materials in Solar Thermal Collectors, and the Evaluation of Task 13 Houses

Contents

1. Introduction

Daylight is an essential resource that is readily available – and unlikely to run out for theforeseeable future. It also has the very special characteristic of having the ability to transform an internal space from uninspiring uniformity into a psychologically uplifting experience. This ability to both illuminate an area and to make it more interesting, is one of the main reasons that architects try to make provision for daylight to come into a building wherever practical.

Daylight varies in intensity and quality from moment to moment and how much variation is desirable or can be tolerated will depend on the particular use of a space. Lighting requirements can be very strict for certain uses, e.g. in museums, but are more flexible in many applications. However, to provide good lighting there are three factors that should always be considered: the quantity, and quality of light, and its distribution. Intense sources of light (sunlight or electric light) can lead to severe glare which can be both irritating and debilitating for a user's task. It is for this reason that controlling the admission of sunlight into a space requires the careful design of openings in a building's fabric.

Providing and controlling daylight in buildings received special attention in a series of studies under the aegis of the International Energy Agency Solar Heating and Cooling (SHC Task 21) and Energy Conservation in Buildings and Community Systems (ECBCS Annex 29) Programmes. By admitting daylight into a building the potential is created to save energy in the daytime and this can be substantial. Designing for, and realizing this potential, whilst balancing the needs of building occupants were the main drivers for these studies, and the following sections summarize the findings from the SHC and ECBCS project.

Section 2 describes the many ways in which daylight and sunlight can be brought into a building and how well the different options perform.

Section 3 examines the ways of controlling daylight and electric light so that internal conditions are maintained within design limits, and energy use reduced.

Section 4 reviews the tools available to help incorporate daylight into building design and predict its performance.

Section 5 gives examples from case studies where both traditional and innovative daylight systems have been demonstrated and evaluated.

Each section is preceded by a link to relevant document(s) in the source reports.

2. Introducing Daylight into a Building

There are many texts that describe the basic principles of daylighting and here only a brief introduction is provided. More emphasis is placed on the aspects of design related to innovative lighting systems that redirect light.

2.1. Principles

Daylight needs to be considered at the outset of designing a building as daylighting strategies and architectural design strategies are inseparable. Daylight can not only replace artificial lighting, reducing lighting energy use, but also influence both heating and cooling loads. Planning for daylight therefore involves integrating the perspectives and requirements of various specialities and professionals.

Daylight strategies depend on the availability of natural light, which is determined by the latitude of the building's location and the conditions immediately surrounding the proposed building, e.g., the presence of obstructions. Daylighting strategies are also affected by climate and it is important to identify seasonal variations, prevailing climate conditions, particularly ambient temperatures, and sunshine probability. Knowing the climate, and the daylight availability at each façade of a proposed building, is an essential first step in the designing for daylight.

High latitudes have distinct summer and winter conditions and in winter when daylight levels are low, designers usually aim to maximize daylight penetration in a building. **Redirecting 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 daylight** entering a building. This can be achieved by obstructing large parts of the sky, especially areas near the zenith, and admitting daylight only from lower parts of the sky, or, indirectly, by using light reflected from the ground.

2.2. Strategies for Different Light Conditions

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

2.2.1. <u>Skylight</u>

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 facades facing the North/South pole (in the northern/southern hemisphere respectively). 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. Thus, systems that provide solar shading sufficient to prevent overheating my not be adequate for glare control.

2.2.2. <u>Cloudy Skies</u>

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. Systems that provide sun shading and glare protection are therefore 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. 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.

2.2.3. 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.

2.2.4. 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. Apertures designed for beam daylighting do not usually provide a view to the outside and should therefore be combined with other view openings. Because beam daylighting requires only small apertures, it can be applied as an added strategy in an approach that otherwise focuses on cloudy skies.

2.3. Daylighting Systems Overview

A daylighting system combines simple glazing with some other element that enhances the delivery or control of light into a space. Whilst ordinary windows deal adequately with some of the daylight needs of a space, there are new technologies and solutions that extend performance beyond that of the conventional solutions:

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

These work by introducing reflective or refractive components into the glazing system. In addition, they may or may not combine this with shading the interior from sunlight or daylight to reduce glare or solar gain.

2.3.1. Daylighting Systems With Shading

Two types of daylighting systems with shading have been reviewed: 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.

Conventional solar shading systems, such as pull-down shades, often significantly reduce 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.

2.3.2. 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 divided 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 (around three times) 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 fibre-optics or light pipes

Table 1 lists the different types of window systems, and shows which climate they are suitable for, and where they are normally placed in a building. It also gives information on:

- their ability to protect against glare
- if they allow a view to outside
- can guide light into the depth of a room
- can provide homogeneous illumination
- can save energy use by artificial lighting
- whether they need tracking, i.e. to move with the sun's position
- and their availability

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

Table 1(i): Types of daylighting systems: with shading (1A &1B) and without (2A-2D)
(abbreviations in table: Y=yes, D=depends, N=no, A=available, T=testing phase)

1. Shading Systems

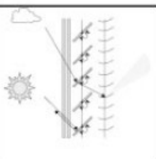
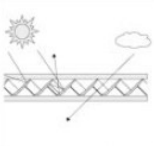
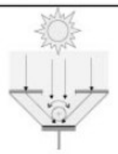
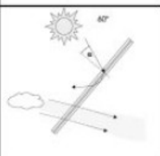
Category	Type/name	Sketch	Climate	Location	Criteria for the choice of elements						
					Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving potential (artificial lighting)	Need for tracking	Availability
1A Primary using diffuse skylight	Prismatic panels		All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

Table 1(ii): Types of daylighting systems: with shading (1A &1B) and without (2A-2D) (abbreviations in table: Y=yes, D=depends, N=no, A=available, T=testing phase)

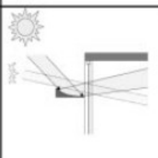
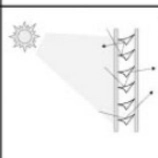
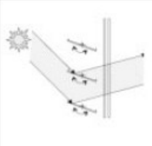
1. Shading Systems											
Category	Type/name		Climate	Location	Criteria for the choice of elements						
					Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving of energy for artificial lighting	Need for tracking	Availability
1B Primary using direct sunlight	Light guiding shade		Hot climates, sunny skies	Vertical windows above eye height	**Y**	**Y**	**D**	**D**	**D**	**N**	**T**
	Louvres and blinds		All climates	Vertical windows	**Y**	**D**	**Y**	**Y**	**Y**	**Y**	**A**
	Light shelf for redirection of sunlight		All climates	Vertical windows	**D**	**Y**	**Y**	**Y**	**Y**	**N**	**A**
	Glazing with reflecting profiles		Temperate climates	Vertical windows, skylights	**D**	**D**	**D**	**D**	**D**	**N**	**A**
	Skylight with Laser Cut Panels (LCPs)		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		All climates	Vertical Windows	**Y**	**D**	**Y**	**Y**	**D**	**N**	**T**

Table 1(iii). Types of daylighting systems: with shading (1A &1B) and without (2A-2D)
(abbreviations in table: Y=yes, D=depends, N=no, A=available, T=testing phase

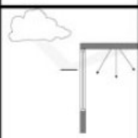
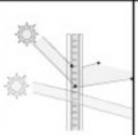
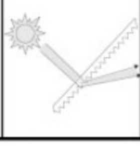
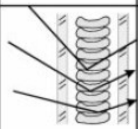
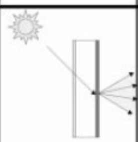
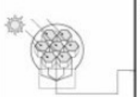
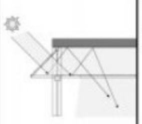
2. Daylighting systems without shading included											
Category	Type/name	Sketch	Climate	Location	Criteria for the choice of elements						
					Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving of energy for artificial lighting	Need for tracking	Availability
2A Diffuse light guiding systems	Light shelf		Temperate climates, cloudy skies	Vertical windows	**D**	**Y**	**D**	**D**	**D**	**N**	**A**
	Anidolic Integrated System		Temperate climates	Vertical windows	**N**	**Y**	**Y**	**Y**	**Y**	**N**	**A**
	Anidolic ceiling		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		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		All climates	Vertical windows, skylights	**N**	**Y**	**Y**	**Y**	**Y**	**N**	**T**
	Prismatic panels		All climates	Vertical windows, skylights	**D**	**D**	**D**	**D**	**D**	**Y/N**	**A**

Table 1(iv). Types of daylighting systems: with shading (1A &1B) and without (2A-2D)
(abbreviations in table: Y=yes, D=depends, N=no, A=available, T=testing phase)

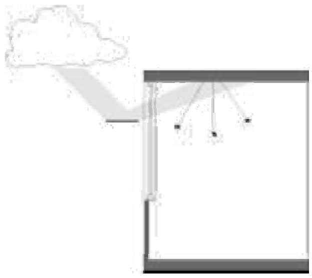
2. Daylighting systems without shading included

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		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
	Light-guiding ceiling		Temperate climates, sunny skies				Y	Y	Y	N	T

2.4. Daylighting System Details

There is a wide choice of daylighting systems and often many alternatives within each choice. The main characteristics of each system are described in the following sections.

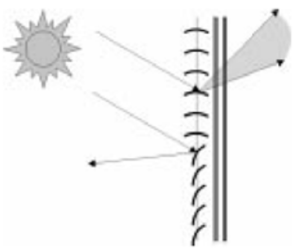
2.4.1. Light Shelves



A light shelf is a classic daylighting system, known to the Egyptian Pharaohs, which is designed to shade and reflect light on its top surface and to shield direct glare from the sky. It is mounted approximately horizontally either inside or outside a window (or both) and usually above eye height, dividing a window into a lower part with a view, and an upper clerestory above. The lower the height of a light shelf, the greater is the light reflected onto a ceiling, but also the incidence of glare is likely to increase.

Light shelves inside a window decrease the total light in a room, but distribute it more evenly. External light shelves can increase the total light because they can increase the proportion of light that comes from high angles in the sky, where the sky luminance is greater. Light shelves can be fixed or pivoted (and may track the sun) and may have a specular or matt finish.

2.4.2. Louvres and Blind Systems

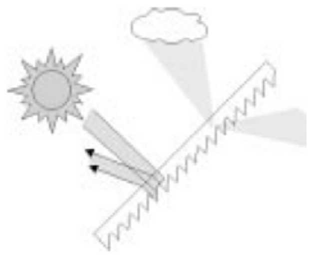


Louvres and blinds are traditional daylighting systems that can be applied for solar shading, to protect against glare and to redirect daylight. They are located on the exterior or interior of a window, or between the panes of glass.

Depending on the slat angle, louvres and blinds partly or completely obstruct directional view to the outside. 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 upwards increases glare as well as visibility of the sky; tilting the blinds downwards provides shading and reduces glare problems. Choosing matt rather than glossy slat finishes can reduce this problem. Both louvres and blinds can increase the penetration of daylight from direct sunlight, and when skies are overcast, louvres and blinds promote an even distribution of daylight. Louvres and blinds can be fixed or pivoted (and may track the sun) and have a specular, matt finish, or be translucent.

Some more advanced designs of blinds are designed specifically to redirect light to the ceiling using concave louvres with a specular upper surface. Silvered blinds can normally be used only in a daylight window above eye height, to avoid potential glare.

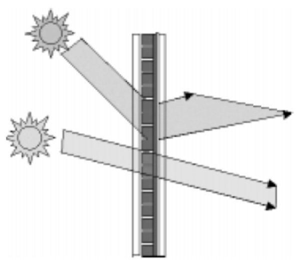
2.4.3. Prismatic Panels



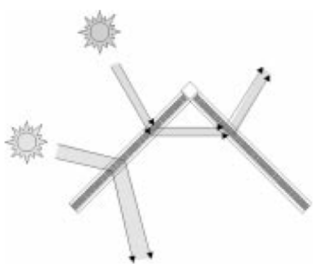
Prismatic panels are thin, planar, sawtooth devices made of clear acrylic that are used in temperate climates to redirect or refract daylight. When used as a shading system, they refract direct sunlight but transmit diffuse skylight. They can be applied in many different ways, in fixed or sun-tracking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

If used for redirecting sunlight, prismatic panel designs may redirect some sunlight downwards, causing glare. However with a correct profile and seasonal tilting, these downward beams can be avoided.

2.4.4. Laser-Cut Panels



A laser-cut panel is a daylight-redirecting system produced by making laser cuts in a thin panel made of clear acrylic material. The laser-cutting divides the panel into an array of rectangular elements. Each cut surface then becomes a small internal mirror that deflects light passing through the panel. An advantage of the panel is that in between the cuts, a view to outside of the window is maintained, although this is somewhat distorted.

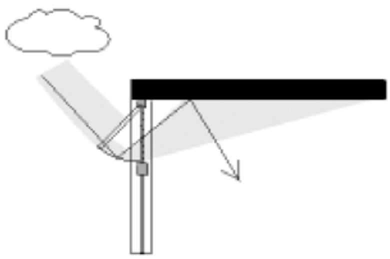


2.4.5. Angular Selective Skylight (Laser-Cut Panel)

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

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 a building on summer days. The 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.

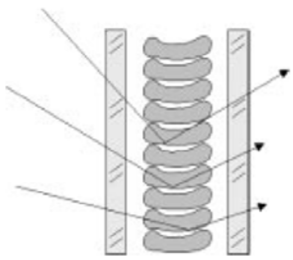
2.4.6. Light-Guiding Shades



Light-guiding shades are external shading systems that redirect sunlight and skylight onto the ceiling. They are designed to improve the daylighting of rooms in subtropical buildings that have often have deep external shading from wide eaves to reduce radiant heat gain through windows. They are more complicated and more precisely defined than conventional shades and highly reflective material must be used for their inner surfaces.

The shading system 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 (usually 0-60°). The light-guiding shade is fixed in the same way as an external shade over a window, shading the window from direct sunlight as a normal shade does. Compared to shading from an opaque overhang, the light-guiding shade much improves the illuminance and its uniformity in the room interior.

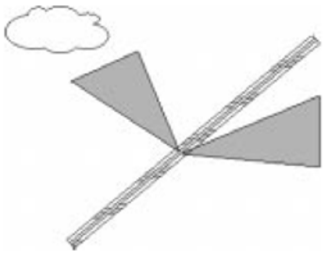
2.4.7. Sun-Directing Glass



The main component of a sun-directing glass system is a double-glazed sealed unit that holds concave acrylic elements. These elements are stacked vertically within a double-glazed unit and redirect direct sunlight from all angles of incidence onto the ceiling. The sealed unit is normally placed above the view window. 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.

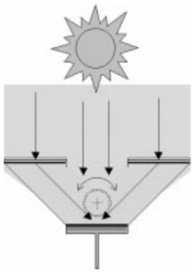
The system is designed for use in direct sunlight. The best orientation on a façade is south in moderate climate zones (in the northern hemisphere). On west or east facades, it is useful only in the morning or afternoon. The system also deflects diffuse light, but the illuminance level achieved is much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

2.4.8. Zenithal Light-Guiding Glass with Holographic Optical Elements



Zenithal light-guiding glass redirects diffuse skylight into the depth of a room. The main component 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 façades that do not receive direct sunlight.

The glass can be integrated in a vertical window system or attached to the façade in front of the upper part of a 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 a window.

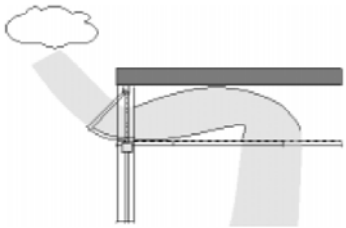


2.4.9. Directional Selective Shading Systems using Holographic Optical Elements

Directional selective shading systems reject incident light from a small angular area of the sky vault. They can therefore 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.

In this system, holographic diffraction gratings are embedded in a glass laminate and the optically selected direct radiation can either be directed out again (rejected) or directed to a secondary area (for conversion to electricity or thermal energy). In either case, the whole shading assembly has to track the sun’s path (on a single axis) to achieve optimal shading. Normally the assembly would be attached in front of the main vertical glass façade or roof as a shading system. Internal mounting is possible if the solar gain can be adequately rejected, e.g. into the roof.

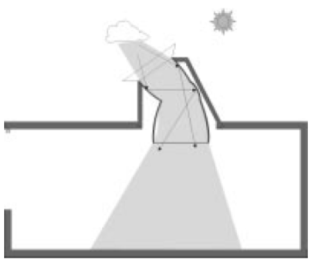
2.4.10. Anidolic Ceilings



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 and is designed for side lighting of non-residential buildings.

On the outside of a building, an anidolic (non-imaging) optical concentrator captures and concentrates diffuse light from the upper (brighter) area of an overcast sky, and efficiently introduces the rays into a light 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.

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.

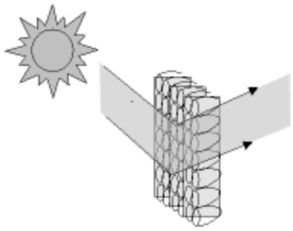


2.4.11. Anidolic Zenithal Openings

The anidolic zenithal opening is a daylighting system used to collect diffuse daylight from a large portion of the sky vault without allowing direct sun to penetrate. 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.

The roof collector is based on a linear, 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. A compound parabolic deconcentrator, similar to the compound parabolic concentrator but reversed, is placed at the emitting end of the opening to guide the daylight flux towards the bottom of the room.

2.4.12. 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 innovative feature of anidolic solar blinds compared to other anidolic systems (anidolic ceilings, anidolic zenithal openings) is their use of three-dimensional reflective elements 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.

The anidolic solar blind system can be applied either as a fixed louvre 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 the 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.

Anidolic blinds are a fixed system to control daylight and thermal gains in south-facing or other façades 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. Although the system is mainly designed to control daylight in sunny climates, it may be used under predominantly cloudy skies.

2.5. Performance

The different types of daylighting systems were tested using models, full-scale test rooms, in real buildings, or by computer simulation. From these tests, some conclusions can be made about the performance of the different systems in terms of their ability to block, or redirect daylight. When combined with a daylight responsive control system for electric lighting, energy savings can be made (See section 3).

2.5.1. Shading Systems Using Diffuse Light

Louvres

Fixed, mirrored louvres are designed principally for direct sun control. High altitude sun and skylight reflected off the louvres increase interior daylight levels. Daylight levels from low-altitude skies (i.e. from approximately 10° to 40° above the horizon) are reduced. Fixed, mirrored louvres 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.

2.5.2. Shading Systems Using Direct Sunlight

Light Shelves

Optically treated light shelves are an improvement over conventional internal light shelves, and 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.

2.5.3. 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 five metre 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.

2.5.4. Non-shading systems using Direct Sunlight

Laser-Cut Panel

Similar to the prismatic panel, the laser-cut panel increases light levels by 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.

3. Controlling Lighting in Response to Daylight

It is desirable to be able to control both the daylight entering a space and the electric lighting within it. In this way, the benefit of receiving daylight can be achieved whilst minimizing the electricity used for artificial lighting, and maintaining the illuminance within the required limits. Excess solar gain can be avoided and occupants remain comfortable. To achieve this level of control and for it to be successfully accepted by users are two of the main goals of good daylighting.

3.1. Controlling Daylight

The primary control of daylight should be made by the choice of window size and position. The daylight transmittance of the glazing then determines the maximum light that can be received in the room.

Manual control over the quantity and quality of daylight in the rooms can be provided either by simple, but widely-used diffusing curtains or venetian blinds, or by the more sophisticated light re-directing systems, as described in the previous section. The latter aim to optimize the quantity, and quality of the incident natural light, i.e. avoiding glare.

Automatic systems can perform a wide range of control actions. They can tilt or turn horizontal/vertical lamellae, lower or raise curtains, rotate sun-tracking systems, etc. However, many of these systems do not respond to the overall daylight availability, rather their actions may depend on the direct sunlight or solar position alone. Examples are shading controlled on the basis of direct sunlight, using a roof-based sensor measuring total radiation on a tilted surface; controls for tilting blinds based on astronomical data for solar position; and controls of heliostats based on solar position.

Daylight responsive daylight control systems consist of a sensor, measuring incident flux, and a control system acting according to the sensor’s signal. For all control systems, the best functioning ones are preferably unnoticeable to a room’s occupants.

3.2. Controlling Electric Lighting

In recent 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. 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 practice.

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.

With the advent of inexpensive handheld remote controls, occupant-controlled dimming is becoming an affordable option and has received a high occupant satisfaction rating. 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 between 23 and 44% savings, depending on the control technique used.

Energy savings from occupant sensing versus dimming depend to a large extent on the behaviour of occupants. 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.

3.3. Components of an Electric Lighting System

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 more appropriate.

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.

3.3.1. 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.

3.3.2. 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.

3.3.3. 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. 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.

3.3.4. Occupancy Sensors

Studies have shown that many workers are out of their offices 30% – 70% of the time during working hours. 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. There are systems that 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.

3.3.5. Types of Control Strategies

A control system may use a photosensor located so that it is able to detect **both** the electric light that the system controls and the available daylight (a "**closed loop**" system). 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.

3.3.6. 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 (see section 2.4.9), can be included in the daylighting system. In Section 2, daylighting systems are described as either shading systems (i.e., they are designed to provide both shading and daylighting) or as unshaded systems. For the latter, 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.

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.

3.3.7. 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. 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.

Satisfaction with lighting controls can increase if users can alter settings using a remote-control device. 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.

Occupancy-linked controls can switch off or dim lighting, reactivating them on a manual signal, and leaving the judgement of lighting adequacy to the user. 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.

A lighting control system is better accepted if it reacts in a predictable way, for example when the sun shines on the façade and the electric lighting level is dimmed. Changes in illuminance are mostly accepted when the control system reacts quickly when an action is needed, e.g. sudden dark clouds reducing the daylight, and slowly when the user should not notice, e.g. increasing daylight in the morning allowing electric lighting to be dimmed.

3.3.8. Electricity Savings

Energy savings from daylight design in buildings cannot be realized 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.

Some of the daylighting systems that have been tested, 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 also 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 louvres have proved 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.

Overall, daylight-responsive systems have used up to 40% less than non-controlled systems, and additional electricity is saved through cooling load reductions, especially in hot climates.

4. Using Tools to Design for Using Daylight

Design tools are intended to help designers with the qualitative and quantitative elements of daylighting design through features that commonly include:

- visualization 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 this range of information, design tools play a significant role in the decision-making process that characterizes 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 need to fit in with the main 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, is especially significant when advanced daylighting systems are considered.

This section gives an overview of the state of the art of daylighting design tools at the time of IEA Task 21 work. Special emphasis is placed on tools that address advanced daylighting systems.

4.1. Simple Tools

Decisions in the early stages of building design have a large impact on a building's daylight performance. It is at this stage that simple design tools are most useful. They 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. However, they 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. The daylight factor is the ratio, as a percentage, of the illuminance in a room from daylight to the illuminance from the whole sky on a horizontal plane outside. It is measured or calculated for overcast conditions, and there are recommended daylight factors (ranging from 1-5%) for different room types and requirements.

A new generation of "simple" computer tools embodies complex evaluation models, athough 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 reflectance, the size and the location of windows and skylights, and the proportions of the space and exterior obstructions. Table 2 gives the results of a survey of the simple design tools available to practitioners.

Table 2. Simple daylighting design tools
(each row of squares represents one daylighting tool)

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
1. Formulae (f(x))		■		■				
	■	■	■	■				
2. Tables	■		■					
		■		■				
3. Nomograms	■	■	■	■	■			
	■				■			
4. Diagrams	■	■	■	■		■	■	■
	■		■					
						■		
						■		
5. Protractors	■	■	■	■				
6. Computer Tools	■	■	■	■		■	■	
							■	
							■	
						■		
	■	■	■	■		■		
7. Typology	■	■	■	■			■	■
8. Scale Models (1:X)	■	■	■	■	■		■	■

Most of the tools listed in Table 2 are based on practical experience or simple calculation methods. Older tools, such as empirical equations, tables, nomograms, diagrams, and protractors, reflect historical conditions when computer technology was not available, but new simple design tools are typically computer-based. However, the limitations of simple design tools remain, and accuracy reduces in particular when calculating light levels or daylight factors deep within a room where most light is received from inter-reflection.

Another category of simple tools is dedicated to estimating the impact of obstructions on daylight availability at a construction site or on a façade. These tools generally provide a method of superimposing a sun chart or daylight availability chart on a representation of obstructions. The obstruction information can be gathered manually by measurement, optically at the site in question using a camera with a fisheye lens with an equidistant projection, or can also be generated by using a computer-aided design (CAD) system as long as all the obstructions have been included in the model.

4.2. Advanced Tools

More advanced software tools have become widely available as computer processing power has increased and cost reduced. They have fewer limitations than simple tools in their ability to address the geometry and the photometry of the modelled 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 modelled spaces. The input requirements are more complex than for simple tools, but the geometric input has been much simplified by linking the tools to standard CAD software. Some daylighting analysis tools allow linking to energy simulation software to calculate the effect of different daylighting schemes on annual energy use. Table 3 shows some of the advanced tools available and types of information they can provide to a designer.

Table 3. Advanced Daylighting Design Tools

		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	
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	
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

Advanced tools model the flow of light through a design in one of two main ways: the **radiosity method** and the **ray-tracing technique**.

4.2.1. Radiosity Method

The radiosity method was originally developed to determine the exchange of radiant energy between a set of surfaces, and used for energy calculations. However, it can also be used to model the exchange of light, given that:

- wall surfaces, including external obstructions, must be subdivided into small finite elements characterized by homogeneous photometric properties (e.g., reflection coefficient)
- all elements must be perfectly diffusing

The 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.
The SUPERLITE programme was one of the first widely available daylighting computer tools based on the radiosity method. It can handle both daylighting and electric lighting as well as rather complex room geometries (e.g., L-shaped rooms). Glazing can be transparent or diffusing, and windows can have shades, although more complex shades (e.g. venetian blinds) and light shelves cannot be modelled. A significant limitation is that all other surfaces are considered by SUPERLITE to have perfectly diffuse reflection, i.e. no specularly reflective surfaces can be modelled.

4.2.2. 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 optimized for calculation of daylighting within building spaces. 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).

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.

For all types of light calculations, the ray-tracing technique can:

- account for every optical phenomenon that can be analytically expressed by physical equations
- take into account specular materials, like window panes and glossy surfaces
- 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 1 shows the numerical simulation of a room equipped with two different daylighting systems (a conventional window and a zenithal anidolic collector (see section 2.4.11)) created by the programme RADIANCE using a backward ray-tracing technique. This simulation allows a designer to compare the luminous performance of the two daylighting systems.

Several validations of ray-tracing programmes have demonstrated their reliability for daylighting performance assessment and advanced systems design.

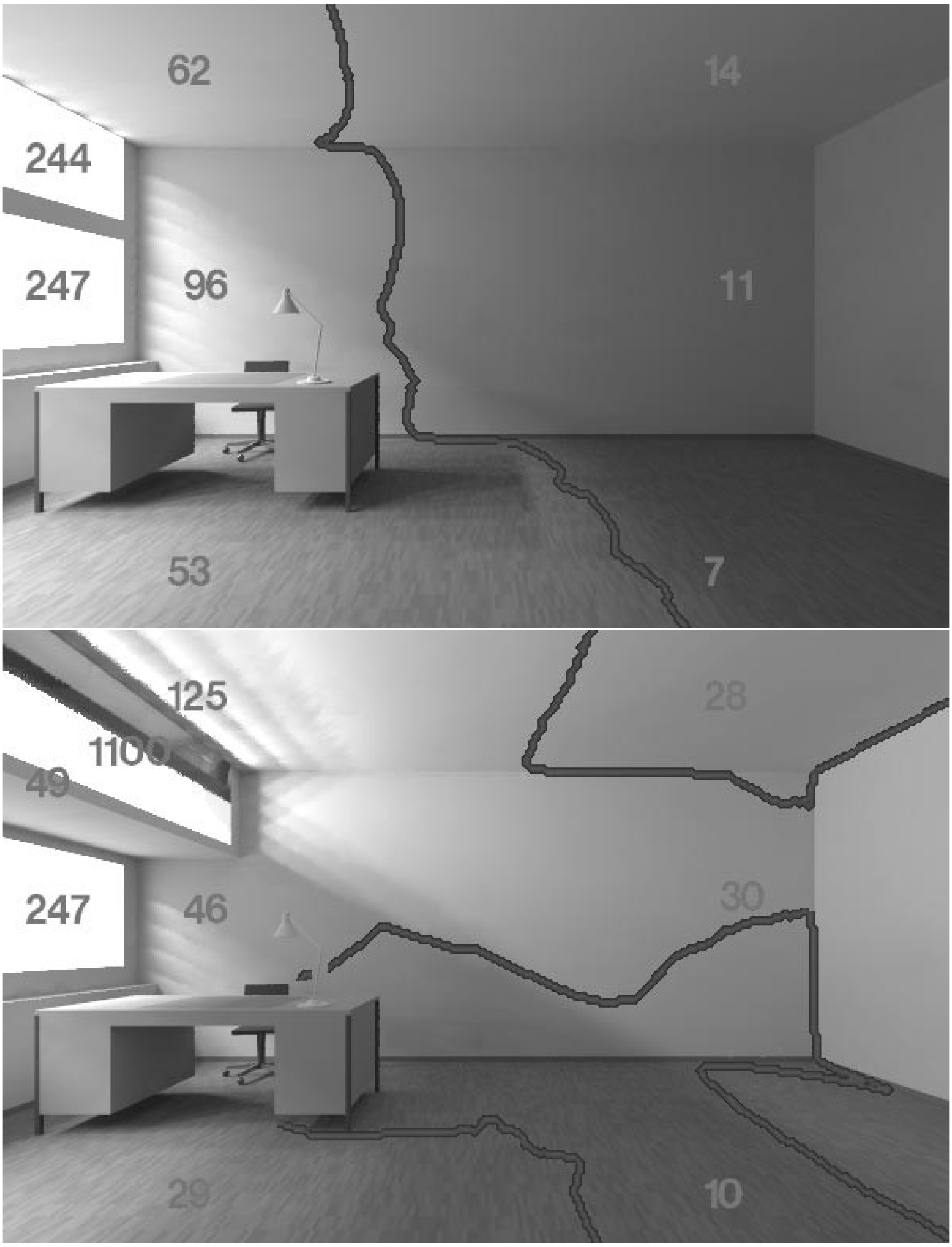


Figure 1. Simulated light distribution in a room: TOP: with simple double glazed windows; BOTTOM: with an anidolic zenithal collector. Output from the ray-tracing programme RADIANCE.

4.3. Integrated Software – ADELINE

The model input for advanced software tools can be extremely complicated and time-consuming. In addition, the results may not be linked or transferable to other kinds of software tools, e.g. energy demand programmes. The existing programme package ADELINE (Advanced Daylight and Electric Lighting Integrated New Environment) was further developed in this IEA project to address these issues and improve the user interface. 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 lighting calculations are executed using the algorithms of SUPERLITE and RADIANCE. Different modules in the programme offer a simple input mode for early design, a graphical scene editor with object libraries for adding furniture and luminaires, with graphical output showing the results in contours of illuminance or daylight factors. Hourly data can also be generated for input to dynamic building simulations programmes, e.g. DOE-2, taking into account: the daylighting system, a variety of lighting control strategies, different lamp types, desired work surface illuminance, occupancy hours, and hourly sunshine probability. Figure 2 shows an example of the output that can be generated.

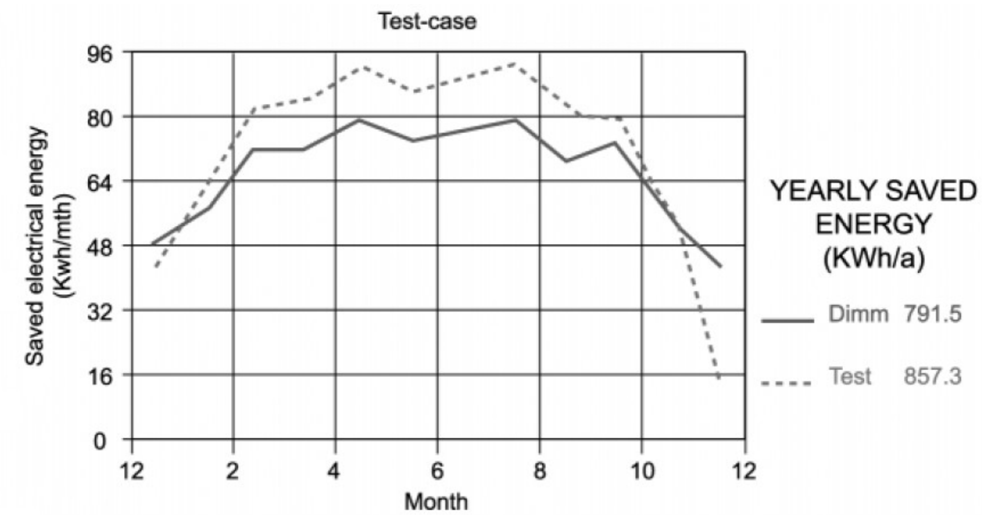


Figure 2. Annual electricity saved with different daylight-responsive lighting control strategies. An example of the output possible with ADELINE and its built-in tools.

4.4. 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

Models can be used to assess advanced lighting systems, depending on the skills of the model-maker to select and shape the materials carefully.

For testing, models are ideally placed within artificial skies, which can present a fixed, known sky luminance distribution from electric lighting; this enables different designs to be compared more accurately. As well as a totally uniform (isotropic) sky, other “standard skies” have been defined by the CIE (International Commission on Illumination):

- CIE overcast sky
- CIE clear sky
- CIE intermediate sky

5. Case Studies

5.1. Overview

The daylighting strategies in more than thirty non-residential buildings around the world were studied in this IEA project to produce a “Survey of Architectural Daylighting Solutions”. Of these, 14 selected case study buildings and one design case study were monitored and evaluated in detail, using a common monitoring procedure. In five buildings, post occupancy evaluations were also performed.

The latitude varied from 41 °S in New Zealand to 64 °N in Norway, and the sample included buildings for commercial and educational purposes as well as museums, libraries and research-centres. A range of daylighting strategies were assessed: daylighting strategies used skylight and sidelight, some of them using innovative daylighting systems, others used conventional shading systems, or relied purely on architectural daylighting design features. All the case study buildings had been constructed or refurbished later than 1990.

In nine case study buildings, office-type rooms were selected for monitoring. Cellular offices, group offices and open plan offices were among the selected spaces. Four educational buildings were monitored, assessing classrooms and seminar rooms. In most of the selected spaces, side-lighting strategies were applied, but three skylight strategies were monitored.

In some of the case study buildings, the focus was on the evaluation of advanced daylighting systems, such as light directing glass at **Geyssel**, or holographic light guiding glass in the **ADO** building. One major issue of monitoring in the **Bayer Building** was the user reaction to the non-retractable blinds that had been applied. The post-occupancy evaluation showed that the occupants were generally not satisfied with the shading system; they complained that the shading blocked the view out.

Most case study buildings were equipped with advanced electric lighting controls. Monitoring in the **Nortel Research Centre** as well as in the **Solar Energy Research Facility** *(*SERF*)* building at the. National Renewable Energy Laboratory *(*NREL*)* (SERF) showed that the location of sensors and the adjustment of controls needed careful consideration in order to realize predicted energy savings. In the **Götz** building, both electric lighting and façade systems were controlled by a building energy management system. The Götz building had a fully-glazed double skin façade with integrated louvre blinds.

Some of the case study buildings such as the **Environmental Office of the Future** and **Green on the Grand** represented an overall approach to low energy architecture and have been monitored extensively. The selected space in the Environmental Office of the Future was an open plan office, where the south façade was equipped with motorized louvres backed up with manually controlled roller blinds to protect occupants from glare. Monitoring here, as well as in other examples, showed the impact of user behaviour on the performance of daylighting strategies.

The **Zehdenick School** represented an architectural approach to daylight. Classrooms had a two-sided daylighting strategy, fixed systems controlled solar gains, and a moveable device controlled glare. The comparison of two electric lighting control strategies showed that daylight responsive controls in this case did not save energy when compared to the reference system.

The **Park Ridge Primary School** in Melbourne and the **SERF** were located in sunny climates where overheating during the summer was a major design issue. The design of the Park Ridge Primary School used “tunnel” lights consisting of an exterior shade, an opening and internal deflectors to shade direct sunlight but to distribute daylight to the classrooms.

In the **Bobst-Mex factory** a large workshop with north-facing sheds was the selected space. Monitoring results showed details about the performance of this widely-used industrial daylighting scheme.

Some of the selected buildings used further developments of conventional daylighting systems, such as the dual interior shade in the **Professional Faculties** or the blinds integrated in the window pane used in the **Bayer Nordic Headquarters**.

Innovative daylight redirecting systems described in Section 2, have been applied in some case studies. Lightshelves were a design feature in the **SERF** building, and in the atrium added to the **Victoria University School of Architecture** during its refurbishment. Light guiding glass was used at **Geyssel**, holographic elements had been applied in the **ADO** building, mirrored angular selective lamellas were integrated in the atrium glazing of the **Zehdenick school**. In the **Environmental Office of the Future** and in the **EOS Building**, motorized louvres were used to adjust the daylight level. The Survey of Architectural Solutions included more buildings using innovative daylighting systems. **The Waterford school** in Brisbane, Australia, had angular selective skylights that used laser cut panels. The **Centre for Desert Architecture in Cairo**, Egypt used hologram glass to redirect daylight.

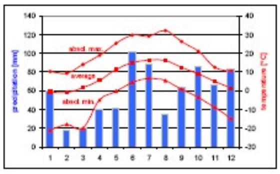
5.2. Example case study

An example is given here of one of the case studies, for the **Bayer Nordic Headquarters**. Only an extract is given here (building description, lighting strategy, and conclusions) with the full case study available on-line.

Case Study 15

Bayer Nordic Headquarters

office building, Lyngby
Denmark, Europe



MAP

climate		temperate			
HDD	[18°]	3 235 K·d	**latitude, longitude**		55.5°N, 12.3°E
CDD	[26°]	0 K·d	**summer solstice**	[noon]	57.3°
altitude		20 m	**winter solstice**	[noon]	10.8°

		jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	year
sunshine probability	[%]	33	31	44	35	44	38	44	48	42	42	34	21	38
sunshine hours	[h]	66	79	134	200	271	263	248	245	180	120	71	45	1922
sun altitude at noon	[°]	12.7	20.7	31.8	43.8	52.9	57.3	55.4	47.9	36.9	25.3	15.5	10.8	
temp., average	[°C]	-0.5	-1.0	1.7	5.6	11.3	15.0	16.4	16.2	12.5	9.1	4.8	1.5	7.8
temp., absol. max	[°C]	10.3	9.2	14.0	18.9	25.3	29.7	29.2	32.1	26.2	21.2	12.5	10.6	32.1
temp., absol. min	[°C]	-21.1	-18.0	-20.1	-4.9	-0.2	4.5	6.7	5.4	0.8	-3.4	-8.9	-15.0	-21.1
precipitation	[mm]	60	18	20	40	42	101	89	35	64	86	66	83	714
wind speed, average	[m/s]	5.0	4.4	4.8	4.5	4.1	3.8	3.9	3.5	4.4	4.5	4.5	4.9	4.4

table 1: Climatic data

figure 1: View of Bayer from west

figure 2: Wide angle interior view of the atrium

major issues

Nordic headquarters for Bayer, the German chemical and medical company, is located in Lyngby, Denmark. The building is a 4-storey, L-shaped building with an atrium following the long axis of both wings. The offices open to the atrium. Most of the offices are single occupancy with a few double occupancy offices.

The daylighting design uses bi-directional lighting. Daylight not only enters through the facade via two daylight windows (placed near the ceiling), but also through a glazed door opening to the atrium. Two additional windows on the facade are used as view glass. Finally, the corridors are both top and side lit.

Blinds are integrated between the windowpanes in the vision windows to optimise the offices for computer work. Glare-free lighting was the major design criterion for the offices because the occupants spend most of their time using computers. The blinds can be tilted, but they are not retractable.

The design intent was to reduce the use of electric lighting and increase daylighting. Presence detectors and light sensors control the electric light. This is done via the EIB system, an Intelligent Installation Bus from Siemens. However, the users can manually override the automatic control of the electric lighting.

site

The office building is located in Lyngby, north of Copenhagen. The urban environment is mostly commercial, 3- and 4-storey office buildings. The land is flat and there are no obstructions.

site data:			
land use	a mix of commercial and residence	**Footprint**	1 600 m^2
site area	5 332 m^2	**Footprint to site area ratio**	0.30

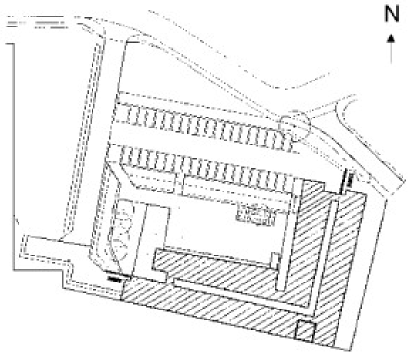


figure 3: Site plan (KHR Architects A/S)

figure 4: Overview of the site. Bayer is in the back of the picture

building

The building is L-shaped with an atrium in the centre of each wing. Approximately 150 people work in the building.

The architect's intention was to create a non-traditional building. The concept was two "streets" – the atrium – with a centre where the two wings meet (see figure 5). In a technological society, information exchange is important, and the atrium promotes a spirit of co-operation.

Oversized glazed doors join the offices with the atrium, creating a feeling of openness. This enhances circulation and enables easy and effective exchange of information.

building data:			
		number of storeys	4 (+ basement)
building construction period	1995-1996	**floor to floor height**	3.4 m
building owner	PFA (a pension fund)	**floor to ceiling height**	2.7 m
building costs	7 600 kr/m^2 (1 080 USD/m^2)	**number of occupants**	150
architect	KHR A/S (Jan Søndergaard)	**total energy use**	140 kWh/m^2
lighting consultant	KHR and Birch & Krogboe	**heating system**	central heating (water based)
HVAC engineers	Birch & Krogboe A/S	**cooling system**	no mechanical cooling
total floor area	6 400 m^2		
floor area of typical floor	1 600 m^2		

heat insulating properties, glazing types:			
wall	U-value: 0.3 W/m^{2}K	**windows**	double, low e
roof	U-value: 0.2 W/m^{2}K	**atrium**	double, low e
window	U-value: 2.1 W/m^{2}K		

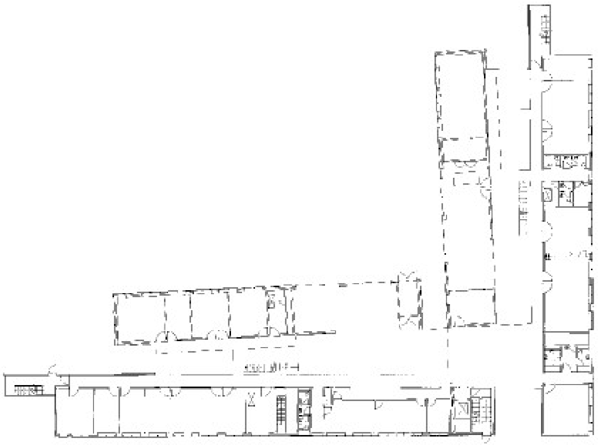


figure 5: Floor plan, ground floor (KHR Architects A/S)

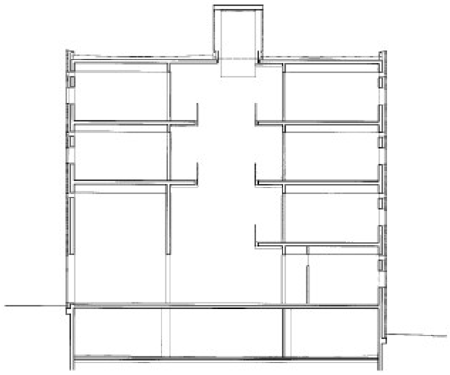


figure 6: Cross section (KHR Architects A/S)

figure 7: South facade

figure 8: Circulation area

daylighting strategies

The building is intended to optimise working conditions using integrated blinds and split windows (figures 7 and 9). The windows serve two functions: the lower part, vision windows, allows for a view of the outside, and the higher-placed windows are designed for daylighting. Electric lighting use is reduced by the use of daylight. The lights are controlled by the EIB.

To encourage daylighting, the offices have a depth of 5.2 metres.

The integrated blinds can be tilted, but not retracted from the window surface. The upper windows do not have blinds, so daylighting is not adversely affected. Privacy blinds are also integrated in the doors between the office and the atrium. The occupants can manually adjust all the blinds with an electric switch.

data for selected space:	
floor area of typical office	15.6 m²
depth	5.2 m
width	3.0 m
material, colour, reflectance	
floor	carpet, grey, 25%
side walls	paint, white, 85%
rear wall	paint, white, 85%
ceiling	paint, white, 85%
window and glazing properties:	
window area (glazed + frame)	2.2 m²
glazed area	1.8 m²
window area to window wall ratio	0.27

floor to ceiling height	2.7 m
energy transmittance blinds 45°/closed	25%/10%
door	paint, grey / glazed
shading device	blinds integrated between windowpanes
glazed area to window wall ratio	0.22
visible transmittance incl. shading device	28%/11%

Selecting blinds with a lower reflection could solve the problem that the blinds themselves can cause glare. This should be taken into consideration when selecting solar shading.

Solar shading placed outside is more effective than shading placed between the windowpanes. If changing the windowpanes in the atrium roof could not have solved the overheating problem during summertime, the best solution would have been to add external shading to the offices. This might not have been accepted for architectural reasons.

The low daylight factors seen in figure 13 can be explained by the fact that the integrated blinds are not retractable. During periods with overcast sky, electric lighting is turned on to meet lighting needs. If the blinds had been retractable, the amount of daylight coming to the offices could be increased on overcast days without glare problems.

The monitoring of daylight and electric lighting started with a test to see the influence of the light coming from the atrium via the oversized glazed door into the offices. The amount was small compared to the amount from the windows. But psychologically, it had a big effect. The occupants liked the large doors because it opened the building and made it "light and friendly." The small amount of light from another source balances the sunlight through the external windows.

The presence detectors and the light sensors are important for the energy strategy of the building. Lack of proper user education caused some dissatisfaction with the sensors when the building was new. When the lights were turned off due to a high daylight level, some occupants thought that the presence detectors were out of order – they did not understand why the lights were turned off even if the office was occupied. Many occupants were more satisfied with the system after they understood the control strategies.

The occupancy questionnaire showed it takes time to get used to new technologies. The number of people who were dissatisfied with the automatic control of the light was lower the second time the questionnaire was administered.

The main conclusions from the monitoring and post occupancy evaluation are:

- It is possible to save a considerable amount of electricity using presence detectors and light sensors.
- The non-retractable blinds are well functioning as glare protection, but they are disliked by the occupants because they block too much of the view.
- Bi-directional light is important for balance.
- External shading is better for solar control.

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6. References & Links to Participants

Daylight in Buildings: A Sourcebook on Daylighting Systems and Components
http://www.iea-shc.org/task21/source_book.html

Survey of Architectural Daylight Solutions
http://www.iea-shc.org/task21/publications/A_survey_architectural_solutions/1-intro.pdf

Application Guide for Daylight Responsive Control Systems
http://www.iea-shc.org/outputs/task21/8-8-1%20Application%20Guide.pdf

Daylight simulation: Methods, algorithms, and resources
http://gundog.lbl.gov/dirpubs/daysim_algo.pdf

Daylight design tools
http://btech.lbl.gov/pub/iea21/documents/cdrom/Appendix8.09/8.9.1.pdf

The majority of the Task 21/Annex 29 project reports are available from the IEA at: www.iea-shc.org/task21/deliverables.htm

and from the ECBCS at:
www.ecbcs.org/annexes/annex29.htm

Many reports and the Case Studies are also available at:
btech.lbl.gov/pub/iea21/ieacd.htm

The main documents are:

SUBTASK A: Performance evaluation of daylighting systems
Survey of Architectural Daylight Solutions (IBUS)
Daylight Monitoring Protocol (NRC / IRC Canada SBI/TUD)
Measurement of luminous characteristics of daylighting materials (TUB)
Source Book on daylighting systems and components (LBNL)
Document on test room facilities (SBI)
Scale model measurements on daylighting systems (EPFL)
Daylighting Systems Data Base (TUB)

SUBTASK B: Daylight responsive lighting control systems
Daylight Monitoring Protocol (NRC / IRC Canada SBI/TUD)
Application Guide for Daylight Responsive Control Systems (TNO et al.)
Database of daylight responsive lighting control system (TUB)
Introduction Brochure to Application Guide
Case studies of daylight responsive lighting control systems

SUBTASK C: Daylighting design tools
Validation of daylighting design tools (ENTPE)
Applicability of daylighting computer modeling in real case studies (NRC)
LESO DIAL (EPFL)
Daylight simulation: Methods, algorithms, and resources (LBNL)
Survey of simple design tools (FhG-IBP)
Methodology of Atria tool (EMPA)
Adeline 3.0 and brochure (FhG-IBP)
Results of Subtask C: Daylighting Design Tools (FhG-IBP)

SUBTASK D: Daylight in Buildings, Case Studies
Daylight Monitoring Protocol (NRC / IRC Canada SBI/TUD)
Post Occupancy Evaluation Procedures and results
Daylight in buildings – 15 monitored case studies

7. Appendix: Participants

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International Energy Agency (IEA)
Energy Conservation in Buildings & Community Systems (ECBCS)
& Solar Heating and Cooling (SHC) Programmes

The International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Co-operation and Development (OECD) in 1974, with the purpose of strengthening co-operation in the vital area of energy policy. As one element of this programme, member countries take part in various energy research, development and demonstration activities. The Energy Conservation in Buildings and Community Systems Programme has co-ordinated various research projects associated with energy prediction, monitoring and energy efficiency measures in both new and existing buildings. The results have provided much valuable information about the state of the art of building analysis and have led to further IEA co-ordinated research. The Solar Heating and Cooling Programme similarly co-ordinates research and conducts a variety of projects in advanced active solar, passive solar and photovoltaic technologies and their application in buildings and other areas, such as agriculuture and industry.

www.iea-shc.org

www.ecbcs.org

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

International Energy Agency
Energy Conservation in Buildings and Community Systems Programme